

Experimental Investigation of Magnetic Hybrid Nanofluids for Enhancing Heat Transfer in Forced Convection Internal Flow through Transition and Turbulent Regimes

By

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DECLARATION

I, Victor Omofe Adogbeji, hereby declare that the content presented in this thesis, titled *EXPERIMENTAL INVESTIGATION OF MAGNETIC HYBRID NANOFLUIDS FOR ENHANCING HEAT TRANSFER IN FORCED CONVECTION INTERNAL FLOW THROUGH TRANSITION AND TURBULENT REGIMES*, is the culmination of my independent research conducted at the Department of Mechanical and Aeronautical Engineering, University of Pretoria, South Africa, under the guidance of Prof. M. Sharifpur and Prof. J. Meyer. This work represents my original contribution towards the attainment of the degree Philosophiae Doctor. I confirm that this thesis has not been submitted elsewhere for any academic credential. During this study, I have diligently acknowledged and credited the contributions of fellow researchers in accordance with academic conventions.

Signature

Date.....

Dedication

This study is gratefully dedicated to the Almighty God, the compassionate Father of our Lord Jesus Christ, from whom all blessings flow. To my cherished soulmate, Onome Adogbeji, whose unwavering love and encouragement have been my guiding light. To my precious son, Divine Benefit, whose laughter brings joy to my heart every day. To my darling daughter, Rejoice, whose smile illuminates even the darkest of days. To my beloved princess, Melody, whose presence fills our home with song and laughter. And to my late father, Mr. James Enajome Adogbeji, whose wisdom and guidance continue to inspire me, even in his absence. With deepest gratitude for their boundless love and support, this work is dedicated to them with all my heart.

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ABSTRACT

Title: Experimental Investigation of Magnetic Hybrid Nanofluids for Enhancing Heat Transfer in Forced Convection Internal Flow through Transition and Turbulent Regimes

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Efficient heat transfer is critical for optimizing the performance and safety of industrial and engineering systems. While nanofluids have demonstrated Outstanding heat transfer efficiency juxtaposed to deionized water (DIW), the exploration of Magnetic Hybrid Nanofluids (MHNFs) in forced convection heat transfer within transition and turbulent flow regimes remains limited. This study investigates the thermal and hydrodynamic characteristics of MHNFs, specifically $\text{Fe}_3\text{O}_4/\text{TiO}_2$, $\text{Fe}_3\text{O}_4/\text{MgO}$, and $\text{Fe}_3\text{O}_4/\text{ZnO}$, flowing through a heated pipe. The research examines their performance across laminar, transition, and turbulent flow regimes, with suspension concentrations between 0.00625% and 0.3%. The study was conducted in four phases, addressing critical aspects of MHNFs stability, thermophysical properties, and heat transfer dynamics under varied conditions.

In the first phase, the effects of hybridization mixing ratio (HMR), nanoparticle size, and temperature on the stability and thermophysical properties of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ -DIW, $\text{Fe}_3\text{O}_4/\text{MgO}$ -DIW, and $\text{Fe}_3\text{O}_4/\text{ZnO}$ -DIW were evaluated. Results showed that $\text{Fe}_3\text{O}_4/\text{ZnO}$ -DIW at an 80:20 HMR demonstrated the highest thermal conductivity enhancement (31.28%) and lowest viscosity at 50°C, achieving the best thermal conductivity-viscosity balance. $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18 nm)-DIW exhibited the highest electrical conductivity (4.23 mS/cm) at 50°C. Temperature emerged as the most influential factor on thermal conductivity, emphasizing the potential of MHNFs for advanced cooling applications, such as in proton exchange membrane (PEM) fuel cells.

The second phase analysed the heat transfer capabilities of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ fluids across Reynolds numbers and volume fractions. Significant improvement in the convective heat transfer coefficient (CHT) were observed, particularly at lower concentrations; at 0.3 vol.% is 11.42% , at 0.2 vol.%, is 14.03% , at 0.1 vol.% is 18.04%, at 0.05 vol.% is 19.98%, at 0.025 vol.% is 22.91%, peaking at at 0.0125 vol.% is 26.33%, and at 0.00625 vol.% is 24.30%. at 0.3 vol.% (21% at Reynolds number 5019) the pressure drops were highest and progressively reduced with lower concentrations: 13.10% at 0.2 vol.%, 11.94% at 0.1 vol.%, 9.82% at 0.05 vol.%, and minimal at 0.0125% and 0.00625 vol.%. The Total Efficiency Index (TEI) was maximized at 0.0125 vol.%, indicating the optimal balance between heat transfer enhancement and minimal hydraulic resistance.

The third phase focused on $\text{Fe}_3\text{O}_4/\text{MgO}$ MHNFs, revealing unique thermal transport behavior in the transition region. Results indicated delayed transition at higher Re juxtaposed to DIW. The thermal transport enhancements were observed across volume fractions, with increases of 26% at 0.3 vol.%, at 0.2 vol.% is 25.8%, at 0.1 vol.% is 25.7%, at 0.05 vol.% is 17.9%, at 0.025 vol.% is 25.6%, at 0.0125 vol.% is 31.6%, and at 0.00625 vol.% is 30.2%. Optimal performance was achieved at 0.0125% and 0.00625 vol.%. However, higher concentrations resulted in increased pressure drops, demonstrating the intricate relationship between fluid dynamics and thermophysical characteristics.

In the final phase, the effects of magnetic field strength and waveforms parameters were investigated for $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids. Magnetic waveforms sine, square, and triangular enhanced heat transfer, with increases of 27.87%, 28.21%, and 26.74%, respectively, at 0.0125 vol.%. Magnetic field frequency (40 Hz to 1000 Hz) and voltage (2V to 12V) demonstrated a direct correlation with thermal performance, with optimal results achieved at 60 Hz and 4V.

These findings advance the understanding of MHNFs in forced convection heat transfer, offering practical insights for thermal management in power generation, HVAC systems, and chemical processing. The demonstrated ability of MHNFs to optimize heat transfer efficiency while minimizing pressure losses at lower concentrations presents a promising avenue for improving energy efficiency in heat exchangers and thermal systems.

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NOMENCLATURE

Abbreviations

AC	Alternating current
ACMF	Alternating current magnetic field
Al	Aluminium nanoparticles
Al ₂ O ₃	Aluminium oxide nanoparticles
Au	Gold nanoparticles
C _p	Specific heat transfer
Co ₂ O ₃	Cobalt (III) oxide nanoparticles
Cu	Copper nanoparticles
CuO	Copper oxide nanoparticles
CHT	Convective heat transfer
CNTs	Carbon nanotubes
DC	Direct current
Di	Internal diameter of the tube
DIW	Deionised water
DW	Distilled water
EC	Electrical conductivity
EG	Ethylene glycol
Fe ₂ O ₃	Iron (III) oxide nanoparticles
Fe ₃ O ₄	Iron (IV) oxide nanoparticles
G	Gauss
GA	Gum Arabic
GMO	Graphene magnetite oxide
I	Current (Ampere)
$\dot{m}$	Mass flow rate
MF	Magnetic fields
MHNFs	Magnetic hybrid nanofluids

MNFs	Magnetic nanofluids
MNPs	Magnetic nanoparticles
MWCNT	Multiwalled carbon nanoparticle
NPs	Nanoparticles
mT	Millitesla
mV	Millivolts
SF	Sedimentation Factor
SiO ₂	Silicon oxide nanoparticles
STDEV	Standard deviation
TC	Thermal conductivity
TFR	Transition flow region/regime
TEM	Transmission electron microscopy
TiO ₂	Titanium oxide nanoparticles
TEI	Total efficiency index
UV-Vis	Ultra Violet-Visible
V	Voltage
x/d	Axial distance
Greek symbols	
φ	Mass ratio of nanofluids
Φ	Volume concentration (vol%)
μ	Viscosity (kg/m.s)
κ	Thermal conductivity (W/m·K)
σ	Electrical conductivity (mS/cm)
ρ	Density (Kg/m ³)
η	Thermal efficiency
$\dot{q}$	Heat flux, (W/m ²)
$\dot{m}$	Mass flow rate (Kg/s)

Subscripts

A_0	Initial Absorbance
A_t	Final Absorbance
avg	Average
u_B	Bias error
u_p	Precision error
bf	base fluid
C_p	Specific heat capacity of particles (J/kg-K)
C_{pnf}	specific heat capacity of nanofluids (J/kg-K)
C_{pbf}	specific heat capacity of base fluids (J/kg-K)
C_{pnp}	specific heat capacity of nanoparticles (J/kg-K)
ρ_{nf}	Densities of the nanofluid (Kg/m ³)
ρ_{bf}	Density of base fluid (Kg/m ³)
$\varphi\rho_{np}$	Density of nanoparticles (Kg/m ³)
h_{avg}	Average heat transfer coefficient (W/m ² -K)
T_o	outlet °C temperature
T_i	inlet °C temperature
T_w	wall temperature °C
T_b	bulk temperature °C
n_f	nanofluid
n_p	nanoparticles

Dimensionless Numbers

Nu	Nusselt number
Re	Reynold number
Pr	Prandtl number

PUBLICATIONS IN JOURNALS AND CONFERENCE PROCEEDINGS

Throughout this research, several articles were prepared and underwent thorough and unbiased peer review processes, receiving insightful feedback from reviewers. As a result, certain sections of this thesis may share content with these published articles. Copyright agreements were carefully completed with the respective publishers to comply with copyright laws and to obtain the necessary permissions for content reuse.

Published Articles in International Journals

- i. Experimental Investigation into Heat Transfer and Flow Characteristics of Magnetic Hybrid Nanofluid in Turbulent Region **Applied Therm.** <https://doi.org/10.1016/j.applthermaleng.2024.124630>
- ii. Experimental Investigation of Heat Transfer Enhancement, Thermal Efficiency, and Pressure Drop in Forced Convection of Magnetic Hybrid Nanofluid ($\text{Fe}_3\text{O}_4/\text{TiO}_2$) Under Varied Magnetic Field Strengths and Waveforms **Case Stud. Therm. Eng.**, <https://doi.org/10.1016/j.csite.2024.105313>
- iii. Experimental Investigation of Heat Transfer and Thermal Efficiency, Pressure Drop, and Flow Characteristics Fe_3O_4 -MgO Magnetic Hybrid Nanofluids in Transitional Flow Regimes. **Int. J. Therm. Sci.**, <https://doi.org/10.1016/j.ijthermalsci.2024.109515>
- iv. Experimental Investigation and Machine Learning Modelling of the Effects of Hybridization Mixing Ratio, Nanoparticle Type, and Temperature on the Thermophysical Properties of $\text{Fe}_3\text{O}_4/\text{TiO}_2$, $\text{Fe}_3\text{O}_4/\text{MgO}$, and $\text{Fe}_3\text{O}_4/\text{ZnO}$ DI Water Hybrid Ferrofluids. **Journal of Thermal Analysis and Calorimetry JTAC D-24-01932. (Status: Under Review).**
- v. Heat transfer, entropy generation, and thermal performance factor analysis of $\text{Fe}_3\text{O}_4/\text{TiO}_2$, magnetic hybrid nanofluids and the influence of magnetic waveform positioning in turbulent regime. **Int. J. of Heat and Mass Transfer HMT-D-2406545 (Status: Under Review).**
- vi. Magnetohydrodynamics of nanofluid internal forced convection: a review and outlook for practical. **Journal of Results in Physics. RINP-D-24-03014 (Status: Under Review).**

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Effective thermal management is critical across various industrial applications, from power generation to chemical processing, electronic cooling, and HVAC systems. The effectiveness of these systems largely depends on their ability to transfer heat efficiently, a task traditionally performed by heat exchangers. These devices facilitate the exchange of thermal energy between multiple fluids at varying temperatures, and their performance is directly tied to the CHT rates [1]. The need to enhance heat transfer rates, reduce energy consumption, and minimize pressure drops has driven significant research into innovative materials and techniques aimed at optimizing the thermal performance of these systems.

i. **Advancements in heat transfer fluids**

The conventional working fluids used in heat exchangers, such as ethylene glycol, water, and paraffine oils, have limited thermal conductivity. This constraint has led researchers to explore advanced heat transfer fluids with improved thermal properties. Nanofluids (NFs), which are dispersions of nanoparticles (NPs) within a base fluid, have gained recognition as a potential innovation solution due to their enhanced thermal conductivity (TC) and CHT capabilities [2]. These NFs typically consist of metallic or oxide nanoparticles, such as copper, aluminum oxide (Al_2O_3), or titanium dioxide (TiO_2), dispersed in fluids like water or oil. By increasing the TC of the base fluid, nanofluids allow for more efficient thermal transport, making them suitable for a various applications, including automotive cooling systems, electronics, and renewable energy systems [3].

Beyond traditional nanofluids, Hybrid nanofluids (HNFs), which combine two or more types of nanoparticles, have garnered attention for their potential to enhance heat transfer performance. While these fluids aim to integrate the complementary characteristics of different nanoparticles such as thermal conduct, stability, and dispersion behavior their overall thermal performance depends significantly on the specific hybridization ratios, nanoparticle interactions, and operating conditions, which can sometimes lead to trade-offs or unexpected outcomes. HNFs have been shown to exhibit superior convective heat transfer characteristics compared to single-component nanofluids, offering new possibilities for optimizing the thermal management of systems [4].

ii. Emergence of magnetic hybrid nanofluids

One of the most exciting developments in the exploration of thermal fluid dynamics is the introduction of magnetic hybrid nanofluids (MHNFs). These fluids consist of magnetic nanoparticles, such as magnetite (Fe_3O_4), maghemite ($\gamma\text{-Fe}_3\text{O}_4$), hematite (Fe_2O_3), and nickel (Ni), dispersed in a carrier fluid along with non-magnetic nanoparticles. The key advantage of MHNFs lies in their ability to be manipulated by an external magnetic field, which can influence their rheological and thermal properties [5]. Under the effect of a magnetic field, these fluids experience changes in viscosity and flow behavior, allowing for more precise control of heat transfer performance. This magnetic excitation provides an additional degree of control over the fluid's heat transfer characteristics, making MHNFs particularly suitable for applications requiring dynamic thermal management.

Magnetic nanofluids, commonly referred to as ferrofluids, these materials were initially created by Papell during his work at NASA in the 1960s. These are stable mixtures of magnetic nanoparticles dispersed in non-magnetic fluids were initially intended for use in spacecraft propulsion systems [6]. Since then, ferrofluids have found applications in various industries, including electronics cooling, lubrication, biomedical devices, and energy storage. Their ability to respond to external magnetic fields makes them ideal candidates for enhancing heat transfer in systems where precise thermal control is needed.

iii. Challenges and opportunities in the transitional flow region (TFR)

Several studies on forced convection heat transfer (FCHT) focus on laminar and fully developed turbulent flow regimes, where fluid behavior is relatively well understood. However, the TFR, which occurs between the laminar and turbulent states, presents a unique set of challenges and opportunities. In the transition regime, fluid behavior becomes increasingly complex [7] and the flow is unstable and unpredictable [8], with localized turbulence and laminar flow coexisting [9]. This phase is particularly sensitive to changes in flow conditions, such as velocity and temperature gradients, and represents a critical point for optimizing heat transfer performance.

Despite its critical role in heat transfer, the transitional flow region remains relatively underexplored in the context of nanofluids, and even more so for MHNFs, where the influence of their unique properties on the transition process is not yet fully understood. Traditional studies have primarily focused on fully turbulent or laminar flows, where the heat transfer mechanisms

are more easily understood. However, the transition flow regime offers a significant opportunity for optimization, as it represents a critical point where flow conditions can be adjusted to maximize heat transfer efficiency while minimizing energy consumption. By investigating the behavior of MHNFs in this regime, this research seeks to address a void in the existing literature and provide new insights into how magnetic field excitation can enhance convective heat transfer while moving from laminar to turbulent flow. The research specifically examines the application of magnetic hybrid nanofluids in forced convection internal flow under both turbulent and TFR, with a focus on understanding the impact of magnetic excitation on thermal transports performance in the transition region.

The study aims to explore the thermophysical properties of MHNFs, particularly their potential to boost thermal transport performance while limiting pressure drop. The research will focus on MHNFs composed of Fe_3O_4 , TiO_2 , MgO , and ZnO nanoparticles, leveraging their magnetic and thermal properties to enhance heat transfer performance in dynamic flow conditions.

The potential advantages of MHNFs in forced convection systems are numerous. These fluids can offer enhanced thermal conductivity compared to traditional working fluids, and their magnetic properties allow for greater control over heat transfer processes. This dynamic response to magnetic field changes provides an additional layer of control for optimizing thermal performance in systems where energy efficiency is crucial. By improving heat transfer rates and reducing pressure losses, MHNFs have the abilities to significantly boost the capabilities of heat exchangers, leading to lower energy consumption, reduced operational costs, and enhanced reliability in industries where efficient thermal management is essential.

This research has significant practical implications for industries that rely on efficient heat transfer systems, including power generation, chemical processing, HVAC systems, and electronic cooling. As global energy demands continue to rise due to population growth, industrial expansion, and climate change, the need for more efficient thermal management solutions has become more pressing. MHNFs represent a promising avenue for addressing these challenges by offering a scalable, cost-effective, and energy efficient solution for optimizing heat transfer in a wide range of applications.

1.1.1 CHT characteristics of Magnetic nanofluids

Fu et al. [10] conducted study on Fe_3O_4 /EG nanofluids within circular tubes, highlighting the necessity of heat input, flow velocity, and temperature modifications to ensure efficient convective

heat transfer with optimal distribution NFs. In another experiment by Sundar et al.[11] performed an investigation with Fe_3O_4 /oil nanofluid showed a 9% augmentation in thermal conduct at 0.5% volumetric ratio. They observed 1.75 times increase in viscosity at 60°C, along with enhancements of 13.1% and 17.8% in convective heat transfer and an increase of 8.95% and 13.48% in Nusselt number (Nu). Moreover, this increase led to a drag coefficient that was 1.21 times greater than that of the base fluid. In another study by Sundar et al. [12] conducted a study on Fe_3O_4 nanofluids in a tube without a magnetic field. Their findings revealed 30.96% enhanced CHT transfer and a 10.01% rise in drag coefficient at a 0.6% nanoparticle concentration, with Reynolds numbers ranging from 3000 to 22,000 and volume fractions up to 0.6%. Similarly, Askari et al. [13] explored the CHT behavior of Fe_3O_4 /graphene nanofluids under turbulent flow with Reynolds numbers between 2000 and 5000 and particle concentrations ranging from 0.1% to 1%. They reported a 14 to 32% improvement in thermal conductivity at 1% nanoparticle concentration for Fe_3O_4 , and Fe_3O_4 /graphene nanofluids at temperatures of 20°C and 40°C compared to the base fluid. Additionally, the CHT coefficient showed an 8.5% increase for Fe_3O_4 nanofluids and a 14.5% improvement for Fe_3O_4 /graphene nanofluids. Alsarraf et al. [14] investigated the thermal transport performance of hybrid nanofluids consisting of CNT and Fe_3O_4 particles. Their results indicated significant enhancements in average pressure drop and Nusselt number, with increases of 52.54% and 23.76%, respectively, for a 0.9% ferrofluid and 1.35% CNT hybrid nanofluid at a Reynolds number of 500. The study concluded that the presence of a magnetic field improved both the pressure drop and Nusselt number for Fe_3O_4 /MWCNT/water nanofluids.

1.2 Problem Statement

Recent studies have demonstrated that magnetic NFs can significantly enhance the heat transfer efficiency of thermal systems through forced convective heat transfer. These fluids, particularly those containing Fe_3O_4 magnetic nanoparticles, have been extensively studied, with experiments showing that the application of an external magnetic field enhances their heat transfer properties. However, most of these studies have focused on single-component magnetic nanofluids, using only one type of nanoparticle [15]. There has been a growing interest in Magnetic Hybrid Nanofluids (MHNFs), which are suspensions composed of two or more types of nanoparticles. These MHNFs can improve and enhance thermal efficiency by integrating the distinct thermophysical attributes of various nanoparticles. The inclusion of non-magnetic nanoparticles

like TiO_2 , MgO , or ZnO with Fe_3O_4 can improve thermal conductivity, stability, and viscosity, providing a more optimized solution for forced convective heat transfer. However, despite the promise of MHNFs, the experimental studies on their heat transfer properties remain limited. The literature review revealed that most research on magnetic fields and nanofluids has focused on single-component ferrofluids, with very few studies on MHNFs. Moreover, the available research on MHNFs is largely limited to numerical studies or experiments conducted within the laminar flow regime. Little attention has been paid to transitional and turbulent flow regimes, where heat transfer dynamics are more complex and the potential for improvement is greater. This represents a significant gap in the current body of knowledge.

Prior to this study, experimental research had not directly compared the CHT performance of single-component magnetic nanofluids to that of MHNFs under the impact of external magnetic fields, particularly in internal flow systems operating in both transition and turbulent flow regimes. This research fills this gap by examining the unique behaviours of MHNFs in these complex flow conditions. Additionally, there was a lack of detailed investigation into the thermophysical attributes of MHNFs, involving their thermal conductivity, pressure drop, and viscosity as functions of nanoparticle concentration and temperature. This absence of experimental data limited the understanding of how MHNFs enhance heat transfer under magnetic field excitation, particularly in these more complex flow regimes.

To bridge this gap, a comprehensive experimental study was carried out to analyze the characteristics of forced convective thermal energy transfer of Fe_3O_4 based MHNFs specifically, $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluid and hybrid $\text{Fe}_3\text{O}_4/\text{MgO}$ and $\text{Fe}_3\text{O}_4/\text{ZnO}$ combinations. The experiments focused on evaluating the CHT and pressure drop under varying magnetic field intensities in the transitional and turbulent flow regimes at different nanoparticle concentrations (from 0.3 vol % to 0.00625 vol %).

Through this investigation, the thermophysical properties of these magnetic hybrid nanofluids, particularly their thermal conductivity, viscosity, pH, and electrical conductivity, were evaluated. The experimental results provided critical insights into the potential of MHNFs to enhance forced convective heat transfer in industrial applications, offering a more efficient solution for thermal management in systems requiring high heat transfer efficiency with minimal pressure losses.

1.3 Aim of research study

This study seeks to explore the influence of MHNFs in both turbulent and transitional flow regimes. Heat transfer performance was evaluated in terms of the Nusselt number and average heat transfer coefficient, considering the impact of different waveforms under the influence of an electromagnetic field. Additionally, pressure drop characteristics were also analysed to provide a comprehensive understanding of the fluid behavior.

1.4 Research objectives

- i. to explore the thermophysical characteristics, including pH, viscosity, electrical conductivity, and thermal conductivity, of the developed magnetic hybrid nanofluids and determine the most effective nanoparticle size combination for optimizing heat transfer efficiency.
- ii. to characterize the morphological properties using transmitted electron microscopy (TEM)
- iii. evaluate the heat transfer performance of $\text{Fe}_3\text{O}_4/\text{TiO}_2/\text{water}$, $\text{Fe}_3\text{O}_4/\text{MgO}/\text{water}$, nanofluids compared to those of DIW in both turbulent and transitional flow regimes
- iv. to determine the optimum magnetic field of magnetic field for heat transfer enhancement before the experimental measurement.
- v. investigate the impact of different waveform patterns on heat transfer characteristics, considering the application of an electromagnetic field.
- vi. analyze the Nusselt number and average CHT to understand the effectiveness of MHNFs in improving thermal energy transfer.
- vii. Assess the impact of MHNFs on pressure drop characteristics to comprehend the fluid behavior under various conditions.
- viii. investigate of the effect of magnetic field strength on flow resistance.
- ix. Provide insights into the feasibility and potential applications of MHNFs for improving heat transfer in forced convection internal flow systems.

The research objectives outlined earlier may be connected to advancements in the field and the existing gaps in knowledge regarding forced convection using magnetic hybrid nanofluids. This relationship is depicted in **Figure 1.1**.

By addressing these gaps, this research provides significant experimental insights into the behavior of MHNFs in forced convection thermal energy transfer., expanding their potential application in industries where efficient thermal management is critical.

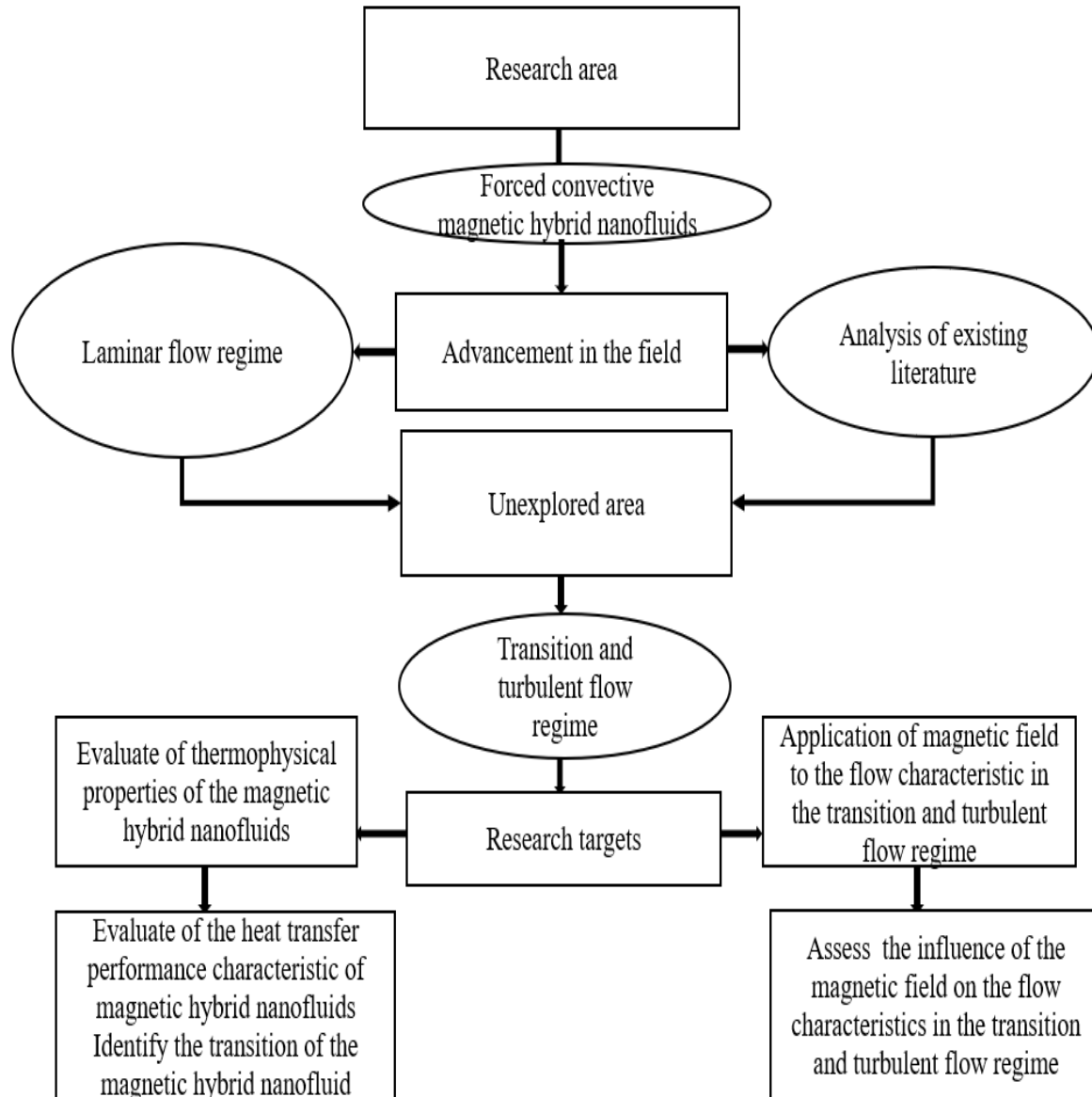


Figure 1. 1 Schematic relationship between research goals research and lack of knowledge in this area.

1.5 Research boundaries

This study focuses on the experimental investigation of magnetic hybrid nanofluids (MHNFs) for their application in forced convective heat transfer within transitional and turbulent flow regimes.

The MHNFs were synthesized using Fe_3O_4 , TiO_2 , MgO , and ZnO nanoparticles in a hybridization ratio of 80:20, and the nanoparticle concentrations were varied between 0.00625 vol% and 0.3 vol%.

The scope of this study covers the following key aspects:

- i. **Synthesis of MHNFs:** The preparation of Fe_3O_4 -based magnetic hybrid nanofluids was carried out using a two-step method, with precise control over the nanoparticle volume fractions and hybridization ratios. The nanofluids were dispersed in a non-magnetic base fluid, and Gum Arabic was employed as a surfactant to enhance stability.
- ii. **Thermophysical Property Assessment:** The effects of nanoparticle concentration on key thermophysical properties, including pH, viscosity, electrical conductivity, and thermal conductivity, were evaluated across an experimental temperature span from 10°C to 50°C. This characterization is critical for understanding how MHNFs behave under varying thermal conditions in practical applications.
- iii. **Stability Evaluation (Zeta Potential & Sedimentation Ratio):** The stability of the MHNFs was assessed using zeta potential measurements to determine the surface charge of nanoparticles and evaluate their tendency to agglomerate. Sedimentation ratio tests were also performed for each volume fraction, providing additional insight into the long-term dispersion stability of the nanofluids. High zeta potential values indicate that the nanofluids have excellent stability, which is crucial when subjected to magnetic fields and varying thermal conditions.
- iv. **Magnetic Field Application:** The MHNFs were subjected to an electromagnetic field with different waveforms to investigate their magnetothermal behavior. This component of the study focuses on how magnetic excitation influences the thermal efficiency and stability of MHNFs within a forced convection system.
- v. **Heat Transfer Experiments:** Experiments were conducted to assess the convective heat transfer enhancement of MHNFs in forced internal flow, specifically focusing on the transitional and turbulent flow regimes. The influence of the magnetic field on the heat transfer coefficient, friction factor, and overall thermal performance was analysed to different nanoparticle concentrations and magnetic field strengths.

The experimental setup was designed to simulate realistic conditions, providing insight into the practical application of MHNFs in industries such as HVAC systems, power generation, and chemical processing, where efficient heat transfer and thermal management are critical.

This study offers a comprehensive investigation into the thermal, rheological, and stability properties of MHNFs and their potential to optimize energy efficiency in systems that operate in transitional and turbulent flow regimes. By focusing on the experimental analysis of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ and $\text{Fe}_3\text{O}_4/\text{MgO}$ hybrid nanofluids, this research contributes valuable data to the limited body of work on MHNFs, particularly in the context of FCHT with magnetic field excitation.

1.6 Structure of the work

The research study is structured into seven chapters, each dedicated to specific aspects of investigating MHNFs and their role in enhancing heat transfer:

Chapter 1: Introduction

This chapter sets the stage by defining magnetic nanofluids and emphasizing their significance in enhancing heat transport. It includes background information, defines the problem statement, and outlines the goals and extent of the research. This foundational chapter provides the context for the subsequent research.

Chapter 2: Literature review

The literature review is divided into two main sections:

Hybrid nanofluids: This section covers the fabrication methods, thermal properties, and CHT characteristics of hybrid nanofluids. It highlights advancements and challenges in the field, setting the stage for understanding their role in heat transfer enhancement.

Magnetic hybrid nanofluids: This section discusses the synthesis methods, properties, and heat transfer performance of magnetic hybrid nanofluids. It examines how magnetic fields affect thermal conductivity, viscosity, stability, and CHT, providing insights into potential applications in thermal systems.

Chapter 3: Experimental setup

This chapter details the experimental setup and methodology, including equipment specifications, procedures, and data reduction techniques, providing a comprehensive overview of how experiments were conducted.

Chapter 4: Data reduction and analysis

Focuses on the techniques and equations used for data reduction. This chapter presents the analysis of instrument uncertainties, validation results, and a comparison of heat transfer measurements with established correlations. It ensures that the data analysis methods are robust and reliable.

Chapter 5: Characteristics of nanoparticle material

This chapter introduces the nanoparticle materials used in the study, including $\text{Fe}_3\text{O}_4/\text{TiO}_2$, $\text{Fe}_3\text{O}_4/\text{ZnO}$ and $\text{Fe}_3\text{O}_4/\text{MgO}$. It discusses the preparation processes, stability assessments through visual inspection and viscosity measurements, and evaluates the thermal properties of the nanofluids.

Chapter 6: Heat transfer analysis

Focuses on the heat transfer performance of $\text{Fe}_3\text{O}_4/\text{TiO}_2$, and $\text{Fe}_3\text{O}_4/\text{MgO}$ nanofluids. It provides a detailed analysis of heat transfer variations, entropy generation, and thermal performance factors. The chapter also explores the effects of different magnetic waveform positioning and field strengths in turbulent regimes and examines pulsating parameters across diverse waveforms in transitional flow regimes.

Chapter 7: Conclusions and recommendations

Summarizes the research findings, draws conclusions based on the results, and offers recommendations for future research. This chapter wraps up the study, highlighting the significance of the findings and proposing directions for further investigation.

CHAPTER 2

SURVEY OF EXISTING RESEARCH

2.1 Introduction

The forced convection has been used to efficiently transfer a significant amount of thermal energy in industrial processes with applications in central heating, air conditioning and heat exchange, etc. The improvement of heat transfer equipment has become a very important area in thermal engineering and the industrial revolution around the world due to the increasing energy demand. Various methods and techniques have been studied to improve the thermal conductivity of traditional heat transfer fluids such as water, ethylene glycol, mineral oil, and oil, but these have been caused by the introduction of nanometer-sized particles due to their shortcomings in thermal properties, which are small compared to those of solids to improve the thermal properties of these conventional fluids by dispersing nanometer-sized particles in a conventional base fluid, which has led to scientific development in the study of heat transfer in thermal engineering. The correct dispersion of nanometer-sized particles in a conventional base liquid as so-called nanofluids. These nanometer-sized particles include copper (Cu), silver (Ag), nickel (Ni), and gold (Au), metal oxides such as copper oxide (CuO), titanium dioxide (TiO₂), ferric oxide (Fe₂O₃), and silicon dioxide (SiO₂), Zinc Oxide (ZnO), Iron(II) Oxide (Fe₃O₄), Zirconium Oxide (ZrO₂) and Aluminum Oxide (Al₂O₃); and carbon materials such as Graphene, Carbon nanotubes, and diamond; metal nitrides such as Boron Nitride (BN) and Aluminum Nitride (AlN); and metal carbides such as Silicon Carbide (SiC) [4]. The suspension of these nanometer-sized particles in a convective base fluid improves the thermal properties in the fluid, resulting in improved heat transfer characteristics.

2.2 Heat transfer of nanofluids

Several experimental and computational studies conducted on FCHT of nanofluids in different flow regimes are well documented.

In 1995, Choi and Eastman [2], were the first to study and publish nanofluid, they dispersed nanoparticles within a conventional base fluid and referred to it as nanofluids and thereafter many researchers vigorously investigated the studies of nanofluids.

Nanofluids have been gaining significant recognition from the scientific world due to their potential applications in different fields. On the contrary, there are still some setbacks and fundamental challenges to the use of NFs as heat transfer fluids on large scale both industrially and commercially. One of the most fundamental setbacks is the stability NFs over long period of time to maintain the thermal properties and performance of the NFs after preparation and cost of nanoparticles.

Regardless of any setbacks in using NFs, the benefits of NFs outweigh the current limitations, although researchers are currently still working on the best way to improve the stability of NFs, which cannot be compared to the benefits over traditional base fluids in heat transfer amplification are documented in several references, nanotechnology textbooks, and heat transfer textbooks etc., These benefits include: higher surface area, resulting in greater heat transfer surface area between fluids and particles; high thermal conductivity which could lead to efficient heat transfer in heat exchangers, micro-channels, car radiators, heat pipes and heat sink devices Particle size reduction helps less clogging compared to traditional suspensions; different particle concentrations can be used to meet the needs of different applications; lower pump power; low friction factor; surface wettability; higher stability of the colloidal suspension; With magnetic particles it is possible to localize and increase the local concentration and conductivity by applying a magnetic field.

2.2.1 Convective heat transfers of MNFs with magnetic field

Sha et al. [16] investigated the impact of magnetic fields on the forced CHT properties of $\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$ NFs. They experimentally examined the influence of perpendicular uniform and gradient magnetic fields on CHT in turbulent flow regimes. Their findings revealed that heat transfer coefficient improved with higher NPs concentration, temperature, and magnetic intensity. Particularly, the application of a gradient magnetic field resulted in greater improvement compared to a uniform magnetic field. Without magnetic field effects, Fe_3O_4 /water nanofluids exhibited higher convective heat transfer coefficients than distilled water. When subjected to uniform and gradient magnetic fields, nanofluids showed 4.2% and 8.1% increases in average convective heat transfer, respectively, at a volumetric ratio of 3% and a temperature of 40°C.

Yarahmadi et al. [17], found that CHT increased in ferrofluid compared to distilled water, with an oscillating magnetic field yielding a 19.8% enhancement.

Abadeh et al [18] noted an 11.85% and 14.8% increase in Nu using an alternating magnetic field with frequencies of 10 Hz and 100 Hz, respectively.

Sun et al. [19] reported a 4.36% increase in local Nusselt number with a 415 G magnetic field and a 0.5 vol% Fe_3O_4 /water nanofluid, increasing to 7.19% at 700 G. A 32.0% increase was observed using a magnetic field variation of 28.6 gauss per millimeter. Goharkhah et al. [20] found up to a 13.5% improvement in average CHT using a 2% volume fraction of Fe_3O_4 ferrofluid at $\text{Re} = 1200$, increasing to 31.4% under the influence of a 500 G alternating magnetic field.

Xuan et al. [21] observed improved thermal transport with a magnetic field gradient parallel to fluid flow and noted that perpendicular gradients could either enhance or suppress heat exchange depending on orientation.

Motozawa et al. [22] reported a maximum 20% increase in heat transfer coefficient for ferrofluid flow with a magnetic field up to 500 mT.

Şeşen et al. [23] observed improved heat transfer in ferrofluid due to particle circulation in a magnetic field compared to without

Li and Xuan [24] noted an 8.0% increase in heat transfer compared to deionized H_2O , with magnetic field gradient parallel to flow direction.

Mei et al. [25] observed that the Nu increased with NPs mass fraction but decreased as parallel magnetic induction intensity increased. Nanofluids with 5.0% mass fraction showed the best heat transfer enhancement.

Azizian et al. [26] found a substantial enhancement in CHT coefficient with increasing magnetic field strength and gradient. At Re numbers below 830, they observed a fourfold improvement compared to the case with no magnetic field, particularly notable at $\text{Re} = 745$ and a magnetic field gradient of 32.5 mT/mm. However, they also observed a considerable rise in pressure drop in the presence of the magnetic field, reaching up to 7.5% with a magnetic field strength of 430 mT and gradients ranging from 8.6 to 32.5 mT/mm

Wang et al.[27] noted substantial heat transfer improvements with increasing magnetic flux density, especially with more magnets, showing enhancements of 26.5% and 54.5% at specific Reynolds numbers.

Asfer et al. [28] reported a 35% increase in average CHT with a constant magnetic field of 0.3T compared to the base fluid, while without the field, only a 10% increase was observed.

Guzei et al. [29] reported a 35% increase in average CHT with a constant magnetic field of 0.3T compared to the base fluid, while without the field, only a 10% increase was observed.

Esmaeili et al [30] found a remarkable 48% augmentation of the heat transfer with alternating magnetic fields, juxtaposed to a 15% enhancement with a constant field.

Hatami et al [31] used Fe_3O_4 /water nanofluid to experimentally studied the forced convection heat under the influence of magnetic field in the laminar flow regime with uniformly heated horizontal tube under a constant heat flux conditions. They observed a 25% reduction in heat transfer under the influence of an external magnetic field but found that adding magnetic nanoparticles improved heat transfer by over 60%.

Ashjaee et al.[32] empirically studied the forced convection heat transfer and pressure drop of a water-based Fe_3O_4 /pure water NFs in a miniature heat sink under the effect of an external magnetic field . They reported a maximum heat transfer improvement of 14% compared to pure water with no magnetic field, increasing to 38% with a 1,200 G magnetic field.

Tekir et al.[33] empirically studied the use of constant and alternating magnetism in forced CHT of Fe_3O_4 /water nanofluid under a laminar flow regime of Reynolds number in the range of ($1122 < \text{Re} < 2124$) with constant heat flux applied externally to the straight aluminum tube surface under constant was and magnetic alternating field effect. observed a 13% augmentation in CHT with a constant magnetic field and a 35% enhancement with an alternating magnetic field, particularly with lower frequencies.

Gavili et al [34] empirically studied the change in CHT under the influence of a magnetic field on Fe_3O_4 /water nanofluid by applying a magnetic field generated by Helmholtz coils and whose intensity was controlled by the electric current. observed a 200% increase in convective heat transfer compared to distilled water with a 5.0% volumetric fraction of NPs, with TC improvements under the impact of magnetic fields.

Ahangar et al. [35] They observed significant local heat transfer coefficient improvements of 23.4%, 37.9%, and 48.9% for a 2 vol% Fe_3O_4 magnetic nanofluid under the influence of a magnetic quadrupole field at a Reynolds number of 580. However, they also noted a notable increase in the total pressure drop of 1% at Re 580 when the magnetic field was applied.

Ebaid et al. [36] experimentally studied the improvement of heat transfer using (Fe_3O_4 /water) in a heated tube using a magnetic field. They used different volume concentrations of (1.2, 0.6, 0.3 wt%) ($\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$) NFs with various Re ranging from 2180 to 9160. found that the Nu increased

with increasing Reynolds number for Fe_3O_4 nanofluids, with an average increase of 16.7% compared to H_2O when neglecting the magnetic field effect. With the influence of the magnetic field ($F = 15:5, 30:3, 45:5$ mT), they reported average heat transfer coefficient and Nu increases of 9.4%, 26.1%, 31.3%, 8.8%, 13.1%, and 23.9% compared to water without a magnetic field.

Ghafrani et al [37] empirically studied the effect of an alternating magnetic field and uniform heat flux on the heat transfer properties of aqueous ferrofluid flowing via a copper tube. They observed a maximum improvement in CHT of 27.6% in an alternating magnetic field compared to water. They concluded that increasing the frequency of the alternating magnetic field, or volume fraction, gave improved heat transfer enhancement, and they found that the effect of the magnetic field was greater at low Re.

Lajvardi et al.[38] found an increased heat exchange coefficient of Fe_3O_4 /water flowing via heated copper pipe with the influence of magnetic fields.

Sadrhosseini et al. [39] observed significant improvements in heat transfer coefficient, ranging from 19% to 75%, with increasing ferrofluid volume fraction and Reynolds number under different magnetic field frequencies and modes.

Vidhya et al. [40] investigated the thermophysical characteristics and CHT efficiency of pipes filled with (ZnO-MgO) hybrid nanofluids. Zinc oxide (ZnO) and magnesium oxide (MgO) nanoparticles were synthesized through co-precipitation and sol-gel method. The nanoparticles were characterized by Fourier transform infrared spectroscopy analysis, energy dispersive X-ray spectroscopy methods, X-ray diffraction studies, and scanning electron microscopy. The prepared nanoparticles were converted into nanofluids by adding a base solution as a mixture of ethylene glycol and water (60:40%) and a surfactant such as cetyltrimethylammonium bromide (CTAB) using an ultrasonic method in a two-step process. Hybrid nanofluids with different concentrations (0%, 0.0125%, 0.025%, 0.05%, 0.075% and 0.1%) were prepared and the influence of thermal conductivity, density, and viscosity at different temperatures (30-80 °C) was determined. Heat pipe was analyzed with ZnO-MgO hybrid nanofluids by convective heat transfer method for three thermal power inputs (30-90 W). ZnO-MgO hybrid nanofluids exhibit improved thermophysical properties compared to the base fluid alone. A decrease in thermal resistance and an improvement in the heat transfer coefficient of nanofluids were observed by 4.07% and 28.9%, respectively.

Mehrali et al. [41] studied the forced laminar CHT characteristics graphene-magnetite hybrid nanofluids to determine the entropy generation rate under the influence of a permanent magnetic

field. They used graphene oxide- Fe_3O_4 /hybrid. The results showed that the improvement in heat exchange of nanofluids juxtaposed to distilled material was minimal without magnetic field. In addition, under the magnetic field, the heat transfer properties are significantly increased. They found that the rate of entropy generation became decreased as much as 41% in comparison to distilled water.

Lee et al. [15] studied forced CHT properties of $\text{H}_2\text{O}/\text{EG}/\text{Fe}_3\text{O}_4$ and $\text{Fe}_3\text{O}_4/\text{MWCNT}$ hybrid nanofluid under the influence of a magnetic field. They observed that the CHT coefficient of magnetic nanofluids improved due to the increase in magnetic field strength. When they varied the magnetic field strength from 0 to 750 G, they also observed the maximum CHT coefficients of 2.78% and 3.23% for MWNCT nanofluids with 0.2 wt% Fe_3O_4 and 0.1 wt%, respectively % Fe_3O_4 . In addition, they also observed an increase in average pressure drop of 4.73% and 5.23% for 0.2 wt% Fe_3O_4 and 0.2 wt% Fe_3O_4 –MWNCT NFs, respectively. They determined that the external magnetic field caused the nanoparticles to aggregate over a larger area, resulting in a 5% increase in the heat transfer coefficient of the 0.1 wt% Fe_3O_4 -MWNCT hybrid nanofluid compared to the 0.2 wt% Fe_3O_4 nanofluids.

Tekir et al. [42] experimentally studied the CHT of Fe_3O_4 –Cu/water hybrid nanofluid flows and to determine the optimal mixing ratio of the hybrid nanofluid in a straight aluminum tube with 16 mm diameter and 1500 mm length under the action of a constant magnetic field of $B = 0.3 \text{ mT}$, plotted perpendicular to the direction of flow. They consider various parameters such as the flow rate with a Reynolds number in the range of ($994 < \text{Re} < 2337$) and the volume concentration of the nanoparticles ($0 < \phi < 0.02$). The outcome of the experimental results showed that an increasing flow rate affects an increased Nu number. They also observed that adding both Fe_3O_4 and Cu nanoparticles to the distilled water increase CHT inside the tube. They noticed a 14% augmentation in CHT when a constant magnetic field was applied juxtapose to no magnetic field. Furthermore, they also observed that 1.0 vol% Fe_3O_4 1.0 vol% Cu/water hybrid nanofluid caused stronger CHT under the influence of the constant magnetic field.

Shi et al.[43] experimentally studied the magnetically controllable convective heat transfer of nanofluid through a straight tube, using magnetic nanocomposite (MCNT) containing carbon nanotubes (CNTs) and magnets on Fe_3O_4 with based fluid showing the effects of horizontal spacing of electromagnets from (0 mm, 50 mm, 100 mm, and 150 mm) rotation angles of (120,60,30,0) and a magnetic strength of (800 Gs,400Gs, 200Gs,100 Gs,) with different Reynolds

numbers and volumetric force. They observed that the temperature difference is smaller for the MCNT nanofluid than for deionized water and the Fe_3O_4 nanofluid, indicating that the MCNT can absorb more heat from the heated tube and the average Nusselt numbers of the MCNT nanofluid compared to the other higher are liquids. They also observed that a small Reynolds number also implies a small flow rate in the MCNT nanofluids and this could lead to MCNT nanofluids absorbing more heat over a longer period of time at the same distance and quickly reaching a higher temperature in the tube and they increase the Reynolds number. The inlet velocity varies with the magnetic force and remains constant, therefore the effect of the bulk magnetic force on the flow rate is significantly small, indicating that the velocity of the magnetic nanofluids is controlled by the same bulk magnetic force at the entrance of the tube could be strongly influenced at low Reynolds number. Furthermore, they observed that the direction and gradient of the magnetic field could be used to enhance the forced CHT of the MCNT nanofluid, and they concluded that the heat transfer was limited by the thermophysical properties and magnetism of the nanofluids and however, a stronger magnetic field could further increase the heat transfer coefficient, and the heat transfer coefficient could be controlled by adjusting the magnetic field strength.

Talebi et al [44] studied the forced convection of Cu and Fe_3O_4 and Cu/ Fe_3O_4 hybrid nanofluids with three volume fractions of 1, 2, 4% and three Re numbers of 600, 1200, and 1800 to determine the local Nusselt number. They observed that nanofluid with single and hybrid particles increases with the volume fraction of the nanoparticles and the Re number, leading to an increase in the heat transfer coefficient. Furthermore, they found that the heat transfer augmentation with the HNFS is more significant at 11.9%. compared to Cu/water 7.8%

Alsarraf et al. [14] investigated the hydrothermal performance of a water-based hybrid nanofluid containing both Fe_3O_4 (magnetite) nanoparticles and carbon nanotubes (CNTs) in a horizontal heated tube under the action of a constant, non-uniform magnetic field. They used three pairs of permanent magnets to create the magnetic field. They observed that water-based hybrid nanofluids containing both Fe_3O_4 (magnetite) nanoparticles and carbon nanotubes (CNTs) achieved higher values of heat transfer and pressure drop in the absence of a magnetic field because of using nanofluid compared to water. They also noticed that the Nu and pressure drop of the water-based hybrid nanofluid containing both Fe_3O_4 nanoparticles (magnetite), and carbon nanotubes (CNTs) increase significantly under the magnetic field. They also observed that the effect of the magnetic

field increases with increasing nanoparticle concentration and a stronger magnetic field decreases the Reynolds number. They found that the maximum improvement in heat transfer was 109.31% and 25.02%, respectively, compared to the case without the effect of the magnetic field, and the average Nu and average pressure drop were found to be 0, 9% magnetite and 1.35% CNT at Reynolds number obtained of 500.

2.2.2 Method of preparation of nanofluids

Nanofluids are created by suspending nanoparticles at a specific concentration in a standard base fluid, enhancing the beneficial thermal properties of the fluids. A very suitable dispersion is essential for the application of the nanofluid. Nanofluid fabrication is a very important exercise to obtain a very stable nanofluid with exceptional properties that does not agglomerate at high temperatures or over a period. Several factors must be taken into account when preparing a stable nanofluid, such as ensuring the synthesis and suspension of non-agglomerated or uniformly distributed nanoparticles. Over time, the distribution of these NPs can decline due to particle clustering, influenced by Van der Waals forces and surface energy of the NFs as it acts as a heterogeneous dispersion medium. This phenomenon can result in a Thermodynamically unstable blend. Nevertheless, vigorous Brownian motion of the NPs can mitigate sedimentation effects induced by gravity. Furthermore, it is crucial to avoid any chemical reactions between the base fluid and the NPs during the use of the NFs [45].

These are two main types of processes used in the production of nanofluids, such as: A step process or bottom-up approach and two-step process or top-down approach. The main problems are the agglomeration of nanoparticles in all nano powder technologies for both methods to create good nanoparticle suspensions [3].

i. One step method or Bottom-up approach

Eastman et al. [46] developed a one-step physical vapor condensation process to produce Cu/ethylene glycol nanofluids. The one-step process involves the simultaneous preparation and mixing of NPs in the conventional base liquid. In this method, the processes of drying, storage and transportation, which led to the stable suspension of nanoparticles in the conventional base liquid, are avoided, so that the agglomeration of NPs is reduced and the stability of liquids could be increased, however, this method is mostly preferable for liquids with low vapor pressure and cannot be used for the synthesis of NFs on a large commercial scale because it is very expensive.

ii. Two step method or Top-down approach.

This is the most cost-effective approach for the large-scale manufacturing of nanofluids. In this process, ultrasonic stirrers, high shear mixing homogenizers and ball mills, etc. were used, first the nanoparticles were prepared and then dispersed in the conventional base liquid. This method of the production process is very cheap, but the limitation of this method is the aggregation and agglomeration of nanoparticles that appear instantly, which led to the instability of the nanofluids. Because of the instability, surfactants are used that improve the stability of nanofluids [47]. This two-step process is mostly preferred for oxide nanoparticles and has proven to be unsuitable for metallic nanoparticles. At present, the chemical process is the emerging technology in the production of nanofluids.

2.2.3 Utilization of nanofluids in FCHT

Following the introduction of nanofluids by Choi and Eastman in 1995, so many studies have been performed experimentally and theoretically and documented in various literature on applications of nanofluids in forced CHT in internal flows, however results of the last application in the past 10 years are considered, because they would have been an improvement over previous study. The results are summarized in **Table 2.1 below**.

Table 2. 1 Summary empirical studies of the FCHT of nanofluids in internal flow under steady state and heat flux

Authors	Reynold number	Flow Regime	Conduit Type	Nanoparticles	Volume concentration (wt.%)	Heat transfer enhancement mechanisms
Ilhan and Ertürk (2017) [48]	$800 \leq Re \leq 1700$	Laminar	circular pipe	hexagonal boron nitride (hBN)	$\Phi = 0.001, 0.005, 0.01$	Increased volume concentration It is observed that the increase in the convective heat transfer coefficient of hBN-water nanofluids is proportional to the observed increase in thermal conductivity.
Ho et al (2018)[49]	$120 \leq Re \leq 2000$	Laminar	circular tube	Al_2O_3	$\Phi = 0, 0.05, 0.09$	Volume concentration increases the increase in Nusselt number while also causing an increase in pressure drop across the tube and decreasing wall temperature.
Mehrali et al (2015) [50]	$290 Re \leq 12000$	Laminar	Horizontal tube	GNP	0.025,0.05,0.075, 0.1	GNP nanofluids between 0.075 wt% and 0.1 wt% are more energy efficient than other wt%
Mojarrad et al (2014)[51]	$650 Re \leq 23000$	Laminar	Stainless tube	Al_2O_3	0.25, 0.5, 0	The average heat transfer and average Nu increase with the volume fraction and
Bhanvase et al (2014)[52]	$900 Re \leq 1500$	Laminar	Copper tube	TiO_2	0.1,0.2,0.3,0.4, 0.5	Heat transfer increases with the volume fraction
Ho and Li (2014)[53]	$4000 Re \leq 13000$	Turbulent	Horizontal pipe	Al_2O_3	2, 5, 1	Enhancement of heat transfer is affected by the operating temperature
Hashimoto et al (2020) [54]	$1000 \leq Re \leq 100,000$	Turbulent	circular tube	SiO_2	$\Phi = 0, 0.02, 0.05, 0.07, 0.10$	The heat transfer coefficient of the SiO_2 nanofluids increases with a particle concentration of up to 7% by weight and then goes into saturation.

Salari et al(2022)[55]	$0 < Re \leq 4500$	Laminar / Turbulent	copper metal foam	MgO	$\Phi = 0, 0.1, 0.2, 0.5, 1$	The use of porous media led to an increase in the effectiveness of nanoparticles in enhancing heat transfer. The results showed a significant improvement in the performance evaluation criteria
Esfe et al (2014)[56]	$3200 \leq Re \leq 19,000$	Turbulent	circular tube	MgO	0.0625%, 0.125%, 0.25%, 0.5% and 1%	The findings indicated that incorporating a small amount of NPs into the base fluid significantly enhances heat exchange. Additionally, the measurements reveal that while the pressure drop of the NFs is marginally greater compared to the base fluid, it does not escalate with increasing nanoparticle volume fraction.
Qi et al (2019)[57]	$3000 \leq Re \leq 12000$	Turbulent	shell-side and tube-side	TiO ₂	0.0%, 0.1%, 0.3% and 0.5%	GNP nanofluids between 0.075 wt% and 0.1 wt% are more energy efficient than other wt% indicates that nanofluids (= 0.1%, 0.3% and 0.5%) increase the heat transfer rate can improve by 10.8%, 13.4% and 14.8% at best compared to deionized water, and the number of units of transfer (NTU) and efficiency are all improved. At best, the pressure drop can be increased by 51.9% (tube side) and 40.7% (shell side) when using both nanofluids and corrugated inner tube.
Sundar et al (2018)[58]	$3000 \leq Re \leq 23000$	Turbulent	Circular twisted tape	ND-Ni	0.1, 0.	The heat transfers enhancement of hybrid nanofluids (ND-Ni) is predicted to be higher than single-phase nanoparticle nanofluid
Yarmand et al (2017)[59]	$5000 \leq Re \leq 17500$	Turbulent	Stainless tube	F-GNP	0.02, 0.06, 0	The heat transfer enhancement increases up to 19.68 % at 0.1 wt.% and $Re = 1750$

Hamid et al (2018)[60]	3000 Re ≤ 17500	Turbulent	Horizontal tube	TiO ₂	0.5,1.0,1.5	The heat transfers enhancement increases with both volume fraction and operating temperature
Azmi et al (2016)[61]	3000 Re ≤ 18000	Turbulent	copper tube	TiO ₂	0.5, 0.7, 1.0, 1.3, 1.5	The heat transfers enhancement up to 22.8% and 289% increases with both volume fraction and operating temperature of 50°C and 70°C respectively
Osman et al (2019) [45]	200 Re 7 000	Transition	Rectangular channel	Al ₂ O ₃	0.3, 0.5, and 1%	The 1.0% rise in heat transfer coefficients for the nanofluids demonstrated the highest improvements, with a 54% increase in the transitional flow regime and an 11% increase in the turbulent regime. It was noted that the CHT efficiency in the transitional flow regime outperformed that of both the turbulent and laminar regimes.
Li et al. (2015).[62]	1000 Re ≤ 5000	Transition	copper tube	ZnO/EG-W	Φ = 0, to 5,	The heat transfers enhancement up to 30% with 2.5%wt and decrease with 5%wt

2.3 Forced CHT of hybrid nanofluids

Recently, hybrid nanofluids have received more attention due to their superior thermophysical characteristics and rheological behavior, which could help improve heat exchange properties compared to a traditional base fluid and a single nanofluid. This superior property has opened a new generation of nanofluids for researchers to use to see the utility of this hybrid nanofluid to enhance it for various practical heat transfer applications in thermal engineering. A hybrid NFs is a mixture of two or more different materials of nanometer-sized nanoparticles of uniform structure or composition with novel physical and chemical bonds, dispersed in a conventional base fluid. The main goal of the hybrid NFs is to achieve improved thermophysical properties, hydrodynamic properties and high heat transfer property compared to a conventional base fluid and a single nanofluid because of the synergistic effect of the mixture of the nanometer-sized nanoparticles.

2.3.1 Preparation of hybrid nanofluid.

Several researchers have consistently used these three methods using the conventional base liquid for the preparation of hybrid NFs to determine the thermal properties of the nanofluids; They are water-based hybrid nanofluids, ethylene glycol-based hybrid NFs and oil-based hybrid nanofluids. These methods typically used hybrid NPs with a size of 100 nm to achieve stable hybrid nanofluids.

2.3.2 Thermophysical characteristics of hybrid nanofluid

The heat transfer properties of hybrid nanofluids are significantly influenced by their thermophysical characteristics, such as specific heat, viscosity, density, and thermal conductivity [4], which vary with particle concentrations and temperature conditions, as demonstrated in various studies [63], [64]. Numerous investigations have shown that incorporating hybrid nanofluids leads to notable enhancements in thermal conductivity [65]., outperforming both traditional base fluids and single nanofluids [66]. However, this improvement in thermal performance is often accompanied by an increase in viscosity, contributing to higher frictional resistance, as noted in several works [67].

The viscosity of the fluid is a crucial factor as high viscosity fluids tend to yield lower heat output and may result in increased pressure drop, leading to higher pumping costs. Many researchers have observed that the viscosity of NFs rises with increasing volume concentration and decreases with rising temperatures, albeit with notable increases at higher concentrations. Consequently, the rise

in friction factor for hybrid nanofluids is a critical consideration, particularly in industrial and commercial applications where energy efficiency is paramount [68], [69].

Exceeding a certain threshold of friction factor necessitates a significant amount of pumping power, which could offset the benefits of improved heat transfer [70], [71]. Therefore, achieving an optimal balance between enhanced thermal conductivity and manageable viscosity is essential for the practical utility of hybrid NFs as heat transfer fluids in thermal systems [72].

In conclusion, ongoing research aims to identify the most effective combination of nanometer-sized nanoparticles, volume concentration, and thermophysical properties to maximize heat transfer efficiency. The quest for optimized hybrid nanofluids continues with the goal of harnessing their comparative advantages over traditional base fluids in various thermal applications.

2.4. Application of hybrid nanofluids in forced CHT

Few studies have been carried out experimentally and theoretically and documented in various literatures on applications of hybrid NFs in forced CHT in internal flows, and intensive research work is still ongoing. however, results from the last use in the last 10 years are considered as they would have been an improvement over previous study. The results are summarized in **Table 2.2** below

Table 2. 2 Summary experimental investigation of the FCHT of HNFs in steady state and heat flux

Authors	Reynold number and Flow Regime	Nanoparticles Hybrid composition	Particle weight conc. (wt. %)	Volume concentra tion (vol. %)	Conduit Type	Heat transfer enhancement mechanisms
Zubir et al (2015)[71]	2500 Re>20000 Laminar	RGO:Carbon nanofiber(mixture)/water RGO:MWCNT (mixture)/water RGO:GNP (mixture)/water RGO/water	50/50	0.05	stainless steel tube	RGO/water mono-nanofluid achieves local convective heat transfer and Nu gains (from 63 to 144%) higher than hybrid samples. Minimum increments of change in pressure drop and friction factor are given for all nanofluids. No information is provided on changes in pressure drop and friction factor.
Allahya et al (2016)[73]	1000 Re >5000 Laminar	AL ₂ O ₃ :Ag (composite)/water	97.5/2.5	.1–0.4	Tube	The maximum heat transfer rate can be achieved by using the hybrid nanofluid in a concentration of 0.4% by volume, which is 31.58% higher than that of distilled water
Megatif et al (2016)[74]	0>Re >1950 Laminar	CNT–TiO ₂ , /water	50/50	0.1, and 0.2	Copper tube	There is a significant improvement in heat transfer coefficient Of 38% was achieved by using 0.2 wt% CCNT–TiO ₂ , at 38°C,
Hussien et al (2017)[75]	200 Re> 500 Laminar	MWCNTs-GNPs/water	75/25	(0.075, 0.125, and 0.25	Mini tube	The volume concentration of 0.25 wt% MWCNT + 0.035 wt% GNP)/water hybrid nanofluid shows the highest increase in heat transfer coefficient of 43.4% with an 11% increase in pressure drop
Hameed et al (2018)[76]	500 Re>2100 Laminar	AL ₂ O ₃ :Cu (composite)/water AL ₂ O ₃ :CNT (composite)/water	90/10	0.1 and 0.3	Copper tube	Convective heat transfer experimental results showed greater improvement with Alumina CNT/water hybrid fluid compared to Alumina Cu/water hybrid

						fluid. The maximum increases of 30.65% and 20.48% in Nusselt number were compared for 0.3% volume fraction of Alumina CNT/water hybrid nanofluid and Alumina Cu/water hybrid nanofluid, respectively, at a Reynolds number of 1350 obtained for the Nusselt number of water.
Arunachalam and Edwin (2017)[77]	0 Re >2000 Laminar	AL ₂ O ₃ -Cu/water	50/50	0.4 vol% AL ₂ O ₃ + 0.01 vol% Cu	stainless tube (with and without V-cut twisted tape insert	The heat transfer coefficient for (0.01% Cu + 0.4% Alumina)-water hybrid nanofluid is 25.8% higher than that for water and with ribbon liner it is 42% higher than that for water in a smooth tube. The change in pressure drop increases 0.89-fold without band insertion and 15-16-fold with band insertion for the hybrid sample
Bhattad et al (2019)[78]	150 Re>350 Laminar	AL ₂ O ₃ /MWCNT/water AL ₂ O ₃ /CuO/water	80/20	0.01	Plate heat exchanger	A maximum increase of approximately 31.2% was observed in the heat transfer coefficient for AL ₂ O ₃ -MWCNT hybrid nanofluid, with a negligible 0.08% increase in pumping work and a 12.46% increase in performance index. The maximum increase in irreversibility is about 1.6% for AL ₂ O ₃ /CuO hybrid nanofluids.
Hashemzadeh and Hormozi (2019)[79]	490 Re > 3100 Laminar/Transition	γAL ₂ O ₃ /SiO ₂ /water	75/25	0.05, 0.1, and 0.2	Mini channel heat sink	Thermophysical properties indicated that the hybrid nanofluid provided higher values of thermal conductivity and viscosity compared to the single fluids. The Nusselt number increased with increasing Reynolds number and volume fraction of nanoparticles for all

						nanofluids. Hybrid nanofluid with 75% alumina, 25% silica and 0.2% volume fraction and the single alumina nanofluid with 0.2% volume fraction provided the highest and lowest increases in Nusselt number with mean increase values of 46 % and 11% respectively.
Kumar and Sarkar (2020)[80]	50 Re > 500 Laminar	AL ₂ O ₃ / CNT/water	50/50	0.1	Mini channel heat sink	Convective heat transfer coefficient and pressure drop increase by about 42.3% and 22%, respectively, for AL ₂ O ₃ + CNT nanofluid. The maximum reduction in thermal resistance of 26.6% is achieved for the AL ₂ O ₃ + CNT nanofluid compared to the base fluid. The heat transfer efficiency and figure of merit are above one for all hybrid nanofluids, concluding that hybrid nanofluid is a better option over base fluid for minichannel heatsinks. AL ₂ O ₃ + CNT hybrid nanofluid is better in terms of heat transfer efficiency, but AL ₂ O ₃ + AlN hybrid nanofluid gives higher heat transfer coefficient to pressure drop ratio and coefficient of performance.
Kumar and Sarkar (2020)[81]	50 Re > 500 Laminar	AL ₂ O ₃ -MWCNT/water	50/50	0.1	Mini channel heat sink	CHT coefficient and pressure drop are increased by about 42.24% and 22% for AL ₂ O ₃ + MWCNT hybrid nanofluid. The maximum thermal drag reduction of 21.36% is achieved for AL ₂ O ₃ + MWCNT hybrid nanofluid compared to DI water.

Ataei et al (2020)[82]	400 Re > 1000 Laminar	AL ₂ O ₃ /TiO ₂ (mixture)	50/50	0.5	Mini channel heat sin	AL ₂ O ₃ /water mono nanofluid shows higher Nu increases under most conditions. TiO ₂ /water mono-nanofluid shows the higher P increases, up to 29.5%. Significant improvements in thermal properties by using nanofluids as coolant instead of pure water. The convective heat transfer coefficient improved by up to 16.97% compared to pure water. Using AL ₂ O ₃ /TiO ₂ ,-water hybrid nanofluid instead of pure water reduced the wall temperature by up to 5 °C.
Gupta et al. (2020)[83]	2200 Laminar	Ag/MWCNT (mixture)/water	75/25	0.02, 0.05, 0.1, 0.2 and 0.5	Tube	The improvement in heat transfer was find out as the Re improved. With an improvement in Reynolds number from 1275 to 1875 at 0.5% by mass, the increase of 26.7, 19.3 and 20.7% was observed for Ag, Ag-MWCNT and MWCNT nanofluids, respectively
Bhattad et al (2020)[84]	150 Re>350 Laminar	AL ₂ O ₃ /MWCNT/water AL ₂ O ₃ /Cuo/water	80/20	0.01	Plate heat exchanger	Maximum improvement of about 16.91% and 4.5% are reported for convective heat transfer coefficient and heat transfer rate with AL ₂ O ₃ (5:0) hybrid nanofluid along with 0.013% (insignificant) improvement in pumping work for TiO ₂ , (0:5)- Hybrid reported - nanofluid observed. The maximum reduction in exergetic efficiency of 4.01% is observed for TiO ₂ , (0:5) hybrid nanofluid. The study shows that the energetic and exergetic performance decreases continuously

						with increasing TiO_2 content in the mixture, so that the nanoparticle mixing ratio is not optimal. Al_2O_3 /water mono-nanofluid shows the largest increase in h with 16.9%. TiO_2 /water mono-nanofluid shows the highest P increase at 0.013%
Sundar et al (2015)[85]	2500 <Re> 22500 Turbulent	(CNT)- Fe_3O_4 /water	74/26	0.1.and0.3	Twisted Tube	The thermal conductivity increased by 29% and the viscosity by 1.5 times at a particle concentration of 0.3% in the base liquid at a temperature of 60 °C. The improvement in Nusselt number for 0.1% CNT- Fe_3O_4 hybrid nanofluid is 9.35% and 20.62%, for 0.3% CNT- Fe_3O_4 hybrid nanofluid it is 14.81% and 31.10% in Reynolds numbers of 3000 and 22,000 respectively compared to base liquid.
Sundar et al (2016)[86]	2500 <Re> 22500 Turbulent	MWCNT- Fe_3O_4 /water	74/26	0.1 and 0.3	Copper Tube	Maximum 31.10% increase in Nusselt number with a penalty of 1.18 times increase in pumping power for the 0.3% particle loading at a Reynolds number of 22,000 compared to base fluid data.
Huang et al (2016)[87]	Not stated	Al_2O_3 /-MWCNT/water	15/85	1.89% Al_2O_3 /water + 0.0111% MWCNT/ water	Plate heat exchanger	the heat transfer coefficient of the hybrid nanofluid mixture is slightly greater than that of the Al_2O_3 /water nanofluid and water when the comparison is based on the same flow rate. The hybrid nanofluid mixture also exhibits the highest heat transfer coefficient at a given pump power. The pressure drop of the hybrid nanofluid

						mixture is smaller than that of the Al_2O_3 /water nanofluid and only slightly higher than that of water.
Askari et al (2017)[13]	2000 Re >5000 Turbulent	Fe_3O_4 /Graphene	50/50	0.1, 0.2 and 1%.	Copper tube	Thermal conductivity improved by 14% and 32% for 1 wt% mass fraction for Fe_3O_4 /graphene nanofluids at 20-40°C. In addition, compared to the base fluid, for Fe_3O_4 and Fe_3O_4 /graphene nanofluids at a Reynolds number of 4248, an 8.5% and 14.5% increase in heat transfer coefficient, respectively, was observed
Hameed and Suresh (2017)[88]	9000 Re > 23000 Turbulent	Al_2O_3 -CNT/water	90/10	0.1	Copper tube	The average improvement in Nusselt number of 15.41% and 22.11% for 0.1% and 0.3% nanofluids compared to plain tube with water. The average increase in friction factors was 29.51% and 39.82% for 0.1% and 0.3% Al_2O_3 - CNT, respectively, compared to water.
Sundar et al (2018)[58]	3000Re >22,000) Turbulent	Nanodiamond-Ni/water	74/26	0.1and 0.3	Twisted Tube	The increase in Nusselt number at a concentration of 0.3% volume of the hybrid nanofluid is 35.43% with a friction factor penalty of 1.12 times at a Reynolds number of 22,000 compared to distilled water data.
Ramadhan et al (2020)[89]	2900 Re > 11200 Turbulent	TiO_2 - SiO_2 EG/water	20/80	1.0, 2.0 and 3.0	Plan tube	The improvement in Nusselt number at a concentration of 0.3% volume of the hybrid nanofluid is 35.43% with a friction factor penalty of 1.12 times at a Reynolds number of 22,000 compared to distilled water data. The heat transfer increases with Re both numerically and

						experimentally in the smooth tube, TiO_2 , SiO_2 , had the highest Nusselt amount at a volume concentration of 3.0% and the highest friction factor was followed by 2.0% and then 1.0%. Volume concentration of 1.0, 2.0 and 3.0%
Mukherjee et al (2022)[90]	7743 $\text{Re} > 23,228$. Turbulent	$(\text{SiO}_2\text{--ZnO})/\text{water}$	50/50	0.025 and 0.01	Stainless steel tube	Thermal conductivity and viscosity of SiO_2/ZnO compared to water. The convective heat transfer coefficient of SiO_2/ZnO increased with increasing volume and Re . A maximum gain of 29.44% was achieved at a volume of 0.10 at $\text{Re} = 20,131$ compared to water. Furthermore, the friction factor and pressure drop of $\text{SiO}_2\text{--ZnO}$ increased with increasing volume concentration. At a volume of 0.10 at $\text{Re} = 23,228$ compared to water, a maximum increase in friction factor of 17.45% and a maximum increase in pressure drop of 24% was recorded

2.5. Introduction to magnetic nanofluid

Magnetic nanoparticles (MNPs) are special ferromagnetic NPs with a particle size in the range of 5-40 nm composed of magnetite (Fe_3O_4), maghemite ($\gamma\text{-Fe}_3\text{O}_4$), cobalt (Co_2O_3), hematite (Fe_2O_3) and (nickel (Ni)). These nanoparticles can be manipulated with magnetic fields. Fe_3O_4 possesses the most influential properties compared to other magnetic nanoparticles due to the two valence states Fe_2O_3 and Fe_3O_4 in the inverse spinel structure. Magnetic nanofluids (MNFs) are the dispersion of magnetic NPs in a conventional base fluid, Extensive research is currently being conducted on the use of MNFs, since MNPs improve the thermal conductivity of NFs and offer more outstanding properties due to their magnetic nature [91]. MNFs are usually prepared in polar-based liquids that are miscible with water, such liquids include ethylene glycol and propylene glycol, or non-polar-based liquids such as kerosene, motor oil, and transformer oil [91], [92]., but the thermal properties and heat transfer are polar-based or non-nanofluids on a polar basis are very important to determine the ranges of thermal applications of the MNFs since the thermal properties such as thermal conductivity, viscosity and convective heat transfer are very important factors in the thermophysical properties of heat transfer fluids [11], [93].

2.5.1 Preparation of magnetic nanofluid

Berger et al [94] reported that they are two major methods in synthesizing a magnetic nanofluids.

The first step is to prepare the magnetic nanoparticles, which are dispersed in the colloidal suspension using co-precipitations, microwave-assisted synthesis, solvothermal methods, sol-gel synthesis and hydrothermal synthesis, etc [5]. Then these particles should be chemically stable in the base fluid carrier. The second method of synthesis is to disperse the magnetic particles in a carrier base fluid using a surfactant to produce a colloidal suspension. Ferrofluids with excellent stability have been successfully developed in oil-based media. In contrast, water-based systems face challenges due to the inherent tendency for particle aggregation in aqueous environments. This aggregation results from the stronger interactions between particles, leading to decreased long-term stability as confirmed by small-angle neutron scattering and static and dynamic light scattering analyses. Additionally, the choice of surfactant plays a crucial role in determining the stability of the ferrofluid. The surfactants are used as dispersants for particles of the base fluid, adhering to the particles and creating a net repulsion between them (steric and/or coulombic), thereby increasing the energy required for the particles to agglomerate and stabilize the colloid.

Sundar et al [11] they dispersed Fe_3O_4 nanoparticles in a vacuum pump oil using a chemical reduction method without adding a surfactant and characterized magnetic nanofluids using X-ray powder diffraction (XRD) and vibrating sample magnetometer (VSM) techniques and the synthesized nanoparticles showed magnetic behavior despite the fact that they reside in the vacuum pump oil to distribute. They observed a lower value of magnetization saturation, resulting in small synthesized nanoparticles that resulted in structural distortions and the presence of a nonmagnetic surface layer.

Chien and Weng [95] they synthesize Fe_3O_4 nanoparticles to make a magnetic nanofluid and then coat oleic acid as a surfactant in deionized water. They studied the effects of magnetic nanofluid droplets on machined surfaces under the influence of a magnetic field, and with magnetic nanofluids, without the magnetic field, there was a higher degree of adhesion between the liquid and the solid.

Sundar et al [96] they synthesize Fe_3O_4 nanoparticles to produce magnetic nanoliquids using the chemical co-precipitation method. They used a 2:1 molar ratio of ferric chloride and ferrous chloride dissolved in 20 mL of distilled water in a beaker with magnetic stirring. After the iron salts are completely decomposed in distilled water, an aqueous NaOH solution and the magnetic nanofluid are added dropwise. The nanoparticles synthesized during the addition of NaOH solution were characterized by X-ray diffraction XRD Siemens D-500.

Wei et al.[97] They synthesize magnetic nanoparticles Fe_3O_4 with sodium citrate and oleic acid as modifiers through the usage of co-precipitation techniques. The saturation magnetization of Fe_3O_4 magnetic nanoparticles decreased due to the surface modification due to these modifiers, and the magnetic nanofluid showed very good dispersibility and excellent surface energy and dipolar attraction of the surface-coated magnetic nanoparticles.

Agnihotri and paritosh [91]. They used co-precipitation methods to prepare magnetic nanofluids, followed by sonication and oleic acid coating, the Fe_3O_4 nanoparticles were dispersed in kerosene as a carrier liquid. The stability of the coated particles was improved by preventing agglomeration and weak attraction. They used high-resolution transmission electron microscopy, field emission scanning electron microscopy, dynamic light scattering, zeta potential, X-ray diffraction, Fourier

transform infrared spectra, thermogravimetric analysis, rheometry, and superconducting quantum interference devices to analyze the magnetic nanofluids.

Reza et al. [98] They used a chemical precipitation method to synthesize pure magnetic Fe_3O_4 nanoparticles, followed by functionalization of aminopropyltriethoxysilane. These coated nanoparticles adsorb anionic dye from aqueous solutions, thereby forming a stable magnetic nanofluid.

Anbarasu et al. [99] used chemical co-precipitation method to synthesize Fe_3O_4 nanoparticles using Polyethylene glycol (PEG) as a stabilizer and dispersant. The coated Fe_3O_4 nanoparticles characterizations and structure of particles Fe_3O_4 nanoparticles showed roughly spherical in shape with small size distribution and homogenous shape. The synthesized PEG-coated Fe_3O_4 nanoparticles showed superparamagnetic behavior and high saturation magnetization.

Alsarraf et al. [14] used gum arabic (GA)-coated CNTs and tetramethylammonium hydroxide (TMAH)-coated Fe_3O_4 nanoparticles dispersed in pure water to synthesize the magnetic nanoparticles. They made a hybrid nanofluid by mixing the actual amount of magnetite-water ferrofluid and CNT-water nanofluid and sonicating for 5 minutes. The magnetic nanoparticles interacted between the TMAH and GA molecules, resulting in physical binding of the magnetite and CNT nanoparticles.

In summary, compared to other methods, the co-precipitation method for the synthesis of magnetic nanoparticles seems to be more advantages and a more convenient method to synthesize metal oxides and ferrites from aqueous salt solutions [92].

Li et al. [100]; Chen and Meng [101] they reported that the co-precipitation usually occurs at relatively low temperature, evolves into high product yield and its environmentally friendly solvents, and finally offers a comparatively small size distribution of nanoparticles. The quality of the magnetic nanoparticles is reproducible when the reaction conditions are tightly controlled. Basically, the sizes of the magnetic nanoparticle particles vary from 5 to 15 nm, and these sizes usually show ferromagnetic behavior in a single domain [102].

2.5.2 Thermal conductivity of magnetic nanofluid

Thermal conductivity is a crucial variable in heat transfer fluids, as it directly affects the performance improvement of these fluids. Since liquids generally exhibit lower thermal

conductivity compared to metals, the introduction of nanoparticles into base fluids is expected to enhance thermal conductivity, thereby improving heat transfer performance [5], [103]. Numerous studies have investigated the thermal conductivity of magnetic nanofluids, highlighting their potential in this regard [104], [105], [106] .

These studies can be broadly categorized into two main groups: those conducted without the influence of a magnetic field, including investigations by Zhu et al. [107], Abareshi et al. [108], Fertman et al.[109], Yu et al. [110] , Hong et al.[111] , Pastoriza et al.[112] , Wei et al. [113], and Colla et al. [114]; and those with an external magnetic field applied during testing, such as the works by Gavili et al.[34], Philip et al.[106], Nkurikiyimfura et al. [115], Horton et al.[116], Wensel et al.[117] , Li et al.[118], Karimi et al. [119], and Parekh and Lee [120].

A thorough evaluation of research on magnetic nanofluids reveals trends like those seen in other nanofluids. Specifically, an increase in particle volume concentration leads to enhanced thermal conductivity and elevated temperatures, though the extent of enhancement reported varies across different studies. When a magnetic field is introduced, as observed in the second group, the thermal conductivity of ferrofluids is measured under specific volume fractions and temperatures, demonstrating further improvements in heat transfer performance.

2.5.3 Determinants influencing the thermal conductivity (TC) of magnetic nanofluids

The factors affecting the TC of magnetic nanofluids in both the absence and presence of an applied magnetic field are particle clustering/structure [106], [115], Brownian motion [43], [119], [121], and the interface layer, and these factors are also similar to other nanofluids [43], [119], [121].

2.5.3.1 Brownian motion

Brownian movement is the unpredictable haphazardly motion of microscopic particles suspended in base liquid or gas, and the movement is due to collision with base liquid molecules, causing particles to undergo zigzag movement as reports by different researchers Vinod and Philip [5], Tsai et al [122], Nkurikiyimfura et al [123], Vicente et al [124], and Huang and Wang [125]. Previous studies showed that Brownian motion is an important factor in helping to improve thermal conductivity. There are two ways that Brownian motion can help improve thermal conductivity via diffusion of nanoparticles as a result of motion of nanoparticles transporting heat and micro-convection of fluid surrounding independent nanoparticles [126], [127]. However, other studies have refuted the results of these earlier studies Vinod and Philip [5], Philip et al.[106],

Nkurikiyimfura et al [123], Shima et al [128] and Philip et al.[129], suggested that the improvement in thermal conductivity of magnetic nanofluids might be a function of particle clustering.

Shima et al. [128] investigated the role of nanoparticle Brownian motion-induced micro-convection in enhanced thermal conductivity in stable magnetic NFs. using nanoparticles with average diameters of 2.8-9.5 nm. They noted that for NFs with a constant particle loading of 5.5% by volume, the thermal conductivity rises from 1.05 to 1.25 as the particle diameter increases. A significant enhancement in thermal conductivity was noted due to the increased aspect ratio of the linear chains in nanofluids. Their study discovered that micro-convection is not the main factor responsible for improving thermal conductivity in nanofluids.

Shima et al [130] studied the thermal conductivity of stable and unstable nanofluids and the influence of the aggregation . They observed that aggregation plays a very important role in thermal enhancement and surface functionalization is an important key factor for enhancing stability and performance of nanofluids.

Shima et al [131] they studied the thermal conductivity (k) of aqueous and non-aqueous nanofluids base on temperature-dependent. They observed that the temperature of the aqueous nanofluids increased with thermal conductivity. In contrast, there was a decline in non-aqueous nanofluids. Nevertheless, the thermal conductivity ratio of both nanofluids with respect to base liquids remains constant with an increase in temperature, regardless of the type of base liquid. Their study results clearly confirm that micro-convection is not a key factor in improving the thermal conductivity of nanofluids.

Philip et al [129] they observed that the micro-convection of the liquid medium around the zigzag movement of nanoparticles does not affect the thermal conductivity of a nanofluid in any way, and the micro-convection model was out of proportion in the thermal conductivity values. They examined the modest improvement in thermal conductivity in a thoroughly dispersed particle. The diffusion of magnetic nanoparticles plays an important role at a low volume fraction (0.2%), which corresponds to the interpretation (Maxwell) theory [5], [121].

Tsai et al [122], [132] studied the influence of viscosity on the thermal conductivity of magnetite-based nanofluids was investigated. It was found that as viscosity increased, the measured thermal

conductivity of the nanofluids gradually approached the values predicted by Maxwell's theory. This indicates that viscosity plays a role in influencing the thermal conductivity of magnetic nanofluids. The diffusion of magnetic nanoparticles may be a crucial factor in enhancing thermal conductivity. Many researchers have suggested that, in the absence of magnetic fields, the thermal conductivity of magnetic nanofluids can be estimated using combined models, with predictions derived from Maxwell's theory [121], [133], [134], [135].

Maxwell [136] formulate theory was developed to analyses nanofluids as a two-phase flowing mixture, assessing their properties using mixture theory, which combines the characteristics of both solid particles and the fluid. This model is grounded in effective medium theory, which assumes that particles are fully dispersed within the liquid. However, if the particles form aggregates or clusters within the liquid, the model's predicted thermal conductivity will often be much higher than what has been observed by various researchers. [5], [106], [130], [137].

2.5.3.2 Nanoparticle clustering

Particle aggregation into sparse clusters or into linear chains and its influence on the properties of nanofluids has been studied by many researchers, which is the main mechanism of thermal conductivity of the nanofluids [5], [121], [130], [138]. The presence of particle clusters in the nanofluid results in extensive and highly conductive paths for heat flow and hence rapid heat transport over long distances [121].

Bishop et al.[139] They reviewed the critical study of the various interparticle forces (van der Waals, electrostatic, magnetic, molecular and entropic) that can be exploited in nanoscale self-assembly, and their magnitudes. Surprisingly, they observed that this occurs without the influence of an external magnetic field; Magnetic interaction-induced self-assembled aggregation could take place in magnetic nanofluids. The thermal conduction in the magnetic nanofluids could be controlled by the aggregation structure of magnetic particles. They found that without the influence of an external magnetic field, the distribution of particles in the magnetic nanofluids is disordered and the thermal conductivity of magnetic nanofluids is isotropic. Various researchers observed that during self-assembly, magnetic nanoparticles tend to align their magnetic moments in the direction of the local magnetic field due to the applied fields [5], [121], [140], [141]. This confers properties with different values on magnetic nanoparticles when measured in different directions to form micron-sized one-dimensional chains/wires, rings, two-dimensional aggregates, or even

three-dimensional superlattices. The mechanisms of aggregation need to be understood through their distribution morphology and their manipulation with an external magnetic field are prerequisites to understand the mechanisms of thermal conduction in magnetic nanofluids [115]. Hong et al. [111] studied the effect of magnetic nanoparticle clustering for ethylene glycol-based magnetic Fe nanofluids in the absence of magnetic fields. They observed that the application of ultrasonic vibration to determine thermal conductivity is a function of duration, which could be varied from 0 min to 70 min. They found that increasing vibration time also increased the thermal conductivity ratio, and the rate of this increase decreased with longer vibration time. In addition, the change in thermal conductivity with time after the application of vibration was examined, and it was found that the thermal conductivity decreased with time. In addition, the different average size of the clusters as a function of time was assessed after the vibration application, and the cluster size increased with time. They concluded that the size of the clusters formed by the nanoparticles has a major impact on thermal conductivity.

Philip et al [129] performed an experiment to demonstrate the enhanced thermal conduction through percolating structures in MNF. They found that the maximum improvement occurs when the chains, like aggregates, are thoroughly dispersed without clumping.

In summary, the size of the clusters formed by nanoparticles, the structure of the magnetic nanofluid, the distribution of the morphology, and the ultrasonic oscillation time have an impact on the thermal conductivity of the magnetic nanofluid.

2.5.4 Empirical study on the improvement of thermal conductivity in magnetic nanofluids

Numerous experimental investigations have been conducted to assess the thermal conductivity of magnetic nanofluids. Typically, three primary techniques are employed for measuring the thermal conductivity of conventional (non-magnetic) nanofluids: the temperature oscillation method, the transient hot-wire technique, the stationary parallel plate method. Despite this, the thermal conductivity of magnetic nanofluids is generally measured at room temperature using the same standard approaches applied to conventional nanofluids. [121].

The transient hot-wire method and thermal constant analysis techniques are the most used methods for magnetic nanofluids. This approach involves measuring the temperature response of a wire to an instantaneous electrical impulse and then applying Fourier's law along with temperature data to determine the thermal conductivity. [108], [118], [142], [143].

All experiments conducted using magnetic nanoparticles showed an increase in thermal conductivity for different shapes and sizes of magnetic nanoparticles, the measurement of thermal conductivity is divided into two parts, those measured under the influence of an external magnetic field and those without the influence of field magnets are documented in the literature.

2.5.4.1 Experimental investigation into thermal conductivity enhancement of magnetic nanofluids in the absence of magnetic field.

Abareshi et al [108] they experimentally investigated the characterization and measurement of the thermal conductivity of Fe_3O_4 . They measured the thermal conductivity of the magnetic nanofluids as a function of volume fraction and temperature. They found that the thermal conductivity ratio of the magnetic nanofluids increases with increasing temperature and volume fraction. The highest increase in thermal conductivity was determined at 11.5% in the nano liquid with 3% by volume of nanoparticles at 40°C.

Fertman et al [109] they investigated the temperature- and concentration-dependent thermal conductivity of hydrocarbon-based magnetic Fe_3O_4 liquids using a volume concentration in the range of 0.01 to 0.2 vol% and in the temperature range of 20-80 °C. They observed an increase in thermal conductivity with particle concentration and a decrease in thermal conductivity with increasing temperature.

Yu et al [110] studied the improvement in thermal conductivity of Fe_3O_4 nanofluids dispersed in a kerosene-based liquid prepared via the phase-transfer method. They observed that the thermal conductivity ratios increased linearly with increasing volume fraction and temperature, reaching 1 vol% at a value of 34.0%. In addition, they further investigated the influence of temperature on the increase in thermal conductivity, they carried out measurements in the temperature range from 10 to 60°C. The result showed that the absolute thermal conductivity increased with increasing temperature, while the thermal conductivity ratio was almost constant and the thermal conductivities of the magnetic nanofluids followed those of the carrier liquid.

Hong et al. [111] experimentally investigated the thermal conductivity augmentation magnetic nanofluid Fe disperses in ethylene glycol-based fluid. They observed that the thermal conductivity ratio increased nonlinearly with the increase of volume fraction.

Pastoriza et al. [112] studied, $\alpha\text{-Fe}_2\text{O}_3$ (hematite) and Fe_3O_4 (magnetite), dispersed in ethylene glycol with volume fraction up to 25% by weight, and they determined the thermal conductivity of both nanofluids as a function of volume fraction and temperature. They reported that the

increased thermal conductivity of the nanofluids increases with volume fraction but is independent of temperature.

Colla et al [114] they experimentally studied water-based nano-liquids containing Fe_2O_3 in volume concentrations ranging from 5 to 20% by mass to measure the thermal conductivity and dynamic viscosity of these liquids. They found that the thermal conductivity of the magnetic nanofluids improved with temperature and particle concentration, and they also found that the effects of temperature and magnetic nanoparticle concentration on viscosity with respect to water increased significantly.

Li et al [118] experimentally investigated the effects of particle volume fraction, surfactants and magnetic field on the transport properties of Fe_2O_3 dispersed in water. They observed an increase in the thermal conductivity of magnetic nanofluids with an increase in particle volume fraction both with and without the influence of applied magnetic fields. They also found that the viscosity of the magnetic nanofluid increased with the particle volume fraction of the suspended magnetic nanoparticles and surfactants.

Karimi et al. [119] experimentally investigated the thermal conductivity of water-based nickel-ferrite nanofluids NiFe_2O_3 using volume concentrations between 0 % and 2 % and a temperature range of 25°C. The results showed that the thermal conductivity of magnetic nanofluids increases with increasing concentration and temperature. They observed that the maximum thermal conductivity improvement of the magnetic nanofluids is 17.2% at a concentration of 2% volume and a temperature of 55°C.

Philip et al [106] they study the enhancement of thermal conductivity in magnetite-based nanofluids due to chain-like structures and the tunable thermal properties in magnetic nanofluids. They noticed a significant improvement in thermal conductivity in a magnetic nanofluid with an average particle diameter of 6.7 nm when magnetic field was applied. They observed a maximum gain of 300% at a particle loading of 6.3% by volume. The remarkably large improvement in thermal conductivity in magnetic nanofluidics was attributed to efficient heat transport through percolating linear chain-like aggregates.

Hong et al [144] experimentally studied the thermal conductivity of nanofluids with different volume fractions of Fe nanoparticles dispersed in ethylene glycol-based liquids. They confirmed that the magnitude or magnitude (or intensity) of thermal conductivity increases with particle volume fraction. They observed that the thermal conductivity increased more for iron-based

nanofluids than for copper-based nanofluids. In addition, they also observed that the increase in thermal conductivity was attributed to the nanoparticles in the high-volume fraction fluids, which clustered at a higher rate.

Afrand et al. [145] experimentally investigated the thermal conductivity of water-based Fe_3O_4 nanofluid by measuring the thermal conductivity at temperatures ranging from 20°C to 55°C. The experimental results showed that the maximum thermal conductivity improvement of the magnetic nanofluid was 90% at a volume fraction of 3.0% and a temperature of 55°C. The thermal conductivity of the magnetic nanofluid showed some notable improvements in the absence of a magnetic field.

However, with the few experimental investigations discussed above, most researchers attributed the enhanced thermal conductivity enhancement improvements to volume fraction and temperature.

2.5.4.2 Experimental investigation into the thermal conductivity enhancement of magnetic nanofluids in the presence of magnetic field.

Several experimental studies focus on the influence of an external magnetic field to improve the thermal conductivity of magnetic nanofluids. The aim of these investigations is to determine the effect of the external magnetic field on the thermal conductivity. Many researchers observed that the thermal conductivity of magnetic nanofluids could be affected by the intensity and orientation of the applied magnetic field [5], [92], [115], [121], [126].

Thermal conductivity assessment in the presence of a magnetic field is usually performed at room temperature using the same methods used in the absence of magnetic fields. The magnetic field is generated by permanent magnets or electromagnets.

Djurek et al [143] experimentally studied the thermal conductivity of magnetic nanoparticles of CoFe_3O_4 and $\gamma\text{-Fe}_2\text{O}_3$ ($8\text{--}15 \times 10\text{--}9$ m) dispersed in water and n-decane with temperature of 25 °C in a magnetic field. They observed decreased with increasing the magnetic field strength up to $2\text{--}3 \times 10^{-2}$ T then field independence in higher fields.

Gavili et al [34] experimentally studied the thermal conductivity of magnetic nanofluids containing Fe_3O_4 nanoparticles suspended in deionized water under a magnetic field. They found that thermal conductivity varied with temperature, showing improvement under the influence of a magnetic field, particularly for nanofluids with 5.0% volume fraction of nanoparticles, resulting in enhanced thermal conductivity.

Karimi et al. [146] experimentally studied the thermal conductivity of magnetic MFe_3O_4 ($M = Fe$ and Co) nanoparticles suspended in deionized water with different volume fractions ranging from 0% to 4.8% with magnetic field strengths ranging from 0 to 500 G. They observed an increase in thermal conductivity with both increasing volume fraction and magnetic field strength, reaching a saturation point.

Altan et al. [147] They experimentally studied thermal conductivity using Fe_3O_4 magnetite particles dispersed in both water and heptane under the influence of an applied external magnetic field with increasing volume fraction. They noted continued improvement in thermal conductivity under low volume concentrations and magnetic field strengths, attributing it to thermomagnetic convection.

Kichler and Odenbach. [148] developed an improved plane heat source-based gauge to study the effect of magnetically driven structure formation on heat flux in magnetic nanofluids based on their thermal conductivity measurements in variation of an applied external magnetic field and to compare the result with that used the standard hot-wire method for determination the thermal conductivity. Their results, compared to standard methods, showed qualitative agreement with theoretical predictions for different orientations of magnetic field and heat flow.

Safonenko et al [149] experimentally investigated the thermal conductivity of water-based magnets with a temperature range of 20-70°C and a magnetic field strength range of 0 to 150 kA/m. They observed an increase in thermal conductivity with temperature, concluding that it could be influenced by surfactants in the fluid.

Doganay et al [150] investigate the thermal conductivity of Fe_3O_4 -water magnetic nanofluid with volume concentrations of 1, 2, 3, 4 % and an external magnetic field in the range of 0-400 G applied parallel and perpendicular to the temperature gradient generated by the thermal conductivity measurement probe and thermal conductivity measurements were made carried out with three procedures. They observed an increase in thermal conductivity with increasing magnetic field strength, reaching a maximum enhancement of 10% and 5.6% in parallel and perpendicular orientations, respectively.

Nkurikiyimfura et al [115] experimentally studied the thermal conductivity of magnetic nanofluids dispersed in motor oil under the influence of a magnetic field, considering particle size and particle volume fraction in improving thermal conductivity. They observed increased thermal conductivity with smaller magnetite particles and higher particle volume fractions.

Wensel et al.[117] experimentally investigated the thermal conductivity of nanofluids with metal oxide nanoparticles (Fe_3O_4 and MgO) and carbon nanotubes under the influence of a magnetic field. They found a maximum improvement of about 10% at low particle weight fractions, attributing it to the aggregation of particles and formation of chain structures.

Wright et al.[151] experimentally studied the thermal conductivity of Ni-coated single-walled carbon nanotubes in the presence of a magnetic field. They reported a significant increase in thermal conductivity under a magnetic field, attributing it to the formation of aligned chains of nanotubes.

Sundar et al.[152] experimentally investigated the thermal conductivity and viscosity of Fe_3O_4 nanofluid for heat transfer applications with a solids volume fraction ranging from 0.0% to 2.0% and temperatures ranging from 20°C to 60°C. They observed that thermal conductivity increased as the number of nanoparticles increased.

2.5.5 Investigating and Modelling the thermal conductivity of magnetic nanofluids: An analytical perspective.

The enhancement in thermal conductivity is described by a thermal conductivity ratio, which considers the thermal conductivity of the magnetic nanoparticles themselves, the base fluid, the volume fraction, the shape of the nanoparticles suspended in the base fluid, their surface area, pH variations, and the presence of chemical additives and surfactants. These factors are crucial in determining the thermal conductivity of magnetic nanofluids. Numerous numerical and theoretical models proposed by various researchers aim to predict the unusually high thermal conductivity observed in magnetic nanofluids [86], [87], [119], [145], [152]. These studies showed that the thermal conductivity of magnetic nanofluids is a function of particle diameter, solids volume fraction, and temperature gradient. However, most of these correlations and models did not account for all the factors that make the model work for different magnetic nanofluids with or under the influence of magnetic fields. The most commonly proposed theoretical model for predicting the thermal conductivity of a solid-liquid mixture always takes Maxwell theory into account [136] as the standard reference model because this model is applicable to statistically homogeneous and uniformly sized and non-interacting spherical particles and low volume fraction liquid-solid suspensions with randomly dispersed other models are Bruggeman [153], Jeffrey [154], and Timofeeva [155].

Many studies for magnetic nanofluids to predict thermal conductivity have had their models modified from either the Maxwell, Bruggeman, Jeffrey, and Timofeeva's approach to modeling the thermal conductivity of solid-liquid composites., as shown in Equations 2.1 [136], 2.2, 2.3, and 2.4 respectively.

$$K_{nf} = K_f \left\{ \frac{K_p + 2K_f - 2\varphi(K_f - K_p)}{K_p + 2K_f + \varphi(K_f - K_p)} \right\} \quad 2.1$$

The following Bruggeman's equation is another model generally used to determine the thermal conductivity of nanofluids as shown in Equation 2.2 [153]

$$\frac{K}{K_f} = \frac{1}{4} \left[(3\varphi - 1) \frac{K_p}{K_f} + (2 - 3\varphi) \right] + \frac{K_f}{4} \sqrt{\Delta} \quad (2.2)$$

where Δ is given by

$$\Delta = (3\varphi - 1)^2 \left(\frac{K_p}{K_f} \right)^2 + (2 + 9\varphi - 9\varphi^2) \left(\frac{K_p}{K_f} \right)$$

where K_f is the effective thermal conductivity, K_p , is the thermal conductivity of the particle, φ is the volume fraction and Δ is change.

The Jeffrey formula is given in Equation 2.3[154]

$$K_{naf} = \left\{ 1 + 3\beta + \left(3\beta^2 + \frac{3\beta^3}{4} + \frac{9\beta^3}{16} \frac{\alpha + 2}{2\alpha + 3} + \frac{3\beta^4}{64} + \dots \right) \varphi^2 \right\} K_b \quad (2.3)$$

where $\beta = \frac{\alpha-1}{\alpha-2}$, $\alpha = \frac{K_p}{K_b}$

Timofeeva et al.[155] developed another effective medium theory to calculate the thermal conductivity of nanofluids as shown in Equation 2.4.

$$K_{naf} = K_b(1 + 3\varphi) \quad (2.4)$$

All previous models expressed the thermal conductivity of a nanofluid in equations 2.1 to 2.4 (107, 132-134) as a function of the convective base liquid and the volume fraction, and the particle thermal conductivities. Also, preliminary studies [108], [119], [123], [152], [156] confirmed that thermal conductivity is influenced by factors like particle size distribution., the boundary layer at

the particle/liquid interface, the motion of nanoparticles, the influence of the magnetic field, and the particle size. Many other crowning achievements have been proposed by other researchers to propose a general model that accounts for the effect of all magnetic nanofluid variables.

Karimi et al [119] experimentally determined the thermal conductivity of magnetic Fe_2O_3 and Fe_2O_4 nanofluids were analyzed under a magnetic field range of particle volume fractions of 0% to 4.8% and temperatures spanning 20°C to 60°C ., temperature and magnetic field strength and effects of particle volume fraction on thermal conductivity and proposed a model to predict the thermal conductivity with and without the influence of the magnetic field, as shown in Equations 2.5 and 2.6, respectively.

$$K_{naf} = \left\{ 1 + \varphi + a\varphi \left(\frac{T}{T_{min}} \right)^b \right\} K_b \quad (2.5)$$

where $T_{min} = 20^\circ\text{C}$ and K_b is the thermal conductivity of the conventional-based fluid and a and b are coefficients. They compared their model to the experimental data using (107, 132–134) and found that their proposed correlation provides a better prediction of the thermal conductivity of the magnetic nanofluid. Equation 2.5 considers the thermal conductivity of a magnetic nanofluid as a function of the intensity of a magnetic field and the bulk concentration.

$$K = \left\{ 1 + a\varphi^b \left(\frac{B}{B_{min}} \right)^c \right\} K_{naf} \quad (2.6)$$

$$B_{min} = 1cT$$

were B and φ are the magnetic field intensity and volume fraction respectively, a, b, and c are coefficient, while K_{naf} and K are the thermal conductivity of a magnetic nanofluid in the absence and presence of a magnetic field

Fang et al.[157] investigated the anisotropic thermal conductivity of magnetic fluids under the influence of an external magnetic field. They developed a modified Maxwell model to account for the non-uniform distribution of particles suspended in the fluid, introducing an anisotropic structural parameter. Their experiments revealed that in the presence of a magnetic field, chain-like clusters of nanoparticles formed along the field direction, leading to enhanced thermal

conductivity in that direction compared to others. Their proposed model, depicted in equation 2.7, allowed for the assessment of thermal conductivity along specific directions.

$$\frac{K_i}{K_F} = \frac{K_P + 2K_f - 2\varphi_i(K_f - K_P)}{K_P + 2K_f + \varphi_i(K_f - K_P)} \quad (2.7)$$

where i is the spherical particles with volume fraction in the x , y and z directions. Fu and Gao [158] studied thermal conductivity of magnetic nanofluid based on theory of anisotropic. They used two-step homogenization method by adopting differential effective medium theory to evaluate the equivalent thermal conductivity of magnetisable nanoparticle chains and they generalized self-consistent anisotropic effective medium theory to study the effective thermal conductivity tensors of magnetic nanofluids. They observed that aspect ratio of chain-like aggregated clusters are key determinant in the enhancement of anisotropic thermal conductivity. They proposed non-monotonic dependence of effective thermal conductivity on magnetic field strength model as shown in Equation 2.8.

$$(1 + ARe^\gamma Pr^{0.003} \varphi) \left[\frac{K_P + 2K_f + 2\varphi(k_p - K_f)}{K_P + 2K_f - \varphi(K_P - K_f)} \right] \quad (2.8)$$

Where A is a constant, Re and Pr are Reynolds and Prandtl numbers respectively, and γ is a system dependent coefficient. spherical particles, with high particle volume fraction φ

Ganguly et al. [156] investigated the heat transfer enhancement using a magnetic nanofluid influenced by a line dipole. They assessed the increase in heat transfer attributed to ferrohydrodynamic convection and its correlation with the properties of the applied magnetic field. Their observations revealed localized magnetic effects on the flow, emphasizing the necessity of a sufficiently strong magnetic field to overcome viscous forces. They noted that the magnetic field induces spatial non-uniformity in fluid sensitivity, leading to local asymmetry in the thermal boundary layer around the line dipole. This induced the generation of a local vortex near the cold wall, altering convective energy transport and improving heat transfer. Additionally, they found that increasing the number of dipoles created additional zones of recirculation, further enhancing heat transfer. Varying the distance between two dipoles also affected heat transfer, with the total enhancement depending on the net magnetizing current and relative dipole placement. They developed a model, referred to as the Murshed model, which accounted for spatially non-uniform

magnetic fields and demonstrated the correlation between magnetic field attributes and heat transfer enhancement. This model incorporated various factors such as particle size, nanolayer, particle motions, interactions, and surface chemistry of nanoparticles as shown in Equation 2.9, providing insights for practical applications..

$$K = \left\{ K_f \frac{Q_p \omega (K_p - \omega K_f) (2\gamma_1^3 - \gamma^3 + 1) (K_p + 2\omega K_f) \gamma_1^3 [Q_p \gamma^3 (\omega - 1) + 1]}{\gamma_1^3 (K_p + 2\omega K_f) - (K_p - \omega K_f) Q_p (\gamma_1^3 - \gamma^3 + 1)} \right\} +$$

$$\left\{ Q_p^6 \gamma^6 K_f \left[3\Lambda^2 + \frac{3\Lambda^2}{4} + \frac{9\Lambda^3}{16} \left(\frac{K_p + K_f}{2K_f + 3K_f} \right) + \frac{3\Lambda^4}{2^6} \right] \right\} +$$

$$\left\{ \frac{1}{2} \rho_{cp} C_{p-cp} d_s \left[\sqrt{\frac{3K_B T (1 - 1.5\gamma^3 Q_p)}{2\pi_{cp} \gamma^3 r_p^3}} + \frac{G_T}{6\pi r_p d_s} \right] \right\} \quad (2.9)$$

With $\gamma = 1 + \frac{t}{r_p}$, $\gamma_1 = 1 + \frac{t}{2P_r}$, $\Lambda = \frac{k_{cp} - K_f}{K_{cp} + 2K_f}$, $K_{cp} = K_{lr} \frac{2(K_p - K_f) + \gamma^3(K_p + K_{lr})}{(K_{lr} - K_p) + \gamma^3(2K_{lr} + K_p)}$

ρC_p and C_{p-cp} are density and specific heat of complex particle, respectively, they are $\rho C_p =$

$$\frac{1}{\gamma^3} \rho_p + \left(1 - \frac{1}{\gamma^3} \right) \left\{ \frac{3\rho_p}{pb^3} (2t^2 + 2br_p t + b^2 r_p^2) - \frac{3\rho_f}{pb^3} [(2 + 2b + b^2) + br_p (br_p + 2bt + t)] \right\}$$

$$C_{p-cp} = \frac{1}{\gamma^3} C_{p-cp}$$

$$+ \left(1 - \frac{1}{\gamma^3} \right) \left\{ \frac{3C_{p-cp}}{pb^3} (2t^2 + 2br_p t + b^2 r_p^2) - \frac{3C_{p-f}}{pb^3} [t^2 (2 + 2b' + 2b'^2) b' r_p (b' r_p + 2b' t + 2t)] \right\}$$

where $p = 3r_p^2 + 3r_p t + t^2$; $b = \ln\left(\frac{\rho_p}{\rho_t}\right)$; $b' = \ln\left(\frac{C_{p-p}}{C_{p-f}}\right)$

where

C_{p-p} and C_{p-f} stand for the specific heat capacity at constant pressure for nanoparticles and carrier fluid, respectively. Gr is the total potential energy between two interacting colloidal nanoparticles.

2.6 Viscosity of magnetic nanofluids

Viscosity is also a fundamental parameter to consider before using magnetic nanofluids in heat transfer applications. In addition to the size of the nanoparticles stimulating an increase in viscosity, this causes a large kickback in pump power requirements [92].

Viscosity is a very important parameter in systems that require flow, since flow properties such as pressure drop, Reynolds number, and heat transfer coefficient are very dependent on viscosity, and moreover, when viscosity is very high, the target of thermal system would be due to the Losses in the pump power requirement are not achieved [159]. The main setback of viscosity is the increase due to the suspension of nanoparticles, and this increase is a major obstacle in industry, especially when dealing with flow, such as in heat exchanger or microchannel applications where the pressure drop and pumping power are reduced is of great importance [5], [92], [150], [159].

Numerous studies are available in the literature that have investigated the thermal conductivity and viscosity of magnetic nanofluids with different parameters ranging from the effect of particle concentration [20], [112], [141], [160], [161], [162], particles shape[163], surfactant [164], temperature [108], [152], [165], particle size [97], [166], [167], and effect of external magnetic field strength and direction with different investigators reporting the impacts Paul et al. [142], Li et al.[168], Andhariya et al.[169], Wang et al.[170], Nurdin et al.[171], Thurm et al.[172], [173], Thurm et al, Katiyar et al.[174], Paul et al.[175] and Bian et al [176].

Viscosity is a key parameter that needs to be studied in magnetic nanofluids before they could be used as heat transfer fluids. Many researchers have studied the viscosity of magnetic nanofluids in the absence of a magnetic field and in the presence of a magnetic field due to the possibility of manipulating the properties of the magnetic nanofluid in the presence of a magnetic field. The convective heat transfer coefficient could be affected by viscosity; hence viscosity is a very crucial parameter as thermal conductivity in flow thermal engineering systems.

2.6.1 Empirical investigation of magnetic nanofluid viscosity an experimental insight

This section examines the viscosity of magnetic nanofluids and how it is affected by various parameters, including volume fraction, temperature, shape, and particle size.

i. Effect of particles concentration

Pastoriza et al [112] the increase in thermal conductivity and the volumetric behavior of Fe_3O_4 and Fe_2O_3 nanofluids dispersed in ethylene glycol as a function of temperature and concentration (up to 6.9% volume fraction) as well as the behavior of the density as a function of temperature and pressure were investigated experimentally. Both nanofluids (up to 1% by volume). Their results showed that no significant aggregation occurs for either nanofluid, which they attributed to sufficient repulsion through steric hindrance and magnetic interactions. In addition, they observed that the volumetric behavior of magnetite-containing nanofluids deviates significantly from the ideal behavior.

Anu and Hemalatha [160] experimentally studied the viscosity of water-based magnetite nanofluids with a volume concentration of 0 %, 0.1 to 1 % at room temperature. They observed that the viscosity variation as a function of the shear rate for all volume concentrations from 0 % to 1 % and magnetic nanofluids with a volume concentration of 0.2 % follows the same trend as the base liquid, as results Newtonian behavior was observed. In addition, higher volume concentrations of the particles in the fluid interaction contributed more to the shear thinning behavior. Furthermore, nanoparticles orient themselves in one shear direction with increasing shear rate, a larger increase in shear rate led to the breaking of the agglomeration between the nanoparticles, which led to a decrease in viscosity, and they concluded that the percentage increase in viscosity at the maximum shear rate (100 s^{-1}) for all volume concentrations.

Goharkhah et al [20] they used different volume fractions of =1, 1.5 and 2% for the 20°C-60°C temperature range to study the viscosity and thermal conductivity of the ferrofluid. They observed that the viscosity temperature dependence of the nanofluid is important for all volume fractions. Furthermore, they attributed the decrease in nanofluid viscosity to the decrease in base liquid (DI water) viscosity with temperature.

Guo et al [161] they experimentally studied the viscosity and thermal conductivity of magnetic nanofluids dissolved in ethylene glycol and deionized water with different volume fractions of 0.005%, 0.01%, 0.015% and 0.02% at a temperature ranging from 10°C to 60°C and 5°C were dispersed. They observed that the viscosity of the nanofluids increases with increasing volume fraction, but decreases with increasing temperature. Furthermore, they concluded that the viscosity showed Newtonian behavior and the viscosity of the nanofluids strongly depended on the tested temperatures and nanoparticle loading.

Kim and Park [162] studied density, dispersion and magnetization as a function of concentration and viscosity was also studied at different temperatures as a function of concentration at 200, 300, 400 and 500 mg/ml at a temperature ranging from 20 to 40°C. They observed that the density of the liquids increased proportionally to the concentration from 0.93 g/mL to 1.22 g/mL and the dispersion stability decreased from 97% to 69% as the ferrofluid concentration was increased. The saturation magnetization of ferrofluids is a function of the particle content in the liquid with values from 17.8 to 42.2 mT at concentrations from 200 to 500 mg/ml. In addition, they found that fluid viscosity increased rapidly with increasing concentration over the same range from 5.1 cP to 53.7 cP at 20% and from 3.2 cP to 25.6 cP at 40.69%, with increasing concentrations of the were attributed to agglomeration at higher particle levels.

Yu et al [177] studied the thermal conductivity and viscosity of ethylene glycol-based ZnO nanofluids versus shear rate with volume concentrations from 0.002 % to 0.05 % and temperature for different ranges from 10 to 60°C. They observed that the viscosity of nanofluid increased with increasing particle concentration and with increasing temperature removed. Furthermore, they found that the nanofluid showed Newtonian behavior and non-Newtonian behavior at a lower volume fraction of 0.02 % and a higher volume fraction of 0.03 %, respectively.

ii. **Effect of particle shape**

Laherisheth and Upadhyay [163] studied the influence of the particle shape on the magnetic and stationary magnetorheological properties of nanoparticles based on MR fluids, they studied the interaction between the Fe_3O_4 nanoparticles and the micro-properties of the flake shape and the magnetorheological influence with different volume fractions of 0.2%, 0, 6% and 0.8% to verify the influence of the particle shape and to compare it with liquids based on spherical particles. They observed that the nanoparticles smooth the surface of the flaky particles by magnetically adhering to them, and this causes the viscosity to decrease. In addition, the saturation magnetization of the flake-based magnetorheological fluid increased to about 15% when the volume fraction of nanoparticles was higher than 0.8%.

iii. **Effect of surfactant**

Altan et al [164] they investigated the degradation of the effective thermal conductivity of Fe_3O_4 aqueous magnetic nanofluids dispersed in water and ethylene glycol at different

temperatures as a function of particle concentration and the effect of the surface coating on the thermal conductivity of the magnetic nanofluid. They observed that the thermal conductivity of water and ethylene glycol decreased as the number of magnetic nanoparticles increased, and they attributed the decrease to an increase with particle loading and excess surfactant. Furthermore, they concluded that the experimental results showed that the observed deterioration was due to a combination of different factors, such as: the presence and/or charge of the surfactant layer and the thermal resistance at the interface.

iv. **Effect of temperature**

Sunder et al. [152] experimentally studied the effective thermal conductivity and viscosity of magnetic Fe_3O_4 -water nanofluids with a volume concentration range of 0.0% to 2.0% and a temperature range of 20 °C to 60 °C. They observed that the thermal conductivity and viscosity of the magnetic nanofluid increase with improving particle volumetric fraction. In addition, the increase in viscosity compared to thermal conductivity was greater at the same temperature and volume concentration.

Patel [178] experimentally studied the effective viscosity of magnetic nanofluids through capillaries. They used two types of fluids based on temperature-sensitive and non-temperature-sensitive magnetic nanofluids and the rotation of the particles and the effect of a torque on them due to an externally applied magnetic field. They observed that the nanoparticles move freely in nanofluid without the magnetic field and the magnetic field forms a barrier to the rotation of the nanoparticles, leading to an increase in frictional coupling between nanoparticles and base liquid layers. In addition, both fluids decreased in effective viscosity with temperature and there was variation in both cases, the decrease being due to the temperature dependence of the magnetic moment for the temperature sensitive fluid and the other due to the removal of the secondary surfactant.

Gu et al. [179] experimentally studied the effects of volume fraction of magnetic particles, mass fraction of surfactant, and temperature on viscosity. They observed that the magnetic nanofluid behaved like a Newtonian fluid with a low volume fraction of the nanoparticles, and the viscosity of the magnetic fluid increased with an increase in the volume fraction of the suspended magnetic particles. In addition, they also observed that increasing the surfactant mass fraction also increased the viscosity, while it decreased with increasing temperature. Furthermore, increasing the magnetic

field strength also increased the viscosity, and increasing the surfactant mass fraction and temperature weakened the influence of the magnetic field on the viscosity.

Malekzadeh et al. [180] experimentally investigated the effect of the magnetic field on the viscosity of Fe_3O_4 water with volume fractions in the range from 0 to 1% and temperature ranges from 25 to 45 °C. They observed that increasing nanoparticle volume fractions increased viscosity and decreased with temperature increase in the presence or absence of a magnetic field. In addition, they observed that increasing the magnetic field strength also causes the viscosity of the magnetic nanofluid to increase. Furthermore, they concluded that the magnetic field is a key factor that could affect the viscosity of the magnetic nanofluids and that the magnetic nanofluid flux could be controlled by the application of the magnetic field.

Wang et al. [170] experimentally studied the viscosity of Fe_3O_4 nanofluid under a magnetic field. They used different magnetic induction 0.30 mT, volume fraction 0.5% 5% and temperature 293-333 K. They observed that the viscosity of Fe_3O_4 nanofluid increases with increasing magnetic induction and solid volume concentration and decreases with increasing temperature.

v. **Effect of particle size**

Wei et al. [97] studied the effect of temperature and modifier on the crystal structure morphology, dispersion and size distribution, and magnetic properties of Fe_2O_3 . The values used for samples a, b, c and d are 50.61, 61.36, 56.05 and 55.43 emu/g for the saturation magnetization, respectively. They observed symmetric hysteresis and saturation magnetization, and the prepared Fe_3O_4 -MNPs showed ferromagnetic behavior, which they attributed to the smaller diameter of the MNPs, which coincides with the critical threshold of Fe_3O_4 (25 nm). Additionally, the effect of the small particle size induces a non-collinear spin ordering that occurs mainly at or near the surface, leading to a reduction in the magnetic moment in Fe_3O_4 NPs. Furthermore, they noticed that the saturation magnetization of sample b is larger than that of sample a, which they attributed to the particle size increase of Fe_3O_4 -MNPs. When they modified with sodium citrate and oleic acid, the saturation magnetization in the Fe_3O_4 -MNPs decreased, and they attributed the decrease to the modification-induced surface spin effect on Fe_3O_4 -MNPs.

Lenin and Joy [166] They investigated the influence of particle size distribution on the thermal conductivity of decanoic acid-coated magnetite (Fe_3O_4) nanoparticles of comparable average size

(57 nm) dispersed in toluene as base liquid with different particle size distributions by varying the addition rate of ammonium hydroxide in the co-precipitation method. Their results showed that the particle size distribution shows that a faster rate of base addition gives a small size distribution and a very slow rate of increase gives particles with a broader distribution. In addition, it was found that the improvement in thermal conductivity was correlated with the average size and distribution of the nanoparticles, and thermal conductivity was significantly lower for liquids with a broad particle size distribution. They concluded that the experimental result obtained deviates from the convection model caused by Brownian motion for a broader nanoparticle size distribution.

Shah and Choi [167] studied the influence of particle size on the rheological properties of platelet-shaped iron particle-based magnetorheological fluids at room temperature using the magnetometer, then by the field-dependent rheological properties of these MR fluids. They observed that viscosity increased with increasing particle size and correlated directly with fluid magnetization. They also concluded that the viscosity is a function of the weight fraction due to the magnetostatic interaction between the two different particle sizes.

vi. Effect of magnetic field

Li et al. [168] experimentally studied the effects of the volume fraction of the suspended magnetic particles, the concentration of surfactants, the orientation and the effect of the external magnetic field strength on the viscosity of the magnetic fluid. Their results showed that the viscosity of the magnetic fluids increased as the volume concentration of suspended magnetic particles and surfactants increased. In addition, they also observed that the viscosity increased with the magnetic field and finally reached a constant value when the magnetization reached the saturation state and the maximum viscosity ratio was 25 for the 2.8 vol% concentrated Fe_3O_4 water sample at 0.02 T and 26 for the 4 vol% concentrated Magnetic Nanofluid sample was from Fe/water at 0.014 T. They concluded that the viscosity in a perpendicular magnetic field is greater than that in a parallel magnetic field for the same magnetic field application.

Andhariya et al. [169] studied the effect of capillary diameter and the direction of the applied magnetic field on the rotational viscosity of water- and kerosene-based ferrofluids. They observed that field-induced rotational viscosity changes are larger for the water-based magnetic fluid than for the kerosene-based fluid. In addition, they found that the field-induced rotational viscosity is inversely proportional to the capillary diameter and decays exponentially as a function of the angle

between the field direction and the flow vortex, and the maximum viscosity ratio of the Fe_3O_4 -water and Fe_3O_4 -kerosene samples was 1.71 and 1.74 at 0, respectively .6 T for 0.5 mm capillary diameter.

Wang et al. [181] studied the viscosity of Fe_3O_4 dispersed in water based on different volume concentrations from 0.5 to 5%. under the influence of the magnetic field with the external magnetic field generated by permanent magnets between 030 mT. Their results showed that the viscosity of Fe_3O_4 nanofluid increases with increasing magnetic intensity and particle volume concentration and decreases with increasing temperature. They also found that the maximum viscosity ratio evaluated was about 1.4. ($\gamma\text{-Fe}_2\text{O}_3$)

Nuridin et al [171]. studied the improvement in thermal conductivity and kinematic viscosity of water-dispersed maghemite ($\gamma\text{-Fe}_2\text{O}_3$)nanofluids with a volume concentration of 0.1 to 0.6% and a temperature of 20 to 30 under the influence of a magnetic field determined using Helmholtz coils and a magnetic field strength varied between 50300 G in both directions perpendicular and parallel to the flow. They observed that the kinematic viscosity of the maghemite nanofluids increases with increasing magnetic field strength and the maximum viscosity ratio of about 1.24 and 1.3 for perpendicular and parallel directions, respectively.

Thurm and Odenbach [172] studied viscosity measurements with a commercial magnetic nanofluid made of synthetic Fe_3O_4 ester (APG513A) under the action of an external magnetic field strength ranging from 0 to 35 kAm⁻¹ with different shear rates. They observed that the fraction with a high proportion of larger particles increases the viscosity due to a stronger magnetic field, which is also dependent on the shear rate, while the other fraction shows a small increase in viscosity when the shear rate was smaller. They also found that the maximum increase in viscosity at 1.8, 4.2, and 6.8 s⁻¹ shear rates was 1.98, 1.02, and 0.68%, respectively.

Thurm and Odenbach [182] studied the viscosity of synthetic ester-based Fe_3O_4 magnetic nanofluids with different volume concentrations between 6.63% and 7.35% and under the action of an external magnetic field generated with an electromagnet in the range of 0.25 kAm⁻¹. They observed that the strong magnetic field induced inter-particle interactions that affected a small fraction of the larger particles. In addition, they attributed strong strength to the interaction

between larger particles to form chain-like structures, which in turn dominate the flow behavior and the maximum viscosity ratio increases to nearly 15 with increasing magnetic field strength.

Katiyar et al. [174] studied the viscosity of Fe_3O_4 dispersed in polyethylene glycol magnetic nanofluids with different weight fractions between 5% and 15% and under the action of the magnetic field generated by an electromagnetic coil, and the magnetic field strength was varied between 0.12 T. They found that the maximum viscosity ratio increases to 32.3 when magnetic field was applied.

Paul et al. [175] studied the viscosity of Fe_3O_4 nanofluids dispersed in water at a volume concentration of 1.135 to 4.54% and a temperature of 25 under the influence of a magnetic field strength of 0 - 0.5 T. They reported that the maximum viscosity ratio was about 11.5.

Yang et al. [176] studied the viscosity of Fe_3O_4 dispersed in water with a volume concentration of 2 to 8% before and after freezing under the action of an external magnetic field in the range of 0–920 G generated by permanent magnets. Their results showed a particular trend with decreasing and decreasing magnetic fields and viscosity changes under magnetic fields as a consequence of magnetically induced structures. In addition, the maximum viscosity ratio under external magnetic field is almost 32.

Finally, from the few selected studies, it is observed that the viscosity of the magnetic nanofluid increases with increasing particle loading and the magnetic field strength also influences the increase. The chain formation of the nanoparticles could be due to the fact that the magnetic nanoparticles orient themselves in the direction of the magnetic field when exposed to the external magnetic field, causing an increase in viscosity and thermal conductivity. The influence of the external magnetic field could manipulate the magnetic nanoparticles, which play an important role in changing viscosity and thermal conductivity. Temperature could also be an important factor to consider that could affect the viscosity and magnetization of the magnetic nanoparticles.

2.6.2 Theoretical investigation of viscosity of magnetic nanofluids

There are several models modified from many studies evaluating the viscosity of magnetic nanofluids either by Einstein [183], Kuntiz [184], Robinson [185], Batchelor [186], Brinkman [187], and Masoumi et al [188] became particle suspension viscosity models as shown in equations

2.10, 2.11, 2.12, 2.13, 2.14 and 2.15, respectively, but the viscosity of magnetic nanofluids does not change in the presence and absence of magnetic fields as in other nanofluids.

Einstein correlation (162) state that at low suspension concentrations, the specific viscosity is directly proportional to the volume concentration of the suspended solid, as shown in Equation 2.10, the viscosity showed that the viscosity depends on the volume concentrations of the nanoparticles, and the correlation was validated for a low solid volume fraction of particles, and it is a function of the Brownian motion of the particles within the base convective fluid.

$$\mu_{sf} = \mu_{sb}(1 + 2.4\phi) \quad (2.10)$$

where μ_{sf} is the viscosity of suspension, μ_{sb} is the viscosity of the base liquid and ϕ is the volume fraction.

Kuntiz correlation (163) as shown in Equation 2.11 is used to evaluate viscosity of colloidal suspension with higher concentration of particle (up to about 50%).

$$\mu_{sf} = \mu_{sb} \left(\frac{1 + 0.5\phi}{(1 - \phi)^4} \right) \quad (2.11)$$

Robinson correlation (164) as shown in Equation 2.12 is a modification of the Einstein correlation by considering the effective volume of the particle size distribution and the degree of aggressiveness (higher concentration), the reason being that the solid particles have packed into a porous solid that is liquid under these conditions flow is impossible unless sufficient voltage is applied to change the state of the solid particles, the suspension has become a porous solid and its viscosity is infinite.

$$\mu_{sf} = \mu_{sb} \left(1 + \frac{2.5\phi}{(1 - S'\phi)} \right) \quad (2.12)$$

where S' is the sediment volume.

Batchelor correlation (165) as shown in Equation 2.13 considered the effect of Brownian motion of particles in a statistically homogeneous suspension and correlation is valid for homogeneous solution.

$$\mu_{sf} = \mu_{sb}(1 + 2.5\phi + 6.2\phi^2) \quad (2.13)$$

Brinkman correlation (166) as shown in Equation 2.14 assumed the mixture as continuum by adding more solute particles and modify the Einstein Equation.

$$\mu_{sf} = \mu_{sb} \left(\frac{1}{(1 - \phi)^{2.5}} \right) \quad (2.14)$$

Masoumi et al correlation (167) as shown in Equation 2.15, considered the effective viscosity of nanofluids and the relative velocity between the base liquid and the particles and developed new correlations based on Brownian motion and the function of particle size and volume fraction.

$$\mu_{sf} = \mu_{sb} \left(1 + \frac{1}{\mu_0} \times \frac{1\rho_p V_B d_p^2}{\left(72c \sqrt{\frac{\pi}{6\phi}} \right) d_p} \right) \quad (2.15)$$

$$C = \left[(0.09d_p - 0.393) - \left(\frac{0.1133d_p - 2.771}{s_f} \right) \phi \right]$$

were ρ_p is the particles density, V_B is Brownian velocity and d_p particle diameter.

Sundar et al.[189] studied the viscosity of magnetic nanofluid Fe_3O_4 dispersed in water and developed a new theoretical equation as shown in Equation 2.16.

$$\mu_{sf} = \mu_{sb} \left(1 + \frac{\phi}{12.5} \right)^{6.356} \quad (2.16)$$

Wang et al [170] studied the viscosity of Fe_3O_4 nanofluids under different magnetic fields by proposing theoretical formulas to predict the dependence of the viscosity of magnetic nanofluids on temperature, volume concentration, and magnetic induction, as shown in Equation 2.17.

$$\mu_{sf} = (0.035H^2 + 3.1H - 2788\phi^2 + 4263.03\phi + 316.0629)e^{-0.02T} \quad (2.17)$$

were H being the magnetic induction and T is the temperature.

Amani et al [190] studied the viscous of $MnFe_3O_4$ /water nanofluids in the presence of a magnetic field and proposed a new correlation for the viscosity of $MnFe_2O_4$ /water nanofluids by considering the magnetic field strength, concentration, and temperature, as shown in Equation 2.18.

$$\mu_{sf} = \mu_{sb} a(1 + \phi)^b T^c B^d \quad (2.18)$$

were B being the magnetic field intensity in G, T is the temperature and abc depicts the influence of volume concentration as well as the viscosity ratio of magnetic nanofluid under magnetic fields.

Shahsaras et al [191] studied the effect of the magnetic field on the thermal conductivity and viscosity of a carbon nanotubes (CNTs) loaded magnetic nanofluid and proposed a new correlation for the viscosity for the hybrid magnetic nanofluid based on the viscosity power law as shown in Equation 2.19.

$$\text{Power law of viscosity } \tau = C \dot{\gamma}^n \quad (2.19)$$

$$C = 24.769 \left[\frac{1+608891248B - 7813611.9B^2}{1-621740.5B - 24961.852B^2} \right] \left[\frac{1+8.08\phi_{CNT}}{1+6.949\phi_{CNT} - 0.083\phi_{CNT}^2} \right] \text{ and}$$

$$n = \left[\frac{1+0.06320B - 0.000407B^2}{1+0.0303380B - 0.000212B^2} \right] \left[\frac{0.651+1.59(\phi_{CNT}-0.45)}{1+2.464(\phi_{CNT}-0.45) + 0.05(\phi_{CNT}-0.45)^2} \right]$$

where C is the consistency index and n are the flow behavior index as a function of CNTs volume concentration (ϕ_{CNT}) and B is the magnetic field strength.

2.7 Force CHT of magnetic nanofluid

Forced CHT, propelled by external mechanisms like pumps or fans, is crucial for achieving uniform heat transfer in various industries. Researchers have extensively explored the use of magnetic nanofluids in enhancing heat transfer, often showing improved heat transfer coefficients due to controlled fluid movement and nanoparticle migration under magnetic fields. Heat exchangers, vital in many applications, have been extensively studied for their thermal performance with magnetic nanofluids, aiming to improve CHT while reducing pressure drop and maintaining key parameters like temperature and flow rate. While research has covered laminar and turbulent flows with single magnetic nanofluids, there's a gap in understanding turbulent and transition flow regimes, especially with hybrid magnetic nanofluids. Further exploration is needed on the effects of magnetic fields in these regimes.

2.7.1 Magnetohydrodynamics (MHD) principles and effects on nanofluids

Hussain et al. [192] state that the fundamental principles of magnetohydrodynamics (MHD) are traditionally linked with electrically-conductive mediums like ionized gases, plasmas, and metals. However, these principles also apply to nanofluids containing conductive nanoparticles, introducing distinct interactions under magnetic field exposure. The electrical conductivity of nanofluids is notably affected by the choice of nanoparticles, especially metallic ones such as iron (Fe), aluminum (Al), carbon nanotubes (CNTs), gold (Au), silver (Ag), nickel (Ni), titanium (Ti),

platinum (Pt), and copper (Cu). These nanoparticles are renowned for their superior heat-conducting capabilities and expansive surface areas, making them valuable additions to nanofluids, nanocomposites, and thermal interface materials. When subjected to magnetic fields, nanofluids incorporating these metallic nanoparticles display unique behaviours due to their electrical conductivity. These characteristics find applications in electronics cooling, heat exchangers, thermal management systems, and nanoscale heat dissipation solutions, resulting in improved efficiency and performance across various industries.

The interaction between magnetic fields and nanofluids within confined conduits, such as pipes, introduces a captivating dimension to their behavior. This unique interplay gives rise to the field of MHD, specifically concerning nanofluids in pipes. Explored in detail by [193], [194], [195], the study of MHD in nanofluid conduits is of considerable importance for its potential to enhance heat exchange in diverse applications. The primary focus of MHD lies in unravelling the intricate interactions among nanofluids, pipes, and magnetic fields, elucidating their collective impact on fluid flow, heat transfer, and other properties [15], [24], [196].

The practical applications of magnetohydrodynamics of nanofluids in pipes extend to advanced electronics cooling technology and the optimization of heat transfer efficiency. Magnetic fields are adeptly utilized to manipulate fluid flow, ensuring precise cooling in the face of growing thermal challenges [5]. In this realm, the exploration delves into the interplay between magnetic fields and nanofluids in forced convection heat transfer, leading to dynamics that surpass conventional heat transfer paradigms [25], [31]. **Figure 2.1** illustrates a typical schematic of magnetohydrodynamics in nanofluids forced convection. The significance of magnetohydrodynamics in enhancing forced convection heat transfer and understanding nanofluid behavior under magnetic influence is highlighted [197]. This significance arises from the ability to manipulate fluid behavior with various magnetic field properties.

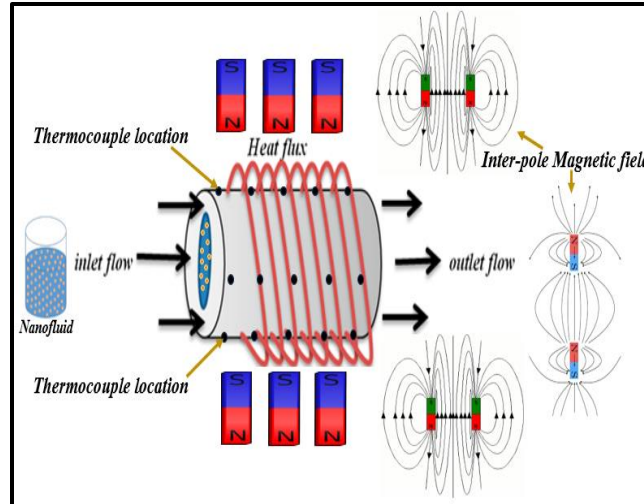


Figure 2. 1 Depiction of a standard schematic diagram illustrating the force convection of nanofluids under the influences of magnetic field.

The interaction between magnetic flux and nanofluids can alter fluid flow dynamics and impact thermal energy transfer. Understanding magnetohydrodynamics (MHD) in nanofluids is crucial for optimizing thermal transfer in practical applications. **Figure 2.1** illustrates the importance of employing various methodologies to explore MHD in nanofluids within pipes, considering both laminar and turbulent flows of single and hybrid nanofluids.

Figure 2.2 presents a visual representation of factors influencing thermal performance, categorized into magnetic effects, nanofluid effects, forced convection effects, and applications. Magnetic effects include parameters like magnet type, inter-magnet gap, magnet inclination, and field strength. Nanofluid effects are influenced by nanoparticle type, concentration, boundary conditions, governing parameters, and heat-related properties. Researchers have observed changes in fluid flow dynamics and thermal properties of nanofluids under magnetic fields by varying these factors.

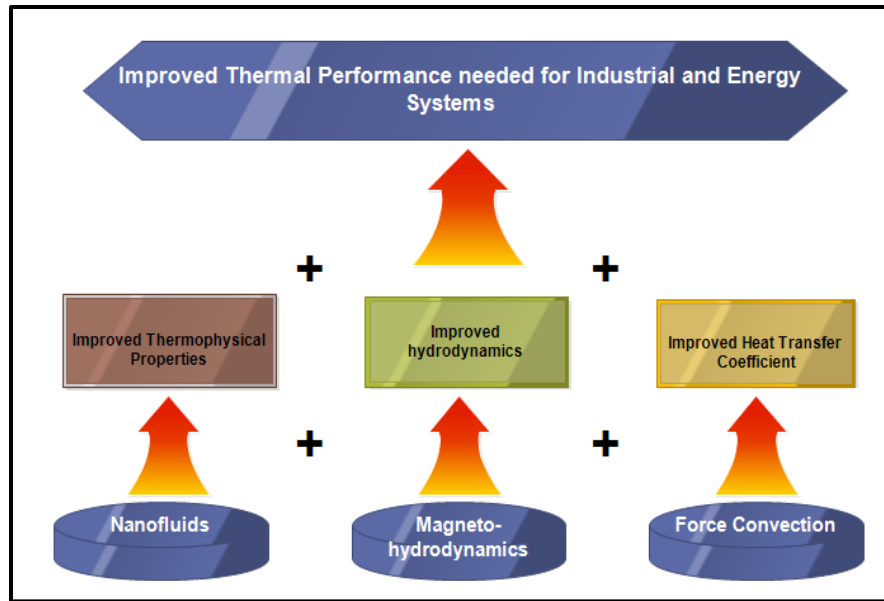


Figure 2. 2 Illustrate the significance of MHD in forced convection with nanofluids regarding heat transfer.

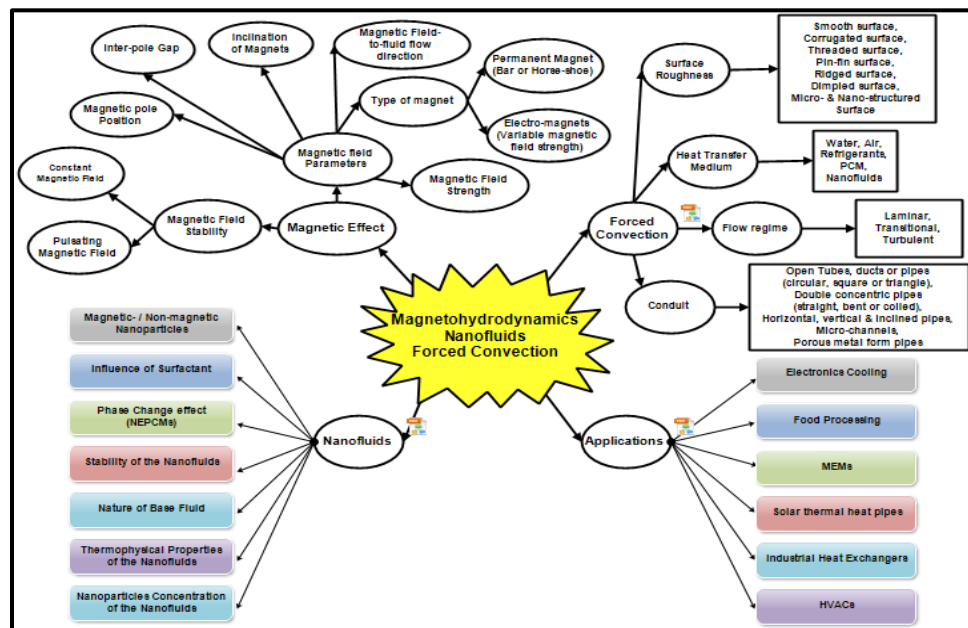


Figure 2. 3 Present a mind map detailing the aspects of MHD in forced convection with nanofluids.

2.7.2 Common impacts and phenomena resulting from MHD in nanofluids.

MHD in nanofluids can give rise to a range of important effects and phenomena that influence the behavior of these fluids. Some noteworthy impacts and phenomena of MHD in nanofluids

encompass magnetically induced motion and clustering, control and dispersion of stability, regulation of nanofluid flow, improved mass transfer, and adaptive rheology. These phenomena are elaborated upon in the subsequent sections.

2.7.2.1 Induction of nanoparticle motion and clustering by magnetic fields

When a nanofluid is exposed to a magnetic field, the magnetic forces exerted on the nanoparticles within the fluid can result in their movement, reorganization, and, at times, clustering. The motion of nanoparticles is contingent on the intensity and alignment of the magnetic field [198]. The occurrence of magnetic field-induced nanoparticle motion and clustering arises when nanoparticles in a nanofluid respond to an applied magnetic field.

Crucial factors influencing this phenomenon include the strength of the magnetic field, magnetic dipole-dipole interactions, and characteristics of the nanoparticles (such as particle size and magnetic properties) [106], [111], [123]. Notably, if appropriately controlled, this phenomenon allows for the customization of nanofluid motion and clustering patterns, proving valuable in applications like gradient materials and magnetic field sensors. In these applications, changes in the external magnetic field influence the alignment of nanoparticles, enabling their use in sensing [115], [141].

2.7.2.2 Control and dispersion of stability induced by magnetic fields

Magnetic fields play a crucial role in regulating the dispersion and stability of nanoparticles within nanofluids, ensuring consistent functionality and prolonging the shelf life, particularly in applications such as electronic cooling and thermal systems [170], [199]. The utilization of magnetic fields is essential for maintaining the dispersion and stability of nanoparticles within nanofluids, ensuring the prolonged preservation of desired properties, which holds significant implications for nanofluid technology [200]. In the realm of nanofluid technology, stability control leverages magnetic fields to uphold a uniform distribution of nanoparticles, preventing agglomeration and guaranteeing sustained performance across diverse applications [199]. Additionally, this control mechanism contributes to extending the shelf life of nanofluids, allowing for prolonged storage without significant degradation of properties [201]. Moreover, the use of magnetic field-based stability control enables precise tailoring of nanofluid properties, enhancing their adaptability and reliability in applications like thermal management, electronics cooling, and materials processing. This adaptability facilitates customized solutions for a variety of engineering challenges [202].

2.7.2.3 Control of flow induced by magnetic fields

Magnetic fields provide accurate manipulation of nanofluid flow within microfluidic devices and lab-on-a-chip systems, offering advantages in biotechnology and materials science applications. The use of magnetic fields for flow control enhances heat transfer, particularly in microfluidic devices, by guiding the movement of nanoparticles. This controlled motion enhances convection currents, resulting in more effective heat distribution and transfer [203]. In microfluidic heat exchangers, precise control of convection ensures uniform heat distribution and optimized thermal performance [204].

The application of magnetic fields can diminish heat boundary regions near solid surfaces, thereby increasing heat transfer rates at the boundaries, a critical aspect for cooling electronic devices. In the realm of heat transfer, flow control based on MHD allows for precise regulation of thermal conductivity. Engineers can dynamically adjust thermal conductivity through magnetic field manipulation, proving beneficial in applications such as heat exchangers and energy generation systems [205], [206].

2.7.2.4 Improvement in mass transfer induced by magnetic fields

As outlined by Felicia et al. [198], MHD in nanofluids introduces an innovative strategy for energy harvesting. This approach leverages the controlled motion of nanoparticles within nanofluids, induced by magnetic fields, to generate electrical power. This concept holds significant relevance for microscale applications, such as microelectromechanical systems (MEMS) and wireless sensor networks. One notable advantage is its scalability, rendering it suitable for powering small-scale devices and sensors. This scalability has considerable potential across various domains, especially for sustaining operations in remote or challenging environments where traditional power sources are impractical. The continuous movement of nanoparticles within nanofluids in ambient magnetic fields provides a reliable and renewable energy source. Moreover, this concept finds applications in energy-efficient microfluidic systems [207]. Its scalability, adaptability to challenging environments, and potential for energy-efficient microfluidic systems contribute to making it a compelling area of research with broad implications for self-powered and autonomous technologies.

2.7.2.5 Rheological response to magnetic fields

The manipulation of rheological behavior in nanofluids can be significantly achieved through the utilization of magnetic nanoparticles (MNPs) and magnetic fields. This is particularly advantageous in applications that require precise control over fluid flow, with a notable focus on microfluidic systems [208], [209]. This phenomenon allows for the meticulous adjustment of viscosity and flow characteristics, thereby enhancing control in diagnostics, drug delivery, and lab-on-a-chip technologies [210]. The implications extend to processes like inkjet and 3D printing as well as pharmaceutical drug formulation, contributing to improved process stability, product quality, and manufacturing efficiency [211]. The capacity to customize rheological properties in response to magnetic fields serves as a versatile tool with significant potential across a range of engineering and scientific disciplines.

2.7.2.6 Alignment of nanoparticles induced by magnetic fields and its influence on physical properties

The alignment of nanoparticles induced by magnetic fields is a significant phenomenon with wide-ranging implications. With the effect of magnetic fields, nanoparticles tend to align along field lines, forming linear chains or aggregates depending on the field strength and nanoparticle concentration. This alignment process allows for controlled manipulation and enhances heat transfer in various applications, including drug transport systems, cancer treatment using MRI contrast media, and energy-efficient cooling.

The fundamental principle of magnetic field-induced alignment involves the reorientation of magnetic nanoparticles in response to external magnetic fields, significantly impacting the behavior of nanofluids. Nanoparticles possess magnetic dipole moments that align with the direction of the field, resulting in magnetic alignment. This alignment occurs due to the interaction between the external magnetic field and the intrinsic magnetic properties of the nanoparticles. As a result, nanoparticles align themselves collectively along the field lines, leading to enhanced thermal conductivity, controlled motion, and the formation of clusters within the nanofluid. These effects have applications in heat transfer enhancement and sensing technology [212]. The following are important to alignment of nanoparticles.

i. **Mechanism governing alignment.**

Alignment in nanofluids induced by a magnetic field results from the torque applied to each nanoparticle, leading to the alignment of their magnetic orientations along the field lines. This mechanism, powered by the rotational force or torque acting on individual nanoparticles, culminates in the collective alignment of particles along the axis of the magnetic field. These regions of alignment are pivotal for diverse applications, including the enhancement of thermal conductivity, facilitation of controlled motion, and the creation of gradient materials. A comprehensive understanding of this torque-driven alignment is essential for effectively utilizing nanofluid properties across various technological domains[121], [141] .

ii. **Increased anisotropy**

Alignment of magnetic nanoparticles introduces anisotropy into the properties of nanofluids, signifying that certain characteristics, like thermal conductivity or electrical conductivity, become dependent on direction [119], [213] . This results in substantial improvements in properties along the alignment direction, particularly notable in heat conduction. When magnetic nanoparticles align in response to external magnetic fields, the nanofluid exhibits anisotropic behavior, where properties such as electrical and heat conductivity become sensitive to direction. This leads to significant variations depending on orientation relative to the alignment direction. For instance, thermal conductivity can experience a substantial increase along the magnetic field lines, providing significant advantages in applications requiring efficient heat transfer, such as cooling electronic devices and microchannel heat exchangers. Harnessing anisotropy through the alignment of magnetic nanoparticles enables the customization of nanofluid characteristics to meet specific engineering requirements, fostering progress in heat transfer and materials science [214], [215].

iii. **Magneto-Optical Phenomena**

The impact of magnetic alignment in nanofluids extends beyond thermal and electrical properties to encompass magneto-optical effects, influencing the interaction of the fluid with light. This opens avenues for applications in sensors and optical devices. The alignment alters the optical characteristics of the nanofluid when subjected to a magnetic field, resulting in modifications to absorption, scattering, and refractive index. These magneto-optical effects show promise in the development of high-sensitivity magnetic field sensors and optical devices such as advanced displays and adjustable lenses. Ongoing research in this field has the potential to steer the creation of innovative technologies [216], [217].

iv. **Viscosity adjustments induced by magnetic fields:**

Magnetorheological fluids (MRFs) revolutionize heat transfer in tubes, presenting dynamic and controllable solutions. Their capacity to modulate viscosity through magnetic fields enhances thermal efficiency and facilitates precise temperature control. This adjustability proves advantageous in various applications that demand meticulous control over flow rates and shear forces [180], [189], [218]. MRFs reshape heat transfer dynamics by allowing fine-tuning of fluid viscosity through manipulation of magnetic fields. This control significantly influences heat transfer efficiency, enabling viscosity increase for improved thermal contact and heat transfer, or reduction to minimize pumping power requirements, ultimately enhancing overall energy efficiency [169]. The versatility of MRFs extends to diverse scenarios, ranging from automotive cooling systems to microfluidic devices [105], [189].

v. **Pressure fluctuations induced by magnetic fields in MHD nanofluids**

In systems incorporating MHD with nanofluids, the magnitude of the applied magnetic field and the concentration of nanoparticles are critical factors influencing pressure changes. Robust magnetic fields have the potential to induce substantial particle motion and alter flow patterns, resulting in heightened pressure fluctuations [14], [17]. Elevating nanoparticle concentration amplifies the viscosity of the nanofluid, contributing to increased flow resistance and consequent elevation in pressure drops. Additionally, the velocity of the flow and the design of the system are pivotal in managing pressure fluctuations. Engineers and researchers must optimize these parameters to strike a balance between the advantages of augmented heat transfer facilitated by MHD in nanofluids and the necessity to effectively manage the increased pressure drop, ensuring efficient system operation without unwarranted energy consumption or pressure loss.

2.8 Enhanced heat transfer mechanisms in MHD nanofluids for forced convection.

The utilization of nanofluids represents a groundbreaking advancement in thermal management, leveraging the exceptional thermal conductivity of nanoparticles to augment heat transfer. Magnetic fields provide precise control over the motion and alignment of these nanoparticles within the nanofluid, resulting in more efficient heat transfer across conduction, convection, and radiation processes. This phenomenon has diverse applications, including electronics cooling and magnetic fluid hyperthermia for cancer treatment, presenting a promising strategy to elevate heat transfer efficiency. The magnetic field-induced motion of nanoparticles in nanofluids enhances thermal performance by optimizing the thermal boundary layer and reducing energy consumption

2.8.1 Reduction of the thermal boundary layer through MHD-induced motion

The motion induced by MHD of magnetic nanoparticles within nanofluids leads to a significant decrease in the thermal boundary layer near solid-fluid interfaces. This reduction enhances heat transfer rates, particularly in applications such as electronic device cooling and microchannel heat exchangers. With the effect of magnetic field, these nanoparticles align and move, effectively thinning the thermal boundary layer. This outcome contributes to energy efficiency in engineering systems, facilitating efficient heat dissipation and absorption [205]. Nevertheless, findings from studies investigated by Mahabaleshwar et al.[219] and Siddheshwar et al.[220] propose that higher magnetic force intensity and lower permeability of the surrounding medium may potentially decrease nanofluid flow and subsequently impact heat transfer performance.

2.8.2 Innovative advancements in thermal conduction

This progressive improvement in thermal conduction, propelled by the motion and alignment of magnetic nanoparticles in response to magnetic fields, finds versatile applications in heat transfer. It is particularly evident in areas such as electronics cooling, energy systems, and targeted thermal management, providing precise control and enhancing heat transfer efficiency within nanofluids. The augmented conduction in nanofluids leverages nanoparticles as highly efficient thermal bridges between fluid layers, minimizing thermal resistance and establishing pathways for efficient thermal energy redistribution within the fluid [221]. The ability to control nanoparticle motion through magnetic fields facilitates precise adjustments to thermal conduction.

2.9.1 Experimental investigation of magnetic nanofluid in forced CHT in laminar region

In experimental investigations of magnetic nanofluids in forced convective heat transfer under laminar flow conditions, researchers examine how the presence of magnetic fields affects heat transfer properties. By subjecting nanofluids to controlled flow conditions within a laminar regime and applying magnetic fields, they observe changes in heat transfer coefficients, fluid behavior, and temperature distributions. These studies provide insights into the potential of magnetic nanofluids for enhancing heat transfer in various engineering applications, including electronics cooling, energy systems, and biomedical devices.

Table 2.3 presented the overview of the empirical study of magnetic nanofluids into laminar regime.

Table 2. 3 Overview of experimental research on magnetic nanofluids in the laminar regime under steady boundary conditions, heat flux, and magnetic fields in forced convection.

Authors	Magnetic nanofluids	Flow regime/ Reynolds number range	Magnetic field structure, type direction, intensity	Mechanisms to improve heat transfer
Yarahmadi et al. (2015) [17],	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	$465 < \text{Re} < 1160$	Constant vertical non-homogeneous magnetic field ($B < 0.07 \text{ T}$) and alternating vertical non-homogeneous magnetic field ($B < 0.07 \text{ T}$; $10 \text{ Hz} < f < 50 \text{ Hz}$)	Increase in particle volume concentration and magnet frequency. Maximum 19.8% enhancement with Oscillating
Abadeh et al. (2015) .[18]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	$0 < \text{Re} < 2500$	Two stable and alternate magnetic fields of 1300 and 770 Gauss, employing four distinct styles of application.	Increase in particle volume concentration and magnetic field. Observations: Nu increased 11.85% at 10 Hz and 14.8% at 100 Hz. Frequency >1000 Hz had no benefit.
Sun et al. (2020) [19]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	$400 < \text{Re} < 2000$	Permanent magnet, 415, 700 gauss and 1.28T, 40KHz	Increasing the magnet frequency and the alternating magnetic field. Maximum 32% enhancement with 700 gauss with 28.6 gauss per millimeter magnetic field gradient.

Goharkhah et al. (2015) [20]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	$400 < \text{Re} < 2000$		Augmentation of particle volume concentration, Reynolds number, and magnetic field intensity.
Zonouzi et al. (2017) .[35]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	$580 < \text{Re} < 820$	5x10x100mm of neodymium drupole magnet, 350mT	Introducing a magnetic field yielded substantial improvements: 23.4%, 37.9%, and 48.9% higher particle concentration and enhanced local heat transfer coefficient.
Tekir et al. (2020) [33]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	1122 to 2124	Constant/Alternative magnet, B = 0T, 2T, 5T and 15Hz	Reducing Changes in magnetic field frequency yielded a 13% boost in heat transfe
Goharkhah et al. (2016) [222]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	200 to 1200	Constant vertical non-homogeneous magnetic field ($0.03\text{T} < B < 0.05\text{T}$), F= 5Hz., osillating vertical Constant vertical non-homogeneous magnetic field ($0.03\text{T} < B < 0.05\text{T}$) F5Hz	Higher particle concentration and magnet frequency raised laminar augmented convective heat transfer by 24.9% and 37.3% with constant and alternating magnetic fields, respectively, when contrasted with the absence of a magnetic field..
Mei et al. (2019) [25]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	600 to 1100	Parallel magnetic induction intensity, B= OG, 100 G, 200G, 300G	Increase in particle density and magnetic field strength. They observed that the nanofluids with x = 5.0% under magnetic induction

				intensity $B = 300\text{G}$ showed the largest resistance coefficient.
Azizian et al. (2014) . [26]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	451 to 1061	permanent magnet, constant vertical non-uniform magnetic field ($B < 0.02\text{T}$, $F = 5\text{Hz}$, 50Hz)	At a Reynolds number of 745 and 32.5 mT/mm magnetic field strength, a notable pressure increase occurred. Adjusting to 430 mT with gradients of $8.6\text{-}32.5\text{ mT/mm}$, the pressure rose by a maximum of 7.5%.
Wang et al. (2019) [27]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	0 to 1000	round hollow permanent magnet of inner dia of 39, outer dia of 62, 10mm thickness	Rising particle density and magnetic field intensity. Ferrofluids with a magnetic probe demonstrated enhancements in heat transfer of 26.5% and 54.5%.
Hatami et al. (2017) [31]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	100 to 500	Electrically powered magnet, Steady vertical homogeneous magnetic field. ($dH/dx < 9.6 \times 10^6\text{ A/m}$)	Heightened particle density and stronger magnetic field led to convective heat transfer improvement exceeding 60% with magnetic nanoparticles.
Ashjaee et al. (2015) [32]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	200 to 900	External Electromagnet, $B < 1,400\text{ G}$	Elevation in particle density and the field intensity. when a field of $1,200\text{ Gauss}$ was employed in the ferrofluid, it increased by 38%.

Sadrhosseini et al. (2016) [39]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	120 to 240	seven ferrite cores used for the magnetic field, 200 gauss. Frequency of 7.81 Hz	A magnetic field improves thermal exchange, and porous media leads to uniform temperature distribution. Among these factors, nanoparticle volume percentage significantly impacts heat transfer.
Amani et al. (2017) [223]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	100 to 1200	Constant magnet 200	Raising particle volume concentration and applying a 100 G (0.01 T) magnetic field significantly improved heat transfer, with a maximum enhancement of 5.9% at 2 wt% and Reynolds number (Re) of 200. This improvement further rose to 8.5% when the magnetic magnitude reached 200 G (0.02 T).
Ghofrani et al. (2013) [37]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	80 to 1350	Electromagnet, constant vertical non-uniform magnetic field and alternative magnet ($B < 0.02\text{T}$), $f = 5\text{Hz}, 50\text{Hz}$	Increasing particle density and magnetic field strength, they found that employing a 50 Hz alternating magnetic field improved convective heat transfer by 5% compared to no magnetic field, while a constant

				magnetic field showed no improvement.
Lajvardi et al. (2010) [38]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	0 to 265		Elevation in particle density and magnetic field intensity.
Sundar et al (2020) [11]	$\text{Fe}_3\text{O}_4/\text{Oil}$	0 to 230, Prandtl numbers 440 to 2534 and Graetz numbers 500 to 3000		Increase in particle volume concentration

2.9.2 Empirical studies of magnetic nanofluid in forced CHT in turbulent regime

In experimental investigations of magnetic nanofluids in forced convective heat transfer under turbulent flow conditions, researchers explore how magnetic fields influence heat transfer characteristics. By subjecting nanofluids to turbulent flow regimes and applying magnetic fields, they observe changes in heat transfer rates, fluid mixing, and thermal boundary layers. These studies aim to uncover the potential of magnetic nanofluids for improving heat transfer performance in turbulent flow applications, such as heat exchangers, cooling systems, and thermal management devices

Table 2.4 presented the overview of the experimental investigation of magnetic nanofluids into turbulent regimes.

Table 2. 4 Overview of experimental research on magnetic nanofluids in the turbulent regime under steady boundary conditions, heat flux, and magnetic fields in forced convection.

Authors	Magnetic nanofluids	Flow regime/ Reynolds number range	Magnetic field structure, type direction, intensity	Mechanisms to improve heat transfer
Sha et al. (2017) [16]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	4000 to 6500	orthogonal, consistent, and varying magnetic field	Increase in particle volume fraction, thermal condition, and magnetic strength.
Guzei et al. (2017) [29]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	1000 to 6000	3 permanent neodymium magnets, 0.3T	The augmentation in both particle volume concentration and the utilization of a magnetic field caused a 35% improvement in heat exchange effectiveness.
Ebaid et al. (2022) [36]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	1000 to 6000	Field magnitude (F= 15:5, 30:3, 45:5) mT	Elevated Nusselt numbers with a magnetic field led to increased average heat exchange coefficients and Nu. The improvements were 9.4%, 26.1%, 31.3%, and 8.8%, 13.1%, and 23.9%, respectively.
Asker et al. (2016)	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	2900 to 9160	constant magnetic field. magnetic intensity of (0.1, 0.2, 0.3 Tesla),	Increase in particle volume concentration and magnetic field. they gain increased to (43.9, 44.3, 46%)

Karamallah et al (2006) [224]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	2900 to 9820	a magnetic intensity of 0.1, 0.2, or 0.3 Tesla	The enhancements ranged from 5.4% to 42.7%. However, when a magnetic intensity of 0.1, 0.2, or 0.3 Tesla was applied, the Nusselt number improvement significantly increased, reaching values of 43.9%, 44.3%, and 46% for a volume concentration of 0.9%.
Zhang and Zhang(2021) [221]	$\text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	944 to 8413	Different frequencies of alternating magnetic fields spanning from 0 to 100 Hz and magnetic field strengths spanning from 0.01 T to 0.09 T	An external alternating magnetic field enhanced heat exchange at lower Re but reduced it at higher Re. Higher nanoparticle concentration and magnetic field frequency increased pressure drop, but beyond 3% volume fraction, frequency had limited impact on heat transfer. Overall, heat transfer improved within the 0–100 Hz range of alternating magnetic fields.

2.9.3 Empirical studies of magnetic hydride nanofluid into forced CHT in laminar regimes.

Experimental investigations of magnetic hybrid nanofluids in forced CHT laminar flow conditions focus on understanding how the combination of magnetic nanoparticles influences heat transfer characteristics. Researchers conduct experiments to observe the impact of magnetic fields on CHT, fluid behavior, and boundary layer dynamics in laminar flow regimes. These studies aim to elucidate the potential of magnetic hybrid nanofluids for enhancing heat transfer performance in various applications, including heat exchangers, cooling systems, and thermal management devices operating under laminar flow.

Table 2.6 presented the summary of the experimental investigation of hybrid magnetic nanofluids in the laminar regime.

Table 2. 5 Overview of experimental research on hybrid magnetic nanofluids in the laminar regime under steady boundary conditions, heat flux, and magnetic fields in forced convection

Authors	Magnetic nanofluids	Flow regime/ Reynolds number range	Magnetic field structure, type direction, intensity	Strategies for augmenting thermal efficiency
Lee et al. (2021) [105]	$\text{Fe}_3\text{O}_4/\text{MWCT}/\text{H}_2\text{O}/\text{EG}$	1000 to 1600	magnetic field intensity was adjusted to 250, 500, and 750 Gauss	The enhancement in particle volume concentration resulted observed, the maximum Convective Heat Exchange Rates exhibited increases of 2.78% and 3.23%, respectively.
Shahsavari et al. (2016) [93]	$\text{Fe}_3\text{O}_4\text{--CNTs}/\text{H}_2\text{O}$	548 to 2190	Magnetic field intensities were set at three levels: 300, 500, and 700 Gauss.	Elevating both particle density and magnetic field strength resulted the hybrid nanofluids in a maximum increase in 62.7% of the local Nu
Tekir et al. (2022) [42]	$\text{Fe}_3\text{O}_4\text{--Cu}/\text{H}_2\text{O}$	994 to 2337	constant/alternative, $B=0.3\text{T}$ At a 90-degree angle to the flow direction	Increasing the magnet frequency and the in the presence of a continuous magnetic field, the maximum convective heat exchange saw a 14% increase over the condition without a magnetic field

Shi et al. (2019) [43]	$\text{Fe}_3\text{O}_4\text{--CNTs}/\text{H}_2\text{O}$	60 to 540	The electromagnets were positioned horizontally at intervals of (0 mm, 50 mm, 100 mm, and 150 mm) while varying the rotation angles (0, 30, 60, and 120 degrees) and magnetic strengths (100, 200 , 400 , and 800 Gs).	As both particle volume concentration and magnetic field presence increased, the Mean heat exchange coefficient improved by 12.2%. Furthermore, the local heat exchange coefficient showed a remarkable increase of over 30.2% when a magnetic field was introduced.
Talebi et al. (2019) [44]	$\text{Fe}_3\text{O}_4\text{--Cu}/\text{H}_2\text{O}$	600 to 1800		As the particle volume concentration, Reynolds number, and magnetic field strength all increased, their research indicated a more substantial heat transfer enhancement with the hybrid-nanofluid, reaching 11.9%, as opposed to 7.8% for Cu/water.
Lee et al. (2021) [105]	$\text{Co} - \text{Zn} - \text{Fe}_3\text{O}_4/\text{H}_2\text{O}$	1000 to 1600	750 G magnetic field	The joint influence of increased particle volume concentration and the existence of a magnetic field led a heat exchange efficiency increase of approximately 2.64% in contrast to the situation lacking a magnetic field.

Alsarraf et al. (2019) [14]	$\text{Fe}_3\text{O}_4/\text{MWCT}/\text{H}_2\text{O}$	500 to 2000	Three sets of NdFeB permanent magnets positioned with opposing poles directed towards each other are situated on both sides of the tube to create a three-dimensional magnetic field.	As volume concentration increased, they observed substantial improvements in the average Nu by 52.54% and a remarkable 2376.4% surge in pressure drag. Furthermore, the use of a magnetic field resulted in enhancements in both Nu and pressure drop.
Sadeghinezhad et al (2017) [225]	rGO/ Fe_3O_4 /DW		NdFe Permanent magnet 1320mT	82% enhancement with the impact of permanent magnetic field
Javadpour et al (2018) [226]	Cuo/CMC/ H_2O	500-2000	Five permanent magnet with flux density of 50mT	13% enhancement with 1% volumetric ratio of nanofluid with the impact of magnetic field contrast to the situation lacking a magnetic field
Javadpour et al (2017) [227]	Cuo/CMC/ H_2O	500-2000	Five permanent magnet with flux density of 50mT	Utilizing an external magnetic field heightens nanofluid heat exchange, with a stronger influence at increased mass fractions. Nanofluids raise the annular tube's drag coefficient, with a 1% volume

				fraction yielding a 22.6% surge compared to the base fluid

2.9.4 Empirical studies of magnetic hybrid nanofluid into forced CHT in turbulent regimes.

Experimental investigations of magnetic hybrid nanofluids in forced CHT under turbulent flow conditions explore the interplay between turbulent fluid dynamics and magnetic fields. Researchers conduct experiments to observe how the presence of magnetic nanoparticles affects heat transfer rates, turbulence intensity, and flow patterns in turbulent flow regimes. These studies aim to uncover the potential of magnetic hybrid nanofluids for enhancing heat transfer performance in turbulent flow environments, which are commonly encountered in industrial heat exchangers, cooling systems, and energy conversion devices.

Table 2.6 presented the summary of the experimental investigation of magnetic hybrid nanofluids into turbulent regime.

Table 2. 6 Overview of experimental research on magnetic hybrid nanofluids in the turbulent regime under steady boundary conditions, heat flux, and magnetic fields in forced convection

Authors	Magnetic nanofluids	Flow regime/ Reynolds number range	Magnetic field structure, type direction, intensity	Mechanisms to improve heat transfer
Sundar et al (2014) [228]	Fe_3O_4 –MWCT/ H_2O /	3000 to 22000		Increase in particle volume concentration
Askari et al (2017) [13]	Fe_3O_4 –Graphene/ H_2O	2000 to 5000		Increase in Reynolds number

2.9.5 Empirical studies into forced CHT in transition regimes

Transition flow is the phase where the flow gradually shifts from a laminar state to a turbulent one, as shown in **Figure 2.3**

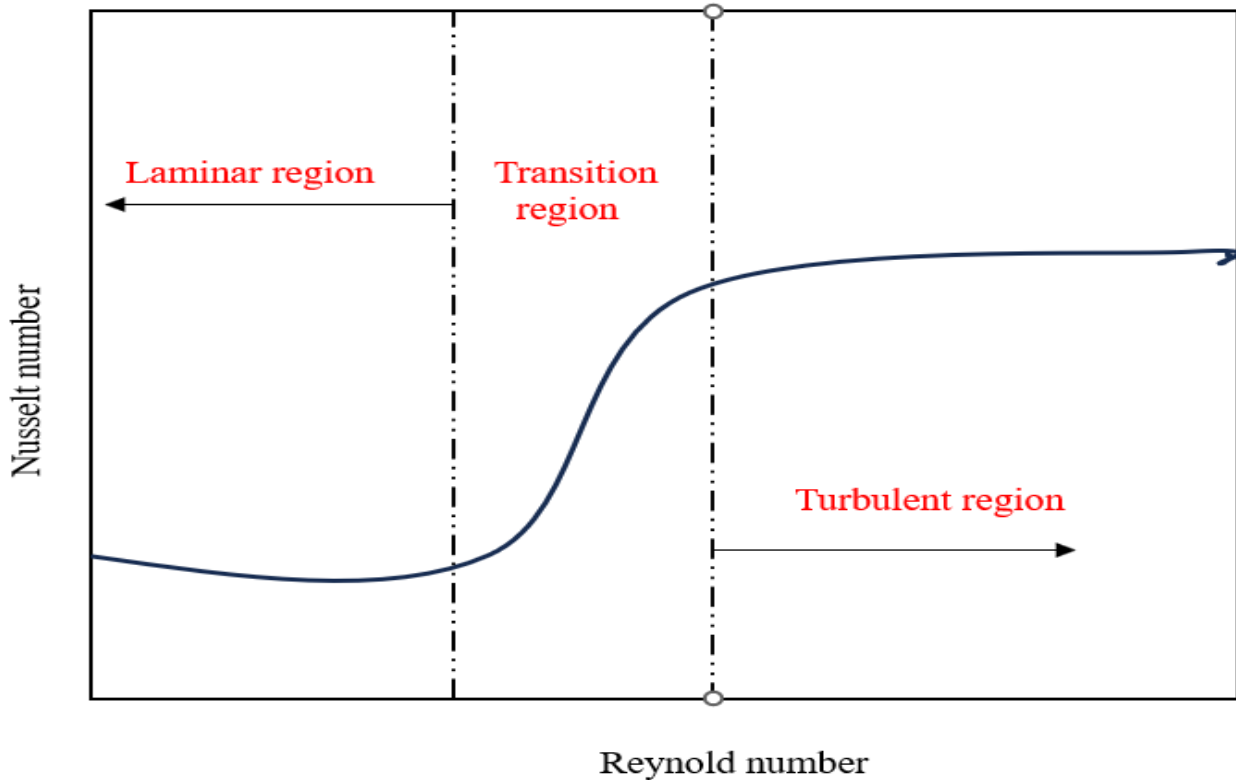


Figure 2. 4 Correlation between Nusselt number and Reynolds number to illustrate flow regimes

In the available literature, there are several documented cases where pressure drop significantly increases, accompanied by flow fluctuations, such as vortices and impulses, within the transition regime. This phenomenon has led many researchers, including those in studies by Tam et al. [229], and Tam et al. [230], to deliberately overlook this regime, citing the challenges in predicting heat transfer outcomes. They advocate for avoiding this region when designing heat exchange equipment due to the perceived complexity in obtaining reliable design data for the transitional region, as noted by Subramanian [231] and Meyer et al. [232].

As a result, design engineers commonly recommend steering clear of operating within this regime Obot et al.[233] , and Duan [234] . However, it is noteworthy that the importance of the transitional regime has gained recognition in recent years, especially with the development of enhanced tube designs. These advanced designs offer a favourable balance between heat transfer efficiency and

pressure drop, challenging the traditional advice to avoid the transition regime, as demonstrated in work by Meyer et al. [233].

Ghajar and Tam [235] pioneered the impact of inlet geometry on pressure drop during the transition phase for Re between 500 and 15,000. They identified transition flow ranges of 1980–2600 for re-entering inlets, 2070–2840 for rectangular inlets, and 2125–3200 for bell-shaped inlets. Using experimental data, they developed a correlation for predicting the friction coefficient in the transition region. Their results showed that at low laminar Re , the friction factor depended not only on (x/D) but also on the Re

Ghajar and Tam [236] investigated the impact of inlet geometry on heat transfer during mixed and forced convection. Their study focused on bell-shaped, rectangular, and re-entrant inlets under conditions of uniform heat flux. They provided data on local CHT coefficients for Re ranging from 280 - 49,000, Prandtl numbers between 4 and 158, and Grashof numbers from approximately 1,000 to 2.5×10^5 . The heat exchange Re was reported to be 2,000 and 8,500 for the re-entrant inlet, 2,400–8,800 for the rectangular inlet, and 3,800–10,500 for the bell-shaped inlet. Additionally, they formulated correlations for heat transfer coefficients applicable to both developing and fully developed flow in mixed and forced convection scenarios for the three inlet types.

Ghajar and Tam [237] studied experimentally to determine a flow regime map for a horizontal tube with constant wall heat flux with three inlet types to distinguish the mixed and forced convection region. The flow pattern applies to laminar, transitional and turbulent regimes with a constant heat flux. The map can pinpoint the influence of buoyancy at a given location (X/D) by calculating the Grashof (Gr) and Prandtl numbers (Pr) for a particular Re , and they recommended a correlation based on the experimental results.

Tam and Ghajar [238] The study evaluated the impact of heat on the coefficient of friction in the fully developed transition region, aiming to measure pressure drop using a differential pressure transducer. The experimental setup involved a straight, circular, horizontal test rig with, ball-mouth-shaped, square-edged, and re-entrant inlets constant heat flux. A mixture of ethylene glycol and water served as the working fluid in the inlet, covering an inlet Reynolds number range from 1,000 to 17,000, encompassing laminar, transient, and turbulent regimes. Results indicated transition ranges of 2900 to 3500 for the re-entering inlet, 3100 to 3700 for the rectangular inlet, and 5100 to 6100 for the funnel inlet. Examining various heat fluxes revealed that the friction

factor increased with a rise of heat rate at the same Re , attributed to secondary flows induced by heat rate. Heat rate also influenced the transition, with the high heat flux of 16 kW/m^2 causing transitions in Reynolds number ranges of 4100 to 5900 for the re-entry, 4500 to 6400 for the angle inlet, and 7300 to 9600 for the bell-mouth inlet.

Oliver and Meyer [239] The study focused on single-phase pressure drop and heat exchange in smooth tubes for transitional flows using adiabatic wells of different inlet geometries. Smooth pipes of $5/8$ inch and $3/4$ inch were employed, featuring four types of inlet: hydrodynamically fully developed, bell-shaped, edged, and re-entrant. Water served as the test fluid, with Re 1000 - 20,000, Pr between 4 and 6, and Gr with 10^5 .

Adiabatic tests demonstrated that the shift from laminar to turbulent flow was significantly influenced by the inlet profile, postponing the transition up to Re as high as 12,000. In contrast, diabatic heat transfer and friction factor measurements indicated that the transition was unaffected by the inlet design, occurring at approximately a Re of 2100. This consistency was attributed to secondary flows mitigating the inlet's impact. Laminar heat transfer and friction factors were noticeably higher than theoretical predictions, which was explained by the presence of secondary flows, as noted in previous studies. A direct correlation between the friction factor and heat transfer showed that 88% of the friction factor data could be predicted with 15% accuracy, yielding a mean absolute error of 8.7%. Additionally, they formulated correlations predicting the critical Re and fully developed pressure drop in the transition region. In a subsequent study supplementing previous inlets with hydrodynamically fully developed inlets, it was found that inlet shape did not affect the transition, initiating at a Re of 2000 and concluding at 3000 [240].

Meyer and Olivier [241] The study investigated heat transfer characteristics in smooth horizontal tubes flow in fully developing and developed in a transitional regime at steady heat flux with Re 700 to 10000 at varying heat fluxes. The researchers defined mathematical boundaries for different flow regimes, noting that the onset of transition was position-independent, occurring uniformly along the tube's length. Conversely, the transition's end was position-dependent, concluding earlier as flow approached maturity. Free convection effects influenced both the onset and termination of the transition, narrowing the Reynolds number range. Correlations predicting transition onset and end were developed for mixed convection conditions. The transition flow regime was divided into three regions, observing significant width reduction in the first region with negligible free

convection effects. In the second region, width decreased with axial position and free convection effects. In the fully developed regime, width was position-independent but narrowed due to free convection, sometimes becoming negligible. The study concluded that heat transfer properties in the developing flow of the transitional regime evolve, differing significantly from fully developed flow.

In parallel to the earlier studies [242], Meyer and Everts conducted laminar flow in mixed convection and the influence of free convection on the transition. they formulated correlations predicting the correlation between pressure drop and heat transfer in three regimes from laminar, transitional, and turbulent [243]. The same authors presented flow regime maps in a separate article. They created six distinct flow regime maps for a steady heat flux boundary and a square-edged inlet, which are considered original for several reasons. First, the maps include contour lines that depict the enhancement in the Nu due to free convection effects. Second, they cover a broad spectrum of pipe diameters and Pr. Third, these maps were formulated based on temperature differences (Gr) and heat flow (modified Gr). Lastly, four of the six maps are applicable not only to developed flow but with fully developing[244].

Meyer et al. [245] performed experiments to study the enhancement of CHT of WMCNT/DIW with a Re of 1,000 - 8,000 at a steady heat flux, spanning the transient flow region. The WMCNT with outer size of 10–20 nm, an inner size of 3–5 nm and a length of 10–30nm. Comparing the data on a Re and -Nu plot, it was found that heat transfer was improved.

Chougule and Sahu [246] They experimentally investigated the CHT properties of AL_2O_3/H_2O and CNT/ H_2O in the transition region with helically twisted tape inserts in the tube with helical tape inserts with twist ratio (TR) = 1.5, 2.5, and 3. Their results showed that the heat exchange efficiency of both fluids increases with increasing particle volume fraction. The CNT/ H_2O nanofluids flow via helical screw tape inserts show higher thermal efficiency compared to AL_2O_3 /water nanofluid. Furthermore, they found that the maximum improvement in heat transfer was obtained by using CNT/ H_2O nanofluid (1%) with helical screw tape inserts with a twist ratio of 1.5 at all twist ratios of helical screw tape inserts, the pressure drops for AL_2O_3 nanofluid with helical screw tape inserts is higher compared to CNT nanofluid.

Naik et al. [247] tested CuO-propylene glycol nanofluid with volume fraction of 0.05, to 0.5%. The study were performed in a smooth tube with spiral inserts with an aspect ratio of 0 to 9 for the Re of 2,500 -10,000. The increase in Nu at 0.5% volume fraction was 28% greater in a smooth tube and improved 5.4 times greater than the base liquid using a three aspect ratio spiral liner. In contrast, the resistance to flow rose by 10% for the smooth tube and by 140% for the spiral insert. Osman et al. [45] experimentally studied the CHT in the transition phase of Al_2O_3/H_2O nanofluids in a rectangular shape with volumetric ratio of 0.3, 0.5, and 1vol% and a Re 200-7000, which was used to correlate measured resistance to flow and temperature to evaluate CHT coefficients, Nu and pressure loss coefficients. Their outcomes showed improvements in CHT for the nanofluids. In addition, the 1.0% nanofluid exhibited the greatest improvements, with increases of 54% in the transitional phase and 11% in the turbulent phase. It was noted that the CHT performance in the transition flow regime surpassed that of both the turbulent and laminar phase. In another study by the same investigators to evaluate the effect of inlet boundary and Boundary Layer Chopping (BLC) in a smooth horizontal tube [248], they compared the hydrodynamic length inlet. The outcomes revealed that BLC inlet due to the sharp flow cutting inlet at Re 2100 cause the transition to occur earlier. while it was delayed at the hydraulic development length to Re of 2900, but no effect on the tails of the transition as well as the laminar and turbulent one's flow regime.

Sharma et al. [249] experimentally investigated the heat transfer coefficient and the friction factor of Al_2O_3 /water nanofluid in a tube with twisted tape inserts in the transition region. At a volumetric ratio of 0.1% Al_2O_3/H_2O nanofluid shows a 23.7% higher heat transfer performance compared to H_2O at Re 9000. The highest resistance to flow is with twisted ribbon at a volumetric ratio of 0.1% nanofluid is more that of water flowing in a smooth pipe. The authors reported the increase in pressure drop behavior of Al_2O_3/H_2O nanofluid compared to water at the same twist ratio.

Osman et al. [250] experimentally studied the impact of highly porous nickel foam on the transitional phase to study the CHT and resistance to flow in a rectangular duct. They found that the friction coefficient values were 24.5 times higher compared to the empty test rig, and the Nu increased by three times when nickel foam was used, as opposed to when no foam was present. Additionally, in the foam-filled section, no transient flow regime was observed in either heat transfer or pressure drop results. In contrast, the laminar-to-turbulent transition occurred in the section without foam. The thermal performance results for the foam-filled section showed that the

thermal factor remained greater than one throughout the entire Re 2000-6500, with a more favorable thermal factor at lower Re.

Ma et al. [251] experimentally studied the CHT in the transition flow region with magnetic nanofluid of Fe_2O_4 dispersed in water with volume concentrations of 0.05, 0.16 and 0.24% and a Reynolds number in the range of 2500 - 5000. They found that the average heat transfer coefficient of the magnetic fluid Fe_2O_4 showed no improvement. On the other hand, they observed that the local heat transfer coefficient in the outlet region showed a modest improvement and then stabilized in the developed regime.

Li et al. [62] experimentally investigated the forced convection heat transfer coefficients of zinc oxide/ethylene/glycol–water (ZnO/EG-W) nanofluid flowing through a circular pipe from laminar to transition and turbulent regime with different volume concentration of 0 to 5 wt.% and with a range of Re 1000-6000. Their experimental results reviewed that the maximum CHT of the magnetic nanofluid was 30% higher compared with the base liquid at volumetric ratio of 2.5 wt.%, then at a higher volume concentration of 5 wt.% they noticed a decreased in the heat exchange coefficient. In addition, they observed the maximal enhancement of the heat transfer were at the highest nanoparticles concentration. Furthermore, the measurements of the resistances to flow of the magnetic nanofluid was greater than the base liquid in the turbulent phase.

Ibrahim et al.[252] conducted an experiment explored the influence of particle size on entropy and exergy characteristics in a hybrid nanofluid (Al_2O_3 -MWCNT) in transitional flow. Four particle sizes were tested (Al_2O_3 : 20 nm, 5 nm; MWCNT: <7 nm, 30–50 nm). Three nanofluids (0.3 vol%) were prepared with different size combinations. The nanofluid with Al_2O_3 (20 nm) and MWCNT (<7 nm) demonstrated superior performance, achieving 54.12% exergy efficiency at turbulent Reynolds number 4500 and 47.85% in the transitional regime. In the transitional regime, it reduced frictional entropy by 6.78% and thermal entropy by 13.53% compared to Al_2O_3 – MWCNT with the small nanoparticles size. The study recommends a larger sample size for conclusive results and exploring different nanoparticle sizes in future hybrid nanofluid investigations.

Ibrahim et al. [253], investigates how different nanoparticle sizes affect the heat transfer properties of hybrid nanofluids in the transitional flow regime. Four distinct particle sizes were utilized to create hybrid nanofluids consisting of Al_2O_3 and MWCNT nanoparticles (5 nm and 20 nm for Al_2O_3 , and <7 nm and 30–50 nm for MWCNT). Three hybrid nanofluids with varying particle combinations of 60:40 of 0.3vol%. The results indicate that nanoparticle sizes have a significant

impact on the convective heat transfer properties of the nanofluids. Different critical Reynolds numbers were observed for each fluid along the transition region. Among them, the Al_2O_3 (20 nm) – MWCNT (<7 nm) combination exhibited superior heat transfer performance, with a Nusselt number enhancement of approximately 48.86% in the transition region. Furthermore, its coefficient of thermal performance (COP) outperformed that of the other combinations, showing enhancements of 43.53% and 21.89% compared to Al_2O_3 (20 nm) – MWCNT (30–50 nm) and Al_2O_3 (5 nm) – MWCNT (<7 nm) nanofluids, respectively. Additionally, its friction factor and pressure drop were lower than those of the Al_2O_3 (5 nm) – MWCNT (<7 nm) nanofluid by 5.2% and 12.78%, respectively. The study concludes that nanoparticle sizes influence heat transfer properties and other flow characteristics in the transitional regime for hybrid nanofluids composed of Al_2O_3 and MWCNT at a 60:40 ratio.

Table 2.7 presented the summary of the experimental investigation of magnetic nanofluids into transition phase.

Table 2. 7 Overview empirical studies of FCHT in transition phase with MNFs with steady heat flux boundary and magnetic fields

Authors	Magnetic nanofluids	Flow regime/ Reynolds number range	Mechanisms to improve heat transfer
Me et al (2013) [251]	$\text{Fe}_3\text{O}_4\text{--}/\text{H}_2\text{O}$	2500 to 5000	Increase in particle volume concentration
Askari et al (2016)[13]	$\text{Fe}_3\text{O}_4\text{--EG}/\text{H}_2\text{O}$	1000 to 6000	Increase in volume fraction

2.10 CONCLUSION

The literature review explores research focused on enhancing heat transfer through magnetic nanofluids, addressing multiple factors that contribute to this improvement. These factors include flow patterns, Brownian motion, thermal conductivity, viscosity, particle density, the heat capacity of base fluids, size, and shape, along with the thermal conductivity of the surfactant layer. The review emphasizes the importance of the fabrication process for producing effective magnetic nanofluids, discussing various fabrication techniques found in the literature.

Additionally, it examines the thermal conductivity of magnetic nanofluids under the influence of magnetic fields, presenting both theoretical and experimental studies, including thermal conductivity models and empirical correlations. The topic of viscosity is also covered, considering experimental and theoretical findings on magnetic nanofluids. The review provides a comprehensive analysis of CHT in magnetic nanofluids across laminar, transition, and turbulent regimes, reporting the observed improvements in heat transfer. However, it highlights that the transition flow regime remains underexplored, with limited studies on heat transfer enhancement and pressure drops in this region.

Beyond magnetic nanofluids, the review delves into the interaction of magnetohydrodynamics (MHD) with forced convection in nanofluids, focusing on their response to magnetic fields and their potential in heat transfer applications. The review outlines fundamental principles, experimental methods, key studies, and practical applications of nanofluids and MHD. By consolidating this information, it aims to encourage further exploration and innovation in thermal management and energy efficiency through MHD-driven nanofluids in confined conduits.

Despite the significant research on nanofluids for efficient heat transfer, a notable gap remains in understanding the combined effects of Fe_3O_4 nanoparticles and other hybrid nanomaterials in turbulent and transition regions, particularly in the presence of magnetic fields during internal forced convection.

CHAPTER 3

Methodology

3.1 Introduction

This chapter provides a comprehensive overview of the experimental setup, equipment specification, utilized to measure the essential data for the detailed evaluation of MHNFs. The methods employed in conducting the experiments are outlined, offering insights into the methodology. The data analysis approach is explained to demonstrate the methodology employed in calculating the Nu friction and CHT coefficients derived from first principles. The precision of the instruments is outlined, and a summary of the expected uncertainties is provided. Additionally, specifications for the circular copper tube employed in the second part of the test are provided, and the description of the electromagnetic field used in the experiments is included.

3.2 Descriptions of experimental setup

It consists of a flow circuit that includes a thermal bath, test rig, a flow meter, a reservoir, and pump. The experimental setup consists of a copper tube with a heating element wrapped around it to maintain a steady heat flux, or an annular space for steam to circulate around the tube, ensuring a steady wall temperature for precise control. The temperature sensors are placed at equal intervals along the tube to measure the wall temperature. An electromagnet generates the magnetic field, which is aligned with the flow direction. The heat transfer coefficient is determined by measuring both the wall and exit temperatures of the tube. The dimensionless Nu is calculated from the heat exchange coefficient and analysed for potential enhancements in heat transfer. Various factors, including structure of the MNPs, volume fraction, size, and shape, as well as the direction and intensity of the magnetic field and its application, can influence heat transfer performance.

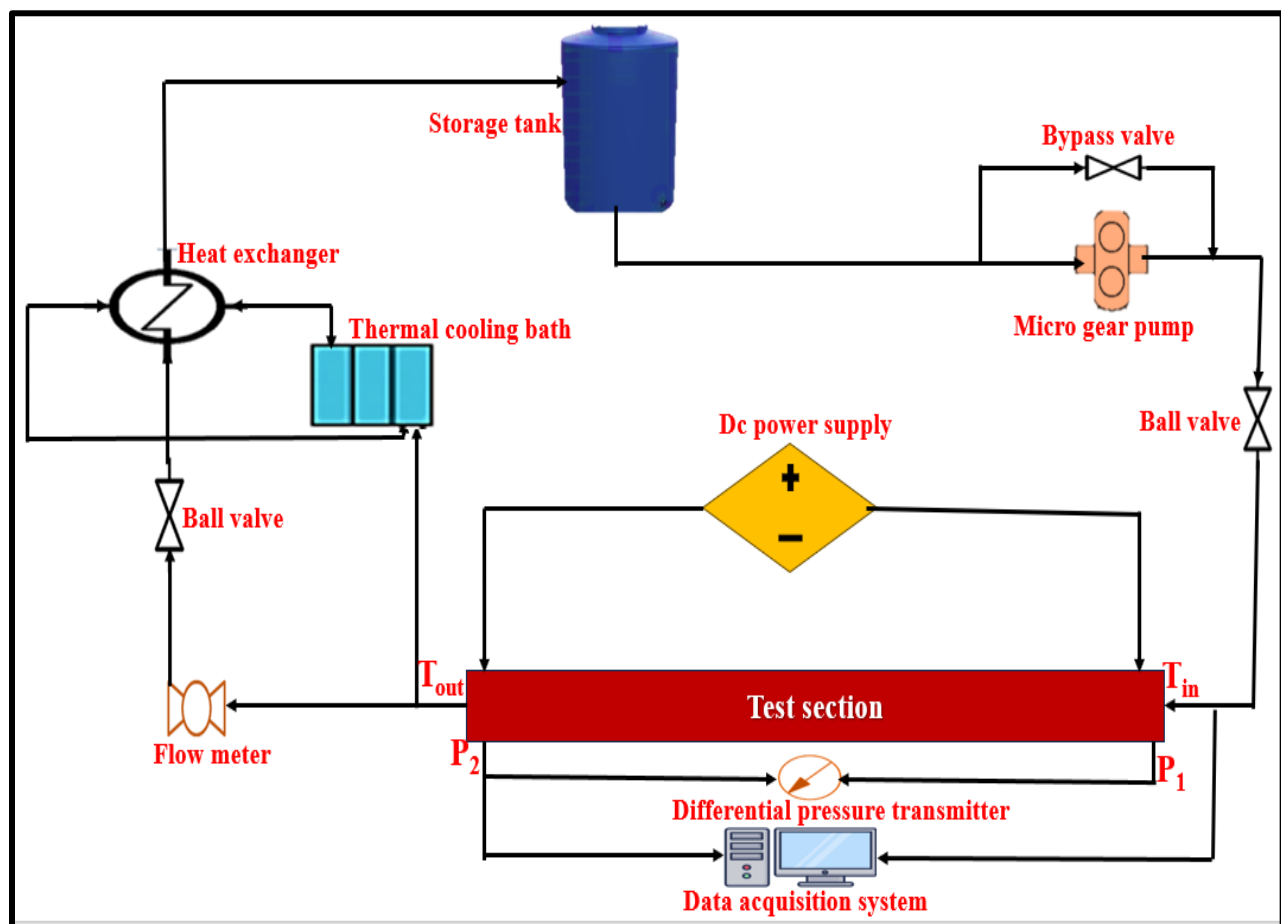
Figure 3.1(a) and (b) displays the experimental configuration and pictorial view for investigating CHT of the MHNFs. The setup comprises essential components such as data acquisition system, a tube-in-tube heat exchanger, reservoir, a DC power supply, a flow meter, a test rig, temperature sensors, pressure sensor, and a micro gear pump. The system is designed with a heating wire made up of Constantine that is coiled around the test rig to deliver heat, In order to reduced heat loss insulation was used. the configuration of the test section utilized in this investigation., it featured an internal diameter of 8 mm and an external diameter of 9.5 mm. The entire test section is composed of a hydrodynamic entry portion 500 mm, a heat transfer

examination segment with 1000 mm length, and a mixer. These segments are segregated by acetal bushes, strategically employed to thermally insulate the mixer and inlet sections from the heat transfer examination segment. Acetal functions as an effective insulating material, preventing axial conduction from the heat transfer examination segment.

To ensure a uniform temperature distribution, a mixer was affixed at the outlet of the test section, post the acetal bush, this design ensures the thermal layer undergoes multiple splits and mixes, resulting in a uniformly distributed temperature across the cross-section.

Additionally, at the commencement and termination of the heat transfer examination segment two pressure taps were affixed. These taps, spaced 1 meter apart, possess an internal diameter of 4 mm.

(a)



(b)

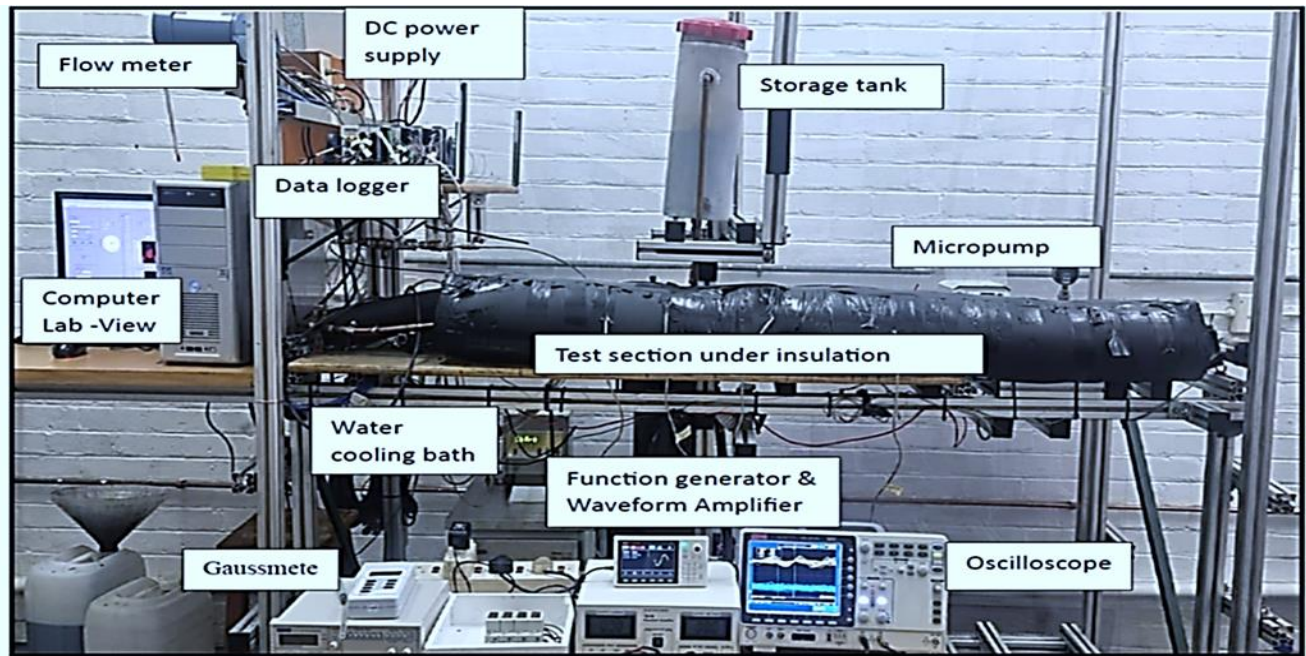


Figure 3. 1 (a) Schematic diagram of experimental set up (b) Pictural of test section

Magnetic hybrid fluids with different weight percentages are circulated at steady at 20°C, via tube, with their mass flow rate evaluated with flow meter. To maintain a constant temperature, fluids are cooled by flowing through a heat exchanger, where heat is transferred to circulating cold water. The data collection devices collects and processes signals from several instruments, such as temperature sensors, pressure sensors, the power supply, and flow meters.

In Figure 3.2, the experimental setup includes a 1500 mm long circular copper pipe with a diameter of 8 mm on the inside and 9.5 mm on the outside. Four thermocouples are strategically positioned at 130 mm intervals around the pipe's circumference, aligned with the four cardinal points to measure the wall temperatures. Temperature readings are also taken continuously at both the input and output of the nanofluid. A 200 W constantan wire generates a steady heat flux, powered by a DC supply that delivers 180 V and 1.22 A with the heat power calculated as $P = IV$. The first 500 mm of the tube ensures fully developed hydraulics, while the remaining 1000 mm section is used to assess heat transfer under steady-state conditions. Data accuracy is maintained through the repetition of experiments three times, and calculations utilize the average wall temperature.

An acetyl brush was employed to segregate the development region from the test reg , preventing any heat transfer loss to axial process. The hydrodynamic inlet length was applied to guarantee

that the flow achieved full hydraulic development in the flow. The tube length was calculated following the methodology outlined by Cengel [254].

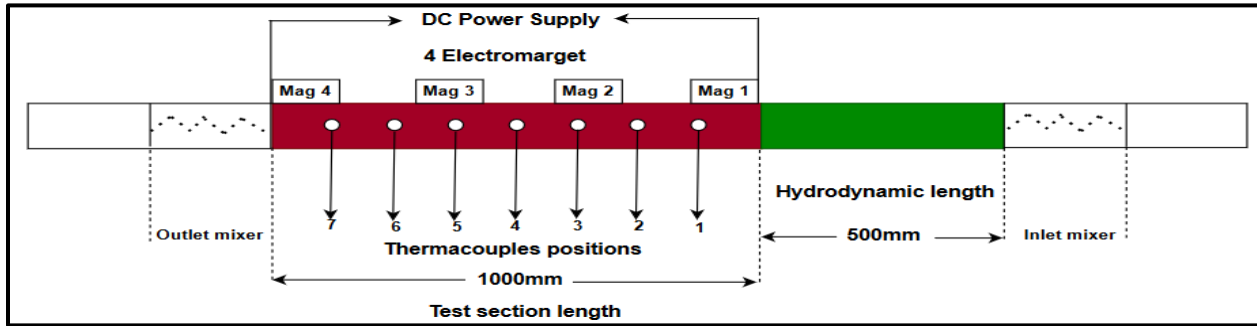


Figure 3. 2 Schematic diagram of test section

3.3 Instruments

In the experimental study of forced CHT using MHNFs in turbulent and transition regimes, a variety of specialized instruments and equipment are employed to ensure accurate and reliable data collection. These instruments are critical for monitoring fluid properties, controlling experimental conditions, and measuring heat transfer characteristics.

3.3.1 Pressure sensors

The pressure drop was measured using a pressure transducer with an accuracy of 0.08% of full scale, with the full-scale range set at 17 kPa. Calibration was performed using a water manometer with a precision of 2.5%, obtaining seven calibration points for accuracy. The differential pressure transducer was employed to measure pressure drops within the smooth tube during the transition and turbulent flow regimes, with pressure drops ranging between 20 Pa and 580 Pa. To accommodate this range, a number 20 diaphragm, capable of measuring up to 860 Pa, was chosen. The transducer's accuracy was 0.25% of its full-scale value.

For calibration, a water manometer with a 50 Pa accuracy was used. The calibration setup involved a thin rubber capillary tube connecting two columns. Water was added to the longer column, and the tap was closed to allow water to flow into the shorter column until the water levels equalized. The manometer reading was zeroed, and the transducer amplifier was adjusted to display approximately 4 mA in the LabVIEW program. The tap was then reopened to achieve a manometer reading close to 17 kPa, just above the maximum test pressure of 580 Pa. This calibration procedure was repeated three times to minimize hysteresis effects. The final LabVIEW reading for 600 Pa was recorded at 13.16 mA.

3.3.2 Flow device

A Coriolis flow device with a highest flow rate of 4.17 L/min was used to calculate the flow.

3.3.3 Power source

The power source was supplied was provided by direct current (DC) rated at 800 Watts to heat the coil with the highest voltage used was 180 voltages with 1.22 Ampere.

3.3.4 Data collection devices

The data collection devices comprised a system equipped with National Instruments LabVIEW software, which was utilized to capture data from temperature sensor, pressure gauges (for pressure drop measurements), and flowmeters (to monitor mass flow rates). Additionally, the system logged the pump provide the values of the mass flow rate readings.

3.4 Examination method

The procedure began with the activation of the pump. The testing fluids was introduced into the tank, and the system's valves were adjusted to allow the liquid to circulate through the test rig and associated equipment, and then return to the tank. Stable conditions were typically achieved after 30 to 40 minutes, depending on the experimental setup, and were confirmed when measurements of temperature, pressure drop, and flow rate remained stable for 30 seconds. Stability was confirmed when the flow rate measurements, pressure drop, and temperature did not change for 60 seconds. After reaching this steady-state, a series of data, from the input and output pressure sensors, flow rate and all temperatures sensors were recorded. With total of 200 data were gathered at one-second intervals. Following this, the flow rate was reduced, and the same procedure was repeated. More data points were collected in the transition flow regime, as the reduction in flow velocity was less pronounced in the turbulent or laminar phase.

3.5 Determination of the nature of the electromagnetic field before experimental evaluation

This experimental study focuses on optimizing heat transfer in magnetic hybrid nanofluids (MHNFs) through the application of electromagnetic fields. The investigation begins by identifying key parameters influencing the magnetic field, such as the type, strength, and orientation of the field. A magnetic field sensor is calibrated to ensure precise measurements, and the field is characterized in terms of both strength and direction.

The study explores strategies for aligning the magnetic field with the fluid flow, emphasizing the importance of uniform distribution, and achieving optimal field intensity. Additionally, the influence of various magnetic field waveforms, such as sine, triangular, and square waves, is investigated to understand their effects on nanoparticle alignment and heat transfer properties.

Practical considerations are addressed, including real-time monitoring and the selection of waveform parameters like frequency, amplitude, and duty cycle. The experimental approach systematically examines these variables to uncover their impact on heat transfer performance.

The study also delves into the energy efficiency implications of different waveform configurations, providing strategies to optimize magnetic field waveforms for improved heat transfer while minimizing energy consumption. By considering factors such as frequency, amplitude, duty cycle, real-time monitoring, temperature control, adaptive strategies, and feedback mechanisms, the research offers a comprehensive framework for achieving energy-efficient heat transfer enhancement in MHNFs.

3.6 Experimental setup for controlled magnetic field to improve heat transfer performance.

The apparatus utilized to enhance heat exchange in MHNFs consists of a meticulously assembled set of advanced tools. Core devices of the system include an Accel Instruments TS250 Waveform Amplifier, a UNI-T UT900E series (Signal Generator), a Digital Storage Oscilloscope (IDS-2000A series), and electromagnets measuring 220 mm in length, 46 mm in width, and 29 mm in depth. A Gaussmeter GM08 is employed to measure magnetic field strength, while a distribution box provides controlled connectivity across the setup.

The system operates on two voltage levels, 12V and 24V DC, with a maximum current draw of 250 mA. The electromagnets are arranged in parallel and powered by the waveform amplifier, which acts as the central energy source. The IDS is used to track and display current and voltage waveforms, linked to the amplifier's output. Meanwhile, the signal generator enables fine-tuned adjustments to waveform properties such as frequency, duty cycle, and period. This generator is linked to the amplifier's input, allowing dynamic control over waveform parameters during operation. The waveform amplifier's output is directed to a distribution module, enabling independent control of four electromagnets. These electromagnets are carefully arranged along the test section to provide full coverage across all seven thermocouple stations, as illustrated in **Figure 3.3**.

To begin magnetic field measurements, waveform parameters, including triangular, square, sine waveforms, are adjusted in accordance with **Table 3.1**. Once the system stabilizes, the magnetic field is activated and synchronized with a constant heat flux to maintain uniform conditions for evaluating heat transfer performance.

By employing this advanced arrangement of instruments, the experimental setup ensures meticulous regulation and observation of magnetic field characteristics, facilitating an in-depth and accurate examination of heat transfer improvements in MHNFs.

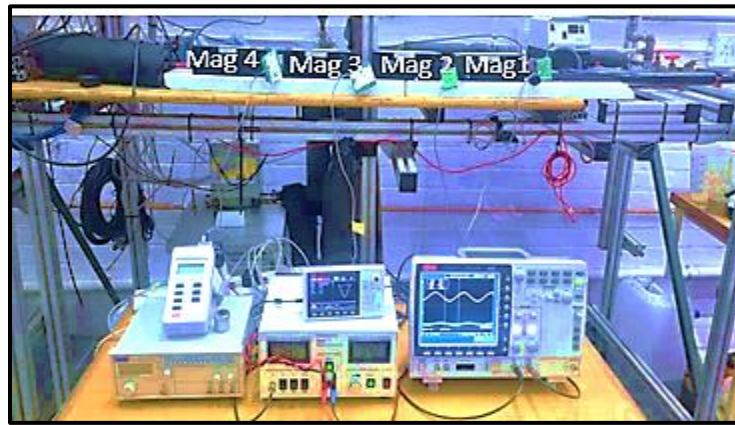


Figure 3. 3 Magnetic field generation and control setup for enhanced heat transfer

Table 3. 1 Magnetic field characteristics and associated evaluations

Waveforms	Voltage (V)	Duty cycle	Frequency (Hz)	Periods (Ms)	Phase
Triangular	2	50%	40	16.67	90°
Square	4		60	12.5	
Sin	6		80	10.0	
	8		100	20.0	
	12		500		
			1000		

3.7 Conclusion

In conclusion, the experimental setup featured a carefully designed test section, optimized for accurate measurements and minimal heat loss. The test track included a pipe insulated with 1000 mm of thermal material to minimize heat dissipation. A heating cable, delivering a consistent

power output of 50 W per meter, was wrapped around the pipe, ensuring a uniform heat flux of $q = 8.7 \text{ kW/m}^2$ on the pipe surface. This design facilitated efficient heat transfer while maintaining thermal consistency throughout the experiments.

Instrumentation played a critical role in the setup. Seven equally spaced T-type thermocouples were affixed along the pipe's surface to capture surface temperature variations. Additionally, four T-type thermocouples were positioned at the inlet and outlet sections to monitor the fluid temperature, enabling an accurate calculation of temperature gradients and heat transfer rates. A high-precision cooling water bath with a 1.5 kW power output ensured a stable inlet fluid temperature, maintaining consistency across all experimental runs. Calibration of thermocouples and pressure transducers was conducted meticulously to minimize measurement errors, enhancing the reliability of the results.

To evaluate the effect of magnetic fields on CHT performance, the study employed various magnetic field waveforms with controlled voltage and frequency. This approach allowed the investigation of different magnetic field intensities to identify optimal conditions for heat transfer enhancement in magnetic hybrid nanofluids.

CHAPTER 4

ANALYSIS AND VERIFICATION OF THE EXPERIMENTAL SYSTEM

4.1 Introduction

The initial section of this chapter outlines the methodologies for data processing and the equations utilized in the calculations. Additionally, it includes the outcomes of the instrument uncertainty assessment and the evaluation of key parameters. The concluding section presents the validation findings, comparing heat transfer and pressure drop measurements for water to well-known prediction reported in existing literature.

4.2 Data processing

Data reduction is a crucial step in the experimental investigation of magnetic hybrid nanofluids, especially in the context of FCHT in turbulent and transition region. This process involves the systematic analysis and interpretation of raw data collected during experiments to derive meaningful insights and conclusions.

4.2.1 Pressure drop

The value of interest when analysing the flow rate in a pipeline is the pressure drop Δp , as it is directly related to the power required by the fan or pump to maintain the flow rate. We have it as show in Equation 4.1.

$$\frac{dP}{dx} = \frac{P_2 - P_1}{L} = -\frac{\Delta P}{L} \quad (4.1)$$

It should be noted that in fluid dynamics the pressure drop P is a positive quantity and is defined as $\Delta P = P_2 - P_1$. In practice, the pressure drops conveniently expressed for all types of internal flow (laminar or turbulent flow, round, or non-circular tubes, smooth or rough surfaces) as shown in Equation 4.2

$$\Delta P = f \frac{L}{d} \frac{\rho V_m^2}{2} \quad (4.2)$$

where the dimensionless quantity f is the friction factor (also called Darcy friction factor) and V_m is the average velocity of the fluid, d is the duct diameter and ρ is the density of the fluid.

$$f = \frac{\Delta P}{\left(\frac{L}{D_i}\right) \left(\frac{\rho v^2}{2}\right)} \quad (4.3)$$

4.2.2 Heat transfer

The bulk temperature refers to the average temperature of a fluid in a system or flow channel, often used in heat transfer and fluid dynamics analysis. It represents the mean temperature of the fluid at a specific cross-section of a pipe or channel and is calculated based on the temperature distribution across the fluid. The bulk temperatures, T_b , of the water of each experiment temperatures as estimated as follow:

$$T_b = \frac{T_i - T_e}{2} \quad (4.5)$$

The heat recovered from water (Q_{water}) as a function of measured inlet temperature (T_i) and measured outlet temperature (T_e), which is calculated specific heat of water (C_p). For all experiment performed at a specific volumetric Reynolds number, the heat transfer rate (Q_{water}) to water and it was determined based on the measured water mass flow rate, the water temperature rise in the inlet T_i and outlet T_e measurements, and the specific heat capacity C_p was determined at the bulk temperature as estimated as follow:

$$\dot{Q}_w = \dot{m} C_p (T_e - T_i) \quad (W) \quad (4.6)$$

where T_e and T_i are the average temperatures of the fluid entering and leaving the tube, respectively, and $\dot{Q}_w$ is the rate of heat transfer into or out of the fluid, the temperature of the fluid flowing through the tube remains constant whether is no energetic interaction across the tube wall.

The heat produced by the heating wire (Q_{Elect}), along with the voltage (V) and current (I) measured across the wire.

$$\dot{Q}_{Elect} = VI \quad (4.7)$$

Energy balance (EB) can be evaluated in equation 4.7.

$$EB = \left[\frac{\dot{Q}_{Elect} - \dot{Q}_{water}}{\dot{Q}_{Elect}} \right] \times 100 \quad (4.8)$$

Thermal conditions at the surface are usually approximated with reasonable accuracy as constant surface temperature (constant T_s) or constant surface heat flux (constant q_s). The mean temperature (T_m), in contrast, is a simple average over the spatial domain and doesn't account for variations in fluid velocity.

The condition of constant surface heat flux is met when the tube is subjected to uniform resistive or radiant heating in all directions. The surface heat flux is estimated as follow:

$$\dot{q}_s = h_x(T_s - T_m) \quad (\text{W/m}^2) \quad (4.9)$$

where h_x is the local heat transfer coefficient and T_s and T_m are the surface area and mean temperature of the fluid at a station located at x distance.

The average temperature T_a of the liquid flowing through the tube must change during heating or cooling. Therefore, if h_x is constant, the surface temperature T_s must vary when $\dot{q}_s$ is constant and the surface heat flux $\dot{q}_s$ must vary when T_s is constant.

Therefore, for constant surface heat flux, $\dot{q}_s$ the rate of heat transfer can be estimated as follow:

$$\dot{Q} = \dot{q}_s A_s = \dot{m} C_p (T_e - T_i) \quad (\text{W}) \quad (4.10)$$

Therefore, the mean fluid temperature at the tube exit is estimated as follow:

$$T_e = T_i + \frac{\dot{q}_s A_s}{\dot{m} C_p} \quad (4.11)$$

the mean temperature of the fluid increases linearly in the direction of flow at constant surface heat flux, since the surface area increases linearly in the direction of flow (A_s is equal to the constant perimeter multiplied by the tube length)

The surface temperature for a constant surface heat flow $\dot{q}_s$ can be estimated as follow:

$$\dot{q}_s = h(T_s - T_m) \quad T_s = T_m + \frac{\dot{q}_s}{h} \quad (4.12)$$

The surface temperature T_s will also increase linearly in the direction of flow since h is constant and thus $T_s - T_m$ is equal to a constant for a fully developed region.

To evaluate the average CHT coefficient ($h_{average}$), the local heat exchange coefficient (h_x), at each thermocouple point is determined by Equation 4.13

$$h_x = \frac{\dot{q}_s}{T_s - T_m} \quad (4.13)$$

The $h_{average}$ is calculated from the local CHT coefficient at each temperature sensors point in the test rig as shown below in the Equation 4.14

$$h_{aveg} = \frac{h_{(x1)} + \dots \dots \dots h_{(xn)}}{n} \quad (4.14)$$

The average Nu for a fluid flow in internal condition can be evaluated using average $h_{average}$, the tube diameter, and the thermal conductivity of the fluid (k) as shown in Equation 4.15

$$Nu = \frac{h_{aveg} D}{K} \quad (4.15)$$

Re is used to predict the flow patterns in different flow conditions and internal flow in pipe is evaluated as with the properties measured by the fluid bulk temperature as shown in Equation 4.16

$$Re = \frac{4\dot{m}}{\pi DL} \quad (4.16)$$

The Prandtl number (Pr) can be define as a function of the specific heat capacity, dynamic viscosity, and the thermal conductivity of the fluid as shown in Equation 4.17.

$$Pr = \frac{C_p \mu}{K} \quad (4.18)$$

4.3 Analysis of measurement uncertainty

The approach outlined by Dunn [255] was applied to determine the uncertainties related to both measured and derived parameters, ensuring evaluation at a 95% confidence level. Comprehensive details of this uncertainty's evaluation are provided in **Appendix B. Table 4.1** outlines the precision specifications of the instruments utilized, including bias errors considered in the analysis, along with their operational ranges and precisions. Calculations of uncertainties were performed at a maximum Re of 7800 and a minimum Re of 650. The resulting uncertainties values for key experimental parameters are summarized in **Table 4.2**.

Table 4. 1 Scope and precision of instruments

Equipment	Rang	Precision
Power supply Current Voltage	0–12.45 A 0–319 V	0.49% of the measured value 0.1% of the determined value
Temperature sensors	200–350 °C	0.11 °C
Flow device	0–252 L/h	0.11%
Pressure sensors	0–17 kPa	0.24%

Table 4. 2 Recorded variables at elevated and low Re.

Properties	Re	ΔP	f	h	Nu	Bulk temperature	$\dot{q}$	$\dot{m}$
High Re	2.145%	1.15%	18%	2.49%	3.69%	0.727	3.49%	0.20%
Low Re	1.09%	0.3%	2.0%	1.35%	2.45%	0.437	3.49%	1.97%

4.4 Verification of the test setup

The measurements of coefficients of friction and Nusselt numbers made it feasible to evaluate the experimental results against theoretical predictions, the data obtained for both laminar and turbulent flow conditions were graphed and contrasted with well-known prediction reported in the literature. DIW was used for validation due to lack of correlation for hybrid magnetic nanofluids like those used in this work.

4.4.1 Verification of Nusselt number findings of laminar phase

The empirical data obtained in the laminar phase is contrasted with predictions developed by Sieder and Tate (1936), Ghajar and Tam (1994) [236], Shah and London (1987)[256] and Palen and Taborek (1985) [257], as outlined in Table 4.3. Figure 4.6 presents the study data comprising 40 data points within the Re 800 to 2,200. Upon comparing the prediction of Sieder and Tate (1936), Ghajar and Tam (1994), and Palen and Taborek (1985), it was observed that the Sieder and Tate (1936) correlation consistently underestimates the data, averaging 28% below with the highest deviation of 35%. Ghajar and Tam (1994) also exhibit an underestimation, averaging 51% below with a highest deviation of 57%. Conversely, Palen and Taborek (1985) [257] tends to overestimate the data, presenting an average deviation of 64% above with a highest deviation of

17%. Sieder and Tate's (1936) correlation, developed for both heating and cooling scenarios, does not account for mixed convection effects. The discrepancy in predictions arises because heating induces effects opposite to those observed during cooling. Specifically, heating causes the liquid in the near wall region to be less viscous than in the centre, resulting in higher fluid velocity near the wall.

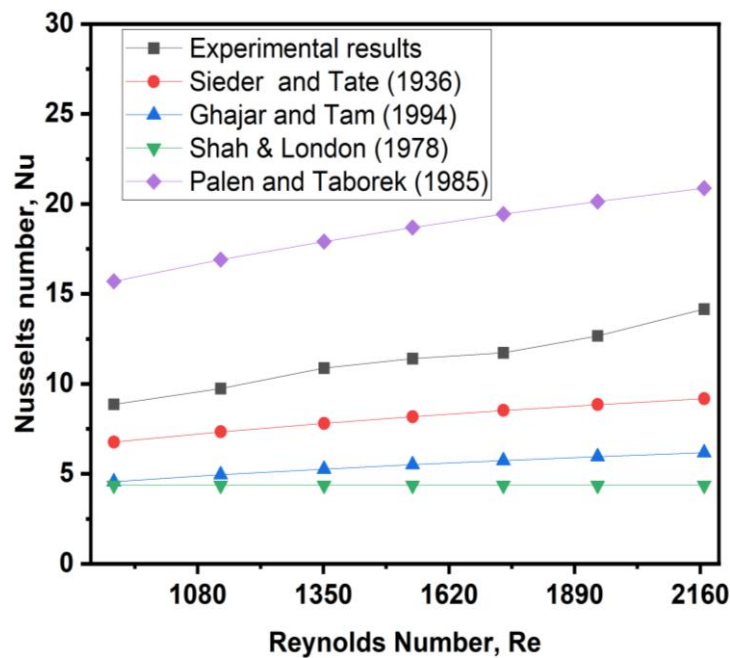


Figure 4. 1 Comparison of laminar heat transfer results for water with literature data

Table 4. 3 Laminar Nusselt number correlation

Author(s)	Correlation	Boundaries	Percentage deviation
Sieder and Tate (1936) [258]	$Nu = 1.86 \cdot Gz^{1/3} \cdot \left(\frac{\mu_b}{\mu_w}\right)^{0.14}$	$1000 \leq Re \leq 2000$ $0.7 \leq pr \leq 17600$ $0.01 \leq \frac{\mu_b}{\mu_w} \leq 10$	$\pm 20\%$
Ghajar and Tam (1994)[236]	$Nu = 1.24[Gz + 0.025(Gr \cdot pr)^{0.75}]^{1/3} \cdot \left(\frac{\mu_b}{\mu_w}\right)^{0.14}$	$280 \leq Re \leq 3800$ $40 \leq pr \leq 160$ $1.2 \leq \frac{\mu_b}{\mu_w} \leq 3.8$	-16.9% to +15.4%
Shah and London (1987)[256]	$\frac{Nu + 1}{5.364 \left[1 + \left(220 \frac{Z^*}{\pi} \right)^{\frac{-10}{9}} \right]^{\frac{3}{10}}} = \left[1 + \left(\frac{\frac{\pi}{(115.2Z^*)}}{\left\{ 1 + \left(\frac{pr}{0.0207} \right)^{\frac{2}{3}} \right\}^{\frac{1}{2}} \left\{ 1 + \left(\frac{220Z^*}{\pi} \right)^{\frac{-10}{9}} \right\}^{\frac{3}{5}}} \right)^{\frac{5}{3}} \right]^{\frac{3}{10}}$		Uncertain
Palen and Taborek (1985) [257]	$Nu = 2.5 + 4.55(Re^* D/L)^{0.37} Pr^{0.17} \left(\frac{\mu}{\mu_w}\right)^{0.14}$ $Re^* = Re + 0.8Gr^{0.5} \exp\left(\frac{-42}{Gr^2}\right)$	$0 \leq \frac{L}{D} \leq \infty; 0.1 \leq Re \leq 2000;$ $20 \leq pr \leq 10^4$ $0 \leq Gr \leq 10^7 \leq \frac{\mu}{\mu_w} \leq 3.8$	$\pm 30\%$

4.4.2 Verification of Nu findings in the turbulence phase

Experimental data in a state of turbulence is juxtaposed with correlations established by Gnielinski, [259], Sieder and Tate [260], and Dittus and Boelter [261]. Table 4.4 presents the formulated correlations along with their respective limitations for reference and analysis.

Figure 4.8 illustrates heat exchange results from 27 data points within the turbulent flow range, specifically for a Re span of 3,000 to 10,000. A comparison of correlations established by Gnielinski (1976), Sieder and Tate (1936), and Dittus and Boelter, is presented in **Figure 4.7**. Notably, Sieder and Tate tend to overpredict, averaging an 11.9% deviation with a maximum of 15%. Gnielinski, on the other hand, exhibits an average overprediction of 3.7%, peaking at 8%. Dittus and Boelter demonstrate an average underprediction of 13.5%, with a highest deviation of 5.6%, Sieder and Tate's (1936) correlation, formulated over 70 years ago for Reynolds numbers below 10,000, shows poor in predicting current study data. Nevertheless, the Gnielinski correlation provided predictions that were in even closer alignment with the experimental data. In summary, despite some specific correlations exhibiting discrepancies, the study values in the turbulent phase generally correspond favorably with existing literature.

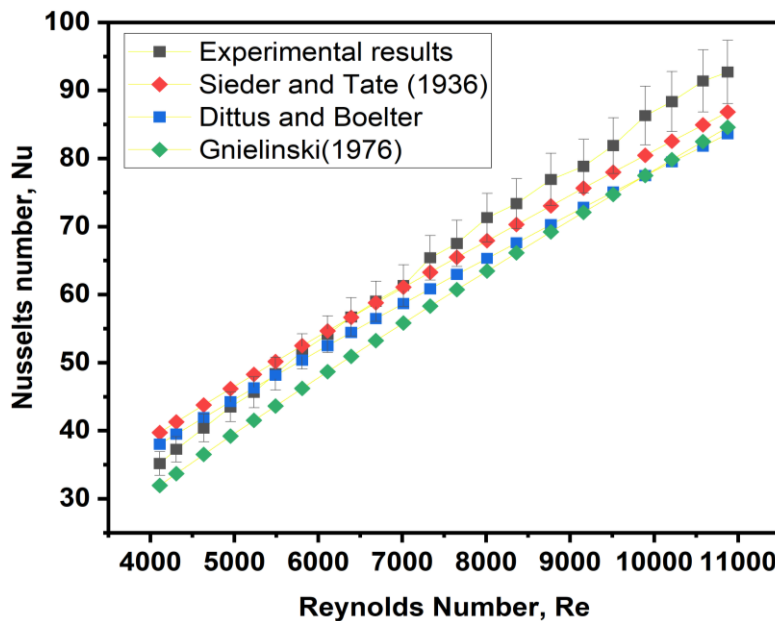


Figure 4. 2 Comparative analysis of experimental data and predictive models in relation to Reynolds number

Table 4. 4 Turbulence Nusselt number correlation

Author(s)	Correlation	Boundaries	Percentage deviation
Sieder and Tate (1936) [258]	$Nu = 0.027 \cdot Re^{0.8} Pr^{1/3} \cdot \left(\frac{\mu}{\mu_w}\right)^{0.14}$	$Re \geq 10,000$ $0.7 \leq pr \leq 17600$	$\pm\%$
Ghajar and Tam (1994)[236]	$Nu = 0.023 \cdot Re^{0.8} Pr^{0.385} \cdot \left(\frac{x}{D}\right)^{-0.054} \left(\frac{\mu}{\mu_w}\right)^{0.14}$	$7000 \leq Re \leq 49000$ $4 \leq pr \leq 34$ $3 \leq \frac{x}{D} \leq 192$ $1.1 \leq \frac{u_b}{u_w} \leq 1.7$	-10.3% to + 10.5%
Olivier and Meyer (2009) [239]	$Nu = 0.026 \cdot Re^{0.788} Pr^{1/3} \cdot \left(\frac{\mu}{\mu_w}\right)^{0.14}$	$3000 \leq Re \leq 17800$ $3.73 \leq pr \leq 5.06$	$\pm 20\%$
Gnielinski (1976) [259]	$Nu = \frac{(f/8)(Re-1000)pr}{1+12.7(f/8)^{0.5}\left(pr^{\frac{2}{3}}-1\right)}$ $f = (0.79 \cdot \ln \cdot Re - 1.64)^{-2}$	$3000 \leq Re \leq 5 \times 10^6$ $0.5 \leq pr \leq 2000$	uncertain
Dittus and Boelter (1933) [261]	$Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4}$	$\frac{x}{D} \geq 60, 0.7 \leq Pr \leq$ 120 and $Re \geq 10,000$	

4.4.3 Average Nu relative to Re of entire flow regime

Figure 4.8 displays experimental outcomes depicting the average Nu relative to Re across the complete flow range. This comprehensive representation encompasses 40 data points and is juxtaposed with by Gnielinski (1976), Sieder and Tate (1936) Dittus and Boelter, predictions for both laminar and turbulent phase.

The transition from laminar to turbulent phase began at a Re 2400 and continued until reaching 3100 in this specific test section. Upon comparing this transition in the test section with that observed in a circular one, It is evident that the transition occurred sooner than predicted by theoretical models, like the one put forward by Cengal et al [8], which usually suggests the transition phase begins at a critical Re of about 2300. Moreover, Additional studies by Ghajar and Tam [236], Nagendra et al.[262], and Meyer and Oliver [240], examined various factors, including test rig,inlet configuration, fluid properties, transition length, design, and heat flux, in the context of water flow. These factors may have different implications when applied to nanofluids. Nanofluids, due to their distinct thermal and rheological properties such as higher thermal conductivity and possible changes in viscosity can exhibit different transition behavior compared to conventional fluids like water. As such, the findings from these studies serve as a useful foundation, but the specific impact of these factors on nanofluids remains an area of active investigation in this study. Therefore, it is evident that the transition to turbulence can be influenced by a combination of these factors, rather than adhering strictly to theoretical predictions. The observation from the graph indicates a strong alignment between the experimental data and the published correlations, affirming a noteworthy correlation between the datasets.

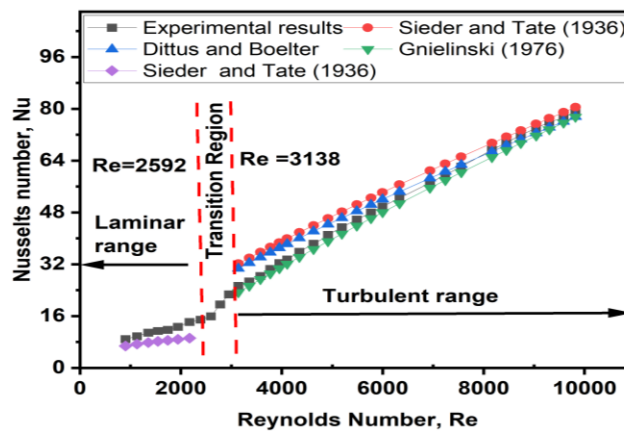


Figure 4. 3 Relationship between Nusselt number and Reynolds number across entire flow spectrum

4.5 Conclusion

The experimental setup was thoroughly described, offering a detailed account of the equipment and instruments utilized in the experiment. The measurement protocols for a wide range of parameters were carefully outlined, enhancing the overall understanding of the experimental approach. The reliability of the setup was confirmed by comparing results from both laminar and turbulent flow regimes against established correlations from the literature, effectively validating the experimental findings.

In the laminar regime, deviations ranged from 28% to a minimal value, highlighting the precision and accuracy of the unit. In the turbulent phase, the average deviation of 3.6% further reinforced the consistency and reliability of the experimental system. These findings confirm the experimental unit's ability to accurately investigate pressure drop characteristics and heat transfer within the transition phase for both DIW and MHNFs.

CHAPTER 5

PREPARATION OF MHNFs AND PROPERTIES ANALYSIS

5.1 Introduction

This section serves as an introduction to the properties and characteristics of NPs materials, laying the foundation for an in-depth exploration. The preparation processes of Fe_3O_4 , TiO_2 and $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids, as well as the magnetic hybrid nanofluids comprising are meticulously discussed. Subsequently, the chapter delves into the assessment of nanofluid stability through both viscosity measurements and visual examination conducted over time.

The discussion extends to the methodologies employed for assessing stability and involves an exploration of the temporal evolution of viscosity, providing valuable insights into the dynamic behavior of the nanofluids. Both qualitative visual inspection and quantitative measurements contribute to a comprehensive understanding of the stability characteristics inherent in the nanofluids. Towards the conclusion of the chapter, attention is directed towards the evaluation and discussion of the thermal properties of the nanofluids. This involves a systematic analysis of the methods utilized for evaluating thermal properties and a thorough examination of the outcomes. By addressing both stability and thermal properties, this chapter sets the stage for a more detailed exploration and analysis in subsequent sections of the study.

5.2 Nanoparticle size and properties

The nanoparticles used in this study were selected based on their unique thermophysical and functional characteristics, which are crucial for enhancing the performance of MHNFs in heat transfer applications. Fe_3O_4 (20–30 nm) nanoparticles, with a purity of 95.5%, were chosen for their strong magnetic properties and excellent thermal stability. These characteristics enable the nanofluids to respond dynamically to external magnetic fields, allowing precise control over heat transfer processes. The nanoscale size of Fe_3O_4 ensures a high surface area, improving both suspension stability and convective heat transfer.

Titanium dioxide (TiO_2) was employed in two particle size variations, 18 nm and 60 nm, with purities of 99.9% and 99.8%, respectively, to study the impact of particle size on heat exchange performance. TiO_2 is renowned for its chemical stability, large specific surface area, and high thermal conductivity, making it an excellent candidate for enhancing thermal efficiency while maintaining resistance to chemical degradation. Magnesium oxide (MgO) nanoparticles, with a

size range of (20–40 nm) and a purity of 99.9%, were incorporated due to their exceptionally high thermal conductivity and low density. These properties enable significant heat transfer enhancement without substantially increasing the fluid's viscosity, thereby maintaining manageable pumping power requirements.

Zinc oxide (ZnO) (20 nm) nanoparticles, with a purity of 99.5%, were included for their high thermal conductivity, stability, and ability to improve particle dispersion in hybrid nanofluid formulations. ZnO also minimizes agglomeration and sedimentation, ensuring long-term suspension stability. By combining Fe_3O_4 with non-magnetic nanoparticles such as TiO_2 , MgO, and ZnO, the study leveraged the synergistic effects of these materials to achieve enhanced thermal performance, improved stability, and optimized flow properties. This hybrid approach exploits the unique attributes of each nanoparticle, resulting in a balanced and effective enhancement of heat transfer and rheological behavior.

These specific nanoparticle sizes were provided by the manufacturers. The particles of ZnO and TiO_2 were acquired from Houston, Texas, USA (Nanostructured and Amorphous Materials Inc. and US Research Nanomaterial Inc). Gum Arabic (GA), obtained from Sigma-Aldrich in Berlin, Germany, with a purity of $\geq 98.5\%$, was used as a surfactant to improve the homogenous of the MHNFs. The thermal characteristics of both the base fluid and the NPs used in the study are detailed in **Table 5.1**.

Table 5. 1 Properties of NPs Materials.

Properties	DIW	Fe_3O_4	TiO_2		MgO	ZnO	Dispersant
			18nm	60nm			
Density (kg/m^3)	997	4950	4175	4230	3580	100-200	Gum Arabic
Thermal conductivity (W/m.k)	0.613	80.4	8.4	8.4	43	29	
Specific Heat capacity (J/kg.k)	4179	670	692	-	903	-	
Shape	-	Plate-like nanosheet	Spherical	Spherical	Spherical	Spherical	

5.3 Nanoparticle size volume fraction used in the study

Two distinct MHNFs, comprising a hybrid of $\text{Fe}_3\text{O}_4/\text{TiO}_2$, and of Fe_3O_4 and MgO dispersed in DIW were employed during this study. The examination of these nanofluids encompassed a comprehensive investigation across seven different concentrations, spanning from 0.3%, 0.2%, 0.1%, 0.05%, 0.025%, 0.0125% and 0.00625%. The thermal characteristics of both the base fluid and the NPs used in the study are detailed in **Table 5.1** provide the material characteristic and parameters, which were gathered from the product specifications supplied by the respective manufacturers. This systematic exploration of various concentrations and the accompanying thermal properties serves as a foundational aspect of the study, contributing valuable insights into the behavior and performance of the nanofluids under consideration.

5.4 Preparation of MHFs nanofluids

The process for preparing MHNFs preparation follows a multi-step procedure. In the first step, the nanoparticles are measured by combining Fe_3O_4 were mixed with TiO_2 , MgO , and ZnO . Specifically, the compositions were 80% Fe_3O_4 and 20% TiO_2 , 60% Fe_3O_4 and 40% MgO , and 40% Fe_3O_4 and 60% ZnO . Initially, in the first step, the nanoparticles are weighed with wight balance with an accuracy of ± 0.01 g (Radwag AS 220.R2, Radom, Poland,). In the second step, a surfactant, Gum Arabic, is added in a 0.75 weight ratio to enhance nanoparticle stability. The third step involves dispersing the nanoparticles, where they are first blended using a mechanical stirrer and then ultrasonically dispersed in deionized water (DIW) for 4 hours using a Qsonica Q-700 Ultrasonicator, applying 5-second pulses with 2-second pauses. Step four controls the dispersion temperature, keeping it at 20°C with a thermal bath (LAUDA ECO RE1225). In the final step, the MHNFs are prepared with concentration 0.00625 vol % - 0.3vol%, after which their stability and thermophysical properties are evaluated. A diagram illustrating this procedure is shown in **Figure 5.1.**, and **Equation 5.1** [263] is used for calculating the nanoparticles.

To ensure the stability of the MHFs, we closely monitored key parameters such as pH, electrical conductivity, viscosity, and thermal conductivity at different temperatures. This monitoring commenced immediately after the sonication process and continued for one week at various temperature settings. Additionally, a follow-up assessment was conducted a month later to assess the long-term stability of the magnetic hybrid ferrofluids (MHFs).

$$\varphi = \left(\frac{Y_{Fe_3O_4} \left(\frac{W}{\rho} \right)_{Fe_3O_4} + Y_{TiO_2} \left(\frac{W}{\rho} \right)_{TiO_2}}{Y_{Fe_3O_4} \left(\frac{W}{\rho} \right)_{Fe_3O_4} + Y_{TiO_2} \left(\frac{W}{\rho} \right)_{TiO_2} + \left(\frac{W}{\rho} \right)_{DIW}} \right) \quad 5.1$$

The ultrasonication process was for 4 hours, employing a applying 5-second pauses with 20°C to maintain the temperature.

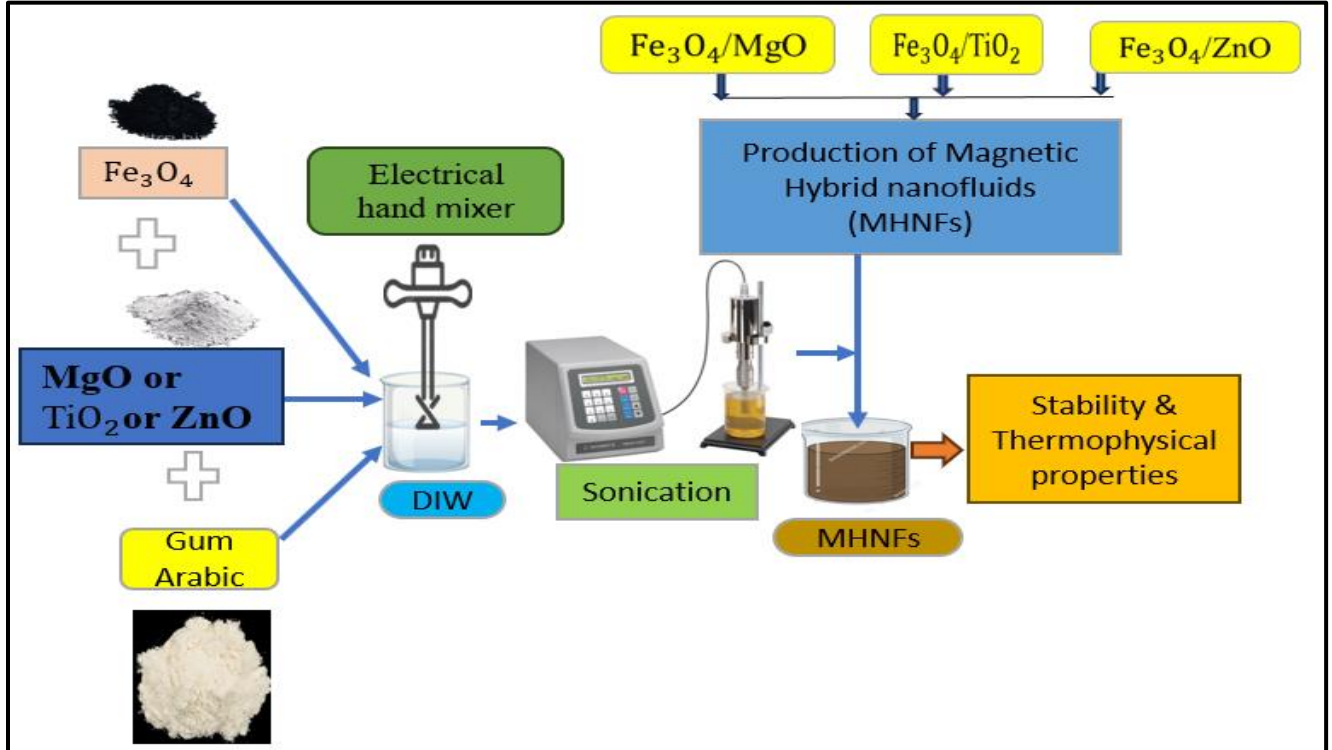


Figure 5. 1 Flow diagram of the MHNFs preparation process

5.5 MHNFs assessment and stability

MHNFs assessment and stability" signifies a systematic approach to understand, measure, and ensure the enduring quality and reliability of MHNFs in different condition, contributing to informed decision-making and sustainable applications.

MHNFs assessment and stability refers to the comprehensive examination and determination of the characteristics and robustness of MHNFs (potentially referring to a material or a system). In this context, the term assessment indicates a thorough evaluation of various properties, while stability highlights the ability of MHNFs to maintain their desired qualities over time and under various conditions.

This process typically involves rigorous testing, analysis, and observation to ensure a clear understanding of the material or system's behavior, performance, and reliability. Assessing MHNFs encompasses factors such as structural integrity, chemical composition, and functional properties. Stability, on the other hand, assesses the material or system's ability to withstand environmental factors, changes, and potential stresses without compromising its intended functionality.

5.5.1 Stability and morphology of MHNFs

A detailed examination of the nanoparticle morphologies was carried out using a Zeiss Crossbeam 540 scanning electron microscope with a field emission gun (FEG-SEM) at the University of Pretoria's Microscopy Department. The investigation into nanoparticles containing Fe_3O_4 , TiO_2 (18nm), TiO_2 (60nm), MgO and ZnO nanoparticles respectively, and the combination of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ and $\text{Fe}_3\text{O}_4/\text{MgO}$. The research involved a comprehensive analysis of the structural characteristics of these nanoparticles, with a specific focus on examining their morphology. Prior to imaging with the FEG-SEM, careful samples preparation of the NPs was performed. **Figure 5.1**. The TEM images depicted in **Figure 5.2**, illustrate the morphological characteristics of the Fe_3O_4 , TiO_2 (18nm), TiO_2 (60nm), MgO and ZnO nanoparticles were imaged were magnified at 100,000x, with voltage of 2.0 kV and a scan rate of 9 $\mu\text{m/s}$. **Figure 5.2** (a) displays the Fe_3O_4 , nanoparticles, revealing a combination of large and small dispersed plate-like nanosheets. On the other hand, **Figures 5.2(b)-(e)** depict the TiO_2 (18nm), TiO_2 (60nm), MgO, and ZnO nanoparticles, all of which exhibit a spherical shape. While **Figure 5.3** Morphological result of the TEM for a hybrid of **(f)** $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm), **(g)** $\text{Fe}_3\text{O}_4/\text{MgO}$, & **(h)** $\text{Fe}_3\text{O}_4/\text{ZnO}$.

The observed morphological characteristics and the successful suspension of nanoparticles in the nanofluid are crucial factors in understanding the stability and overall behavior of the nanofluid, contributing to the broader understanding of its potential applications in various fields.

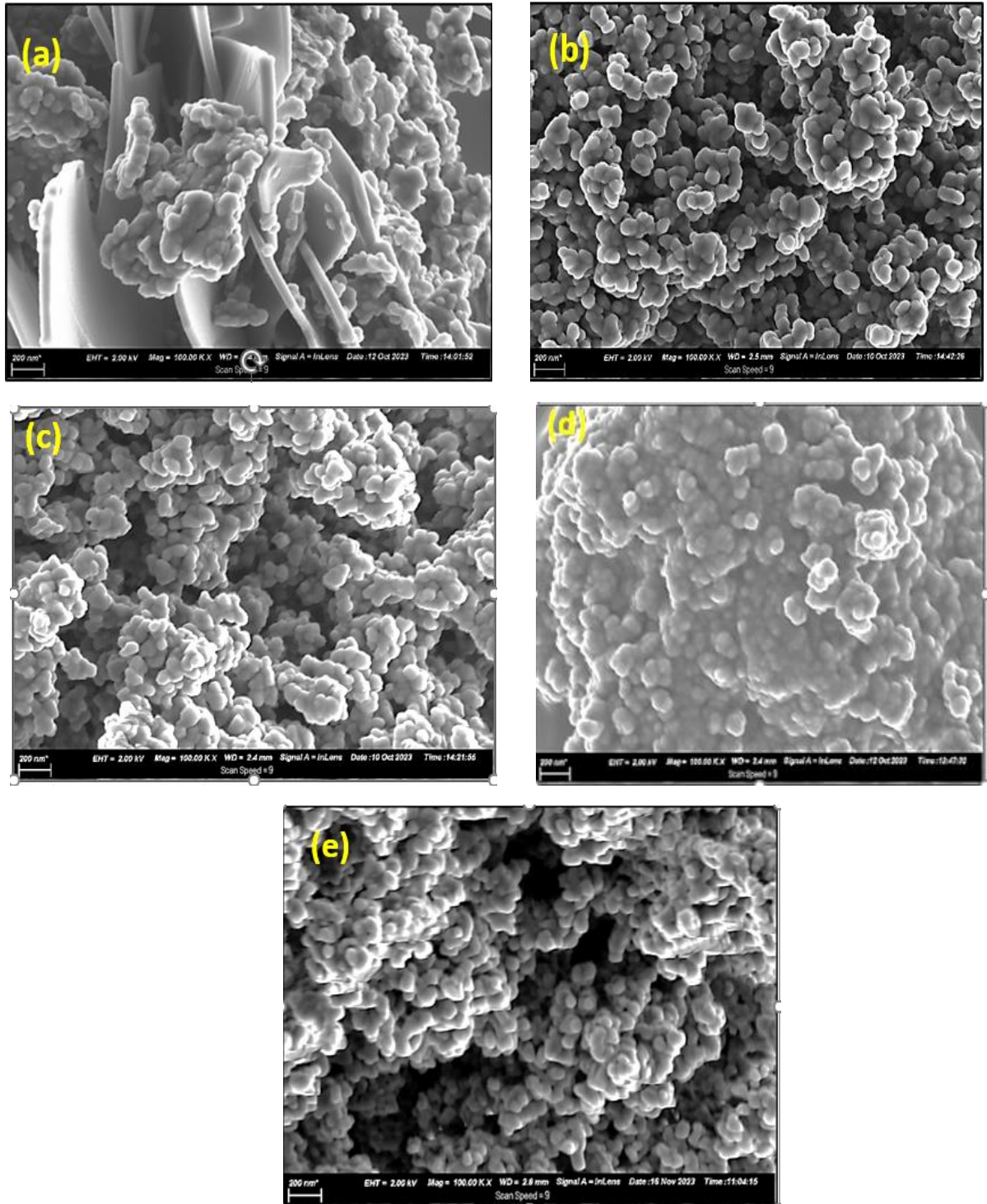


Figure 5. 2 Morphological Result of the SEM (a) (a) Fe₃O₄ (b) TiO₂ (18nm), (c) TiO₂ (60nm), (d) MgO, & (e) ZnO

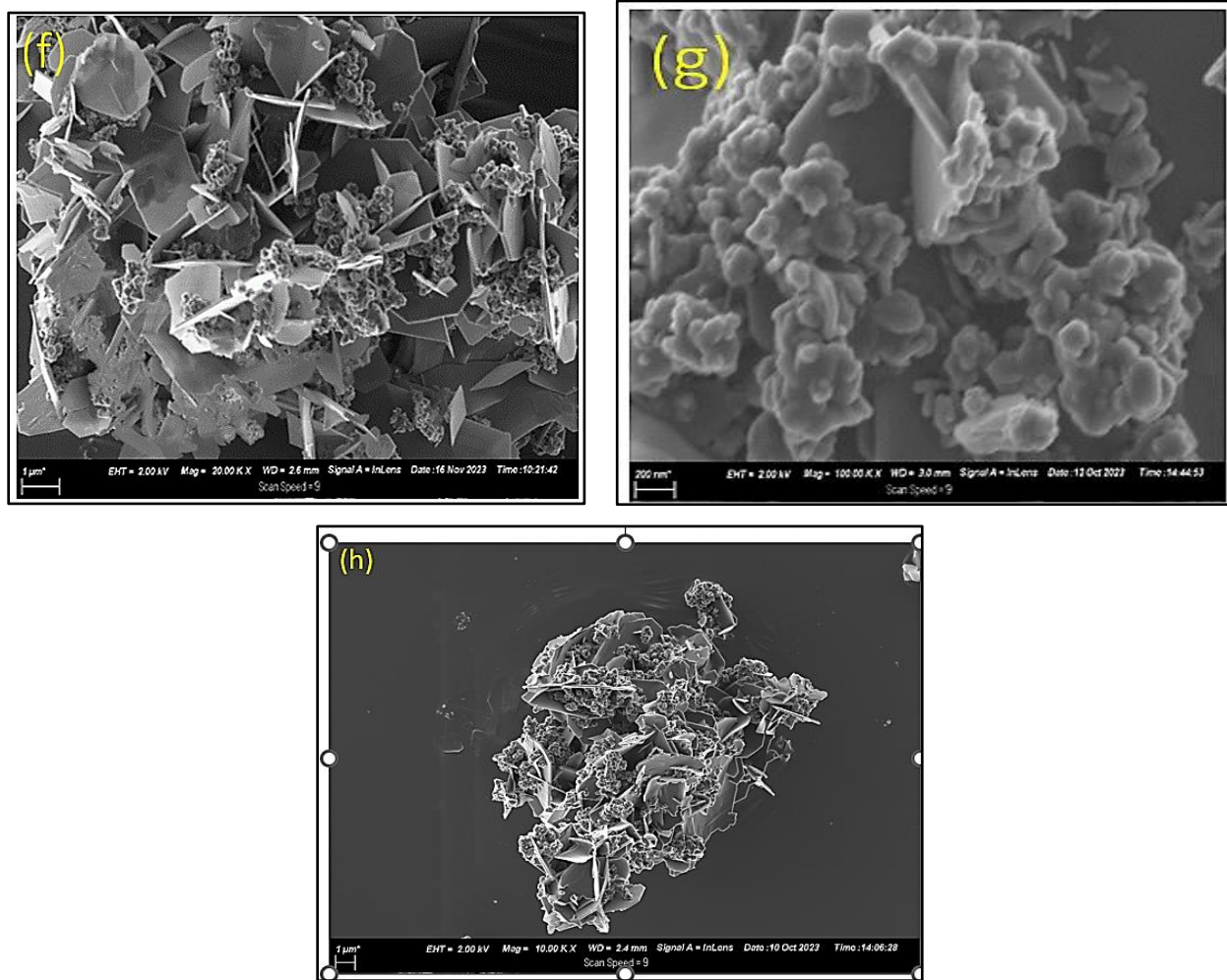


Figure 5. 3 Morphological result of the SEM for a hybrid of MNFs of (f) $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm), (g) $\text{Fe}_3\text{O}_4/\text{MgO}$, & (h) $\text{Fe}_3\text{O}_4/\text{ZnO}$

5.4.2 Observational techniques for sedimentation analysis in MNFs nanofluid samples

A technique involving photo capture was utilized to monitor sedimentation in MNFs nanofluid samples, capturing images immediately post-preparation, at 24 hours, and 30 days later as depicted in **Figure 5.4** (a) $\text{Fe}_3\text{O}_4(20-30\text{nm})/\text{TiO}_2(18\text{nm})$, (b) $\text{Fe}_3\text{O}_4(20-30\text{nm})/\text{ZnO}(20\text{nm})$, (c) $\text{Fe}_3\text{O}_4(20-30\text{nm})/\text{TiO}_2(60\text{nm})$ & (d) $\text{Fe}_3\text{O}_4(20-30\text{nm})/\text{MgO}(20\text{nm})$ various hybrid after 30 days and Figure 5.4 (e) and (f) is for a volumetric fraction of 0.3 to 0.00625%vol for $\text{Fe}_3\text{O}_4(20-30\text{nm})/\text{TiO}_2(60\text{nm})$ and $\text{Fe}_3\text{O}_4(20-30\text{nm})/\text{MgO}(20-40\text{nm})$ respectively.

These sequential images facilitated the visual observation of particles settling, providing qualitative insights into the stability and sedimentation tendencies of the nanofluids. This

qualitative approach complemented quantitative data obtained from other measurements, contributing to a comprehensive understanding of MHFs and their applications.

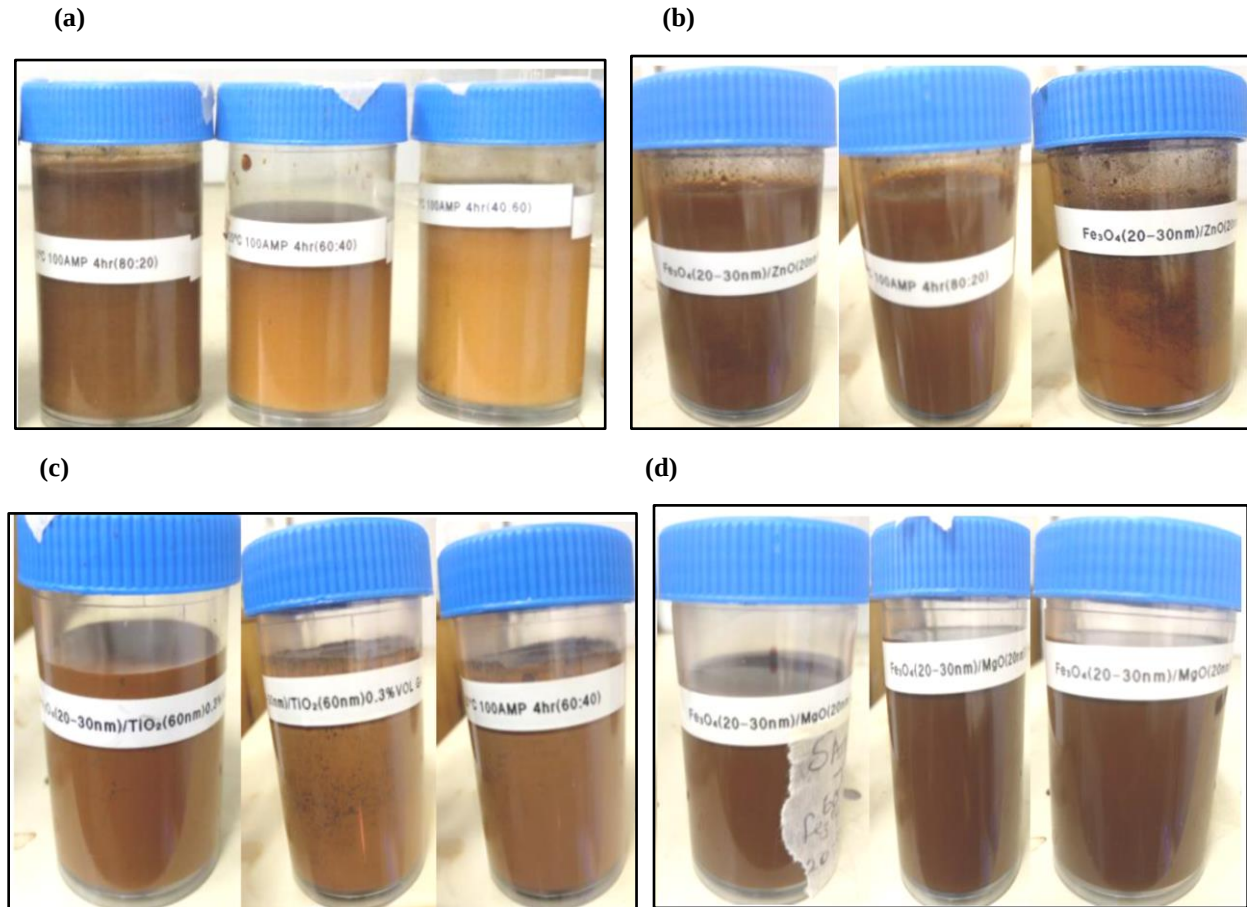


Figure 5. 4 Physical Observing Sedimentation in MHFs Nanofluid Samples (a) $\text{Fe}_3\text{O}_4(20-30\text{nm})/\text{TiO}_2(18\text{nm})$, (b) $\text{Fe}_3\text{O}_4(20-30\text{nm})/\text{ZnO}(20\text{nm})$, (c) $\text{Fe}_3\text{O}_4(20-30\text{nm})/\text{TiO}_2(60\text{nm})$ & (d) $\text{Fe}_3\text{O}_4(20-30\text{nm})/\text{MgO}(20\text{nm})$ various hybrid after 30 days (e) Magnetic hybrid nanofluid samples $\text{Fe}_3\text{O}_4(20-30\text{nm})/\text{TiO}_2(18\text{nm})$, (f) Magnetic hybrid nanofluid samples $\text{Fe}_3\text{O}_4(20-30\text{nm})/\text{MgO}(20-40\text{nm})$.

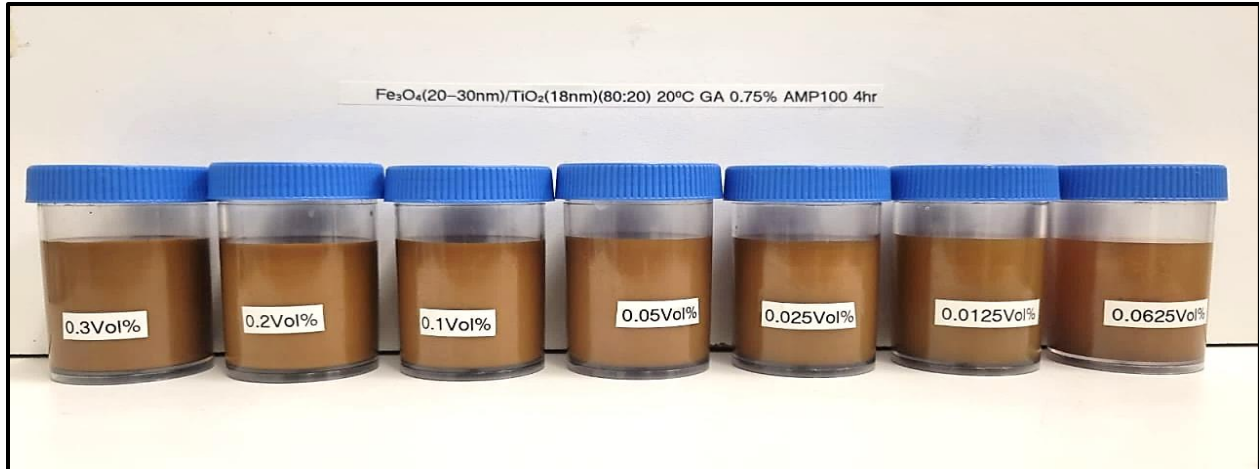


Figure 5.4: (e) Magnetic hybrid nanofluid samples $\text{Fe}_3\text{O}_4(20-30\text{nm})/\text{TiO}_2(18\text{nm})$,

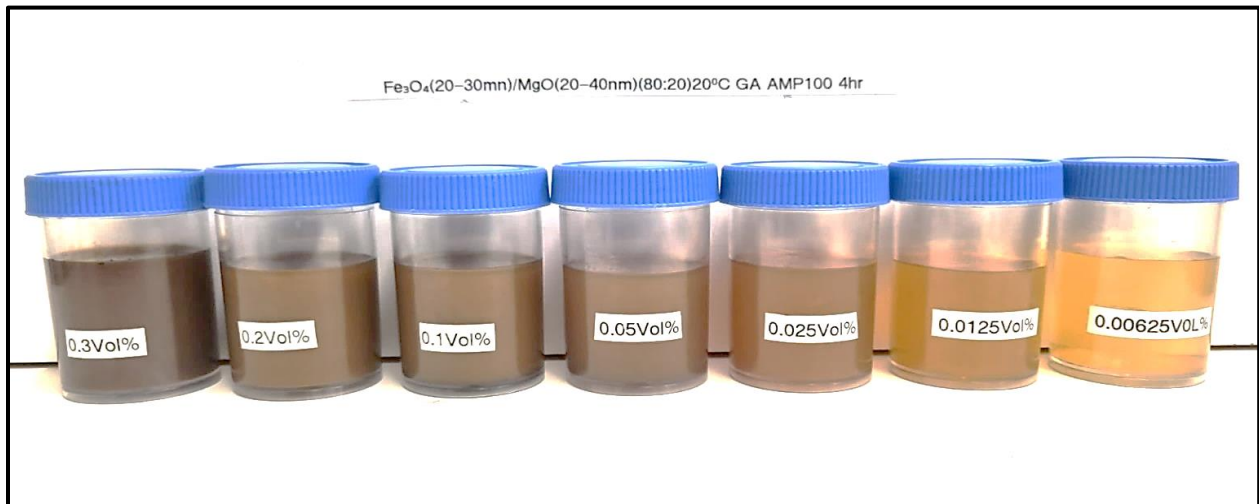


Figure 5.4: (f) Magnetic hybrid nanofluid samples $\text{Fe}_3\text{O}_4(20-30\text{nm})/\text{MgO}(20-40\text{nm})$

5.43 Absorbance Spectra Analysis of MHFs Across Different Wavelengths

For quantitative stability assessment, Ultraviolet-Visible (UV-Vis) spectroscopy was employed on MHFNs nanofluid samples $\text{Fe}_3\text{O}_4/\text{TiO}_2$ -DIW, $\text{Fe}_3\text{O}_4/\text{MgO}$ -DIW, and $\text{Fe}_3\text{O}_4/\text{ZnO}$ -DIW denoted as 80:20, 60:40, and 40:60 respectively, and for the lower volume fraction of ratio (80:20) of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ -DIW, and $\text{Fe}_3\text{O}_4/\text{MgO}$ -DIW, respectively from 0.3Vol to 0.0625Vol%. The Beer-Lambert law ($A = \alpha LC$) was applied, establishing a linear relationship between light absorbance and material properties, where absorbance (A) depended on the absorption coefficient (α), light path length (L), and substance concentration (C). Post-preparation, MHFs were analysed using a UV-Vis spectrometer (ONDATOUCHUV-21 Spectrophotometer, 4nm bandwidth) at room

temperature, with deionized water (DIW) used for calibration. Results were collected six times for accuracy.

Absorbance measurements were taken at different wavelengths with intervals of 10 nm from 200 to 280 nm and intervals of 1 nm from 281 to 300 nm. Standard graphs were generated for each MHFs, enabling relative stability comparisons based on absorbance values as illustrated in **Figure 5.5 a to c** and **Figure 5.6**. To quantify sedimentation, the Sedimentation Factor (SF) was calculated by subtracting the final absorbance (A_t) from the initial absorbance (A_0) for each MHFs, as expressed in **Equation 5.2**.

$$SF\% = \left(\frac{\text{Sedimentation factor}}{\text{Initial Absorbance}} \right) \times 100 \quad 5.2$$

The hybridization mixing ratio (HMR), indicating the proportion of different components in the nanofluid, varies across combinations such as $\text{Fe}_3\text{O}_4/\text{TiO}_2$ -DIW, $\text{Fe}_3\text{O}_4/\text{MgO}$ -DIW, and $\text{Fe}_3\text{O}_4/\text{ZnO}$ -DIW denoted as 80:20, 60:40, and 40:60 respectively. Experimental measurements conducted across different wavelengths reveal intriguing insights into the relationship between absorbance values and hybridization mixing ratios, shedding light on the tendency for sedimentation.

In the case of the 80:20 ratio for $\text{Fe}_3\text{O}_4/\text{TiO}_2$ -DIW, absorbance values consistently increase across wavelengths, indicating stability with minimal fluctuations. A similar stable pattern is observed with $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (80:20). Conversely, $\text{Fe}_3\text{O}_4/\text{MgO}$ -DIW(80:20) starts with lower absorbance values but gradually increases, suggesting reasonable stability. $\text{Fe}_3\text{O}_4/\text{ZnO}$ -DIW (80:20) exhibits a similar trend, but with a potential indication of slight aggregation or sedimentation due to rising absorbance.

However, at 60:40 and 40:60 mixing ratios, there is a noticeable trend of increasing absorbance values, hinting at potential particle aggregation or sedimentation, particularly pronounced at the 60:40 and 40:60 ratios. These observed trends underscore the intricate interplay between nanoparticle interactions, surface chemistry, and concentration.

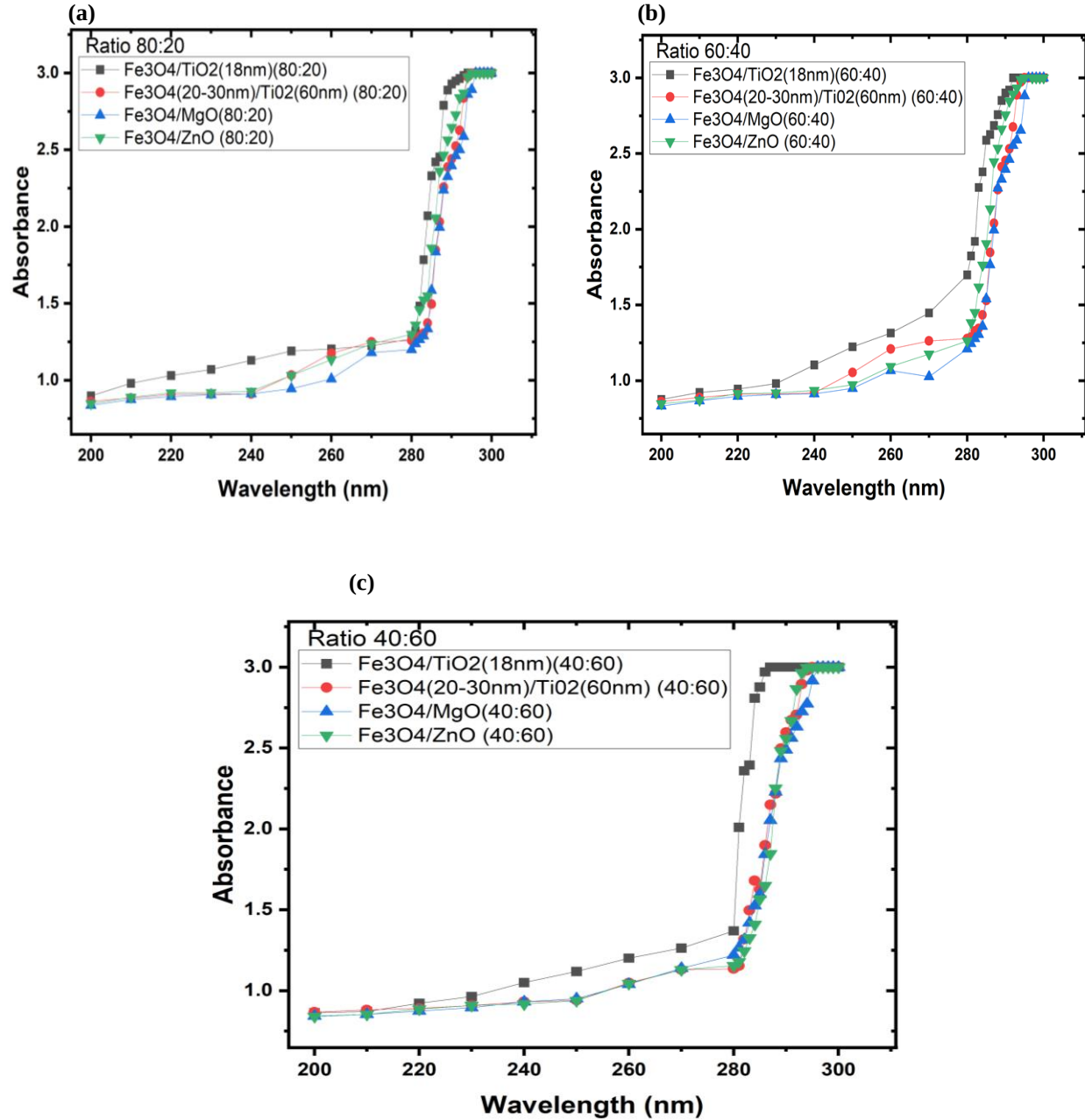


Figure 5. 5 The UV-Vis absorption spectrum of the Magnetic Hybrid Nanofluid suspended in deionized water at a specific ratio (a) 80:20, (b) 60:40, and (c) 40:60.

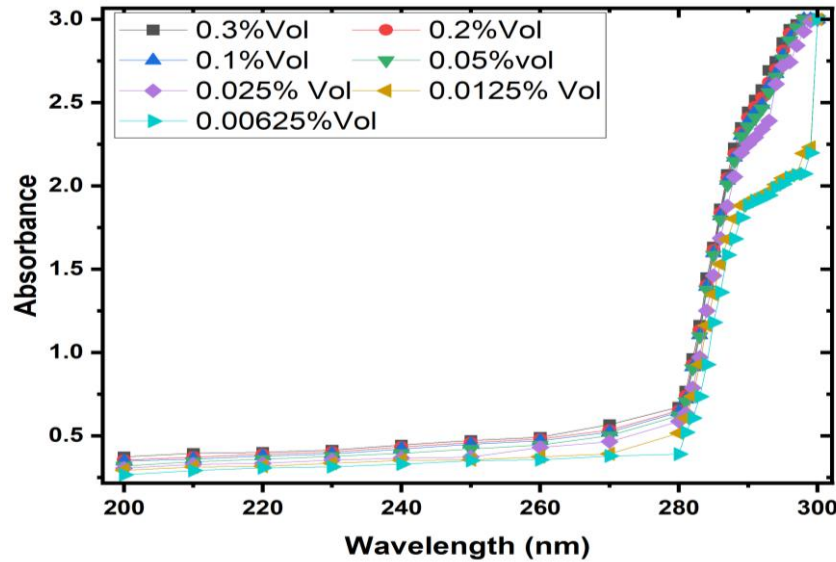


Figure 5. 6 Absorbance with variable (%) Volume fraction of MHNFS $\text{Fe}_3\text{O}_4/\text{TiO}_2$ -DIW

5.4.4 Impact of HMR and particle size on sedimentation factor of MHNFS

The sedimentation factor (%) for MHFs across various HMR was determined using **Equation 5.2**, with the results tabulated in **Table 5.2** and **Figure 5.7** illustrates the percentage sedimentation of magnetic hybrid nanofluids across different hybridization ratios, providing insights into their stability and implications for heat transfer performance. The sedimentation percentages for the 80:20 ratio are as follows: $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm) exhibits 31.97%, Fe_3O_4 (20-30nm)/ TiO_2 (60nm) shows 18.52%, $\text{Fe}_3\text{O}_4/\text{MgO}$ registers 15.59%, and $\text{Fe}_3\text{O}_4/\text{ZnO}$ presents 17.12%. Among these, $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm) demonstrates the highest sedimentation rate, suggesting that it has superior performance in maintaining dispersion compared to others. This increased sedimentation percentage implies that $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm) nanoparticles remain more effectively suspended, which could enhance heat transfer performance due to a more consistent dispersion of nanoparticles, facilitating greater surface area interaction and thermal energy exchange.

Conversely, $\text{Fe}_3\text{O}_4/\text{MgO}$ shows the lowest sedimentation percentage, indicating relatively lower stability and potentially reduced heat transfer efficiency over time due to possible settling of nanoparticles. Thus, nanofluids with higher sedimentation rates, such as $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm) and $\text{Fe}_3\text{O}_4/\text{ZnO}$, are more likely to sustain better thermal performance, especially in dynamic systems where nanoparticle dispersion is critical.

For the 60:40 ratios, the sedimentation percentages are: $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm) at 29.16%, $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (60nm) at 28.72%, $\text{Fe}_3\text{O}_4/\text{MgO}$ at 27.74%, and $\text{Fe}_3\text{O}_4/\text{ZnO}$ at 28.25%. These values indicate

that $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm) has the highest sedimentation rate, suggesting it maintains the best dispersion, thus potentially offering superior heat transfer efficiency compared to others. The slightly lower sedimentation rates in $\text{Fe}_3\text{O}_4/\text{MgO}$ imply a lesser ability to maintain suspension and thus may not be as effective in maintaining optimal thermal performance.

For the 40:60 ratios, the sedimentation percentages are: $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm) at 28.77%, $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (60nm) at 28.90%, $\text{Fe}_3\text{O}_4/\text{MgO}$ at 28.07%, and $\text{Fe}_3\text{O}_4/\text{ZnO}$ at 27.99%. Consistent with the previous findings, $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm) shows the highest sedimentation rate, indicating its superior ability to maintain nanoparticle dispersion across different ratios.

In summary, the optimal hybridization ratio for sustaining effective heat transfer appears to be $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm) across all tested ratios (80:20, 60:40, and 40:60) due to its consistently highest sedimentation percentage. This suggests that $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm) provides a promising solution for applications requiring enhanced thermal performance, given its ability to maintain effective nanoparticle dispersion and thus improve thermal energy exchange.

Table 5. 2 Sedimentation factors of various MHNFs at different HMRs

S/n	MHF	HMR	Peak wavelength (nm)	Sedimentation factor (%)
1	$\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm)/DIW	80:20	293	31.97
2	$\text{Fe}_3\text{O}_4/\text{TiO}_2$ (60nm)/DIW	80:20	295	18.59
3	$\text{Fe}_3\text{O}_4/\text{MgO}$ /DIW	80:20	295	15.59
4	$\text{Fe}_3\text{O}_4/\text{ZnO}$ /DIW	80:20	294	17.12
5	$\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm)/DIW	60:40	291	29.16
6	$\text{Fe}_3\text{O}_4/\text{TiO}_2$ (60nm)/DIW	60:40	294	28.72
7	$\text{Fe}_3\text{O}_4/\text{MgO}$ /DIW	60:40	295	27.74
8	$\text{Fe}_3\text{O}_4/\text{ZnO}$ /DIW	60:40	294	28.25
9	$\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm)/DIW	40:60	280	28.77
10	$\text{Fe}_3\text{O}_4/\text{TiO}_2$ (60nm)/DIW	40:60	294	28.90
11	$\text{Fe}_3\text{O}_4/\text{MgO}$ /DIW	40:60	295	28.07
12	$\text{Fe}_3\text{O}_4/\text{ZnO}$ /DIW	40:60	294	27.99

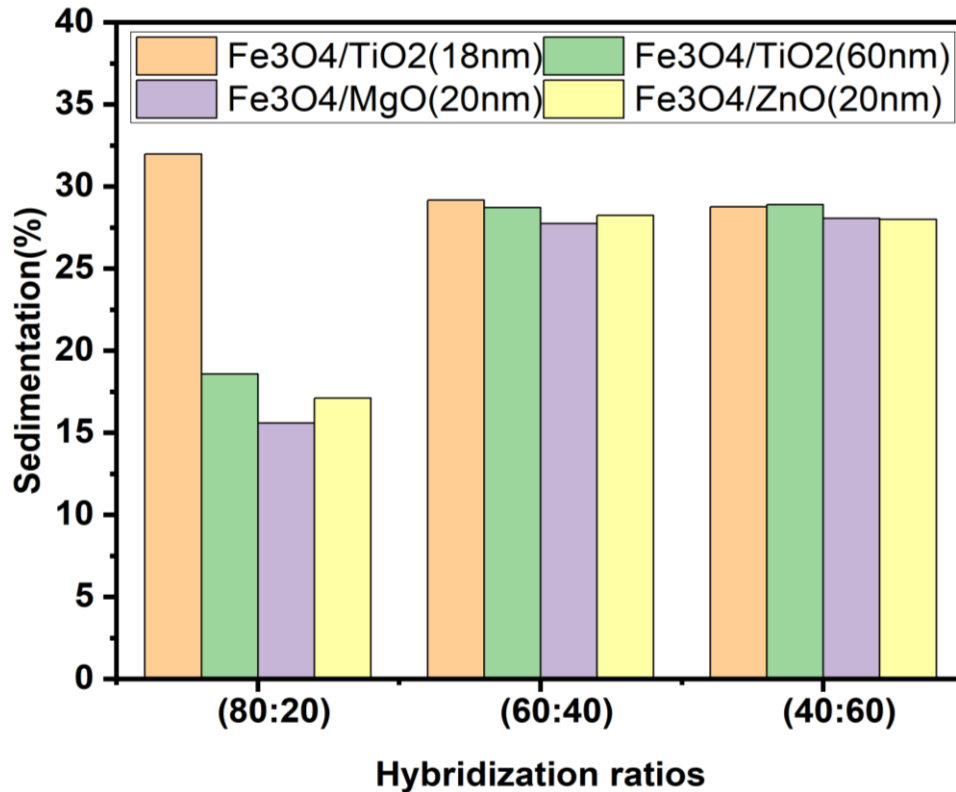


Figure 5. 7 Percentage sedimentation of MHNFs across different hybridization ratios

5.4.5 Sedimentation factor analysis for Fe₃O₄/TiO₂ nanofluids across different volumetric ratio (0.3 to 0.00625% vol)

UV-Vis, adhering to Beer-Lambert's law [264], [265], showed a relationship between the absorption intensity of Fe₃O₄/TiO₂ MHNFs and their volumetric ratio, as demonstrated in Figure 5.8. The results indicated that lower absorption intensities were linked to reduced particle concentrations, which were associated with sedimentation rates. Over a 30-day observation period, significant settling was detected in MHFs with volumetric ratio of 0.1%vol, 0.2%vol, and 0.3%vol, with corresponding SF values the sedimentation factor for each volume fraction of Fe₃O₄/TiO₂ MHNFs was calculated based on the absorbance at 200 nm, using the maximum absorbance value of 3.000 observed at 300 nm. For the 0.3% volume fraction, the sedimentation factor was determined to be 31.79%, and this value progressively decreases with lower nanoparticle concentrations. Specifically, the sedimentation factor for the 0.2% volume fraction is 11.88%, followed by 11.61% for 0.1%, 10.68% for 0.05%, 10.24% for 0.025%, 9.82% for 0.0125%, and the lowest value of 8.89% at 0.00625%. This decreasing trend indicates that higher nanoparticle concentrations lead to greater sedimentation, making the nanofluid less stable over time.

Conversely, lower concentrations slow the sedimentation rate, improving the stability of the nanofluid and ensuring a more homogeneous dispersion of particles.

The sedimentation behavior has significant implications for heat transfer performance. As nanoparticle sedimentation increases with higher concentrations, the nanofluid's stability diminishes, resulting in an uneven particle distribution. This inconsistency can cause localized reductions in thermal conductivity, which in turn weakens the overall heat transfer efficiency. While higher nanoparticle loading theoretically offers greater heat transfer enhancement due to the increased solid content, the instability from sedimentation and particle agglomeration counteracts this potential benefit.

In contrast, lower concentrations exhibit reduced sedimentation factors, contributing to better long-term stability. This stable suspension ensures a more uniform particle distribution, which is crucial for maintaining consistent heat transfer performance. Although lower concentrations may offer slightly lower heat transfer capacity compared to higher concentrations, the improved stability over time ensures reliable thermal performance, avoiding performance degradation.

In practical applications, these findings underscore the need to balance nanoparticle concentration and nanofluid stability. Optimizing this balance is key to achieving both effective heat transfer and long-term reliability, ensuring the nanofluid remains stable without excessive sedimentation, while still offering significant thermal enhancement. These results are consistent with the observation from Krishnan et al [266].

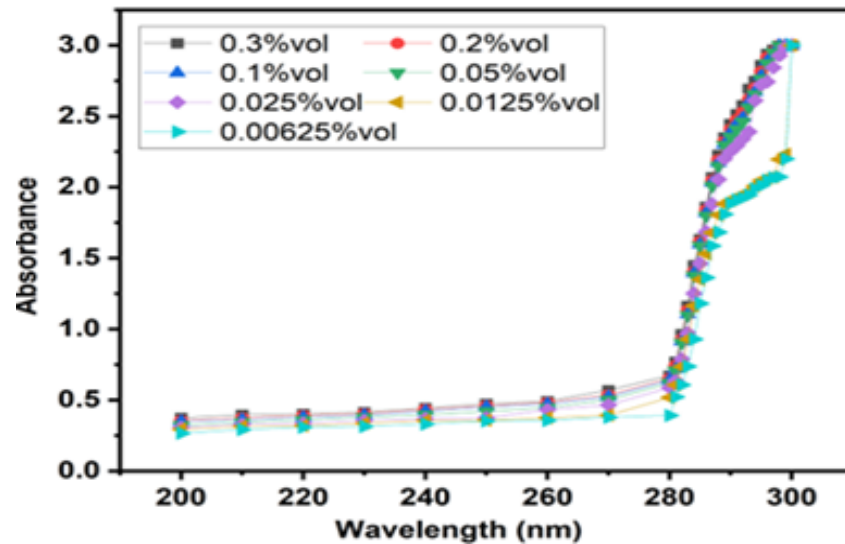


Figure 5. 8 Impact different wavelengths of MHNFs density on absorption of light

5.4.6 Zeta Potential of the MHNFs Stability

The zeta potential represents the electrical potential at the slipping plane of nanoparticles in a fluid, and it is a critical parameter for assessing nanofluid stability. It measures the extent of repulsive or attractive forces between particles within a suspension. A high absolute zeta potential value whether positive or negative indicates strong electrostatic repulsion among particles, which counteracts aggregation and sedimentation, thereby enhancing the stability of the nanofluid. This stability is vital for ensuring uniform dispersion of nanoparticles within the base liquid, maintaining consistent thermophysical characteristics, and optimizing heat exchange performance. The threshold for a stable colloidal system is typically a zeta potential greater than ± 30 mV, as this value signifies sufficient repulsive forces to overcome van der Waals attractions and gravitational settling. The zeta potential value pyramid, depicted in **Figure 5.9**, typically categorizes nanofluid stability based on zeta potential values. Excellent stability is denoted by ZP values greater than or equal to ± 60 mV, while instability is indicated when the ZP value is less than ± 15 mV. Values within the range of ± 15 mV are characterized as unstable.

Table 5.3 offers a summary of the zeta potential values and conductivity for the respective MHNFs, measured at 25°C and pH using a Zeta-potentiometer. It's important to note that when there is a substantial density disparity between the particles and the base fluid, sedimentation can occur despite a high zeta potential value [47].

Figure 5.9 illustrates the percentage sedimentation of magnetic hybrid nanofluids across different hybridization ratios, providing insights into their stability and implications for heat transfer performance. The sedimentation percentages for the 80:20 ratio are as follows: $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm) exhibits 31.97% with a Zeta potential of ± 20.3 mV, indicating moderate electrostatic stabilization. $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (60nm) shows 18.52% with a Zeta potential of ± 21.4 mV, reflecting better stability compared to its 18nm counterpart. $\text{Fe}_3\text{O}_4/\text{MgO}$ registers a sedimentation percentage of 15.59% and a Zeta potential of ± 20.9 mV, indicating superior stability and better nanoparticle dispersion, which could lead to improved heat transfer performance. $\text{Fe}_3\text{O}_4/\text{ZnO}$ presents a sedimentation percentage of 17.12%, with a Zeta potential of ± 11.9 mV, suggesting less effective stabilization compared to the other formulations in this ratio.

For the 60:40 ratio, the sedimentation percentages are: $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm) at 29.16%, with a Zeta potential of ± 19.8 mV, indicating moderate stabilization and a relatively higher sedimentation rate. $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (60nm) shows a sedimentation percentage of 28.72% and a Zeta potential of ± 20.6

mV, reflecting slightly better stability. $\text{Fe}_3\text{O}_4/\text{MgO}$ has a sedimentation percentage of 27.74% with a significantly lower Zeta potential of ± 11.5 mV, indicating lower electrostatic stabilization, which correlates with a higher sedimentation rate and reduced stability over time. Meanwhile, $\text{Fe}_3\text{O}_4/\text{ZnO}$ demonstrates a sedimentation percentage of 28.25% and a Zeta potential of ± 17.7 mV, which suggests better stability than $\text{Fe}_3\text{O}_4/\text{MgO}$, though not as high as the TiO_2 -based nanofluids.

For the 40:60 ratio, the sedimentation percentages are as follows: $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm) at 28.77%, with a Zeta potential of ± 21.0 mV, showing good electrostatic stabilization and effective nanoparticle suspension. $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (60nm) has the highest sedimentation percentage at 28.90% and a Zeta potential of ± 20.6 mV, indicating similar stabilization characteristics. $\text{Fe}_3\text{O}_4/\text{MgO}$ registers a sedimentation rate of 28.07%, with a Zeta potential of ± 11.5 mV, again reflecting less effective stabilization, which could negatively impact its long-term performance. $\text{Fe}_3\text{O}_4/\text{ZnO}$, with a sedimentation percentage of 27.99% and a Zeta potential of ± 17.7 mV, shows relatively higher stability compared to $\text{Fe}_3\text{O}_4/\text{MgO}$, but still less so than the TiO_2 -based nanofluids.

In summary, $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm) demonstrates the highest sedimentation rates across all tested ratios (80:20, 60:40, and 40:60), with Zeta potential values consistently around ± 20 mV, indicating effective nanoparticle dispersion and electrostatic stabilization, which is crucial for maintaining heat transfer efficiency. Conversely, $\text{Fe}_3\text{O}_4/\text{MgO}$, with its lower Zeta potential values and higher sedimentation rates, suggests reduced stability and thus may not perform as well in heat transfer applications. $\text{Fe}_3\text{O}_4/\text{ZnO}$ exhibits intermediate performance, with its Zeta potential values ranging from ± 11.9 mV to ± 17.7 mV, suggesting better stability than MgO -based nanofluids but not as robust as TiO_2 -based formulations. Therefore, the Zeta potential values, in conjunction with the sedimentation rates, shows the significant of selecting nanofluids with the appropriate stabilization characteristics to optimize heat transfer enhancement in practical applications.

The zeta potential values, obtained through measurement, are presented in **Table 5.3**, and the combined apparent zeta potential plots are featured in **Figure. 5.10** The results reveal that most of the hybridizations fall within the low stability range (± 15 mV to ± 29 mV). This pattern aligns with the sedimentation factor, where the 80:20 hybridization mixing ratio demonstrates the best stability compared to others. Specifically, the $\text{Fe}_3\text{O}_4:\text{TiO}_2(60\text{nm})$ -DIW with an HMR of 80:20 displays the highest zeta potential value of ± 21.4 , indicating relatively lower stability with faster settlement, positioning it as the most stable among the various HMFs. In contrast, the $\text{Fe}_3\text{O}_4:\text{MgO}$ -DIW with

an HMR of 60:40 exhibits the least stability with a zeta potential of ± 11.5 . To enhance stability, modifying the surface properties of nanoparticles or adjusting solution conditions could be considered to achieve higher zeta potentials within the stable range ($> \pm 30$ mV).

Table 5. 3 Summary of Zeta Potential Result for the HMFs

S/n	Hybrid nanoparticles	Hybridization Mixing Ratio	Conductivity (mS/cm) @ 25°C	Zeta Potential Value
1	Fe ₃ O ₄ :TiO ₂ (18nm)	80:20	0.1010	± 20.3
2	Fe ₃ O ₄ :TiO ₂ (18nm)	60:40	0.0733	± 19.8
3	Fe ₃ O ₄ :TiO ₂ (18nm)	40:60	0.0962	± 21.0
4	Fe ₃ O ₄ :TiO ₂ (60nm)	80:20	0.0617	± 21.4
5	Fe ₃ O ₄ :TiO ₂ (60nm)	60:40	0.0703	± 20.6
6	Fe ₃ O ₄ :MgO	80:20	0.0573	± 20.9
7	Fe ₃ O ₄ :MgO	60:40	0.4130	± 11.5
8	Fe ₃ O ₄ :ZnO	80:20	0.4710	± 11.9
9	Fe ₃ O ₄ :ZnO	60:40	0.0711	± 17.7

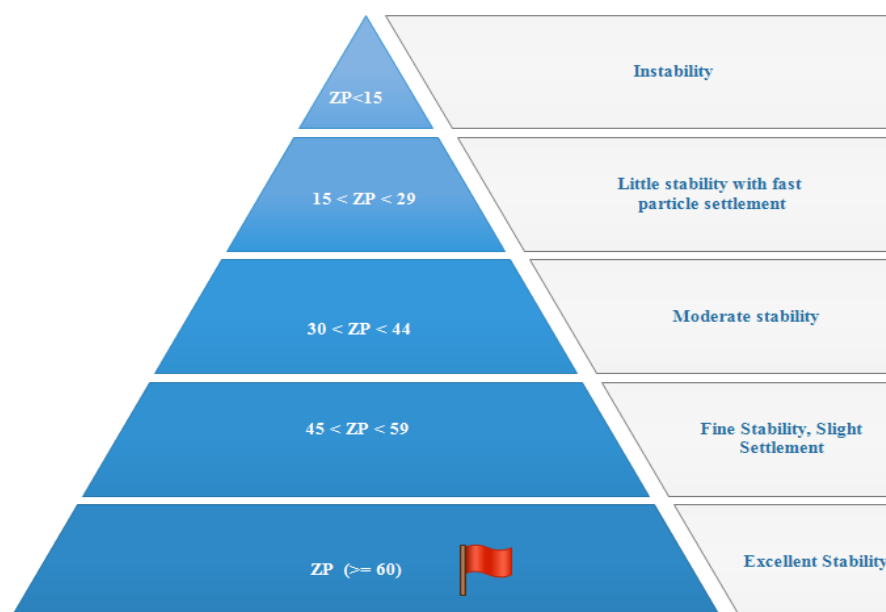


Figure 5. 9 Stability Level and Zeta Potential Value Pyramid

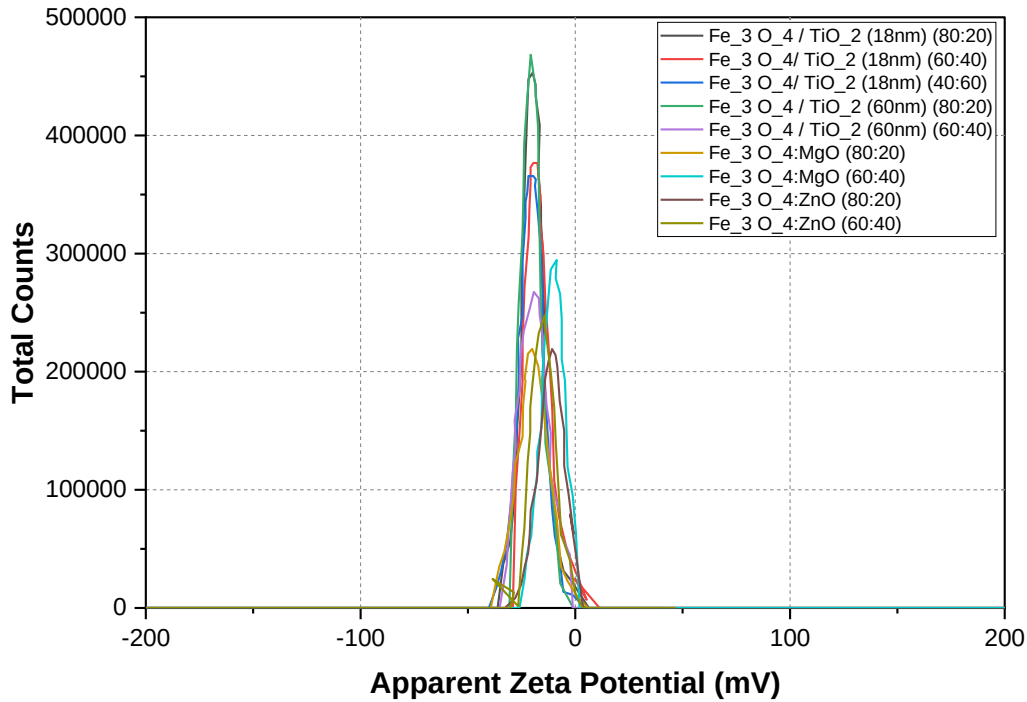


Figure 5. 10 Zeta Potential Quantization for the MHFs at pH = 0

5.4.7 Influence of temperature, shelf-life, and HMR on MHNFs nanofluid thermal conductivity stability

The experimental setup involved utilizing a constant temperature bath to sustain temperature control during continuous thermal conductivity measurements spanning 24 hours and 15 minutes. The temperature range covered was 10°C to 50°C with 5°C intervals, and evaluations were replicated after one month using the KD2. The obtained results, illustrated in **Figure 5.11**, align with theoretical predictions. Verification of the thermal conductivity meter involved comparing measured κ values with an empirical model by Popiel and Wojtkowiak in 1998 [267]. This comparison over temperatures from 10 to 50 °C. The increasing κ values with temperature, alongside a small average deviation and mean absolute error of approximately 0.0031, affirm a high level of accuracy. This suggests close alignment between measured and predicted thermal conductivity values, indicating a reliable and precise measurement process.

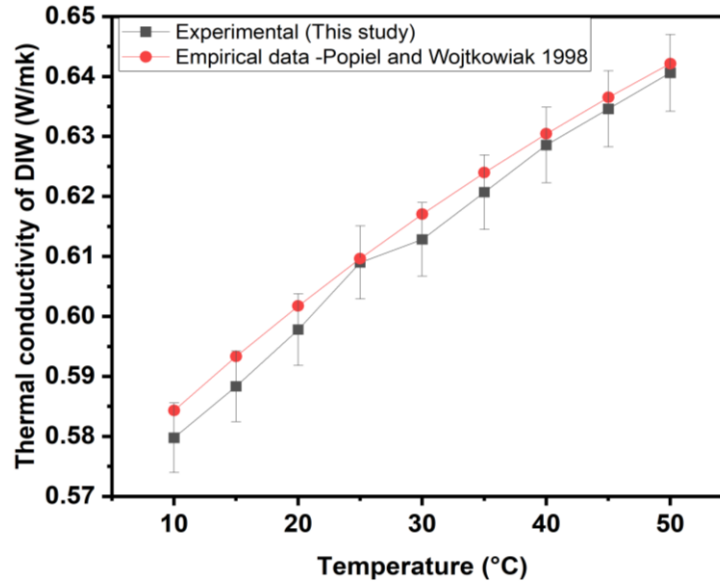


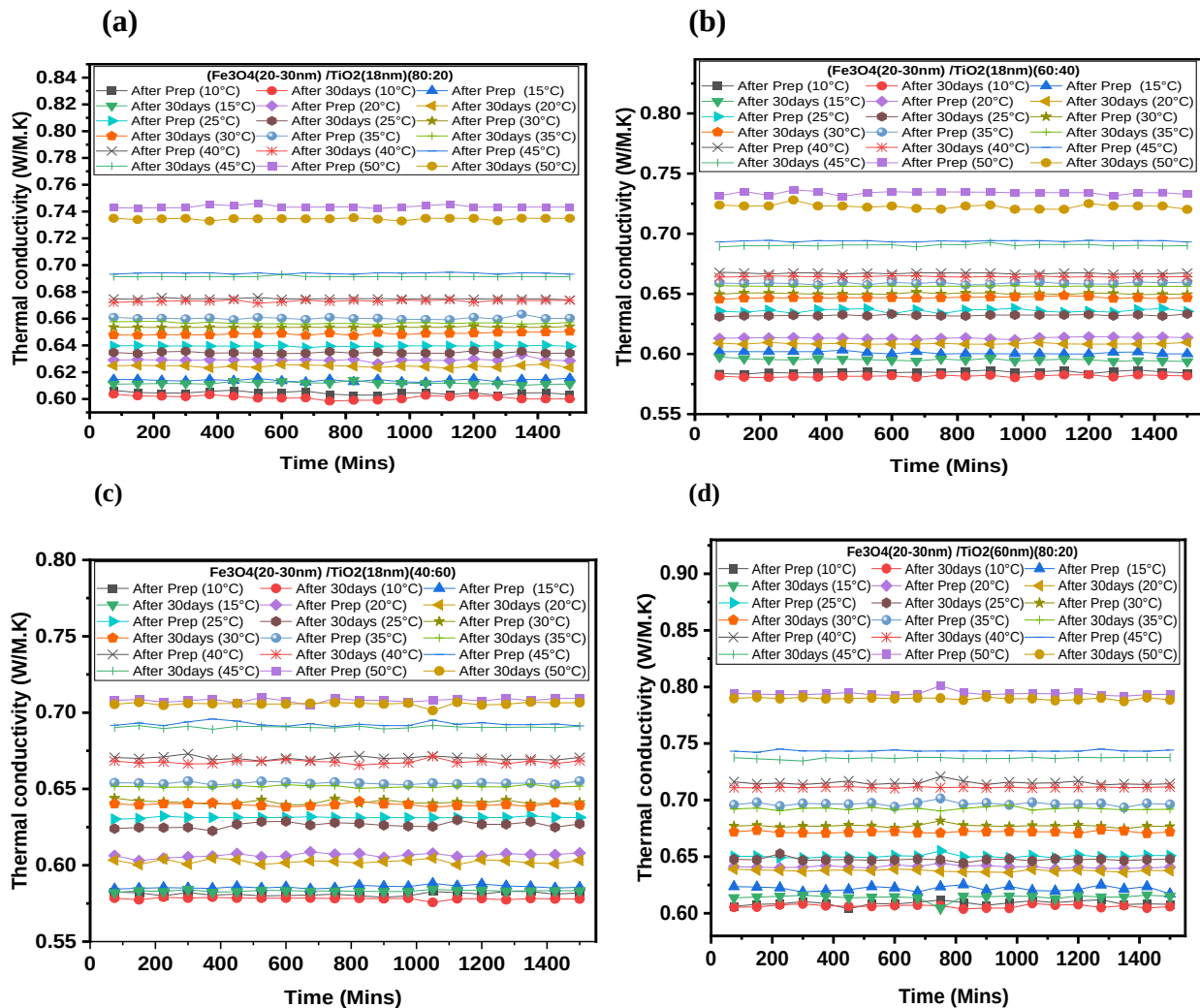
Figure 5. 11 Correlation of predicted and experimental TC

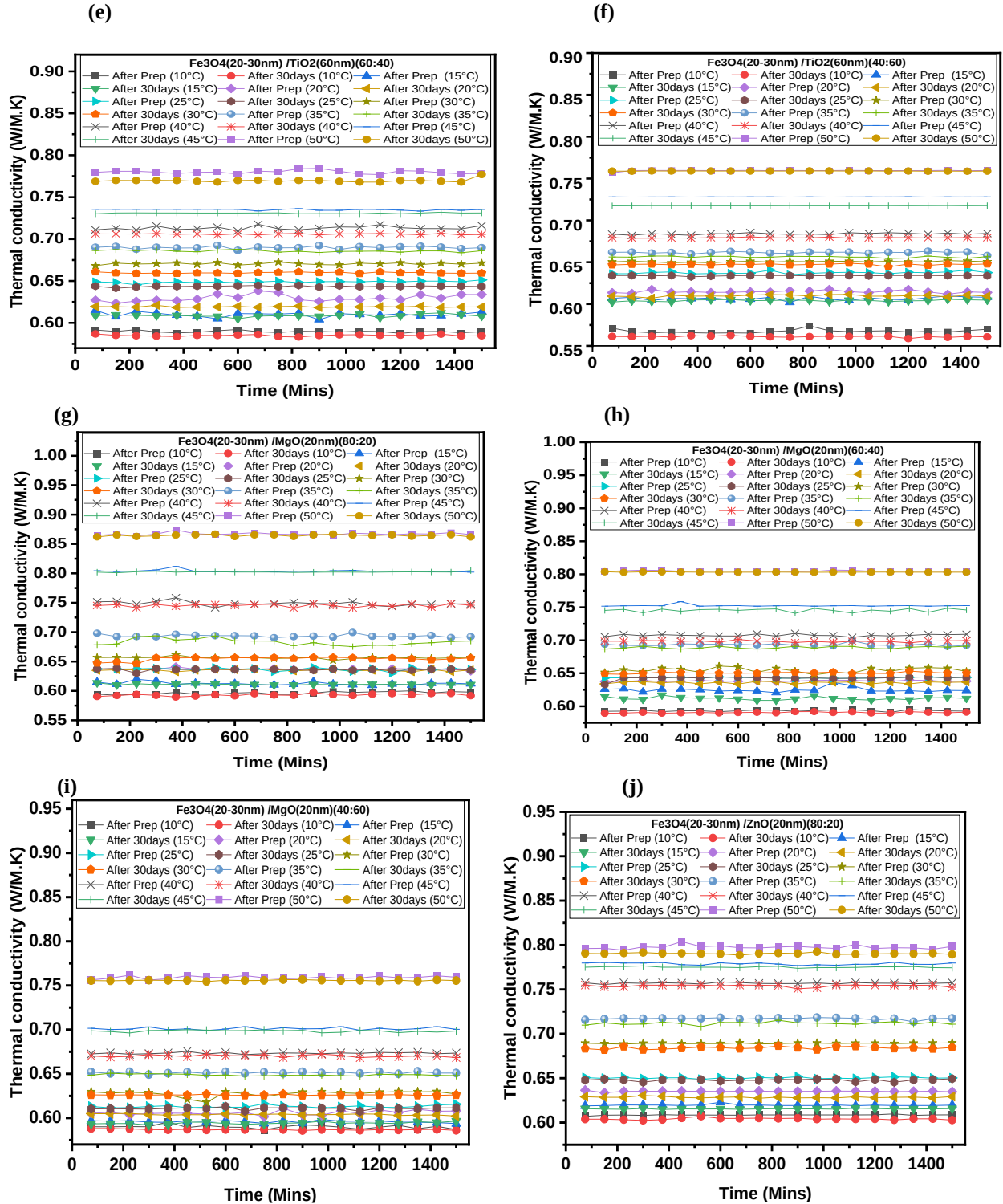
To assess the applicability of MHNFs in heat transfer scenarios, we investigated the stability of their thermal conductivity values temperature 10°C to 50°C over a 30-day period. This evaluation encompassed different hybridization mixing ratios (HMRs) – 80:20, 60:40, and 40:60 – across four distinct MHNFs types; Fe_3O_4 / TiO_2 (18nm)/DIW, Fe_3O_4 / TiO_2 (60nm)/DIW, Fe_3O_4 / MgO (20nm)/DIW, and Fe_3O_4 / ZnO (20nm)/DIW. **Figure 5.12** presents the thermal conductivity values of these MHNFs at a 0.3% volume concentration.

Across all scenarios, the impact of temperature on thermal conductivity values consistently demonstrated an upward trend, with thermal conductivity increasing as the fluid temperature rose. Assessing the stability of thermal conductivity measurements over a 24-hour period revealed minor discrepancies between immediately obtained values and those recorded after 30 days. This suggests that the nanofluids maintained their thermal conductivity consistently over the 30-day timeframe, with average percentage deviation values supporting this stability.

The findings underscored the thermal conductivity stability across different hybridization mixing ratios (80:20, 60:40, and 40:60). MHNFs with an HMR of 80:20 consistently exhibited notable stability, characterized by the lowest percentage deviations and standard deviation (STDEV) percentages across varying temperatures. The highest percentage deviation for the 80:20 hybrid was 0.39% at 15°C, while the lowest percentage deviation was 0.16%, with the lowest STDEV recorded at 0.08% at 40°C. In contrast, the 60:40 hybrid showed the highest percentage deviation

of 0.86% at 30°C and the lowest percentage deviation of 0.52% at 25°C. For the 40:60 hybrid, the highest percentage deviation was 0.67% at 20°C, and the lowest percentage deviation was 0.23%. These results emphasize the considerable influence of hybridization mixing ratios on the stability of thermal conductivity measurements, with HMFs utilizing an 80:20 hybrid consistently demonstrating superior stability and thermal conductivity compared to other ratios. The selection of hybridization mixing ratio plays a pivotal role in determining the stability and dependability of thermal conductivity measurements, with the 80:20 hybrid emerging as the most favorable choice for heat transfer applications. Notably, the 80:20 hybrid consistently displayed lower percentage deviations, indicating enhanced stability and consistency in thermal conductivity measurements relative to other hybrids. This trend persisted across the temperatures study, further highlighting the sustained stability of the 80:20 hybrid in thermal conductivity, which is critical for heat exchange applications.





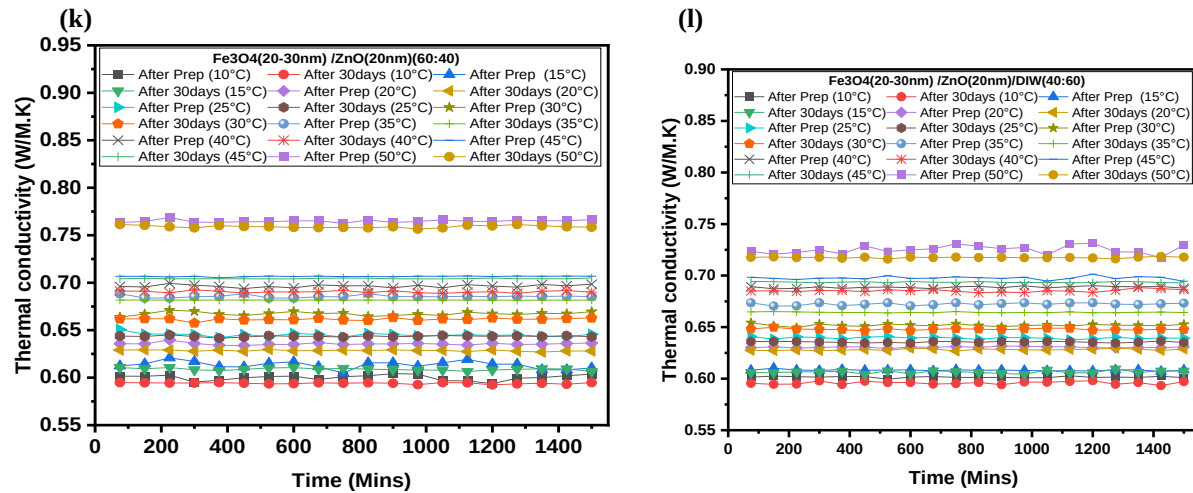


Figure 5. 12 TC of MHNFs against temperature, Shelf Life and Time for (a) $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm)/DIW (80:20), (b) $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm)/DIW (60:40), (c) $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm)/DIW (40:60), (d) $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (60nm)/DIW (80:20), (e) $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (60nm)/DIW (60:40), (f) $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (60nm)/DIW (40:60), (g) $\text{Fe}_3\text{O}_4/\text{MgO}$ (20nm)/DIW (80:20), (h) $\text{Fe}_3\text{O}_4/\text{MgO}$ (20nm)/DIW (60:40) (i) $\text{Fe}_3\text{O}_4/\text{MgO}$ (20nm)/DIW (40:60), (j) $\text{Fe}_3\text{O}_4/\text{ZnO}$ (20nm)/DIW (80:20), (k) $\text{Fe}_3\text{O}_4/\text{ZnO}$ (20nm)/DIW (60:40), (l) $\text{Fe}_3\text{O}_4/\text{ZnO}$ (20nm)/DIW (40:60)

5.4.8 Thermal conductivity performance, effects of temperature and HMRs in MHNFs

The Figure 5.13a to d effectively illustrate how temperature affects the thermal conductivity of different types of MHNFs compared to DIW across various HMRs.

For $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm)-DIW MHNFs immediately after preparation:

- i. (80:20) HMR: At lower temperatures (10°C to 25°C), the enhancement ranged from 4.20% to 5.23%. At elevated temperatures (30°C to 45°C), the highest is around 9.37%.
- ii. (60:40) HMR: This ratio showed enhancements from 0.87% at 10°C to 8.79% at 45°C.
- iii. (40:60) HMR: Enhancements ranged from 0.24% at 10°C to 7.49% at 45°C. These findings highlight the effectiveness of using an (80:20) HMR for immediately improving thermal conductivity following preparation. Over a 30-day period post-preparation, the (80:20) HMR consistently showed enhancements ranging from 4.00% to 7.22% across the temperature spectrum. Comparatively, the (60:40) HMR displayed enhancements ranging from 0.29% at 10°C to 6.19% at 45°C, while the (40:60) HMR exhibited enhancements between 0.29% and 5.41%. Notably, the (80:20) HMR maintained its status as the most

effective choice for enhancing thermal conductivity, especially at higher temperatures, even after the 30-day timeframe.

For $\text{Fe}_3\text{O}_4/\text{TiO}_2(60\text{nm})$ -DIW MHFs:

- i. (80:20) HMR: Immediately after preparation, enhancements ranged from 5.00% at 10°C to 17.17% at 45°C. Even after 30 days, enhancements remained significant, ranging from 4.57% at 10°C to 16.45% at 45°C.
- ii. (60:40) HMR: Initially, enhancements ranged from 1.71% at 10°C to 16.04% at 45°C. After 30 days, though there was a slight decrease, enhancements remained substantial, ranging from 0.90% at 10°C to 15.40% at 45°C.

The results indicate that immediately after preparation, enhancements for the (40:60) HMR ranged from 1.21% at 10°C to 14.76% at 45°C, with values between 0.22% at 10°C and 13.71% at 45°C after 30 days. These findings confirm the efficacy of the (80:20) HMR in enhancing thermal conductivity, especially at elevated temperatures.

For $\text{Fe}_3\text{O}_4/\text{MgO}$ -DIW MHNFs, the percentage enhancements for different HMRs are as follows:

- i. For the (80:20) HMR, enhancements immediately after preparation ranged from approximately 3.26% at 10°C to about 27.92% at 50°C.
- ii. For the (60:40) HMR, enhancements varied from approximately 2.03% at 10°C to 25.91% at 50°C.
- iii. The (40:60) HMR recorded enhancements ranging from around 1.29% at 10°C to approximately 21.04% at 50°C.

These findings highlight the superiority of the (80:20) HMR in enhancing thermal conductivity, both immediately after preparation and after 30 days, across various temperatures.

For $\text{Fe}_3\text{O}_4/\text{ZnO}$ -DIW MHNFs, the percentage enhancements for different HMRs are as follows:

- i. The (80:20) HMR exhibited the best thermal conductivity among other MHNFs and HMRs, with a TC value of 0.793 W/m.K at 50°C and percentage enhancement ranging from about 4.23% at 10°C to about 31.28% at 50°C.
- ii. For the (60:40) HMR, enhancements varied from approximately 3.86% at 10°C to 29.76% at 50°C.

- iii. The (40:60) HMR recorded enhancements ranging from around 1.75% at 10°C to approximately 27.46% at 50°C.

Consistently, these results demonstrate that the (80:20) HMR surpasses the (60:40) and (40:60) ratios in enhancing thermal conductivity, both immediately after preparation and after 30 days, across varying temperatures. This makes the (80:20) HMR an optimal choice for applications requiring efficient forced convection heat transfer.

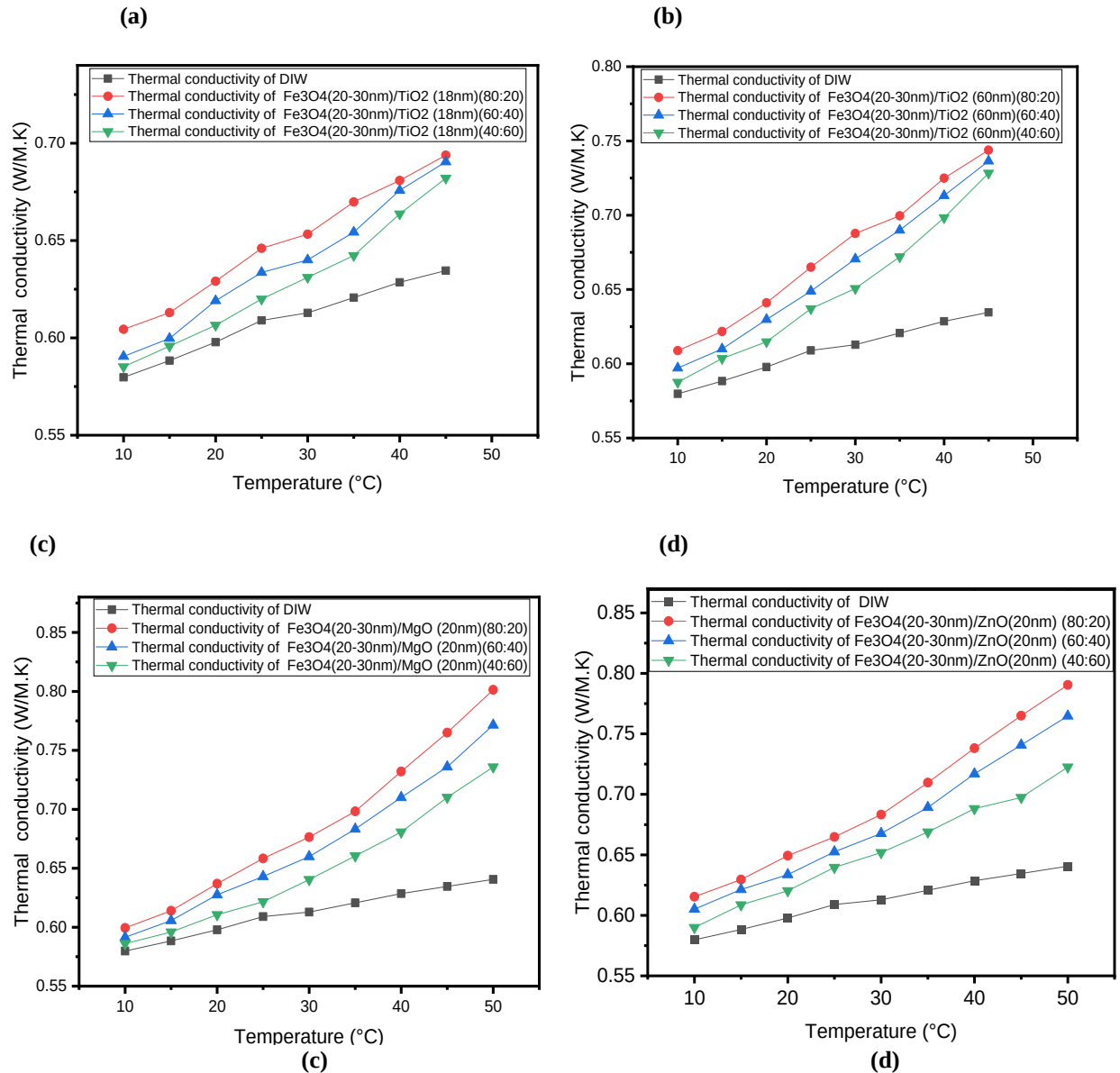


Figure 5. 13 Comparative thermal conductivity measurements across different hybridization mixing ratios with temperature variation for (a) Fe₃O₄/TiO₂(18nm), (b) Fe₃O₄/TiO₂(60nm), (c) Fe₃O₄/MgO (d) Fe₃O₄/ZnO.

5.4.9 Impact of NPs size variation on the TC of MHNFs

The findings indicate that MHNFs incorporating TiO_2 nanoparticles with a size of 60nm demonstrated greater stability and thermal conductivity in comparison to their counterparts containing TiO_2 nanoparticles with a size of 18nm, across various hybridization ratios. This variation in particle size significantly affects the enhancement of thermal conductivity, particularly with TiO_2 . Larger nanoparticles, owing to their increased surface area, facilitate improved conductive heat transfer interactions both within and between the particles and the base fluid (DIW) [108]. This observation can explain the higher percentage enhancements observed in $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (60nm)-nanofluids compared to $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm)-DIW MHNFs. In essence, the particle size of TiO_2 NPs plays a substantial role in influencing the TC enhancement of these nanofluids, suggesting that smaller particles may offer more significant improvements in heat transfer properties.

5.4.10 Thermal conductivity of lower volume fraction MHNFs $\text{Fe}_3\text{O}_4/\text{TiO}_2$ and $\text{Fe}_3\text{O}_4/\text{MgO}$

The thermal conductivity of the HNFs against of temperature and volume fraction (ϕ), is presented in **Figure 5.12. a and b**, In the thermal conductivity analysis of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ and $\text{Fe}_3\text{O}_4\text{-MgO}$ /water nanofluids at various volume fractions (0.00625 vol%, 0.0125 vol%, 0.05 vol%, 0.1 vol%, 0.2 vol %, and 0.3 vol%), and temperatures (10-50°C), the highest percentage enhancements were determined. For 0.3%Vol, **Table 5.4** show the peak enhancement of at 50°C.

Table 5. 4 Enhancement thermal conductivity of lower volume fraction of MHNFs $\text{Fe}_3\text{O}_4/\text{TiO}_2$ and $\text{Fe}_3\text{O}_4/\text{MgO}$

Volume fraction (%Vol)	Temperatures (50°C)	@	Peak enhancement (%)	
			$\text{Fe}_3\text{O}_4/\text{TiO}_2(18\text{nm})$	$\text{Fe}_3\text{O}_4\text{-MgO}(20\text{-}40\text{nm})$
0.3	50°C		14	17.1
0.2	50°C		6.3	13.2
0.1	50°C		4.7	11
0.05	50°C		3.1	7.9
0.025	50°C		1.7	6.8
0.0125	50°C		1.4	3.9
0.0625	50°C		0.5	2.6

The baseline DIW exhibited no enhancement, serving as a reference. Both temperature and ϕ were observed to positively influence the κ enhancement of MHNFs, with the impact of temperature

being more prominent than that of φ . Increasing temperature and φ were found to enhance κ , aligning with previous studies [228], [268], [269].

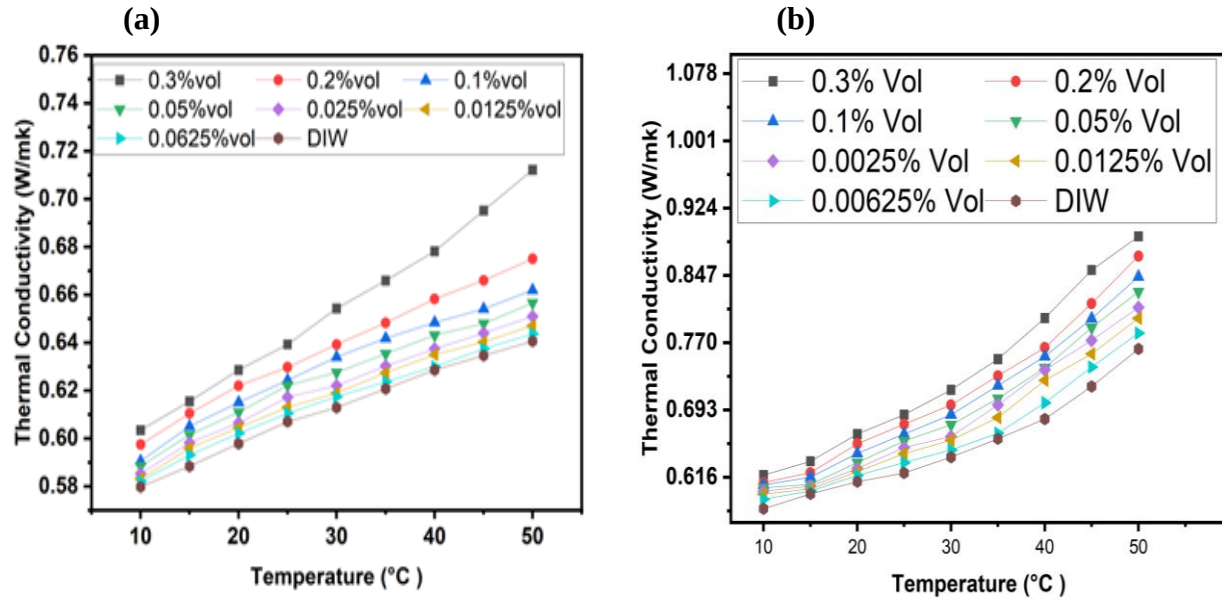


Figure 5.14 Temperature-dependent TC enhancement of (a) $\text{Fe}_3\text{O}_4/\text{TiO}_2$, (b) $\text{Fe}_3\text{O}_4\text{-MgO}$ MNFs across various volumetric ratio

The TC analysis of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ and $\text{Fe}_3\text{O}_4\text{-MgO}$, revealed significant enhancements as a function of both temperature and volume fraction (φ). The percentage enhancements at different volume fractions and temperatures indicate the nanofluid's improved heat transfer capabilities. Generally, as the φ improved, the TC improvement becomes more pronounced. This volume fraction-dependent behavior suggests that the nanofluid's thermal properties are influenced by the concentration of NPs, leading to enhanced thermal conductivity. Furthermore, the positive correlation between temperature and TC enhancement suggests that higher temperatures contribute to increased heat transfer efficiency in the nanofluid. The correlation between temperature and volume fraction underscores the need for a nuanced understanding of these factors to optimize the heat exchange properties of the $\text{Fe}_3\text{O}_4/\text{TiO}_2$ and $\text{Fe}_3\text{O}_4\text{-MgO}$ hybrid nanofluid for specific applications. This enhancement falls within the range reported in the literature [270], [271].

The predominant theoretical model for predicting TC in solid-liquid mixtures is Maxwell's theory, into account [136] often considered the standard reference. Applicable to statistically homogeneous systems with non-interacting spherical particles and low-volume fraction liquid-

solid suspensions, it serves as a benchmark. Alternative models like Bruggeman [153], Jeffrey [154], and Timofeeva [155] are employed for non-ideal scenarios. In studies on magnetic nanofluids, modifications to these models, such as Maxwell, Bruggeman, Jeffrey, and Timofeeva, are common for predicting thermal conductivity in diverse solid-liquid mixtures Equations 5.3.

$$K_{nf} = K_f \left\{ \frac{K_p + 2K_f + 2\phi(K_f - K_p)}{K_p + 2K_f - \phi(K_f - K_p)} \right\} \quad 5.3$$

The thermal conductivity results for the 0.3% volume fraction were juxtaposed with those obtained from the modified Maxwell model and the correlation proposed by Pack and Cho [272], expressed in **Equation 5.2 and 5.3**.

$$K_{nf} = (K_{bf}(1 + 7.47\phi)) \quad 5.4$$

The TC analysis of $\text{Fe}_3\text{O}_4/\text{TiO}_2$, specifically with a 0.3% volume fraction as shown in **Figure 5.15**, involved a comparison with predictions from the Correlation of Pack and Cho and the Modified Maxwell Model across a temperature 10 to 50 °C. The examination revealed an average percentage deviation of approximately 10.24% for the Correlation of Pack and Cho and around 10.45% for the Modified Maxwell Model. This consistent underestimation of experimental thermal conductivity values by both models across the entire temperature spectrum implies the need for refinements to enhance their predictive accuracy for $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids under varying temperature conditions. The disparities between the modified Maxwell model and the Pack and Cho correlation were within a margin of less than 10.25% and 10.54% when compared to the measured outcomes, aligning with similar observations in previous studies by Abu-Eishah [273], and Astanina et al [274]. These positive average percentage deviations underscore the importance of adjusting or refining these models to improve their accuracy in predicting the thermal conductivity behavior of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids under diverse temperature scenarios.

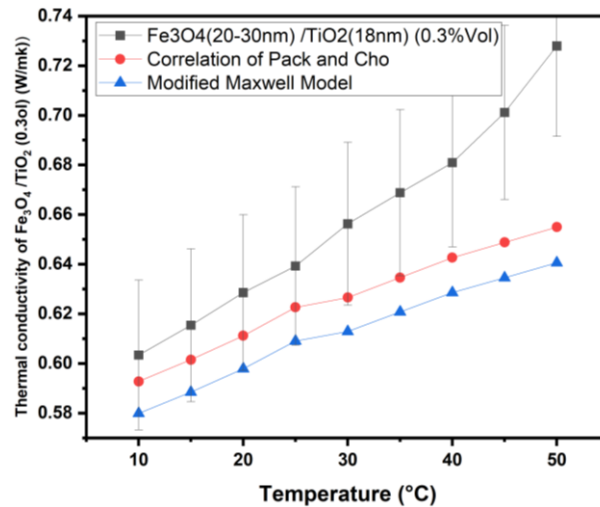


Figure 5. 15 Thermal conductivity comparison at 0.3% volume fraction: measured vs. empirically derived.

5.4.11 Impact of temperature and HMRs on the electrical conductivity(EC)of MHNFs

The electrical conductivity meter was calibrated using a standard calibration fluid provided by the manufacturer, and the average electrical conductivity at 25°C was recorded as 1413.6 $\mu\text{S}\cdot\text{cm}^{-1}$. Subsequently, the electrical conductivity encompassed different hybridization mixing ratios (HMRs) – 80:20, 60:40, and 40:60 – across four distinct MHNFs types; Fe₃O₄/TiO₂(18nm)/DIW, Fe₃O₄/TiO₂(60nm)/DIW, Fe₃O₄/MgO(20nm)/DIW, and Fe₃O₄/ZnO (20nm)/DIWMHNFs was measured at temperatures 5°C intervals from 10°C to 50°C.

Electrical conductivity characterizes the ability of an aqueous solution to conduct electric current under an applied potential difference. When nanoparticles are introduced into base fluids, forming nanofluids, there is a noticeable enhancement in the electrical conductivity of these fluids. This enhancement arises from the increased mobility of electric charges facilitated by the dispersion of nanoparticles. The experimental findings, depicted in **Figures 5.16 and 17**, elucidate the interplay between temperature and the electrical conductivity of various MHNFs considered in this study, each with different HMRs in comparison to DIW.

In **Figure 5.16(a)**, the impact of temperature on the EC of Fe₃O₄/TiO₂(18nm)-DIW MHNFs with varying HMRs (80:20, 60:40, and 40:60) is showcased. Notably, the 80:20 HMR demonstrated the highest electrical conductivity, registering a value of 4.25 and a remarkable percentage enhancement of 972.93% at 45°C compared to DIW. Similarly, the 60:40 HMR exhibited an impressive percentage enhancement of 964.82%, establishing itself as the top performing HMR.

The 40:60 HMR displayed an enhancement of 479.45%. This underscores the substantial impact of HMRs on electrical conductivity, particularly at elevated temperatures.

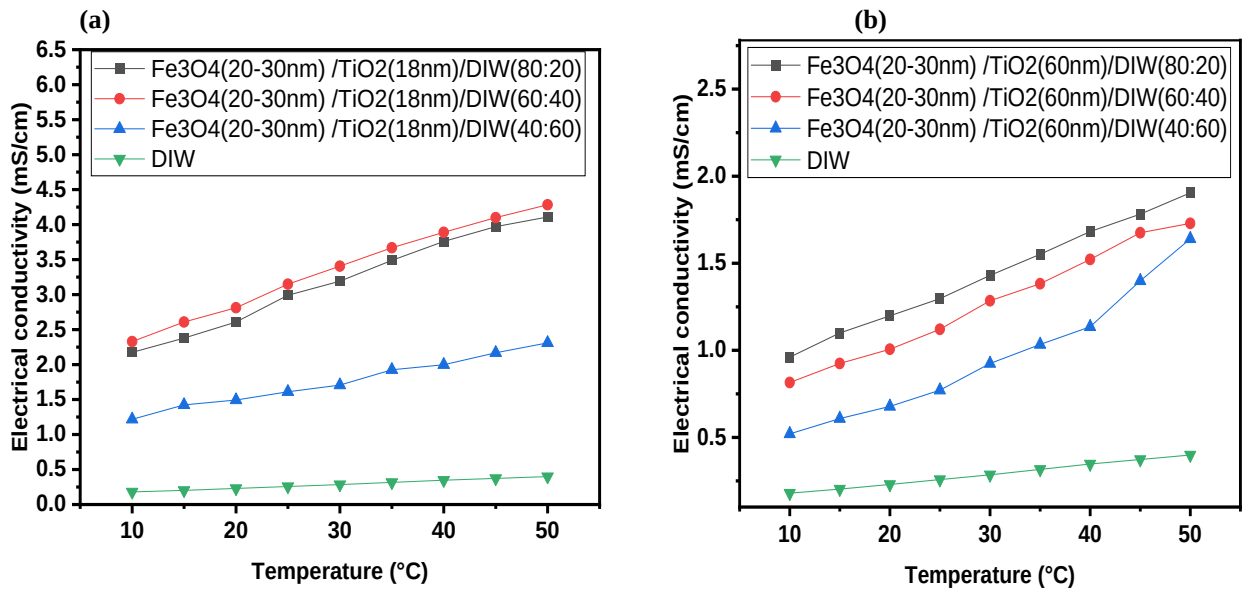
Figure 5.16(b) highlights the impact of temperature on the EC of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (60nm)-DIW MHNFs, also featuring varying HMRs. Across all ratios, there were consistent increases in electrical conductivity with rising temperature, indicating a positive correlation. Notably, the 80:20 HMR displayed the highest electrical conductivity, with an enhancement of 377.12%. The 60:40 ratio showed a 333.35% enhancement, while the 40:60 ratio exhibited an enhancement of 311.28%.

The disparity observed in electrical conductivity between larger (60nm) and smaller (18nm) TiO_2 nanoparticles, as depicted in **Figure 5.17**, could be attributed to variances in nanoparticle density. Denser nanoparticles may impede the mobility of charge carriers, resulting in decreased conductivity due to increased scattering [275], [276], [277]. However, despite lower EC, the 60nm nanoparticles exhibit higher thermal conductivity, suggesting the involvement of divergent mechanisms. Further exploration into the role of nanoparticle density in electrical conductivity within MHNFs is warranted, as it involves a complex interplay among particle size, density, and charge carrier behavior.

In **Figure 5.16(c)**, the dataset illustrates electrical conductivity values across various HMRs of $\text{Fe}_3\text{O}_4/\text{MgO}$ -DIW MHNFs at different temperatures, reaffirming the consistent positive correlation between temperature and electrical conductivity. Remarkably, the 80:20 HMR displayed the highest electrical conductivity, featuring a 502.76% enhancement. The 60:40 HMR exhibited a maximum electrical conductivity enhancement of 298.00%, while the 40:60 HMR demonstrated an enhancement of 289.22% compared to DIW.

The results presented in **Figure 5.16d** depict the electrical conductivity values of $\text{Fe}_3\text{O}_4/\text{ZnO}$ -DIW MHNFs at different temperatures and various HMRs. A thorough analysis of this dataset reveals a consistent relationship between temperature and electrical conductivity. With increasing temperature, electrical conductivity consistently increases across all HMRs. Interestingly, contrary to previous observations, the 60:40 HMR demonstrates the highest electrical conductivity, reaching 1.803 mS/cm with an impressive enhancement of 351.88% compared to DIW. The 80:20 HMR records a value of 1.3986 mS/cm, featuring a percentage enhancement of 250.38%. Similarly, the 40:60 hybridization mixing ratio achieves a maximum electrical conductivity of 1.3286 mS/cm, with a percentage enhancement of 232.08%.

These findings notably exceed those of previous research. For instance, Bagheli et al. [278] reported an electrical conductivity value of 1.90 mS/cm for a 0.6 vol% Fe_3O_4 /water nanofluid at 60°C. Meanwhile, Giwa et al. [263] observed an electrical conductivity range of 1.127–1.265 mS/cm for a 0.1 vol% Al_2O_3 /MWCNT(80:20)-DIW nanofluid at 50°C. In contrast, Giwa et al. [279] found an electrical conductivity ranging from 6.40 to 4.570 mS/cm for a 0.75 vol% Al_2O_3 - Fe_2O_3 (75:25)/DIW hybrid nanofluid at 50°C. Another study by Giwa et al. [280] reported an electrical conductivity value of 4.319 mS/cm for an MWCNT- Fe_2O_3 (20:80)/DIW hybrid nanofluid. These comparisons highlight the intricate interplay of parameters and emphasize the unique contribution of the present study to the understanding of electrical conductivity in hybrid nanofluids.



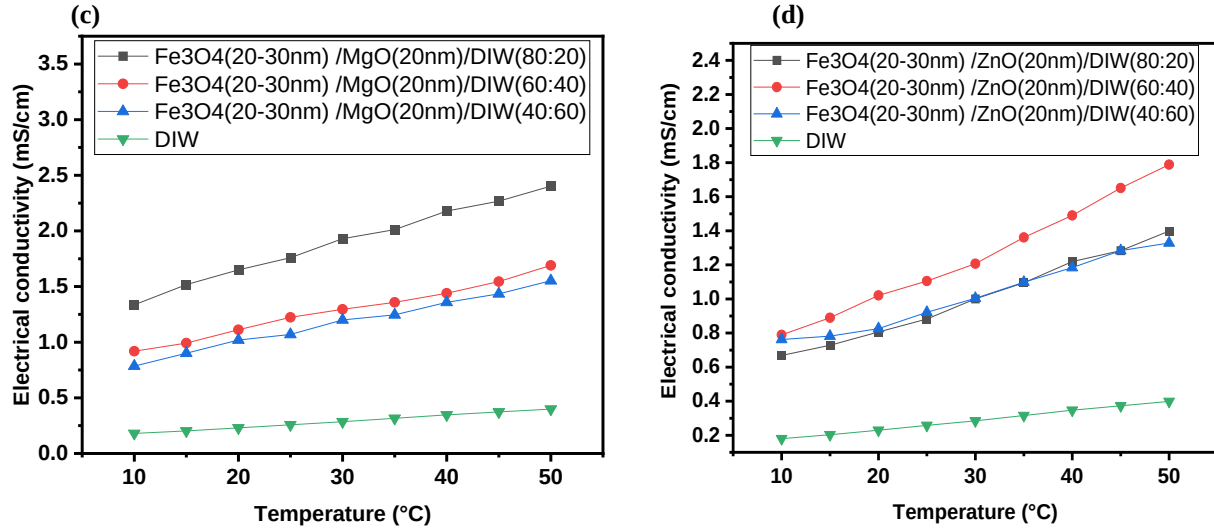
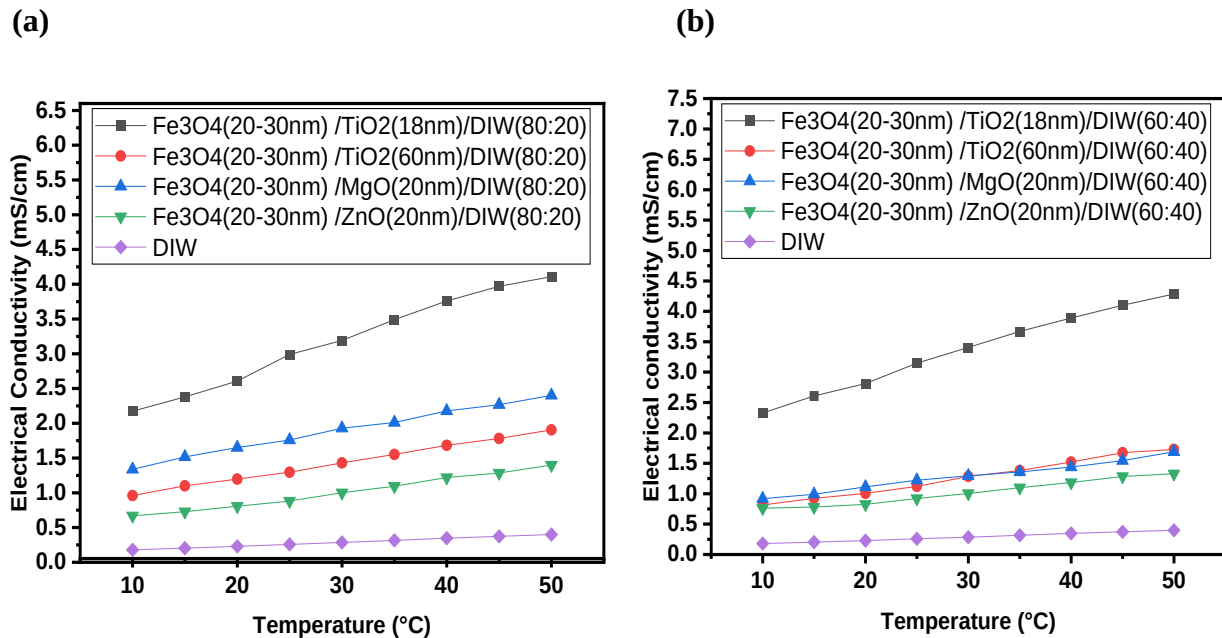


Figure 5. 16 Variation of electrical conductivity with temperature for (a) Fe₃O₄/TiO₂ (18nm), (b) Fe₃O₄/TiO₂ (60nm), (c) Fe₃O₄/MgO, (d) Fe₃O₄/ZnO hybrid nanofluids at different hybridization mixing ratios.



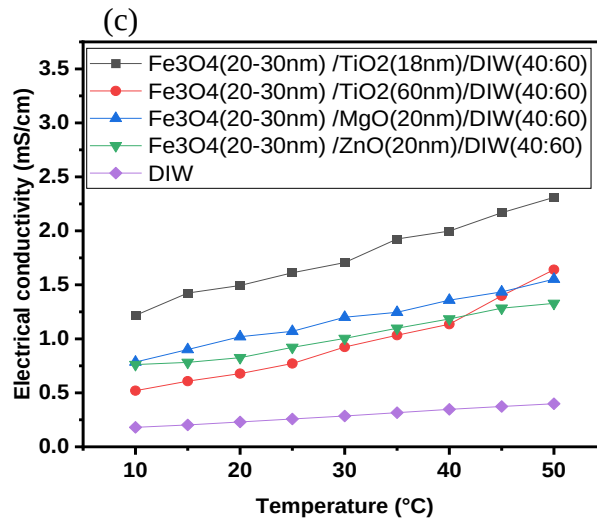


Figure 5. 17 Comparative analysis of electrical conductivity in MHNFs at (A) 80:20, (B) 60:40, and (C) 40:60 hybridization mixing ratios across different temperatures.

5.4.12 Electrical conductivity of lower volume fraction MHNFs $\text{Fe}_3\text{O}_4/\text{TiO}_2(18\text{nm})$ and $\text{Fe}_3\text{O}_4/\text{MgO}(20-40\text{nm})$

The analysis of electrical conductivity in MHNFs, as depicted in **Figure 5.18**, reveals temperature-dependent trends and significant enhancements across various volume fractions. Generally, there is an upward trend in percentage enhancement as temperature increases from 10°C to 50°C, indicating a rise in EC.

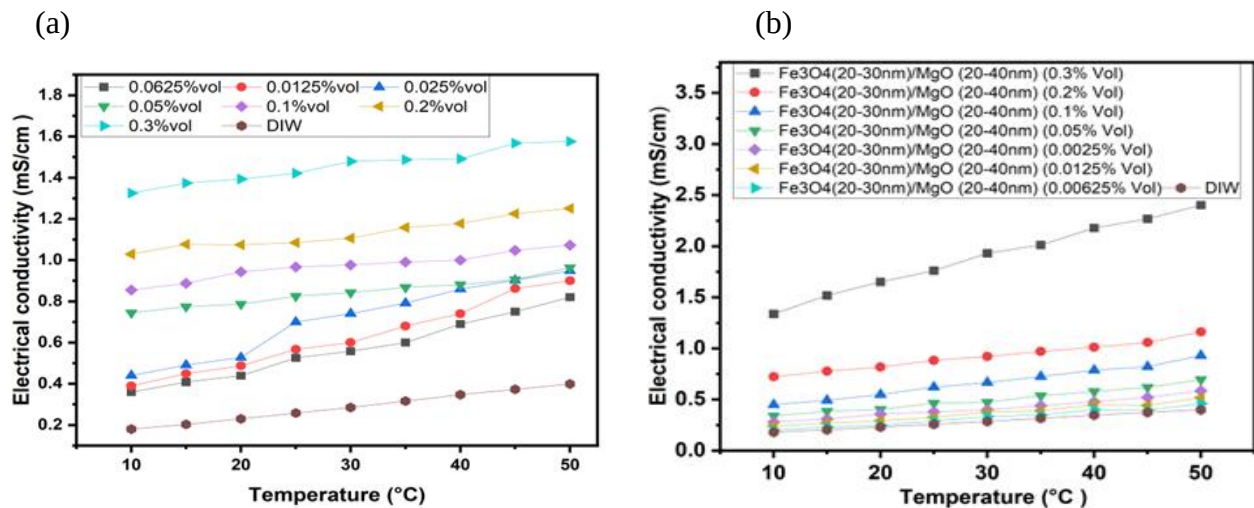


Figure 5. 18 Electrical conductivity dependent on temperature-volume fraction of MHNFs (a) $\text{Fe}_3\text{O}_4/\text{TiO}_2(18\text{nm})$ and (b) $\text{Fe}_3\text{O}_4/\text{MgO}(20-40\text{nm})$

Notable peak enhancements for each volume fraction include at 50°C for 0.0625% vol, to 0.3% vol as depicted in **Table 5.5**. Interestingly, temperature, the percentage enhancement reflects the influence of volume fraction, with higher concentrations generally resulting in more substantial enhancements., a noticeable linear correlation is evident between the enhancement of electrical conductivity and the volume concentration of the nanofluid. This observation aligns with findings from prior research on nanofluid electrical conductivity enhancement [268], [280], [281], [282]. Nevertheless, it's worth noting that some studies have reported either temperature independence in the enhancement or a reduction in electrical conductivity with increasing temperature [70], [268], [283]. The peak enhancement was consistently observed at 50°C for all samples of the hybrid nanofluids. Specifically, at 50°C and 0.3 vol%, a remarkable improvement of 700% was achieved. This comprehensive analysis highlights the intricate interplay of temperature and volumetric ratio on EC, offering valuable insights for optimizing the electrical properties of MHNFs for diverse applications.

Table 5. 5 Enhancement electrical conductivity of lower volume fraction of MHNFs $\text{Fe}_3\text{O}_4/\text{TiO}_2$ and $\text{Fe}_3\text{O}_4/\text{MgO}$

Volume fraction (% Vol)	Temperatures (50°C)	@ ($\mu\text{S}\cdot\text{cm}^{-1}$)	Peak enhancement (%)
		$\text{Fe}_3\text{O}_4/\text{TiO}_2(18\text{nm})$	$\text{Fe}_3\text{O}_4\text{-MgO}(20\text{-}40\text{nm})$
0.3	50°C	268	501
0.2	50°C	213	191
0.1	50°C	169	133
0.05	50°C	141	74
0.025	50°C	130	46
0.0125	50°C	123	30
0.00625	50°C	105	15

5.4.13 Impact of temperature variation on the pH of MHNFs

To determine pH levels, a Bench pH meter was used. Calibration was carried out using standard pH buffer solutions with of 10, 7, 6, and 4 at room temperature.

The pH level of a nanofluid serves as an indicator of its acidity or alkalinity, which, in the context of MHNFs, can influence the surface charge of nanoparticles within the MHNFs. This surface

charge, often stemming from functional groups on the nanoparticle surface, plays a critical role in stabilizing the nanofluid through electrostatic repulsion. In this section, the need to investigate the impact of temperature on the pH of MHNFs with hybridization mixing ratios (HMRs) of 80:20, 60:40, and 40:60, all at a concentration of 0.3 vol% [47], [284].

As illustrated in **Figure 5.19**, the relationship between pH and temperature is examined. Generally, the pH levels of the MHNFs exhibit a slight decrease as the temperature rises from 10°C to 50°C, maintaining a constant 0.3 vol% concentration throughout. Across all the MHFs considered, they tend to lean towards being more alkaline. However, both $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm)-DIW and $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (60nm)-DIW MHNFs consistently show relatively lower pH values across different HMRs, as shown in **Figure 5.19 (a) (c)**. Conversely, the $\text{Fe}_3\text{O}_4/\text{MgO}$ -DIW MHNF exhibits the highest pH value, indicating a more acidic nature. It is also noteworthy that the pH value remains consistent across various HMRs as the temperature increases. The observation that the $\text{Fe}_3\text{O}_4/\text{MgO}$ -DIW MHNF exhibits the highest pH value, suggesting a more acidic nature, could be attributed to the intrinsic chemical properties and surface characteristics of the nanoparticles. MgO is a basic oxide that can influence the pH of a suspension depending on its interaction with water and other components. However, in the presence of Fe_3O_4 , which is amphoteric, the overall pH may shift toward acidity due to the release of Fe^{3+} ions in an aqueous medium.

The acidic nature could also arise from the interaction of Fe_3O_4 nanoparticles with dissolved carbon dioxide from the air, forming weak acids like carbonic acid, which lower the pH. Additionally, the surfactants or stabilizers used during the preparation of the MHNF, such as Gum Arabic, may contribute acidic functional groups, further influencing the pH.

The consistent pH value across varying HMRs with increasing temperature may indicate that the system achieves a dynamic equilibrium, where any temperature-induced changes in ionization or dissociation of components are counterbalanced by buffering effects in the nanofluid.

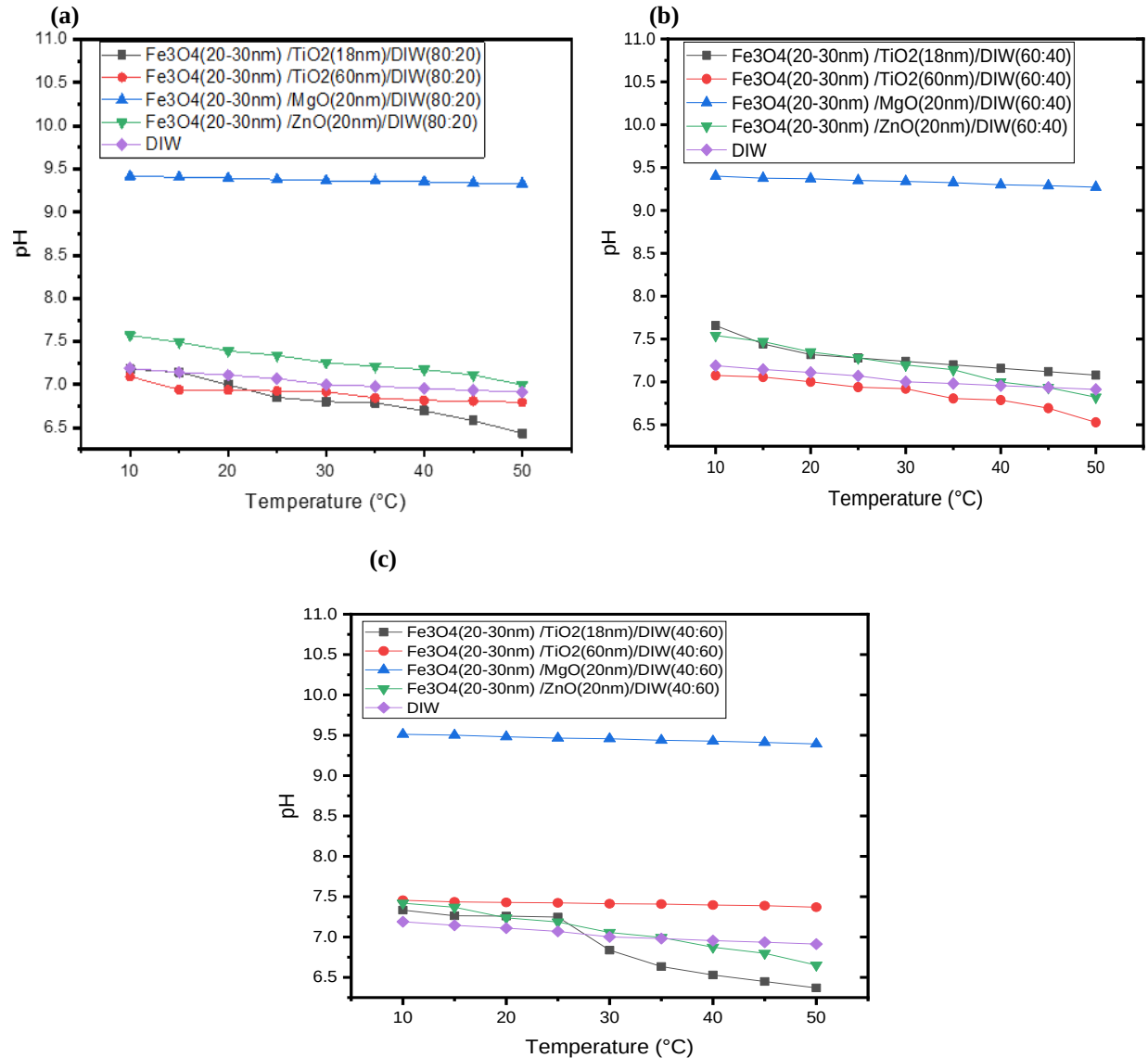


Figure 5.19 pH Variation of MHNFs/DIW at different temperatures for (a) 80:20, (b) 60:40, and (c) 40:60 hybridization mixing ratio

5.4.13 pH of lower volume fraction of MHNFs of Fe₃O₄/TiO₂(18nm) and Fe₃O₄/MgO(20-40nm)

The pH measurements for Fe₃O₄/TiO₂ and Fe₃O₄/MgO MHNFs with different volumetric ratio, spanning from 0.00625% to 0.3%, were systematically compared with the pH of DIW, as shown in **Figure 5.20 (a)** and **(b)** respectively. The experimental results demonstrated a consistent decrease in pH with increasing volume fraction, indicative of a shift towards acidity in the nanofluids. The percentage changes in pH ranged from approximately -2.24% to 6.75%. Notably, the pH decrease was more pronounced for higher volume fractions, with the highest volume fraction (0.3%) exhibiting the most substantial increase in acidity Fe₃O₄/TiO₂ and subsequently, the pH of the

$\text{Fe}_3\text{O}_4/\text{MgO}$ and DIW was evaluated, and the findings are illustrated in Figure 18(d). The outcomes demonstrated a decrease in pH MHNFs as the temperature increased. Higher volumetric ratio of MHNFs intensified this decline in pH from 10.59 to 8.76, indicating a transition from highly basic to alkaline conditions. In contrast, deionized water exhibited a consistently stable pH throughout the experiment. This trend suggests that the introduction of nanoparticles has a discernible impact on the pH of the fluid, possibly attributed to surface charge effects. Additionally, the investigation revealed that the pH variations were influenced by temperature changes. The consistent decrease in pH across different volume fractions and the additional effect of temperature underscore the importance of precise pH control, particularly in applications where the acidity or alkalinity of the nanofluid plays a crucial role. These experimental findings contribute valuable insights into the pH behavior of MHNFs under varying conditions, enhancing our understanding of their physicochemical properties for optimized applications.

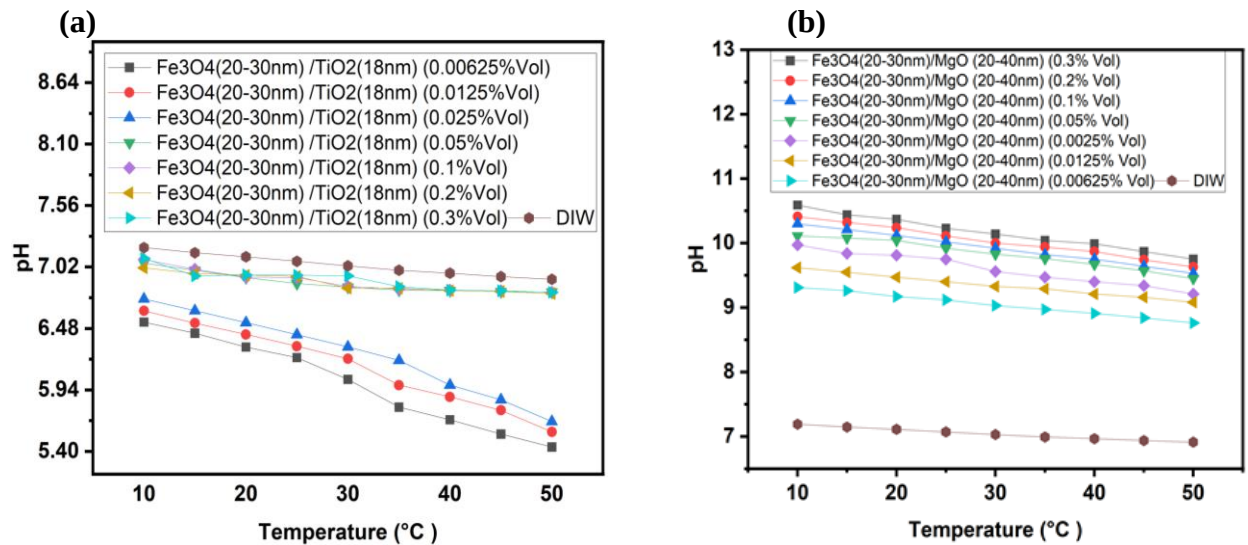


Figure 5.20 pH Variation of different volumetric ratio of MHNFs at different temperatures for (a) $\text{Fe}_3\text{O}_4/\text{TiO}_2$ and (b) $\text{Fe}_3\text{O}_4/\text{MgO}$

5.4.14 Viscosity characteristics of MHNFS understanding the impact of nanoparticles and hybridization mixing ratios.

The viscometer was calibrated using a double-point standard calibration technique employing deionized water (DIW). Subsequently, the viscosity of water was evaluated across with temperature 10°C - 50°C and juxtapose to the data of Senger & Watson [285]. Following this, viscosity measurements were conducted for different MHNFs.

In this investigation, the effect of temperature on the viscosity of various MHNFs, including $\text{Fe}_3\text{O}_4/\text{TiO}_2(18\text{nm})$ -DIW, $\text{Fe}_3\text{O}_4/\text{TiO}_2(60\text{nm})$ -DIW, $\text{Fe}_3\text{O}_4/\text{MgO}$ -DIW, and $\text{Fe}_3\text{O}_4/\text{ZnO}$ -DIW MHNFs, is examined. These MHNFs encompass different hybrid mixing ratios (HMRs) of 80:20, 60:40, and 40:60, all at a 0.3 vol% concentration. Generally, the MHNFs decline with increasing temperature, aligning with the conventional theoretical trend for fluid viscosity. The viscosity measurement method employed in this study is depicted in **Figure 5.20a**.

As depicted in **Figure 5.20 (b) to (d)**, the $\text{Fe}_3\text{O}_4/\text{MgO}$ -DIW MHNF exhibits the highest viscosity among all the nanofluids considered for various mixing ratios. The low viscosity values of $\text{Fe}_3\text{O}_4/\text{ZnO}$ -DIW MHNFs can be attributed to the intrinsic properties of the ZnO NPs and their interaction with Fe_3O_4 within the base fluid. Zinc oxide nanoparticles, compared to other materials like MgO or TiO_2 , tend to exhibit smoother particle surfaces and lower hydrodynamic diameters in suspension, which reduces the overall resistance to flow. Additionally, ZnO nanoparticles may form weaker inter-particle networks compared to other oxides, leading to reduced viscosity. The hybridization mixing ratio (HMR) also plays a critical role. The 80:20 HMR, which has a higher proportion of Fe_3O_4 .

It's important to highlight that higher viscosity in MHNFs influences the heat transfer behavior of the fluid by increasing frictional resistance to flow. Consequently, this results in higher pressure drop and presents challenges for achieving optimal heat transfer efficiency [286].

The rise in viscosity of $\text{Fe}_3\text{O}_4/\text{MgO}$ -DIW MHNFs can indeed lead to a significant increase in the pressure drop across a system, as viscosity directly correlates with the frictional resistance of the fluid. This increased resistance requires higher pumping power to maintain the desired flow rate, which in turn raises the overall energy consumption of the heat transfer system. Although high viscosity can sometimes enhance thermal performance due to improved thermal boundary layer interaction, the associated energy penalties often outweigh the benefits in practical applications.

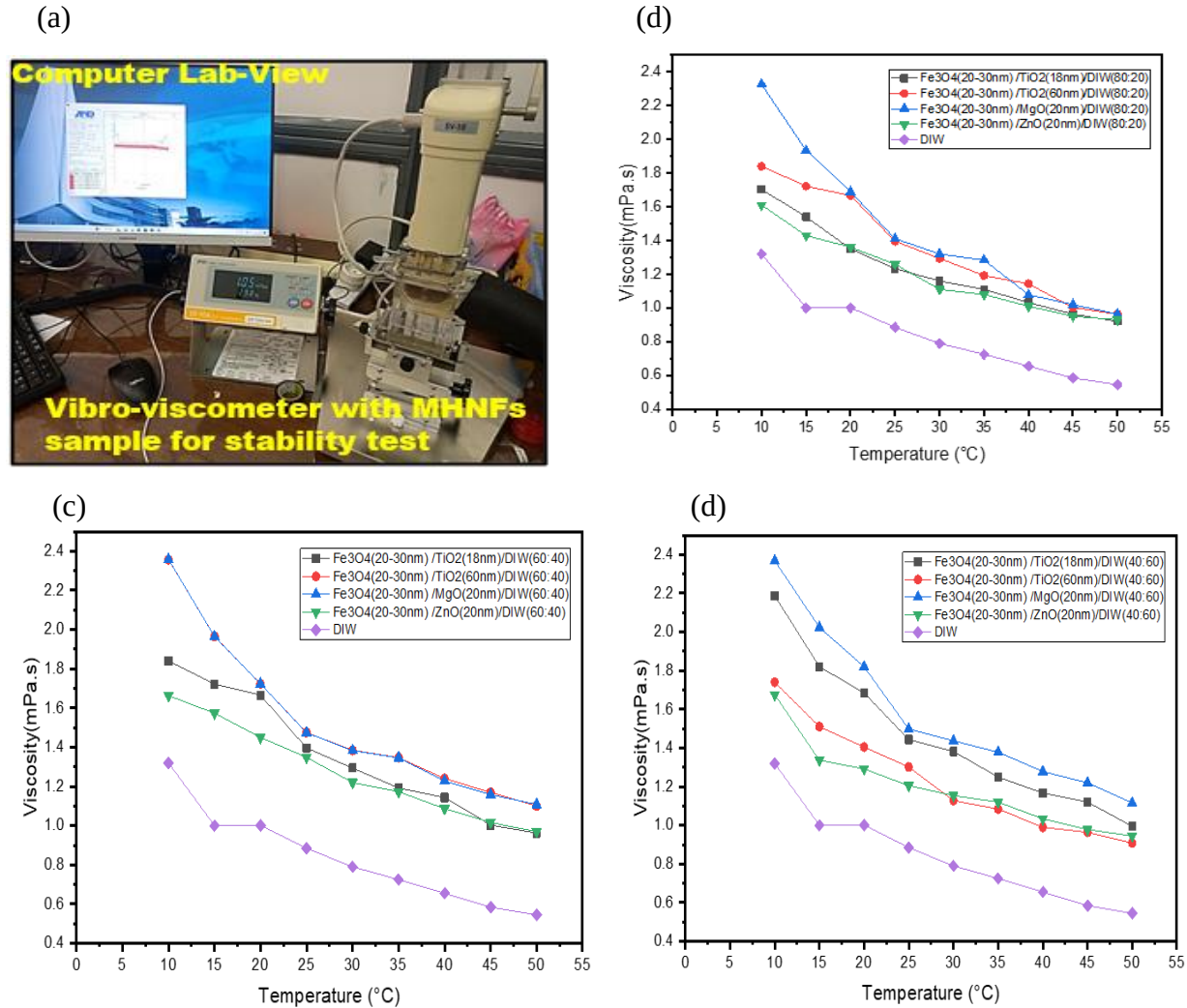


Figure 5. 21 Viscosity of MHNFs/DIW at different temperatures for (a) Determination of MHNFs (b) 80:20, (c) 60:40, and (d) 40:60 hybridization mixing ratios

5.4.15 Viscosity of MHNFs/DIW at different temperatures for lower volume fraction of MHNFs of Fe₃O₄/TiO₂(18nm) and Fe₃O₄/MgO(20-40nm)

Viscosity assessments were conducted for Fe₃O₄/TiO₂ (18nm) and Fe₃O₄/MgO(20-40nm) MHNFs at temperatures 10°C - 50°C.

The experimental data in **Figure 5.21**, provides valuable insights into the viscosity behavior of Fe₃O₄/TiO₂ and Fe₃O₄/MgO. The comparison of MHNFs viscosities with H₂O viscosity, as documented by Popiel and Wojtkowiak [267], illustrates a consistent increase in MHNFs viscosity with higher volume concentration. This observation aligns with prior studies [159], [228], [268], [279], [280], indicating a correlation between the viscosities and TC of MHNFs [287], [288],

[289]. The determined water properties, using the equation by Popiel and Wojtkowiak, serve as a reference for the viscosity analysis. **Figure 5.21** further demonstrates that nanofluid viscosity rises with both volume concentration and temperature. The highest percentage enhancement of nanofluid viscosity compared to DIW viscosity was observed at the maximum tested volume fraction for each concentration. For 0.3% vol, the highest enhancement was approximately 23% for $\text{Fe}_3\text{O}_4/\text{TiO}_2$ and 51% $\text{Fe}_3\text{O}_4/\text{MgO}$ at 50°C . Similarly, for 0.2% vol, the peak enhancement reached around 21% and 42.5 % at 50°C .

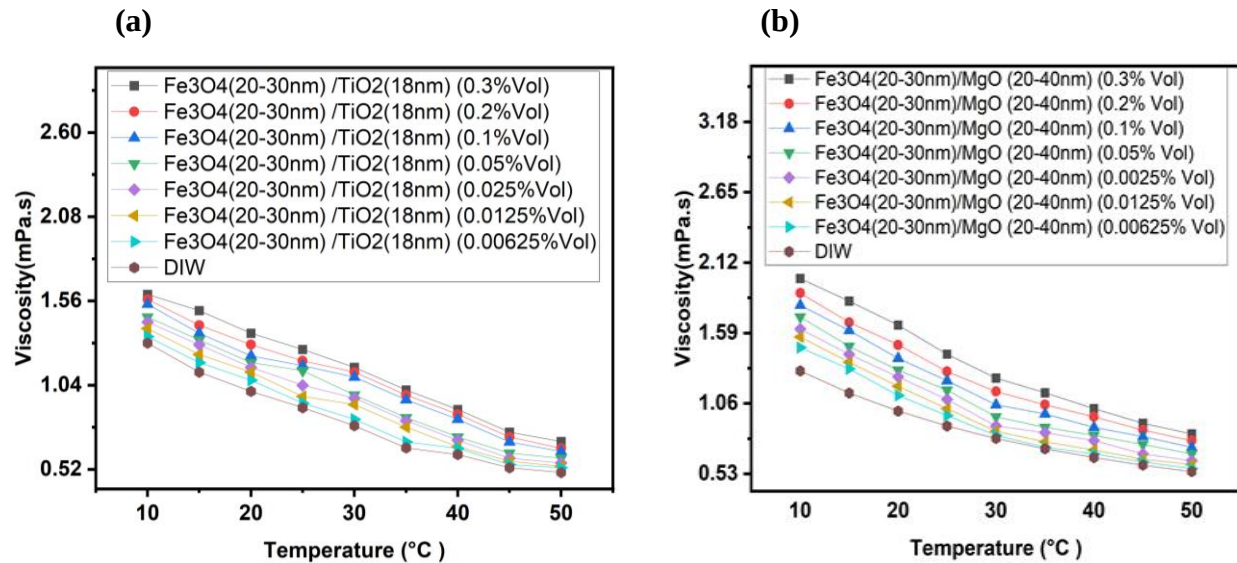


Figure 5. 22 Exploring the impact of temperature on nanofluid viscosity (a) $\text{Fe}_3\text{O}_4/\text{TiO}_2$ and (b) $\text{Fe}_3\text{O}_4/\text{MgO}$

The nanofluid with 0.1% vol exhibited the highest enhancement of about 19% and 33.4% at 50°C , while for 0.05% vol, the maximum enhancement reached approximately 18% and 24.3% at 50°C . For 0.025% vol, the highest enhancement was approximately 14% and 15.4 % at 50°C . Additionally, for both 0.00625 vol % and 0.0125 vol % and, the maximum improvement were about 11% and 10%, and 8% and 4.20, for $\text{Fe}_3\text{O}_4/\text{TiO}_2$ and $\text{Fe}_3\text{O}_4/\text{MgO}$ respectively, both observed at 50°C . These findings highlight the temperature-dependent, particles size and concentration-specific nature of viscosity enhancements in the nanofluid, emphasizing the significance of these factors in tailoring its rheological properties MHNFs for various applications.

5.4.16 Viscosity of lower volume fraction of MHNFs of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm) and $\text{Fe}_3\text{O}_4/\text{MgO}$ (20-40nm) and assessment of stability over time

To determine the stability of the MHNFs, a procedure similar to approaches outlined in prior investigation by Osman et al.[45] and Giwa et al. [280], was deployed. A setup comprising a data logger equipped was established to collate data every 5-minute over a period of 12 and 5 hours respectively, as depicted in **Figure 5.22**. This setup facilitated the assessment of stability under a constant temperature of 30 degree. The viscosity data indicates that the MHNFs are somewhat stable for 0.3 to 0.1% Vol, while demonstrating higher stability for concentrations between 0.05 to 0.00625% Vol.

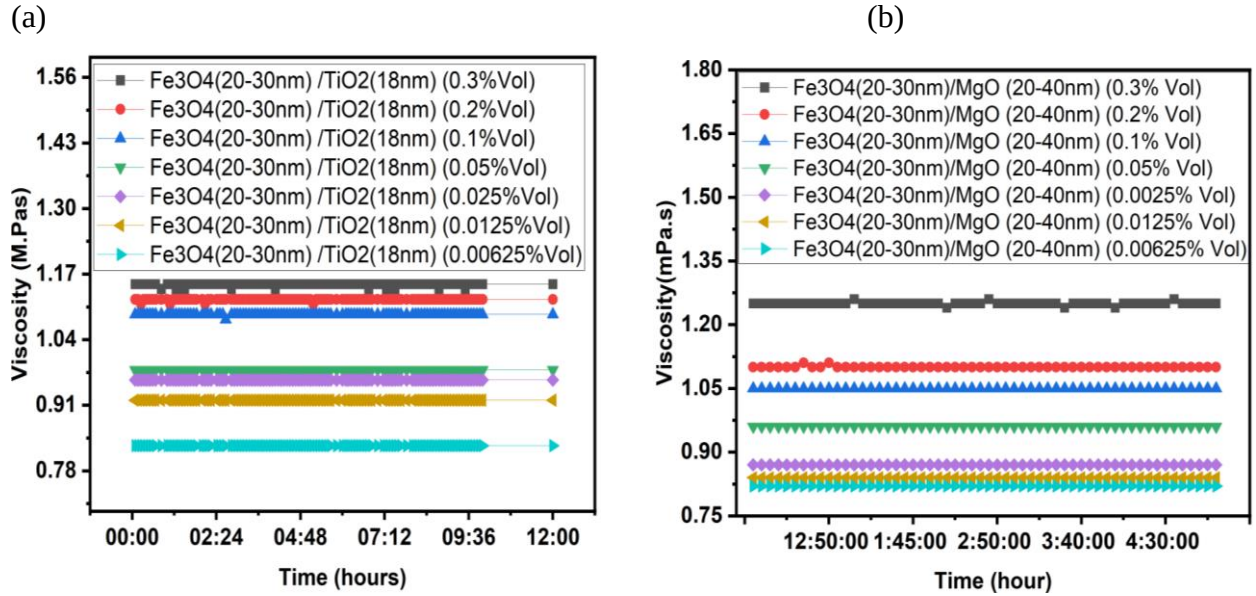


Figure 5. 23 Viscosity of MHNFs over time at 30°C (a) $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (b) $\text{Fe}_3\text{O}_4/\text{MgO}$

5.4.17 Evaluating the effect of temperature on the thermoelectrical conductivity of MHNFs

The thermoelectric conductivity (TEC) of the nanofluid is a crucial aspect relevant to its potential applicability in electrically active environments, such as PEM Fuel Cells, and can be determined using the equation provided in Zakaria et al.'s work [290].

$$TEC = \frac{5K_{nf}}{\sigma_{nf}K_{bf}} \quad 5.5$$

Where, K_{nf} and σ_{nf} are the nanofluid thermal and electrical conductivity respectively, and K_{bf} is the base fluid TC.

Considering the viscosity, TC, and stability of the fluids studied in this research, it is evident that MHNFs with an 80:20 HMR ratio emerge as the most suitable choice for various heat transfer applications, including cooling in PEM fuel cells and diverse industrial and energy devices. Therefore, we investigate the influence of temperature on the TEC of the MHNF with an 80:20 HMR ratio, as depicted in **Figure 5.23**. The results indicate a reciprocal relationship between TEC and temperature.

Fe₃O₄/ZnO-DIW MHNFs demonstrate the highest TEC values, measuring 7.86 cm/mS at 10°C and 4.56 cm/mS at 50°C. Following closely, Fe₃O₄/TiO₂(60nm)-DIW records a TEC of 5.50 cm/mS at 10°C and 3.5 cm/mS at 50°C. Fe₃O₄/TiO₂ (18nm)-DIW shows the lowest TEC, with values of 2.48 cm/mS at 10°C and 1.6cm/mS at 50°C. These significant thermoelectrical conductivity measurements position all MHNFs explored in this study as promising options for maintaining effective electrical and thermal performance in PEM fuel cell systems, particularly in cooling the stacks.

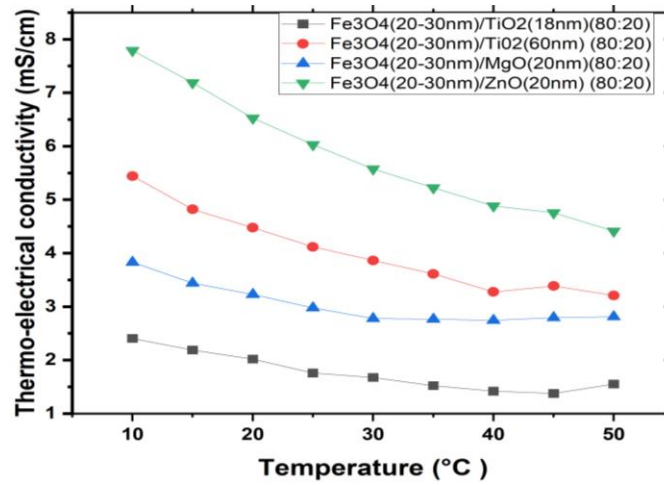


Figure 5. 24 Examining the effect of temperature on the TEC of MHNFs.

5.4.18 Evaluation of density and specific heat of Fe₃O₄/MgO and Fe₃O₄/TiO₂

The density and specific heat of Fe₃O₄/TiO₂ and Fe₃O₄/MgO hybrid nanofluids were obtained using established relations derived from the research conducted by Pak and Cho [272], as applied by Naik et al.[291], Sundar et al. [228], and Ibrahim et al.[252] , as presented in Equations 5.6. and 5.7 respectively.

$$C_{P_{MHNFS}} = \varphi \cdot \rho_p + (1 - \varphi) \cdot C_{bf} \quad 5.6$$

$$\rho_{MHNFs} = \varphi \times \rho_p + (1 - \varphi) \cdot \rho_{bf} \quad 5.7$$

Were the symbols representing various parameters: C_{pMHNFs} and ρ_{MHNFs} denote the specific heat and density of the MHNFs, respectively; φ represents the concentration; ρ_{bf} and C_{bf} are the density and specific heat of the base fluid (deionized water), respectively; and C_p stands for the specific heat of the hybrid nanoparticles.

5.5 Conclusion

This experimental study investigated the impact of temperature, hybridization mixing ratio (HMR), and NPs type on the stability, thermal conductivity, viscosity, and TEC of Fe_3O_4/TiO_2 (18nm)-DIW, Fe_3O_4/TiO_2 (60nm)-DIW, Fe_3O_4/MgO -DIW, and Fe_3O_4/ZnO -DIW magnetic hybrid nanofluids (MHNFs). The findings offer comprehensive insights into the thermophysical properties of MHNFs concerning temperature, HMR, and time.

It was observed that MHNFs with an HMR of 80:20 consistently exhibited superior stability and thermal conductivity, especially when combined with TiO_2 nanoparticles. The main findings can be summarized as follows:

- The increase in TC with temperature for MHNFs is primarily due to the enhanced Brownian motion of nanoparticles at elevated temperatures. This increased motion facilitates better energy transfer between the nanoparticles and the base fluid, resulting in improved thermal conductivity. Similarly, electrical conductivity rises with temperature due to the enhanced ionization of particles and improved mobility of ions within the fluid. The rise in both properties reflects the temperature-dependent behavior of the NPs intrinsic properties and their interaction with the base fluid, making MHNFs particularly effective in applications requiring dynamic thermal and electrical performance.
- The Fe_3O_4/ZnO -DIW MHNF with an HMR of 80:20 exhibited the highest thermal conductivity among all formulations, reaching 0.793 W/m.K, which represents a 31.28% enhancement compared to deionized water at 50°C. This exceptional performance can be attributed to the synergistic effects of Fe_3O_4 and ZnO nanoparticles, where Fe_3O_4 contributes magnetic properties that enhance particle alignment and energy transfer under thermal excitation, while ZnO provides high intrinsic thermal conductivity. The optimal 80:20 HMR ensures a balanced interaction between the two components, minimizing aggregation and maximizing the effective thermal pathways within the nanofluid. This

finding underscores the potential of $\text{Fe}_3\text{O}_4/\text{ZnO}$ -DIW MHNF as a superior candidate for applications demanding enhanced thermal conductivity.

- MHFs with larger particle size TiO_2 hybrid ($\text{Fe}_3\text{O}_4/\text{TiO}_2$ (60nm)-DIW) demonstrated better stability and thermal conductivity compared to smaller particle size hybrid ($\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm)-DIW).
- Specifically, the $\text{Fe}_3\text{O}_4/\text{TiO}_2$ (18nm)-DIW MHNF with an HMR of 80:20 exhibited the highest electrical conductivity of all, with values of 4.23 mS/cm and a 972.93% enhancement compared to deionized water at 50°C.
- Furthermore, regardless of HMR, the $\text{Fe}_3\text{O}_4//\text{ZnO}$ -DIW MHNF exhibited the lowest viscosity among all MHNFs, with the 80:20 HMR achieving the lowest viscosity values of 1.62 mPa·s at 10°C and 0.995 mPa·s at 50°C.
- Both viscosity and TEC showed an inverse relationship with temperature for all MHNFs considered.
- The exceptional thermoelectrical conductivity values of the MHNFs position them as potential candidates for use in cooling stacks of PEM fuel cells.

A comprehensive investigation into the thermal, rheological, and electrical properties of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ and $\text{Fe}_3\text{O}_4/\text{MgO}$ hybrid nanofluids (MHNFs). The systematic exploration covers seven different volumetric ratio providing valuable insights into the behavior and performance of the nanofluids under consideration.

The preparation of MHNFs, involving a two-step method with a specific ratio of Fe_3O_4 , TiO_2 , and MgO ensures stability using Gum Arabic as a surfactant. This meticulous preparation process is foundational to the study and contributes to the understanding of the subsequent property analyses. The morphological characterization of MHNFs through TEM and SEM illustrates the physical and structural attributes of nanoparticles. This information is crucial for assessing stability and understanding the interaction of NPs within the fluid.

Stability assessments, both qualitative through photo capture and quantitative using UV-Vis spectroscopy, provide a thorough understanding of the enduring quality and reliability of MHNFs. The data obtained from these assessments contribute to informed decision-making for sustainable applications.

The study delves into thermal conductivity, revealing a positive correlation with both temperature and volume fraction. The thermal conductivity analysis at various volume fractions and temperatures highlights the potential enhancements, with temperature exhibiting a more prominent influence than volume fraction.

Viscosity evaluations play a crucial role in stability assessments, and the study demonstrates a consistent increase in MHNFs viscosity with higher volume concentration. The viscosity analysis aligns with prior studies, indicating a correlation between viscosities and thermal conductivities of MHNFs.

Electrical conductivity analysis reveals temperature-dependent trends and significant enhancements across various volume fractions. The observed linear correlation between electrical conductivity enhancement and volume concentration aligns with prior research and indicates the intricate interplay of temperature and volume fraction.

pH measurements further contribute to the understanding of MHNFs behavior, showcasing a consistent decrease with increasing volume fraction and an additional effect of temperature. These findings underscore the importance of precise pH control in applications where the acidity or alkalinity of the nanofluid is critical.

The comprehensive property analysis presented in Chapter 5 provides a solid foundation for the study's objectives. The results obtained contribute to the optimization of MHNFs for diverse applications, considering the interplay of temperature, volume fraction, and other key parameters. The chapter sets the stage for informed conclusions and recommendations in subsequent chapters, guiding future research and applications in the field of nanofluid technology.

In summary, this research highlights the crucial effects of temperature, hybridization mixing ratios, and nanoparticle sizes and types on the stability and thermophysical characteristic of MHNFs for heat exchange applications in industrial and energy systems.

CHAPTER 6

EXPERIMENTAL OUTCOMES AND INTERPRETATION

6.1 Introduction

This section provides a thorough interpretation of the heat transfer variations, entropy generation, and thermal performance factor concerning $\text{Fe}_3\text{O}_4/\text{TiO}_2$ magnetic hybrid nanofluids is presented. The discussion encompasses the influence of magnetic waveform positioning, exploration of varied magnetic field strengths, and examination of pulsating parameters across diverse waveforms in turbulent regimes. The overarching goal is to discern the optimal magnetic field strength conducive to enhancing convective heat transfer. Additionally, variations in thermal performance, frictional factor, heat transfer, and Nusselt number of $\text{Fe}_3\text{O}_4/\text{MgO}$ MHNFs in transitional phase are examined. To ensure transparency and precision, the uncertainties associated with the documented augmentation parameters in this analysis are rigorously evaluated and detailed, comprehensively outlined in **Appendix B**.

6.2 Results of CHT of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ MHNFs in turbulent region

The study compares the average CHT coefficients and average Nu evaluation of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ MHNFs with DIW. It examines the behavior of these nanofluids in terms of heat exchange and pressure drop with different Re of 3200 - 5300. The investigation spans volume fractions from 0.00625% to 0.3%vol.

Figure 6.1 presents the impact of varying volumetric ratio on heat transfer at various using $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluid volume fractions. The CHT coefficient enhancements for $\text{Fe}_3\text{O}_4/\text{TiO}_2$ demonstrate a distinct trend when juxtaposed to DIW. At a volume fraction of 0.3%, the increase in CHT reaches approximately 11.42%, while a volume fraction of 0.2% shows an improvement of about 14.03%. As the nanoparticle concentration decreases, the enhancement becomes more pronounced, with a rise of roughly 18.04% at 0.1% and approximately 19.98% at 0.05%. Notably, at even lower concentrations, the performance peaks, achieving enhancements of around 22.91% at 0.025% and approximately 26.33% at 0.0125%. A notable increase of 24.30% is still observed at 0.00625%, underscoring the effectiveness of reduced volume fractions.

These findings reveal that $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids provide substantial heat transfer improvements compared to DIW, with the highest performance occurring at intermediate concentrations. Unlike the traditional view that higher nanoparticle concentrations optimize thermal performance, the data suggest otherwise, with the most effective enhancement occurring at 0.0125%, followed by

0.00625%. This deviation from conventional understanding highlights the influence of factors such as better NPs dispersion, lower fluid viscosity, and optimal interaction with flow conditions at reduced concentrations, contributing to the superior thermal efficiency in this specific flow.

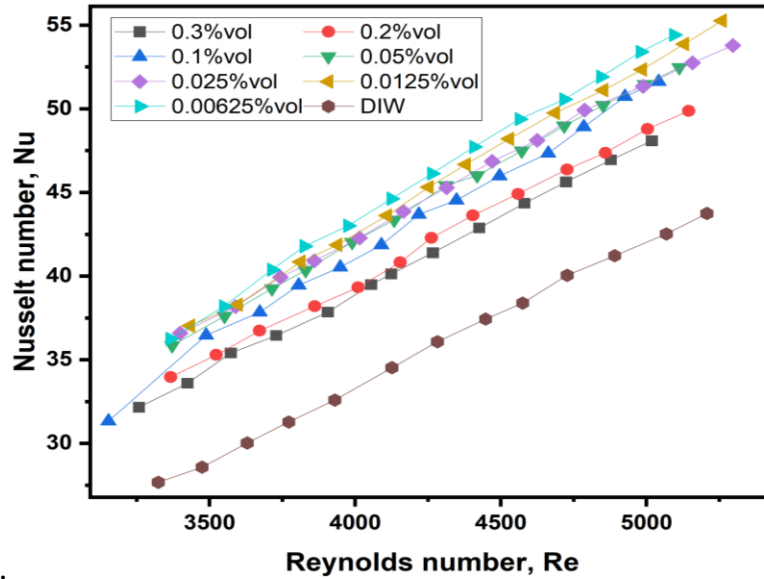
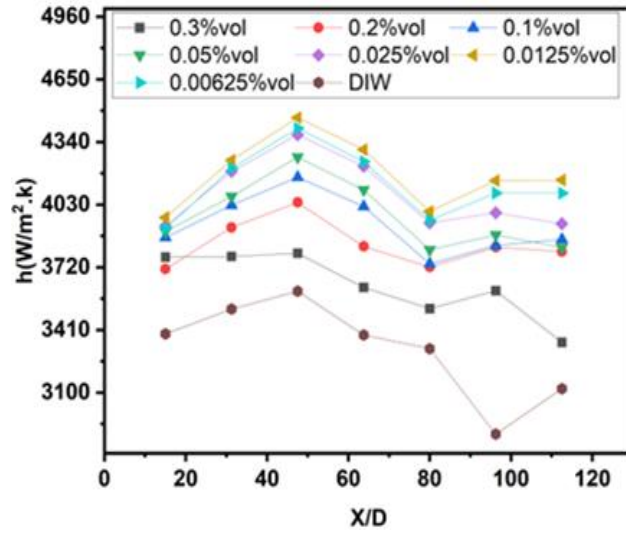


Figure 6. 1 Impact of different volumetric ratio on CHT across various Re

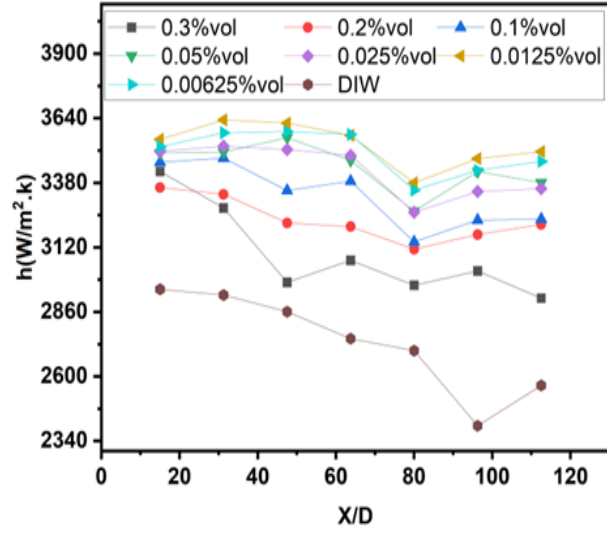
Figures 6.2a, b, and c illustrate the local convective heat transfer coefficients plotted against The position (x/d) of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluid at varying volume fractions was analyzed, with DIW serving as the baseline at the lowest Reynolds number for turbulent flow within a tube. Across all Reynolds numbers, the 0.0125% volume fraction consistently delivered the maximum heat exchange coefficients along different tube positions (x/d), marking it as the best volume fraction for maximizing thermal performance. This pattern remained consistent regardless of the specific flow position. The variations in CHT along the tube length, independent of Re, indicate non-uniform heat transfer rates, underscoring the need to account for positional effects (x/d) when designing applications focused on thermal efficiency.

Interestingly, at a Re of 3214.2, the 0.3% volumetric ratio of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluid demonstrated diminished heat transfer performance juxtaposed to DIW. Similar behavior was observed with the 0.2% and 0.1% volume fractions, particularly at positions $x/d = 15$ and $x/d = 31.25$, likely due to the increased viscosity of the nanofluid, which hindered flow dynamics. These observations reveal the complex nature of heat exchange using nanofluids, where performance is influenced by a combination of factors, including the properties of nanoparticles, their interactions, and specific flow conditions.

(a) Elevated (Re 5200)



(b) Mid (Re 4200)



(c) Lest (Re 3200)

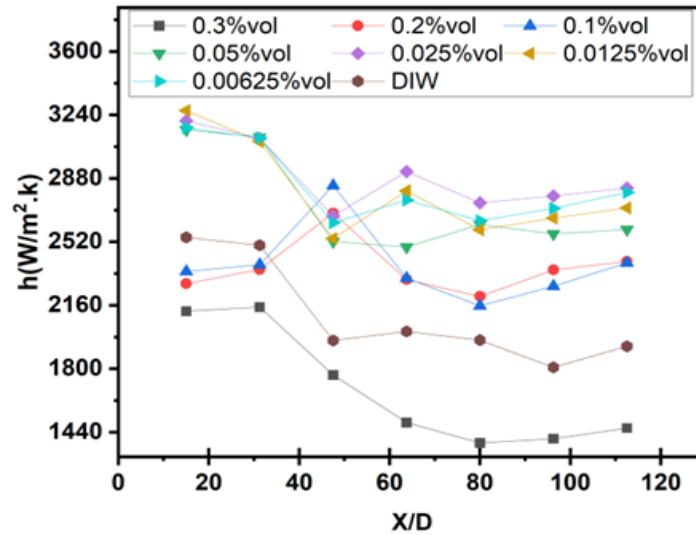


Figure 6. 2 The CHT against relative (x/d) for $\text{Fe}_3\text{O}_4/\text{TiO}_2$ MNFs across various volume fractions.

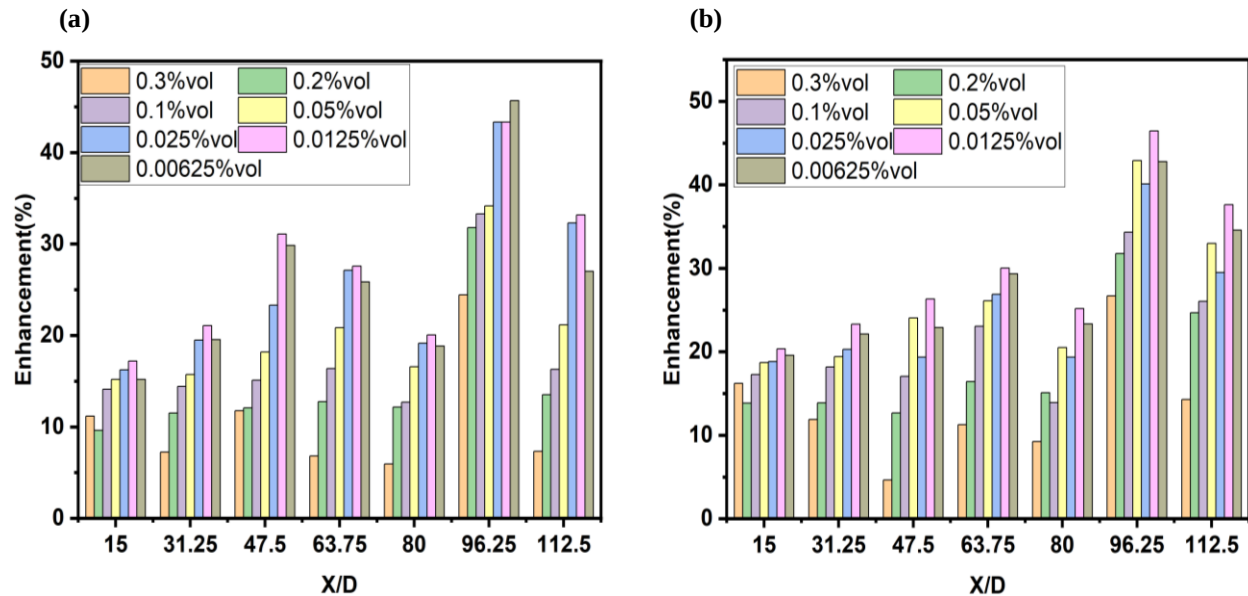
6.2.1 Percentage enhancement $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluid volume fraction at different tube (x/d) across concentrations

In Figure 6.3a, at a Reynolds number of 5200, $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids exhibit consistent improvements in heat transfer performance across different volumetric ratio 0.3vol% to 0.00625vol%, at various x/d. The maximum observed percentage increases in thermal enhancement reach 45.07% and 46.24%, occurring at x/d 96.25 for 0.0125 and 0.00625vol%, respectively. Conversely, the minimum improvement, as low as 6.24%, are recorded at x/d 80 for

the 0.3vol% concentration, countering the traditional belief that higher nanoparticle loadings automatically improve thermal performance.

In **Figure 6.3b**, for a Reynolds number of 4200, a similar trend is noted, with enhancements spanning from around 5% to 36.86%. The greatest improvement is noted at x/d 47.5 for the 0.0125%Vol concentration, while the 0.3%Vol volume fraction records the lowest enhancement, approximately 5%, at the same x/d position.

In **Figure 6.3c**, with a Reynolds number of 3200, the percentage improvements for different volumetric ratio, including 0.00625vol %, 0.0125vol %, and 0.025 vol%, range from about 24.29% to 53.58%. The most substantial enhancement, approximately 53.58%, occurs at x/d 96.25 for the 0.025vol % concentration. However, no enhancement is observed for the 0.3%Vol fraction at any position along the pipe. Similarly, for the 0.2 vol % and 0.1vol% , no improvements are seen at x/d positions of 15 and 31.25, further emphasizing the complex relationship between nanoparticle concentration, flow dynamics, and heat transfer behavior.



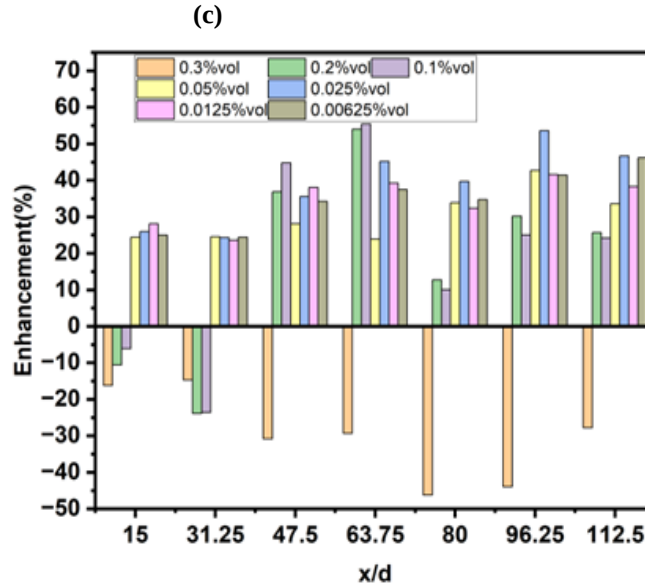


Figure 6. 3 The percentage increases in heat transfer performance corresponding to each nanoparticle concentration are evaluated at different locations of the tube (x/d). (a) Re 5200 (b) Re 4200 (c) Re 3200

In **Figure 6.4**, the evaluation of average CHT coefficients for DIW compared to $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids reveals a notable pattern. Contrary to widely held assumptions that increasing NPs concentration enhances heat exchange, the results consistently demonstrate that the 0.0125vol% delivers the greatest performance, followed closely by the 0.00625% Vol concentration. These finding challenges traditional perspectives and suggests that, within this specific MHNFs composition and flow regime, lower nanoparticle concentrations are more advantageous. Potential reasons for this observation include better nanoparticle dispersion, decreased fluid viscosity, and enhanced compatibility with flow dynamics at concentrations of 0.0125 vol %, 0.00625 vol% , and 0.025% Vol. These results underscore the necessity of adopting a refined approach when determining nanoparticle concentrations, as well as tailoring system configurations to maximize heat transfer efficiency. Gaining deeper insight into these mechanisms is essential for achieving optimal performance with $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids in real-world heat transfer systems.

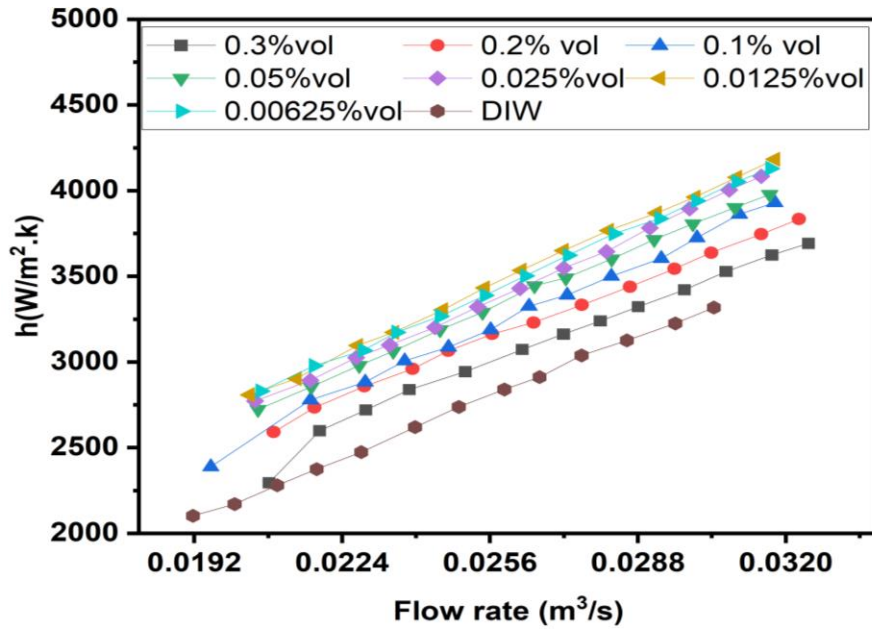


Figure 6. 4 Comparative analysis of average CHT variation with flow rate for DIW and $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluid.

6.2.2 Results of pressure (Δp) of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids

In **Figures 6.5a and b**, the correlation between Δp and both flow rate and Reynolds number provides valuable understanding of the performance of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids in the turbulent phase. This phenomenon is primarily governed by several factors, including nanoparticle concentration, the viscous resistance introduced by $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids, and variations in flow rate. Experimental data reveal that increasing the nanoparticle concentration leads to a noticeable increase in pressure drop, highlighting the intricate interplay between nanoparticle-induced viscosity and fluid dynamics. This behavior can be attributed to the increased viscosity and the enhanced interaction between the nanoparticles within the base fluid at higher concentrations. As the NPs concentration increases, the fluid's resistance to flow (viscosity) becomes higher, resulting in greater frictional losses and, consequently, a higher pressure drop. Additionally, the presence of nanoparticles may alter the flow dynamics, causing more turbulent or complex flow patterns that contribute to the increase in Δp . This effect is crucial when considering the trade-offs between heat transfer enhancement and the additional energy requirements for pumping the nanofluid through the system. Further analysis of the Δp data across various concentrations would provide deeper insights into these dynamics. This volumetric ratio-dependent trend is particularly evident at higher

volumetric ratio, indicating the heightened impacted of nanofluids on hydraulic resistance. This finding is align with prior investigations conducted by Emad et al.[32], [225] and Sundar [228].

Figure 6.5b illustrates the Δp exhibits a multifaceted relationship with varying nanoparticle concentrations when juxtaposed to DIW. The percentage data for Δp shows fluctuations across different Reynolds numbers and nanoparticle volume fractions. Notably, the maximum percentage pressure drop, around 21%, is observed at a Re 5018 for a volume fraction of 0.3%Vol, signifying the most significant pressure loss under these experimental conditions. As the volumetric ratio of NPs decreases, the overall viscosity of the MHNFs also decreases. Since viscosity is directly related to flow resistance, a lower viscosity fluid faces less frictional resistance as it flows through the pipe, which translates to a lower Δp . At higher nanoparticle concentrations, the increased viscosity and the presence of additional particles lead to more flow resistance and consequently a higher Δp . This relationship is well-documented in studies of nanofluids and is important when considering the trade-offs in engineering applications, where optimizing both heat exchange and Δp is crucial for system efficiency. This pattern highlights a possible balance between NPs concentration in the fluid and the resulting pressure losses. When the Reynolds number decreases from 5258.7 to 3200, the Δp for all nanofluid concentrations and DIW follows a non-linear decline, with values reducing progressively. This trend indicates that lower Reynolds numbers are associated with diminished pressure losses, reflecting a decrease in hydraulic resistance within the system.

In conclusion, the findings demonstrate that $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluid under turbulent forced convection exhibits a concentration-dependent rise in pressure drop. These outcomes align with trends observed in earlier research by Chinnasamy et al [292]. While flow rate remains a critical determinant, the nanofluid's overall behavior is strongly shaped by its nanoparticle concentration.

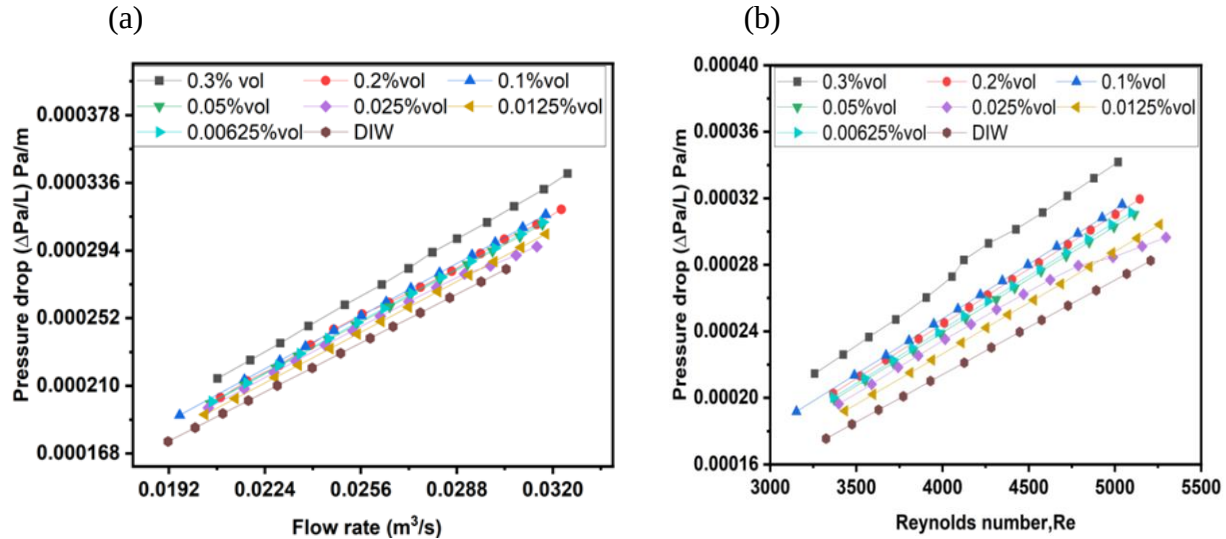


Figure 6. 5 (a) Δp against of flow rate and (b) Δp against of Re

6.2.3 Results of Δp of MHNFs volumetric ratio at different x/d .

Figures 6.6a, b, and c, the plots depicting the correlation between Δp and flow rate for Fe_3O_4/TiO_2 nanofluids at Reynolds numbers of 5200, 4200, and 3200, across different tube positions, reveal a clear correlation between nanoparticle volume fractions and pressure losses. Lower nanoparticle concentrations consistently result in decreased pressure drops across various positions along the tube. Differences in pressure drop levels at specific positions highlight variations in flow resistance and dynamics within the system.

Additionally, the inclusion of nanoparticles leads to higher pressure drops juxtaposed to DIW at all measured x/d , underlining the inherent compromise between improving MHNFs thermal performance and the resulting rise in pressure drop. The position-specific fluctuations in pressure drop underscore the complex interactions governing fluid flow and system behavior, offering critical insights into optimizing flow systems where minimizing pressure losses is essential. These results provide a detailed understanding of how nanoparticle concentration and tube position influence pressure drop, contributing valuable knowledge for improving fluid flow and system efficiency.

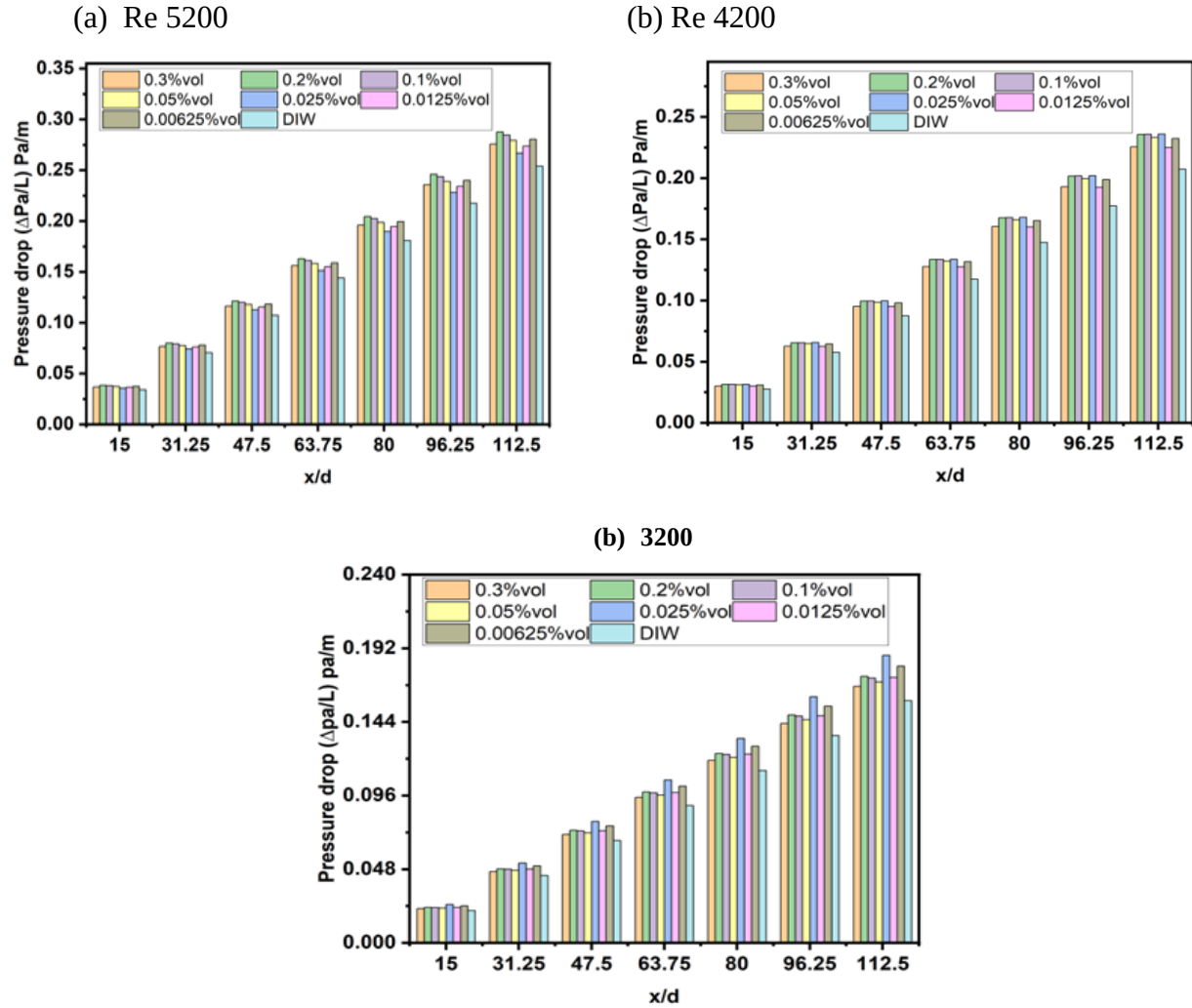


Figure 6. 6 Relationship between Δp and flow rate at different Re for $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids across various x/d and volumetric ratio.

6.2.4 Thermal performance of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ across different volumetric ratio

To determine the overall efficiency of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ MHNFs in heat exchange devices and to identify the optimal volumetric ratio, the Total Efficiency Index (TEI) was calculated. The TEI is a metric that assesses the overall effectiveness of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids, especially in systems using nanofluids for heat transfer. It integrates both the improvement in thermal performance and the penalties incurred due to increased Δp into a single parameter, offering a more holistic measure of the system's performance. The TEI is generally expressed as the ratio between the heat exchange improvement (commonly the CHT MHNFs relative to the base fluid) and the corresponding rise in pump power or Δp , as shown in Equation 6.1[222].

$$\eta = \frac{\frac{h_{avg,bf}}{h_{avg,nf}}}{\frac{\Delta P_{nf}}{\Delta P_{bf}}} \quad 6.1$$

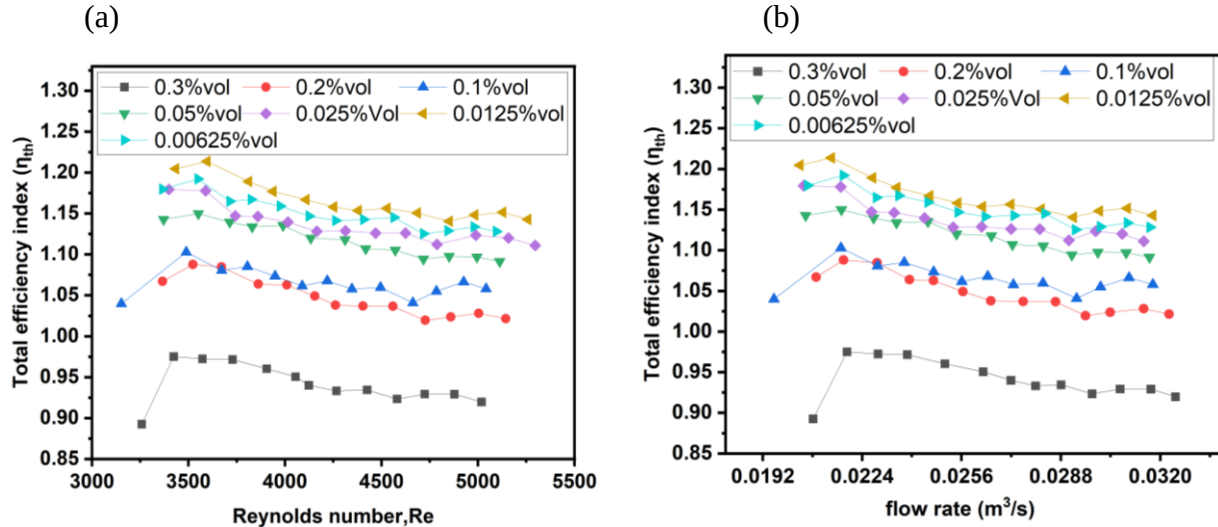


Figure 6. 7 (a) TEI of MHNFs at different volumetric ratio and Re (b) TEI of MHNFs at different volumetric ratio and flow rates

Figures 6.7a and 6.7b depict the TEI analysis for Fe_3O_4/TiO_2 nanofluids across different volumetric ratio of 0.00625% - 0.3%, provides valuable observation in identifying the optimal NPs concentration for heat exchange processes. The results show that lower volumetric ratio of 0.0125vol%, constantly yielded the highest TEI at various flow rates. This suggests that as the as the NPs volume fraction decreases, thermal performance enhanced, possibly due to good dispersion of nanoparticles and reduced frictional flow, which facilitates enhanced CHT and minimizes frictional resistance and the need for the pump energy.

On the other hand, higher concentrations, especially in the 0.2% to 0.3% range, result in lower TEI. This decrease in performance can be likely due to the increased frictional resistance and flow disruption as a results of an increase in concentration of NPs, which hinder fluid flow and reduce overall heat exchange performance. The volumetric ratio of 0.05 vol % to 0.1vol %, indicate average TEI, showing a modest improvement in heat exchange but without the significant enhancement seen at lower volumetric ratio

The optimal volumetric ratio of MHNFs is determined to be around 0.0125vol%, where the TEI achieves its peak all flow rates. This volumetric ratio provides the most effective balance between enhancing heat exchange and minimizing Δp , making it highly suitable for applications suitable for thermal management. This finding has important justification for heat exchange devices, as using a nanofluid with a 0.0125vol% can improve energy performance by optimizing heat exchange rates while minimizing the additional energy required for pumping. In practical systems such as cooling systems or heat exchangers, using MHNFs at this volumetric fraction may result in more cost-effective and efficient operations, enhancing overall system performance. Consequently, this volumetric ratio is recommended as the ideal option for engineers and designers aiming to achieve advanced thermal management across diverse industrial applications.

Table 6.1 compares the results of this study and other relevant research, highlighting the unique contribution of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ MHNFs. Unlike prior studies that identified optimal heat exchange improvements at higher volumetric ratios, this work reveals remarkable heat transfer enhancements even at lower concentrations. Specifically, a heat transfer improvement of 26.33% was achieved at 0.0125 vol % , and 24.30% at 0.00625 vol %, This contradicts previous studies by Lee et al. [105] which reported a 23% increase in heat transfer at 0.2wt for $\text{Co}_{0.5}\text{Zn}_{0.5}\text{F}_2\text{O}_4/\text{DIW}$, and Sundar et al.[228], who found a 31% improvement at 0.3 wt% for $\text{Fe}_3\text{O}_4/\text{MWCTN}/\text{DIW}$. These findings emphasize that $\text{Fe}_3\text{O}_4/\text{TiO}_2/\text{DIW}$ can achieve substantial heat exchange efficiency at much lower volumetric ratio than those reported in earlier studies.

These results underscore the ability of $\text{Fe}_3\text{O}_4/\text{TiO}_2/\text{DIW}$ to achieve notable heat transfer performance at significantly lower nanoparticle concentrations than previously observed.

Table 6. 1 Comparative analysis of CHT of MHNFs current study with existing literature.

Investigator	Nanofluid type	Flow regime	concentrati on	Observation
Lee et al. [105]	$\text{Co}_{0.5}\text{Zn}_{0.5}\text{F}_2\text{O}_4$ /DIW	Laminar	0.025-0.2wt%	CHT Coefficient improved with a maximum of 23% at 0.2wt%
Shahsavar et al.[93]	Fe_3O_4 /CNTs/DIW	Laminar	0.5-0.9wt%	CHT increased with a highest of 20.5% at 0.5wt%
Chinnasamy et al.[292]	Fe_3O_4 /MWCN T/DIW	Laminar	0.025-0.2wt%	The highest improvement was 15.9% at 0.1wt%
Lee et al.[15]	Fe_3O_4 /MWCN T/DIW/EG	Laminar	0.025-0.2wt%	The highest increment was 3.23% at 0.1wt%
Tekir et al.[42]	Fe_3O_4 /Cu/DIW	Laminar	0.5-1.5wt%	CHT improvement with a highest of 10.5% at 1.5wt%
Sunder et al.[228]	Fe_3O_4 /MWCN T/DIW	Turbulent	0.1-0.3wt%	Highest of 31% enhanced in Nu at Re 22,000 with 0.3wt% at 1.18 times increase in pumping power
Current study	Fe_3O_4 /TiO ₂ /DIW	Turbulent	0.00625-0.3wt%	An augmentation at the lower volumetric ratio of 26.33% at 0.0125% vol, and 24.30% at 0.00625% vol

6.3 Results of CHT of Fe_3O_4 /MgO MHNFs in transitional region

The CHT results, are displayed in **Figures. 6.8a, b, and c**, illustrate the average Nusselt number measurements and convective heat transfer coefficients for Fe_3O_4 /MgO MHNFs, covering volume fractions from 0.3% to 0.00625%, compared to DIW, over a Reynolds number range of 1000 to 8000. As shown in Fig. 6.8a, the CHT coefficient improves as the flow enters the turbulent phase. Reynolds number of 8000, the 0.3% volume fraction MHNF did not show any enhancement, while improvements of 1.46%, 3.69%, 4.79%, 3.4%, 5.2%, and 3.48% were recorded for the MHNF concentrations of 0.2%, 0.1%, 0.05%, 0.025%, 0.0125%, and 0.00625 vol%. The increases in the Nu 0.2% vol concentrations, 2.97%, 3.9% for 0.1vol%, 3.2% for 0.05 vol%, 5.1% for 0.025vol% for 0.0125 vol % , 3.4% for 0.00625vol % and no improvement for 0.3vol%. The onset of enhanced heat transfer, as indicated by the transition to higher thermal performance, occurred at the following Reynolds numbers for the respective MHNF concentrations:

- At 0.3% volume fraction, the transition began at a Re 2643.
- At 0.2% volume fraction, the transition occurred at 2726.

- For 0.1% volume fraction, the transition was observed at 2649.
- For 0.05% volume fraction, transition was noted at 2716.
- For 0.025% volume fraction, the transition began at 2751.
- At 0.0125% volume fraction, transition occurred at 2578.
- Finally, at 0.00625% volume fraction, the transition occurred at 2568.

In the transition phase, the Nu enhancements were 23.27%, 23.90%, 24.97%, 23.96%, 23.96%, 31.38%, and 30.13% for the corresponding volumetric ratio.

When comparing heat exchange improvement between the transition and turbulent phases, it was found that the heat transfer was notably greater in the transition phase, as illustrated in **Figure 6.8d**. The heat exchange improvements were recorded as 17.9% at 0.05% volume, 25.6% at 0.025% volume, 25.7% at 0.1% volume, 25.8% at 0.2% volume, 26% at 0.3% volume, 30.2% at 0.00625% volume, and 31.6% at 0.0125% volume. The most significant improvements were observed at 0.0125% and 0.00625% vol concentrations of MHNFs.

A possible explanation for the enhanced performance observed in the transition phase, especially at the higher volumetric ratio, may result from the influence of Brownian motion in the NPs, coupled with the unpredictable nature of the flow. This interaction likely promotes better dispersion and integration with the base fluid. Furthermore, the presence of smaller particles may reduce turbulence by introducing additional energy dissipation, a concept supported by Hetsroni. [293]

In the laminar flow regime, heat transfer enhancements were observed across the different MHNF concentrations. The average improvements ranged from 11% for the 0.3% vol MHNFs to 80% for the 0.0125% vol MHNFs and 78% for the 0.00625% vol MHNFs. This finding aligns with earlier studies that also observed significant improvements in laminar flow under fully developed conditions.

The increased enhancement observed in the laminar flow regime compared to the transition and turbulent regions can be linked to the distinctive interaction of nanoparticles under laminar flow conditions. In laminar flow, the fluid moves in a more structured manner, enabling nanoparticles to interact more efficiently with the fluid and thereby improving heat exchange. The lack of turbulence in this flow regime allows NPs to exert a more consistent effect, resulting in greater improvements in heat transfer. Moreover, the distinct characteristics of MHNFs, including

nanoparticle size, shape, and dispersion, are likely more influential in the laminar regime, further contributing to the observed performance gains.

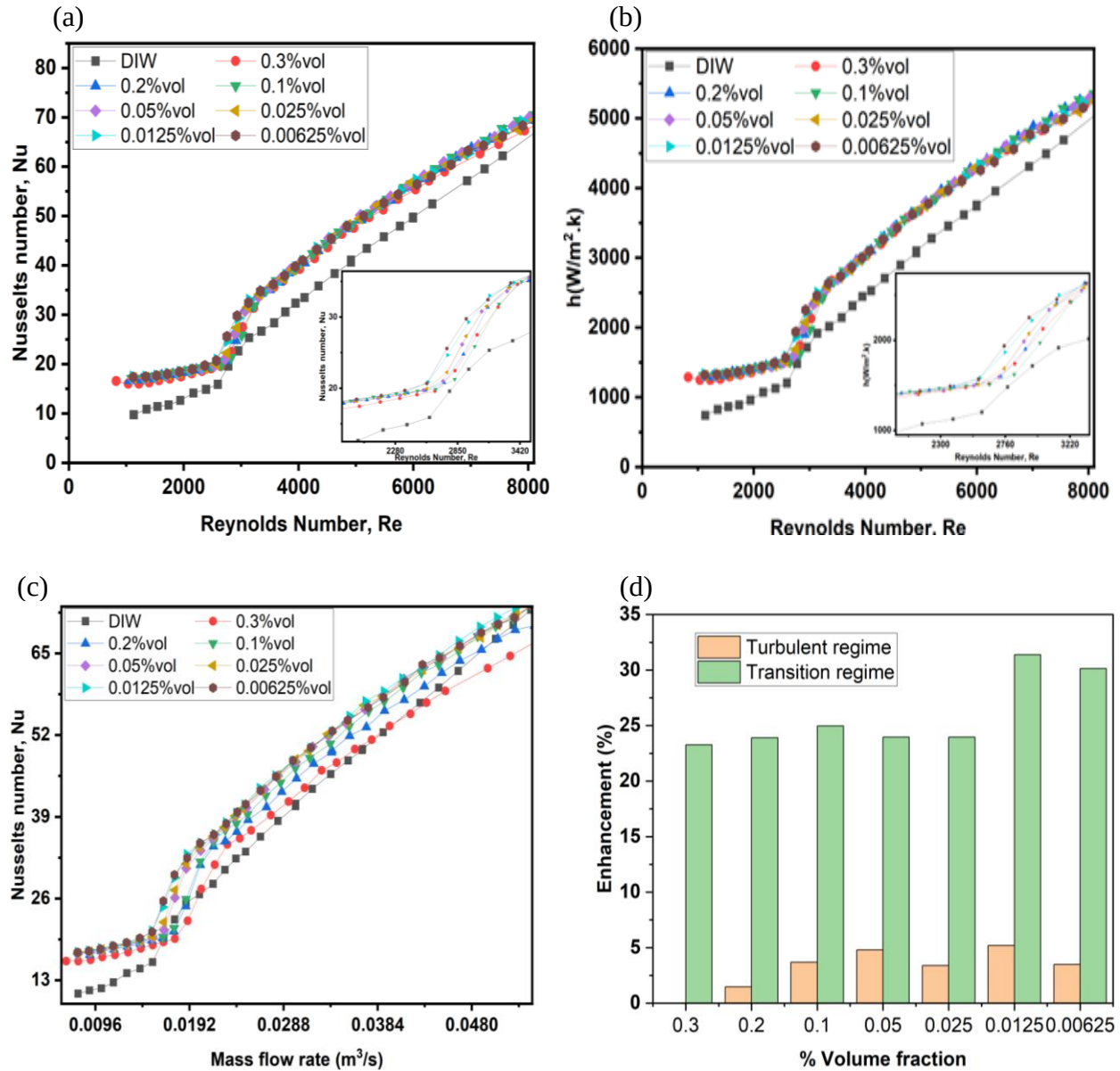


Figure 6. 8 (a) Correlation between Nu outcomes of MHNFs and DIW and Re (b) Comparison of CHT coefficients of MHNFs to DIW (c) Exploration of Nu results and mass flow rates for DIW and various MHNF concentrations.

6.3.1 Influence of nanoparticle concentration on Colburn j-factors

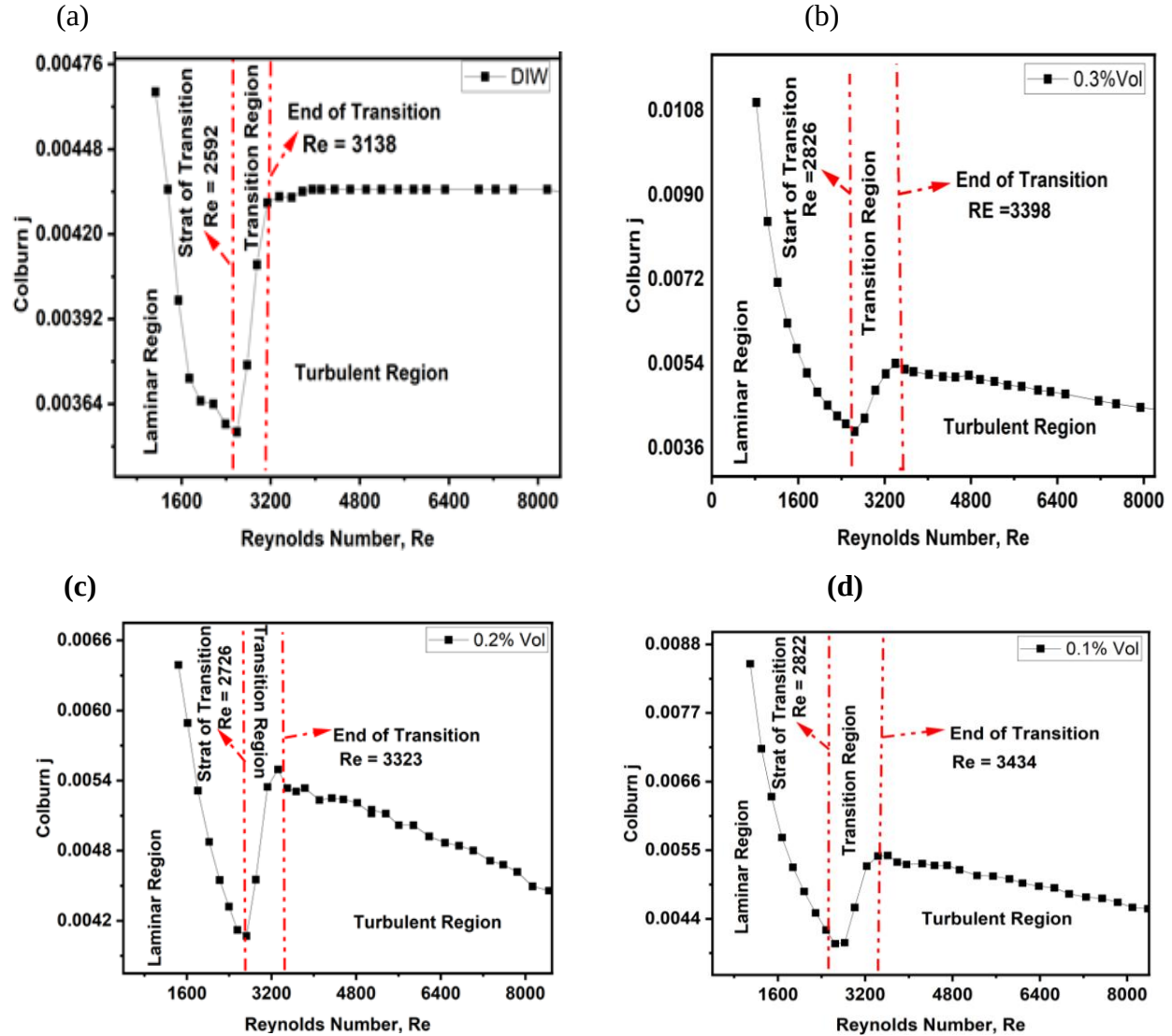
Figure 6.9 (a-i) displays the Colburn j-factor, plotted against the Re for DIW and with different MHNFs, reveals how the transition flow regime begins at various Re depending on the

nanoparticle concentration, ranging from 0.3% to 0.00625%. These plots not only illustrate the distinct transition behaviors of the fluids but also highlight the impact of their thermophysical characteristic on the j -factor.

As detailed in Chapter 5, the thermophysical properties of these MHNFs, including Viscosity and TC are affected by the concentration of NPs. Experimental results show that the MHNFs with a 0.0125% volumetric ratio produce the highest j -factor, with the 0.00625% volumetric ratio following closely behind. The superior performance of the 0.0125% volume fraction in terms of the j -factor, followed by the 0.00625% volumetric ratio, can be attributed to various factors that impact the heat transfer efficiency of MHNFs. At low nanoparticle concentrations, such as 0.0125% and 0.00625%, the nanofluid offers an optimal balance between enhanced thermal conductivity and minimal increase in viscosity. This balance facilitates efficient heat transfer without significantly raising the pressure drop or pumping energy requirements. Additionally, at these lower concentrations, the nanoparticles are more uniformly dispersed within the base fluid, resulting in improved convective heat transfer. Higher concentrations may lead to particle aggregation, which can reduce the overall effectiveness of heat transfer. Furthermore, the reduced agglomeration at these concentrations ensures that the nanoparticles remain well-dispersed, allowing for better heat transfer. The smaller volume fractions also offer a higher surface area-to-volume ratio, enhancing the fluid's capacity for heat exchange. Lastly, in the laminar and transitional flow regimes, these lower volume fractions allow the nanofluid to remain within an optimal range, where the effects of the nanoparticles are most beneficial without causing excessive flow resistance or turbulence. These factors combined likely explain why the 0.0125% and 0.00625% volume fractions yield superior j factors compared to higher concentrations. Furthermore, as the volumetric ratio improves from 0.025% to 0.3%, the j factor diminishes across the transition phase. When compared to viscosity, it becomes evident that the j factor is more strongly influenced by changes in viscosity, likely due to its effect on the Pr .

Viscosity analysis shows that the greatest volumetric ratio corresponds to the greatest viscosity, which reduces as the volumetric ratio reduces, lowering to 0.00625%. The j -factor analysis reveals that MHNFs with greater stability and enhanced heat exchange performances led to higher j -factors, as shown in **Figure 6.8**.

Therefore, fluids with improved stability and lower viscosity at a specific Re generally exhibit higher j-factors in the transition phase, especially when compared to DIW, as depicted in **Figure 6.9i**,



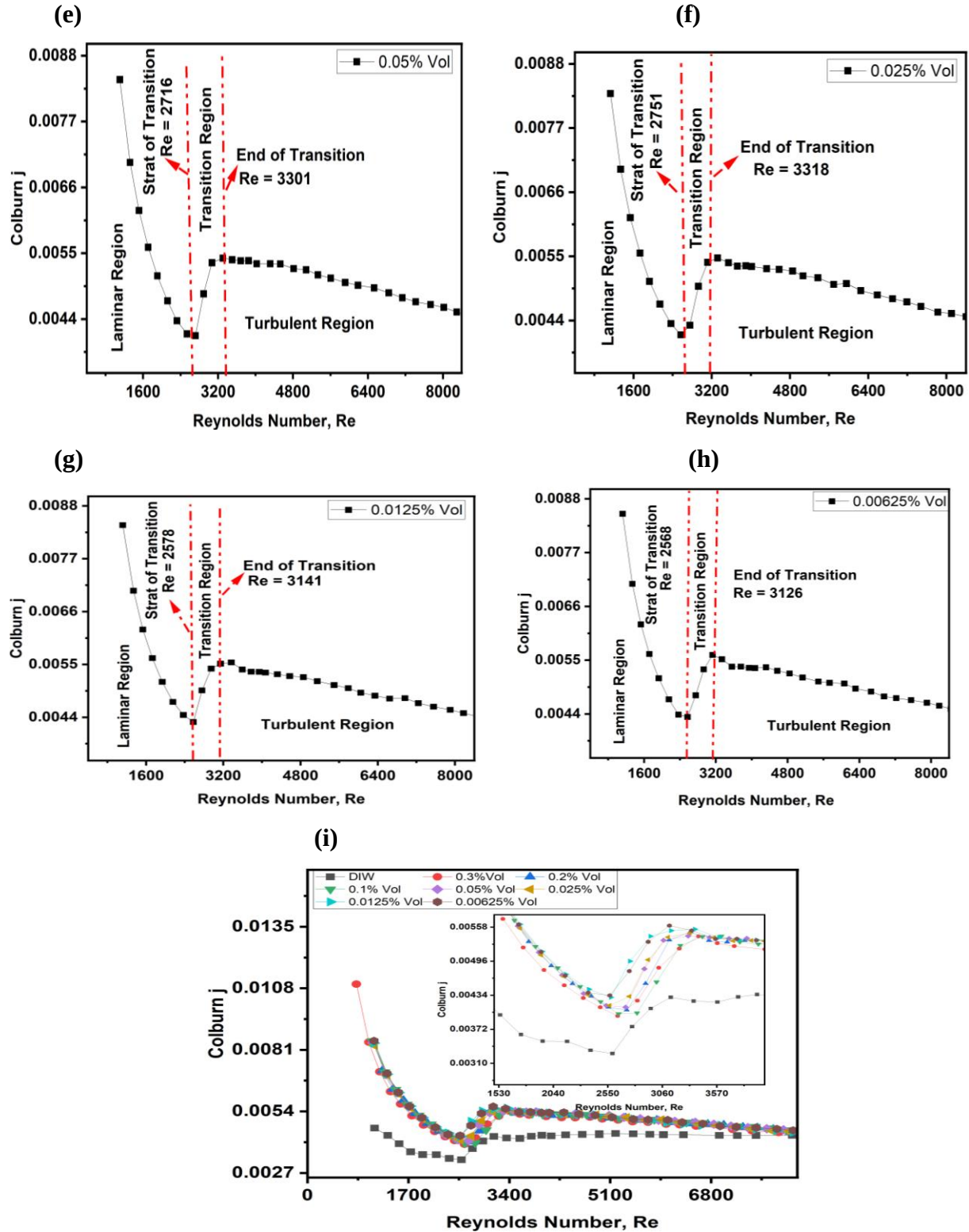


Figure 6. 9 impact of j factor against Re of DIW and various MHNFS (a) DIW, (b) 0.3vol % vol (c) 0.2 vol% (d) 0.1vol % (e) 0.05vol % (f) 0.25vol% (g) 0.0125vol% (h) 0.00625 vol % (i) Combined MHNFS with DIW

6.3.2. The initiation and completion of the transitional flow regime for different nanoparticle concentrations in MHNFs, along with the corresponding improvements in heat transfer.

Theoretical models, such as the one presented by Cengal et al [8], Indicate that the transition flow regime generally initiates at a Reynolds number of around 2300. Nonetheless, subsequent studies by and Nagendra et al.[262],Meyer and Oliver [240], and Ghajar and Tam [9], have highlighted that numerous considerations, such as inlet design, fluid characteristics, heat flux, the length of transition, inlet design, and the geometry of the test rig, can influence the point at which transition occurs. Osman et al.[45] reported that transition happens at lower Reynolds numbers for nanofluids juxtaposed to base fluids such as H_2O , attributing this behavior to the higher viscosity of nanofluids.

To assess the onset of transition for the different MHNFs formulations and DIW, the critical Reynolds number (Re_{cr} ,) was calculated for seven types of MHNFs nanofluids, methodology that was related to that of Everts and Meyer [240], which builds on Cengal et al. [8] approach and is informed by Ghajar and Tam's work [236] , as described in Equation (6.1).

$$Re = Re_{cr}, \text{ when } Re = \left(\frac{dj}{dRe} \right) = 0 \quad 6.2$$

Table 6.2 outlines the characteristics in the transition phase, defined by two critical Reynolds numbers: (Re_{cr} onset) and (Re_{cr} completion). (Re_{cr} onset) marks the Reynolds number at which the flow begins to transition from laminar to turbulent, representing the lower boundary of the transition phase. Conversely, (Re_{cr} completion) indicates the Re of which the fluids transitions into a turbulent state, marking the upper limit of the transition region. The critical Re for the onset and completion of this transition are influenced by the volume fraction of MHNFs and DI water, as detailed in **Table 6.2**. Typically, as the volume fraction of MHNFs increases, the critical Reynolds numbers also rise for both the start and end of the transition. This indicates that higher nanoparticle the onset of turbulence is postponed, and flow behavior is modified. At a minimal volumetric ratio of 0.00625vol%, the onset with the transition beginning at a reduced Re Juxtaposed to DIW, underscoring the unique effects of the nanofluid concentration on flow dynamics. This variability highlights the significant role that MHNFs play in influencing fluid behavior and emphasizes the need to carefully consider these critical Reynolds numbers when designing and optimizing fluid systems.

Table 6. 2 Effect of volumetric ratio on the transition behavior.

Vol% of MHNFs and DIW	Reynold numbers	
	Re _{cr} onset	Re _{cr} completion
DIW	2592.63	3138.187
0.00625	2568.67	3126.45
0.0125	2578.26	3141.44
0.025	2751.74	3318.96
0.05	2716.74	3301.61
0.1	2822.89	3434.00
0.2	2726.65	3323.57
0.3	2826.52	3398.47

The magnetic hybrid nanofluids transition is observed between Re of 2500 to 3340, which falls within the broader range of 2000 to 4000 that spans both laminar and turbulent phase, the experimental outcome shows the transition of magnetic hybrid nanofluids start at a noticeably higher Reynolds number than DIW, challenging earlier reports by Mayer et al. [245], and Osman et al.[45],. Moreover, at the minimal volumetric ratio of 0.00625 vol %, the onset of transition occurs at a lower Reynolds number than DIW, which is consistent with past research. This variation could stem from the unique properties of the magnetic hybrid nanofluids in this study. Unlike DIW, magnetic hybrid nanofluids are composed of NPs suspended in a base fluid, which alters essential fluid characteristic such as density, TC and viscosity.

Table 6.2 demonstrates how different volume fractions affect the transitional flow regime, revealing distinct behaviours across these fractions. These results show the important role of volumetric ratio in defining the transition characteristics. Furthermore, the incorporation of nanoparticles improved the heat exchange performance of the base fluid and alters critical fluids properties, that are vital for heat exchanger design. The onset and conclusion of the transition also shift with varying volumetric ratio, as illustrated in **Figure 6.8 (a–c)**, which maps out the flow regime boundaries for both the DIW and MHNFs. In this study, several factors, including the dispersion of nanoparticles, their size and shape, and the concentration of the nanofluid, may have influenced the observed transition behavior. Nanoparticles have a tendency to form aggregates that

attractive van der Waals forces, which can significantly impact flow characteristics. If the magnetic hybrid nanofluids in this research exhibited a more even dispersion of NPs compared to those in prior studies, this could account for variations in viscosity and other flow-related characteristics, subsequently influencing the transition characteristics. The formation of agglomerates tends to increase viscosity, which in turn raises the flow resistance and may delay the shift from laminar to turbulent flow. Furthermore, the size and shape of the NPs are critical factors in the flow dynamics. Given that the nanoparticles in this study were bigger and had different morphological characteristics juxtaposed to those in earlier works, they may have contributed to altered fluid transition behaviours, possibly affecting the point at which turbulence initiates. Larger nanoparticles may result in higher drag forces in the flow, which could either promote or delay the transition, depending on the concentration. Moreover, variations in nanoparticle concentration directly impact viscosity and thermal conductivity. While higher concentrations generally increase viscosity, they also enhance thermal conductivity, which can accelerate heat transfer and potentially influence the transition to turbulence. Therefore, the combined effects of nanoparticle dispersion, size, shape, and concentration in this study could have contributed to observed differences in the transition from laminar to turbulent flow compared to previous research.

6.3.3 Results of pressure (Δp) of $\text{Fe}_3\text{O}_4/\text{MgO}$ nanofluids

Figure 6.10a shows Δp across different volume fractions, ranging from 0.3% to 0.00625%, was juxtaposed to DIW over the full spectrum of flow rates. In the turbulent regime, the flow becomes erratic and disordered, resulting in heightened frictional resistance and thus greater Δp . **Table 6.3** summarizes the maximum pressure drops for each volumetric fraction within this region, providing a comprehensive view of how Δp changes with varying flow rates and nanoparticle concentrations. As the concentration of nanoparticles increases, Δp tends to rise, peaking at 0.025% volume fraction with a flow rate of 0.05257, before significantly decreasing at higher volumetric ratio. This peak may represent the point where the interaction between the particles and the turbulent flow maximizes frictional forces, causing the most disordered flow pattern.

Within the transitional regime, characterized by alternating laminar and turbulent flow behaviors, variations in frictional forces and Δp are evident. According to **Table 6.3**, the maximum Δp for a 0.3% volume fraction was recorded at a flow rate of 0.020412. In general, pressure drops in this regime are more consistent and lower across various concentrations compared to the turbulent

regime, indicating that particle concentration has a reduced impact on Δp during the transition phase.

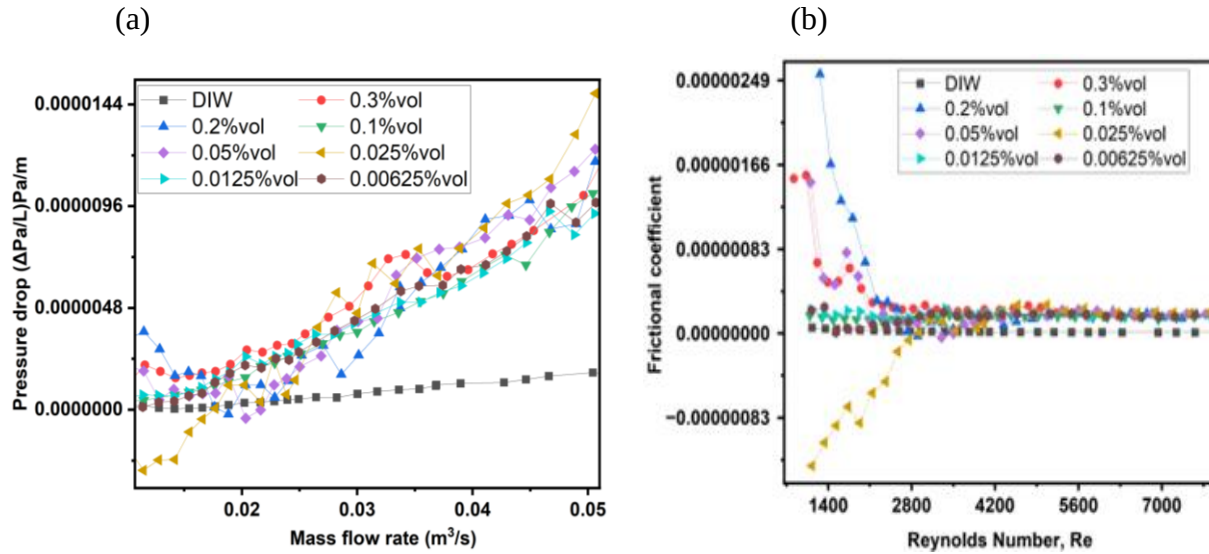


Figure 6. 10 (a) Δp comparison of $Fe_3O_4/MgO/DIW$ to DIW with different flow region (b) Δp fluctuation with Re and volumetric ratio with different flow regimes.

The laminar region, where flow is orderly and smooth (except for the 0.025% volume fraction), there is reduce mixing and minimal frictional forces, which results in minimal Δp . The highest Δp at a 0.2% volume fraction, as presented in **Table 6.3**, occurred at a flow rate of 0.01646. The Δp in this region are considerably minimal than those in the other regimes, showing little variation across different volume fractions. This is because the fluids remains stable, and particle interactions have a negligible effect on frictional resistance.

Table 6. 3 Maximum Δp across various regimes for different volumetric ratio and flow rates

vol%	Highest Δp Laminar	Flow rate (l/m) Laminar	Highest Δp Transition	Flow rate (l/m) Transition	Highest Δp Turbulent	Flow rate (l/m) Turbulent
0.3	1.5×10^{-6}	0.01423	2.82 $\times 10^{-6}$	0.020412	1.1×10^{-5}	0.055034
0.2	1.6×10^{-6}	0.01646	5.81 $\times 10^{-7}$	0.022836	1.34 $\times 10^{-5}$	0.052427
0.1	8.31 $\times 10^{-7}$	0.01541	2.04. $\times 10^{-6}$	0.021641	1.02 $\times 10^{-5}$	0.052219
0.05	6.43 $\times 10^{-7}$	0.01544	-1.3 $\times 10^{-8}$	0.021619	1.27 $\times 10^{-5}$	0.05241
0.025	-1.1 $\times 10^{-6}$	0.01543	3.72 $\times 10^{-7}$	0.021602	1.48 $\times 10^{-5}$	0.05257
0.0125	8.31 $\times 10^{-7}$	0.01569	2.14 $\times 10^{-6}$	0.021738	1.06 $\times 10^{-5}$	0.052427
0.00625	6.52 $\times 10^{-7}$	0.01539	1.98 $\times 10^{-6}$	0.021679	1.09 $\times 10^{-5}$	0.052359

Flow structure plays a pivotal role across these regimes: in turbulent regime, enhanced mixing and particle-fluid interactions increase Δp , while transition region exhibits less chaotic behavior, leading to more stable but less intense interactions. In laminar flow, the structure is orderly and stable, resulting in minimal mixing and the lowest Δp .

The variations in Δp are also linked to Reynolds number. Higher Reynolds numbers, characteristic of turbulent flow, higher Δp are typically associated with increased momentum exchange. On the other hand, in the transitional regime, lower Reynolds numbers lead to flow fluctuating between laminar and turbulent states, resulting in reduced and more consistent Δp . Laminar regimes, defined by low Re, experience smooth, steady flow, leading to the lowest Δp .

Additionally, the distribution and settling of particles contribute to these trends. In turbulent regimes, the intense mixing creates a more uniform distribution of particles, resistance increase

and Δp . In transition flow, reduced mixing could lead to settling of particle, contributing to lower overall pressure drops. In laminar regimes, the absence of significant mixing results in minimal particle movement or settling, with little effect on Δp .

In conclusion, the behavior of pressure drops exhibits notable variations across the laminar, transition, and turbulent phase, driven by distinct flow characteristics and particle interactions. In the turbulent phase, pressure drops tend to be higher and more erratic due to the chaotic nature of the flow and the heightened interaction between the fluid and NPs, typically reaching their maximum at certain nanoparticle concentrations. Conversely, in the transition phase, pressure drops are generally minimal and stable with nanofluids, reflecting a less turbulent state compared to fully developed turbulence. This indicates that while particle interactions still influence flow dynamics, their impact on pressure drop is less pronounced in the transitional phase than in the turbulent regime. This is a result of the transitional nature of the flow, which is not as chaotic as in the turbulent state. In laminar regimes, pressure drops are the lowest and most stable, as the flow remains smooth and steady, with minimal particle interactions. These differences in pressure drop behavior across the flow regimes are crucial for understanding the performance of nanofluids in practical applications, highlighting how factors like flow regime, particle interactions, and nanoparticle concentration influence fluid dynamics and pressure behavior.

6.3.4 Thermal performance of $\text{Fe}_3\text{O}_4/\text{MgO}$ MNHFs across different volume ratio and regime

Figure 6.11a and 11b presents the thermal performance trends across different flow region for magnetic hybrid nanofluids at different volumetric ratio, highlight interesting patterns. The total efficiency index of $\text{Fe}_3\text{O}_4/\text{MgO}$ nanofluids varies across different volume fractions, highlighting their thermal management performance in various flow regimes. With 0.00625vol%, the total efficiency index values remain marginally above 1.00 within all Re, reflecting good thermal performance. Notably, the 1.23 in the transitional flow, total efficiency index is 1.02 in turbulent flow, and 1.26 in laminar flow. These findings demonstrate that even at low concentrations, the MNHFs significantly improves heat transfer performance, with the highest performance observed in laminar flow.

Raising to 0.0125% leads to a significant increase in total efficiency index values, signifying enhanced efficiency. At this level, the TEI reaches 1.25 in transitional flow, 1.04 in turbulent flow, and 1.264 in laminar flow. This concentration delivers the highest performance within all flow

regimes, illustrating that even a modest increase in concentration can greatly boost the performance of the MHNFs.

For 0.025vol %, the TEI values are 1.23 in transitional flow, 1.01 in turbulent flow, and 1.24 in laminar flow. Although this volumetric ratio still boosts thermal efficiency, the slight decline in performance during turbulent flow juxtaposed to 0.0125% may be attributed to increased viscosity or intensified particle interactions at this level.

For a 0.05vol%, the total efficiency index values are recorded as 1.21 in transitional flow, 1.017 in turbulent flow, and 1.22 in laminar flow. Although these figures still indicate improved performance, the reduced efficiency in turbulent flow relative to 0.025% suggests that higher volumetric ratio might introduce setbacks such as high viscosity or nanoparticle clustering, which could disrupt fluid behavior.

At 0.1% volume fraction, the total efficiency index values decrease to 1.17 in transitional flow, 0.997 in turbulent flow, and 1.21 in laminar flow. The peak total efficiency index observed in the transitional flow indicates that this concentration is nearly ideal for maximizing heat exchange efficiency. Moreover, the reduced effectiveness in turbulent conditions implies that elevated nanoparticle concentrations can increase flow resistance, thereby limiting the nanofluid's overall performance in more turbulent environments.

At a 0.2% volume fraction, the total efficiency index values decrease to 1.08 in the transitional regime, 0.940 in turbulent flow, and 1.07 in laminar flow. The reduced performance, especially in transitional flows, and turbulent, can be attributed to adverse effects such as excessive viscosity, inadequate particle dispersion, or diminishing the MHNFS performance. While there is a slight improvement in laminar flow efficiency, the overall thermal efficiency declines compared to lower concentration levels.

For the highest volumetric ratio tested, 0.3%, the total efficiency index values are the lowest recorded, measuring 0.934 in transitional flow, 0.857 in turbulent flow, and 1.17 in laminar flow. These findings indicate that very high nanoparticle concentrations adversely affect the nanofluid's effectiveness, likely due to potential particles settling, elevated viscosity, and disruptions to fluid behavior.

In summary, the optimal performance occurs at a volumetric ratio 0.0125%, achieving superior thermal efficiency across all regimes, particularly in the transitional flow region. Beyond this concentration, thermal efficiency decreases as viscosity and other factors increasingly hinder fluid

dynamics and heat transfer capabilities. This finding is consistent with the findings of Mehrli et al. [41] and Sadeghinezhad et al. [225].

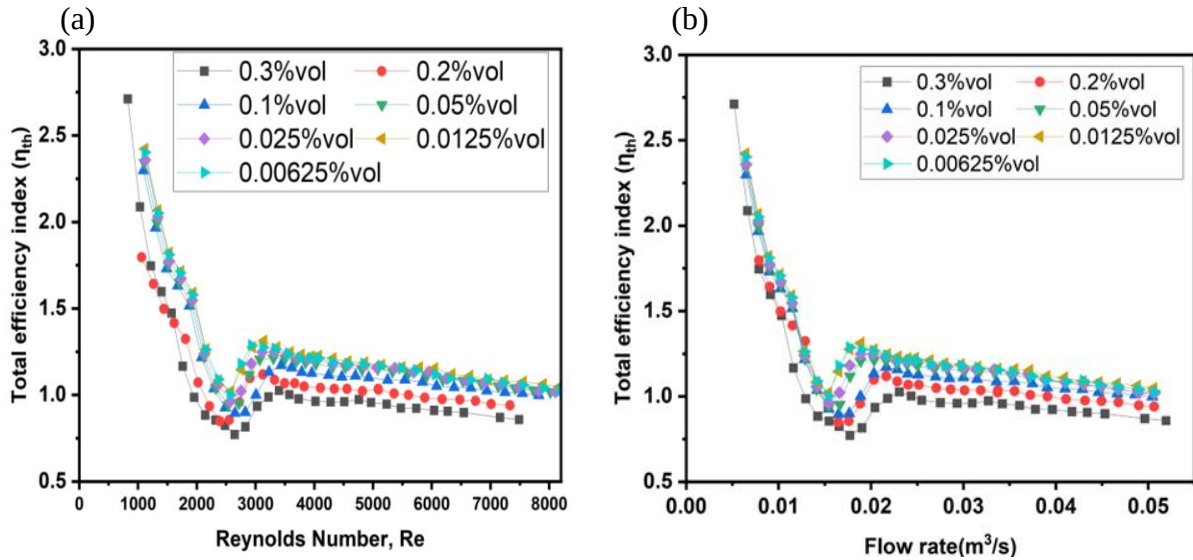


Figure 6. 11 Thermal efficiency trends of Fe₃O₄/MgO MHNFs across different flow regimes and volume fractions. (a) TEI against Reynolds numbers (b) TEI as a function of flow rate.

6.4 Effect of magnetic field on the convective heat transfer in turbulent flow regime

Before magnetic fields can be effectively utilized to enhance CHT in different flow regimes, it is essential to optimize both the magnetic field strength and frequency across various waveform configurations. The impact of magnetic fields on CHT in turbulent flow regimes is a topic of significant interest and research due to its potential for improving heat transfer rates. By systematically varying the magnetic field strength and frequency across different waveforms such as Sine wave, Square wave, and Triangular wave, researchers aim to identify the optimal conditions that maximize heat transfer enhancement. This optimization process involves studying the interaction between the magnetic field and the fluid flow to understand how changes in magnetic field parameters affect heat transfer performance. Ultimately, achieving an optimized magnetic field configuration is crucial for harnessing the full potential of magnetic fields to enhance CHT in turbulent flow regimes.

6.3.1 Optimization of magnetic field intensity and frequency across different wave setups

Figure 6.12 illustrates the complex relationship between total magnetic field intensity across various waveform types and frequencies, including Triangular Square, and Sine, waves. As the

frequency ranges from 40Hz to 1000Hz, a steady increase in magnetic field strength is observed, showing a clear relationship between the two. This trend implies that higher frequencies enhance the magnetic intensity which in turn influence thermal efficiency. Experimental results consistently demonstrate that the Sine wave exhibits the highest magnetic field intensity across the tested frequency range, as detailed in Figure 6.12. This behavior arises from the smooth, continuous nature of the Sine wave, which minimizes harmonic losses and ensures a more efficient magnetic flux generation. In contrast, Square waves, characterized by sharp transitions, introduce higher-order harmonics that reduce magnetic field efficiency, while Triangular waves, though smoother than Square waves, do not achieve the uniformity of Sine waves.

This observation is crucial for the effective manipulation of magnetic hybrid nanofluids, where precise control of the magnetic field directly influences heat transfer and fluid dynamics performance. This highlights the advantages of Sine waves in applications requiring optimized magnetic field effects. By providing these insights, the thesis emphasizes the relevance of waveform selection in enhancing the efficiency of magnetic field-driven systems, addressing a critical factor in the performance of hybrid nanofluids under varying flow regimes.

A notable finding is the intersection point at around 6.0 and 17.11 Tesla for frequencies of 40Hz and 60Hz, respectively, where all three waveform types converge. This point is pivotal for fine-tuning magnetic field parameters, particularly in terms of improving heat transfer within the tube. Recognizing the significance of magnetic field enhancement at this point is essential for identifying the optimal frequency that maximizes heat transfer and boosts overall thermal efficiency. This discovery deepens our understanding of how frequency and magnetic field intensity influence heat exchange argumentation, providing valuable insights into optimization thermal systems under different magnetic conditions.

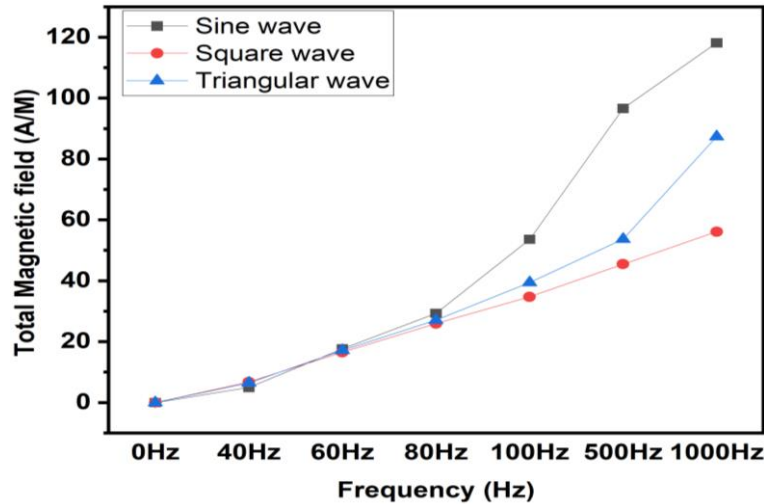


Figure 6. 12 Optimization of magnetic field intensity and frequency across different wave setups

6.3.2 Voltage vs total magnetic field strength across different waveforms.

Figure 6.14 depicts the correlation between voltage and total magnetic field intensity, the data shows a gradual rise in magnetic field intensity as voltage increases from 2V to 12V across various Triangular, Square and Sine, the total magnetic field strength is the combined output from the three electromagnets, as shown in **Figure 6.13**. This configuration provides a clear, direct correlation between the applied magnetic field strength and voltage. Experimental observations confirm that the Sine waveform continually produces the strongest magnetic fields juxtaposed to the other waveforms. This is attributed to the continuous and smooth nature of the Sine wave, which minimizes harmonic distortion and energy loss, thereby enhancing the magnetic flux density. The Triangular waveform, with its linear transitions, produces intermediate magnetic field strengths, as it introduces fewer harmonics than the Square waveform but lacks the fluidity of the Sine waveform. In contrast, the Square waveform, characterized by abrupt transitions, generates significant harmonic interference and energy dissipation, leading to the lowest magnetic field strengths.

This hierarchy of performance is significant for applications involving magnetic hybrid nanofluids, where the efficiency of magnetic field generation directly impacts heat transfer and fluid manipulation. By emphasizing these results, the thesis highlights the critical role of waveform selection in optimizing the performance of systems reliant on magnetic field effects. Intriguingly,

there is a convergence point observed at an average of 17.11 Tesla at 4V, where all three waveforms intersect.

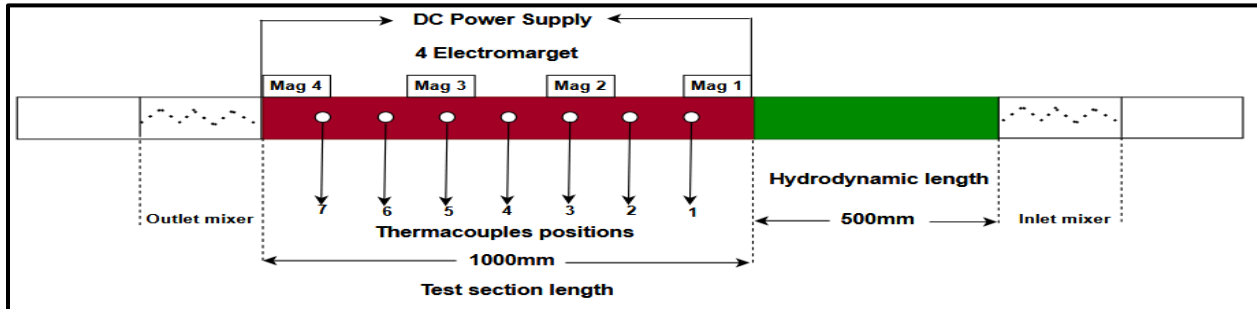


Figure 6. 13 Placement of magnetic field within the experimental setup

This discovery holds significant importance in fine-tuning magnetic field parameters, especially the observed relationship between voltage and overall magnetic field strength highlights the potential for controlling the magnetic field to obtain targeted heat exchange improvements within the tube. This relationship enables fine-tuning of the magnetic field, facilitating accurate alteration to meet specific heat exchange goals. Furthermore, the unique properties of the types of waveform shapes highlight how the waveform type impact the magnetic field intensity. These results are essential for designing and optimizing effective thermal management systems that utilize the influence of magnetic fields to enhance heat exchange performance.

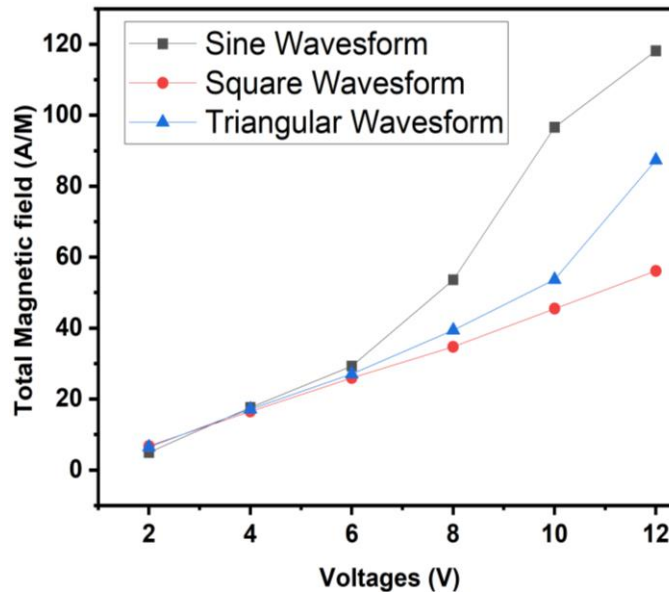


Figure 6. 14 Voltage dependency of total magnetic field strength across different waveforms.

6.3.4 Optimize frequency magnetic field intensity to improved heat exchange.

The data gleaned from **Figure 6.15 a, b, c** highlights that, across varying voltage settings (4V, 6V, 8V, 12V) and with three magnetic fields strategically placed along the test rig, the magnetic field optimization is achieved at a frequency of 60Hz across various waveform types (sine, square, and triangular) within the thermally developed region of the copper pipe, as depicted in Figure 6.13. As illustrated in **Figures 6.16a, b, and c**, which present results at 4V for different Re and frequencies (40Hz, 80Hz, 100Hz, 500Hz, and 1kHz), the 60Hz frequency consistently demonstrates superior heat transfer performance when compared to other frequencies across a range of Reynolds numbers. This consistent pattern highlights the potency of the 4V magnetic field in enhancing the thermal performance.

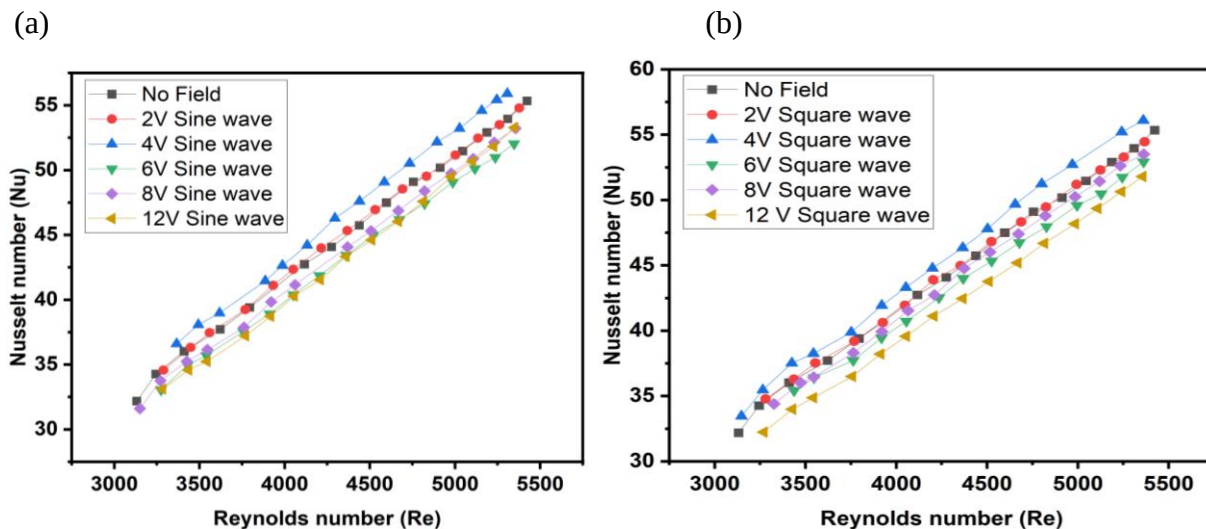
The optimization noticed at 4V is supported by experimental data, which show that this specific voltage, in combination with the tested frequencies, achieves the highest heat transfer rates within the system. This outcome can be attributed to the alignment of the magnetic field strength and the flow dynamics of the hybrid nanofluid, which are most effective at this voltage. At 4V, the induced magnetic field generates sufficient intensity to enhance nanoparticle alignment and thermal conductivity without introducing excessive energy losses or destabilizing the fluid flow. This balance between energy input and heat transfer efficiency underscores the suitability of 4V for optimizing the system's performance.

This observation is particularly important for practical applications, where selecting the optimal voltage can significantly improve system efficiency and reduce operational costs. By correlating these findings with the underlying physical mechanisms and previously reported studies, the thesis demonstrates the robustness of the results and the relevance of this voltage-frequency combination for maximizing heat exchange.

Furthermore, increasing the voltage from 6V to 12V, there is a corresponding increase in magnetic field strength, resulting in a decline in heat exchange efficiency. The finding are in line with the observations of Zhang and Zhang [221], Azizian et al.[26], and Abadeh et al.[18], but contradict with the results reported by Hatami et al. [31] and Sun et al.[19] and. This congruity pattern across the three waveform types indicates that as the fluid moves, its magnetic properties tend to cause it to cling to the surface of the tube, whereas at 4V, these properties remain efficiently dispersed in the fluid, which enhances heat exchange.

The Reynolds number of 5423.12, the 60Hz sine wave at 4V shows a heat transfer value of 55.03, outperforming other frequencies. This pattern holds steady across varying Reynolds numbers, underscoring the efficiency of the 60Hz in boosting thermal efficiency, particularly with the sine wave, as depicted in **Figure 6.17**. The maximization at 60Hz indicates that this voltage and frequency combination is optimal for enhancing heat transfer, potentially reflecting a resonance or resonance-like phenomenon in how the magnetic field affects thermal performance. Heat exchange enhancement may differ at other voltage levels. (6V, 8V, 12V), the 60Hz frequency consistently proves advantageous.

The reduction in heat exchange at greater frequencies may be due to changes in the properties of magnetic or the interactions of the particle within the fluid at these frequencies, impacting the dispersed magnetic particles and thus reducing heat exchange performance. As such, identifying the optimal voltage and frequency for any magnetic fluid is critical to achieving maximum enhancement. Additionally, the results suggest that stronger magnetic fields may be inversely related to heat transfer improvement.



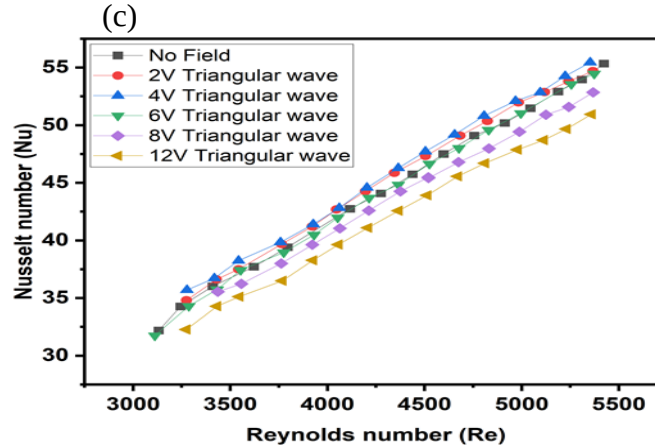


Figure 6. 15 Comparison heat transfer improvement at various voltages for different waveforms (a) sine wave (b) square wave (c) triangular wave

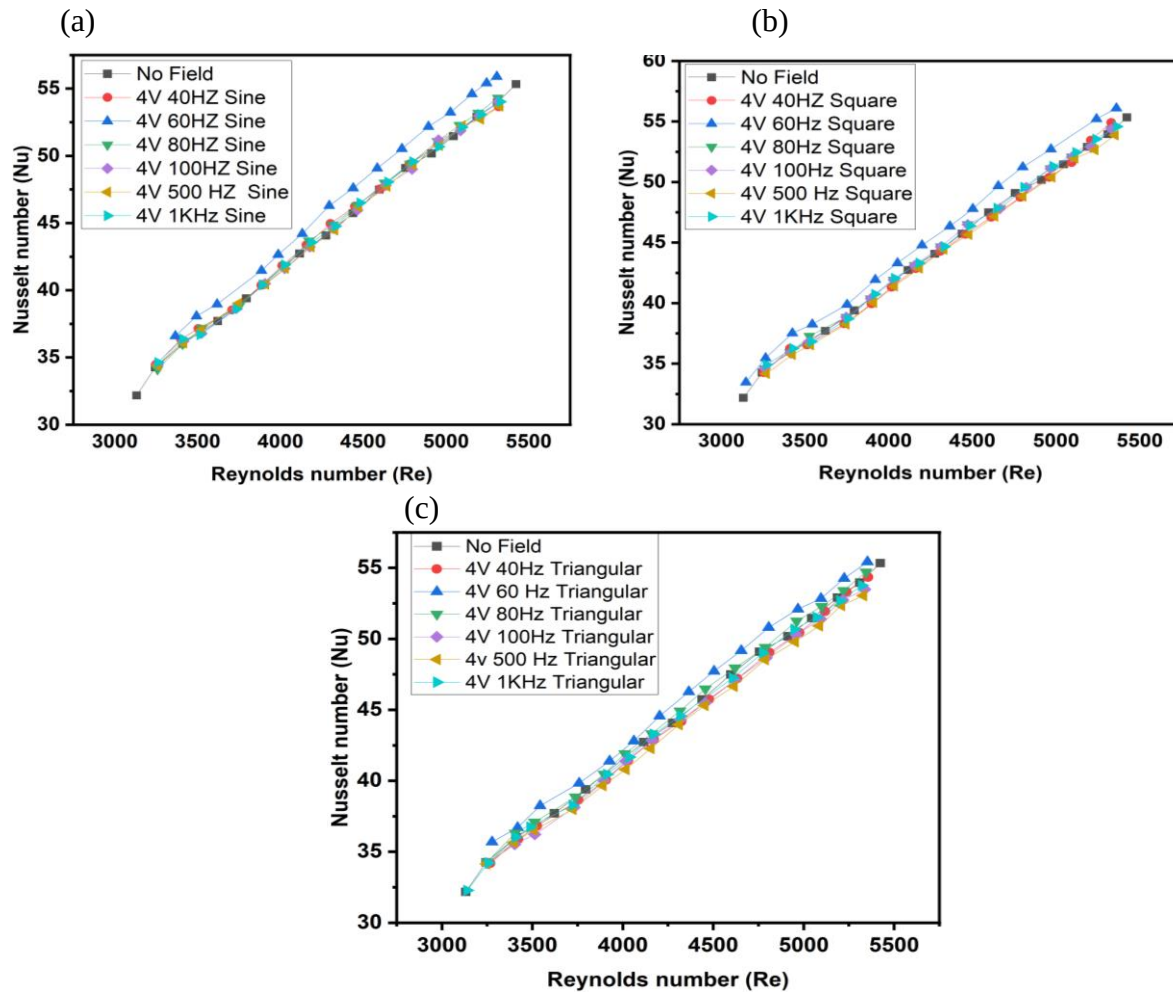


Figure 6. 16 Correlation between the heat exchange improvement at different frequencies for different waveforms (a) Sine wave (b) Square wave (c) Triangular wave

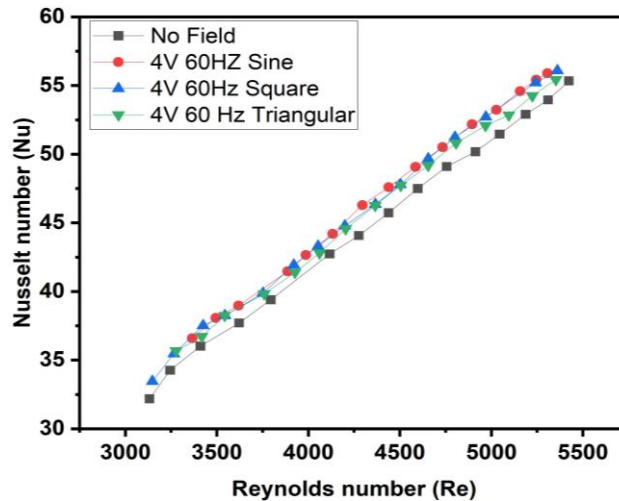


Figure 6. 17 Frequency optimization for heat transfer enhancement at 4 volts across different waveforms.

6.3.5 Analysing heat transfer enhancement across different frequencies and voltages.

Figures 6.18 a, b, c, 6.18a, b, and c illustrate how the frequencies and voltages of sine, square, and triangular waves influence CHT across various flow rates at 60Hz and 4V, considering various Re. The finding constantly shows significant improvements in heat transfer at 60Hz and 4V when juxtaposed to other voltages and frequencies across all waveform types. This highlights the importance of selecting the ideal voltage and frequency to optimize the application of magnetic field, leading to higher heat transfer coefficients along the tube.

This observed pattern can be linked to the magnetic characteristics of the fluid as it flows, influencing the dispersion of nanoparticles, lowering of viscosity, and alignment with the direction of flow. At the optimal frequency and voltage, the magnetic properties remain well- dispersed in the fluid, promoting more efficient heat transfer throughout the system. However, Experimental results confirm that higher frequencies and voltages generate stronger magnetic fields, which can significantly impact the behavior of magnetic hybrid nanofluids during flow. At elevated magnetic field strengths, the magnetic nanoparticles in the fluid tend to align more rigidly along the field lines and can cluster near the tube walls. This phenomenon, often referred to as "magnetic adhesion," reduces the mobility of the fluid near the walls, leading to the formation of a boundary layer with diminished convective heat transfer. As a result, the effective heat transfer rate decreases despite the stronger magnetic field.

This observation is consistent with the physics of ferrofluid behavior under high magnetic field strengths. The findings highlight the significances of balancing magnetic intensity to avoid such adverse effects. By carefully selecting optimal voltage and frequency settings, it is possible to enhance nanoparticle dispersion and thermal conductivity without inducing excessive wall adherence or flow disruption. This explanation substantiates the statement and emphasizes the need to consider the trade-offs between magnetic intensity and heat transfer performance. In summary, optimizing magnetic field variables is significant across all tube sizes and MHNFs to achieve enhanced CHT. This underscores the necessity of meticulous optimization of magnetic field characteristic to improved CHT performance in fluid flow.

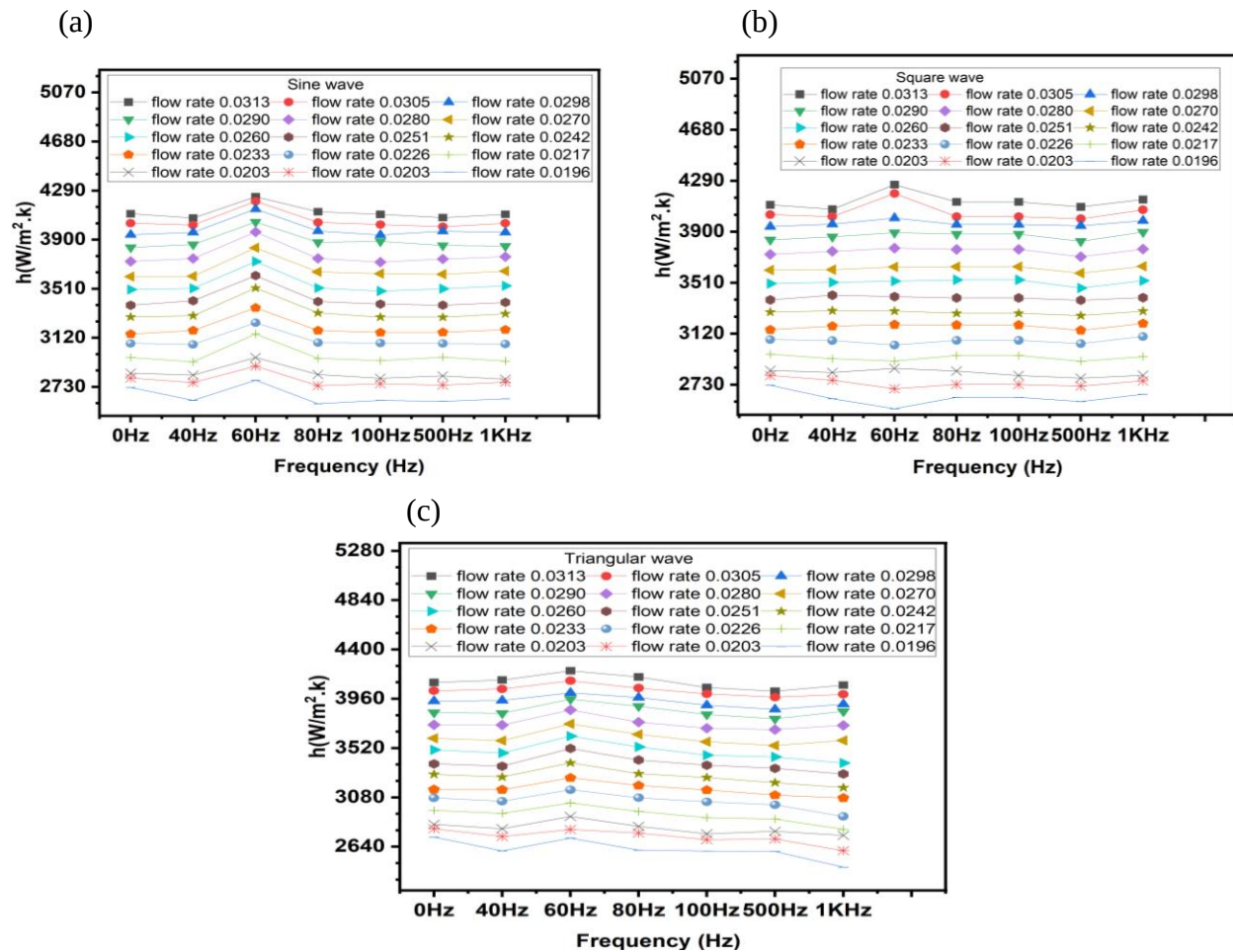


Figure 6. 18 Frequency variations impact on average heat transfer rate. (a) Sine waves (b) Square waves (c) Triangular waves.

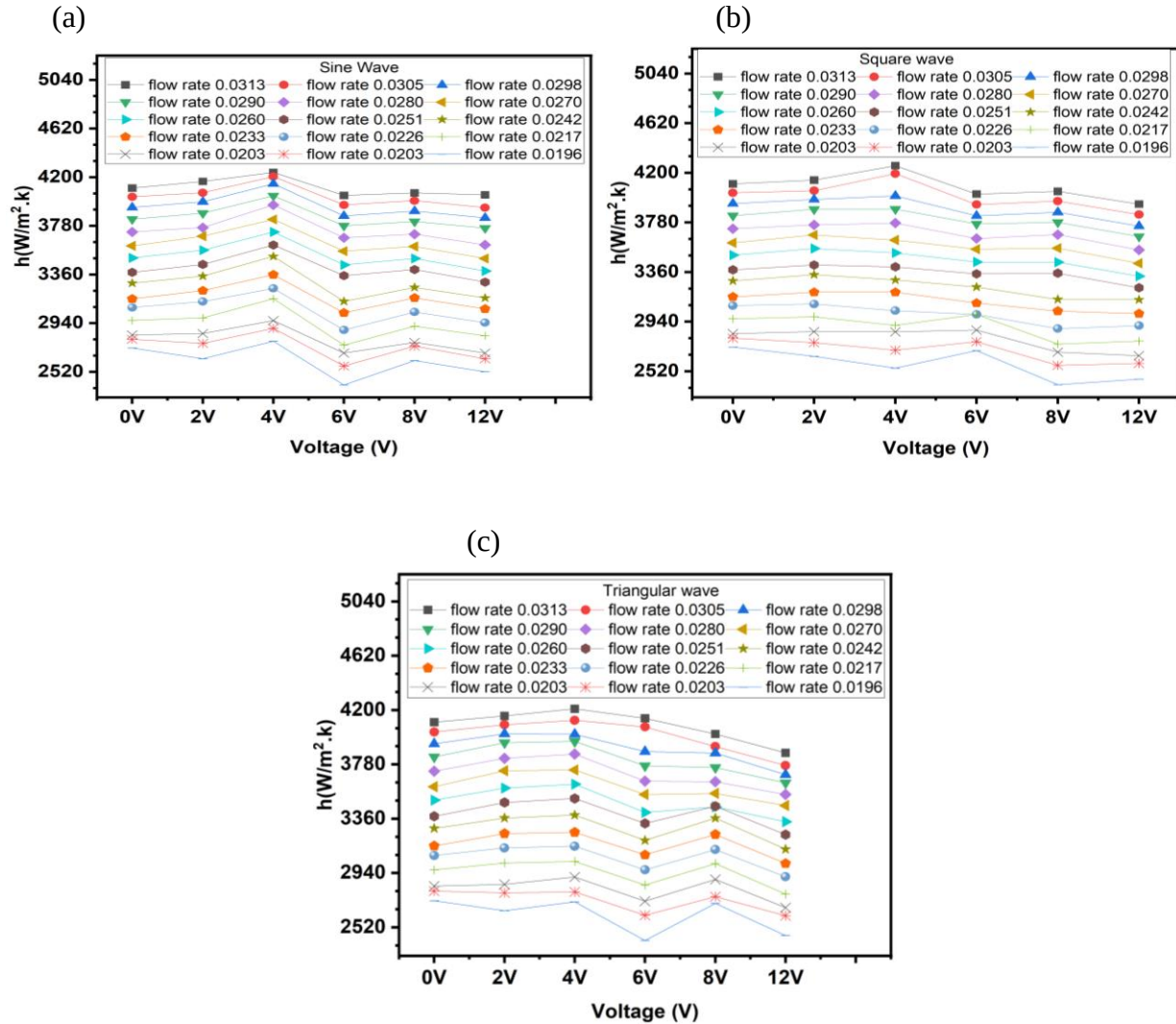


Figure 6. 19 Voltage variations impact on average heat transfer rate. (a) Sine waves (b) Square waves (c) Triangular waves.

6.3.6 Effect of magnetic field waves on $\text{Fe}_3\text{O}_4/\text{TiO}_2$ improvement at varying volume ratio

The results depicted in **Figure 6.20a, b, and c** consistently demonstrate a notable increase in heat enhancement when Magnetic fields induced by triangular, sine, and square, waveforms were applied at various volumetric ratio (0.1%, to 0.00625%), and their effects were compared to with no magnetic field at the same volume fractions. The results reveal a significant enhancement in fluid flow properties due to the application of magnetic wave fields. Notably, heat transfer improvements were observed even at lower volumetric ratio like 0.00625% and 0.0125%, with 0.0125% showing the most substantial augmentation across all waveforms. This highlights the particular sensitivity of heat transfer to the magnetic field's influence on wave concentration.

Moreover, when compared to deionized water (DIW), all concentrations—whether exposed to a magnetic field or not—showed marked improvement in heat transfer, emphasizing the positive contribution of magnetic waves, even at lower concentrations, in enhancing fluid flow behavior and thermal performance.

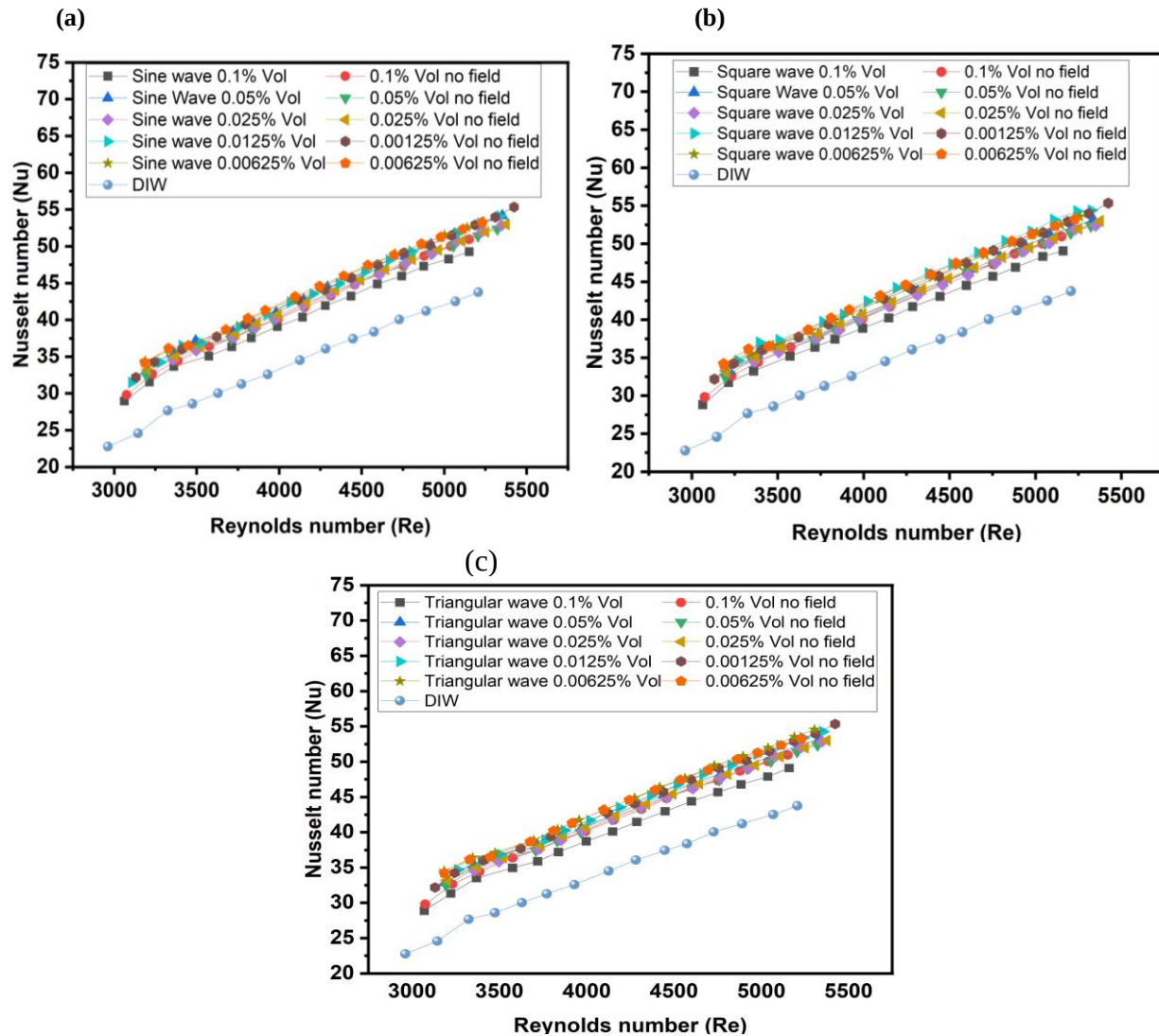


Figure 6. 20 Comparison heat transfer improvement with various magnetic field waveforms at various volumetric ratio (a) Sine waves (b) Square waves (c) Triangular.

6.3.7 Comparison of percentage heat transfer improvement MHNFs with magnetic field waveforms and volumetric ratio.

Figure 6.21 presents a comprehensive analysis of the heat exchange argumentation percentage for a hybrid nanofluid consisting of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ at different volumetric ratio and with magnetic field triangular, square and sine waves, as well as a with no a magnetic field. Upon examination of the

data, several significant findings emerge. Firstly, at higher volume fractions (0.1% Vol), the percentage enhancement in heat transfer generally declines across all waveform types when compared to the control condition lacking a magnetic field. This suggests that the behavior of the nanofluid is contingent on its concentration, potentially influenced by factors like particle distribution and agglomeration that the magnetic field aids in amplifying. Consequently, raising the volume fraction beyond a certain threshold may not substantially improve heat transfer enhancement, even with the applied magnetic field.

Secondly, among the different waveform types, the square wave consistently exhibits the highest percentage argumentation across most volume fractions. This indicates that the square wave magnetic field might be more efficient in improving heat exchange compared to sine and triangular waveforms for the specified nanofluid composition. The observation that the square wave consistently exhibits the highest percentage enhancement across most volume fractions suggests its superior ability to enhance heat transfer in this specific setup. This is likely due to the abrupt transitions of the square wave, which may create sharper and more frequent magnetic pulses. These pulses enhance the mixing and alignment of nanoparticles within the fluid, improving thermal conductivity and convective heat transfer.

The suggestion that this finding has potential applications in thermal management systems is well-founded, as the ability to optimize heat transfer by tailoring waveform characteristics can benefit industries requiring precise thermal regulation. However, it is essential to acknowledge that the effectiveness of sine and triangular waveforms could also be maximized through proper optimization of operating conditions, such as voltage, frequency, and flow regime. This adaptability of waveform types indicates their potential applicability in various scenarios, depending on the specific requirements of the system. Additionally, it is noteworthy that at lower volume fractions (0.00625vol and 0.0125vol %), the percentage enhancement in heat transfer exhibits more significant variations across different waveform types. For instance, the absence of a magnetic field demonstrates a higher percentage enhancement for triangular waves at 0.0125 vol %, while the triangular wave shows the highest percentage compared to sine, square waves, and the control condition. This suggests that the effectiveness of magnetic field waveforms in improving heat exchange may be influenced by the nanoparticle concentration in the nanofluid.

In summary, the analysis underscores the intricate interplay between volumetric ratio and magnetic waveforms on heat exchange enhancement in hybrid nanofluids. Further exploration and

optimization of these parameters are imperative to optimize heat exchange efficiency in practical applications.

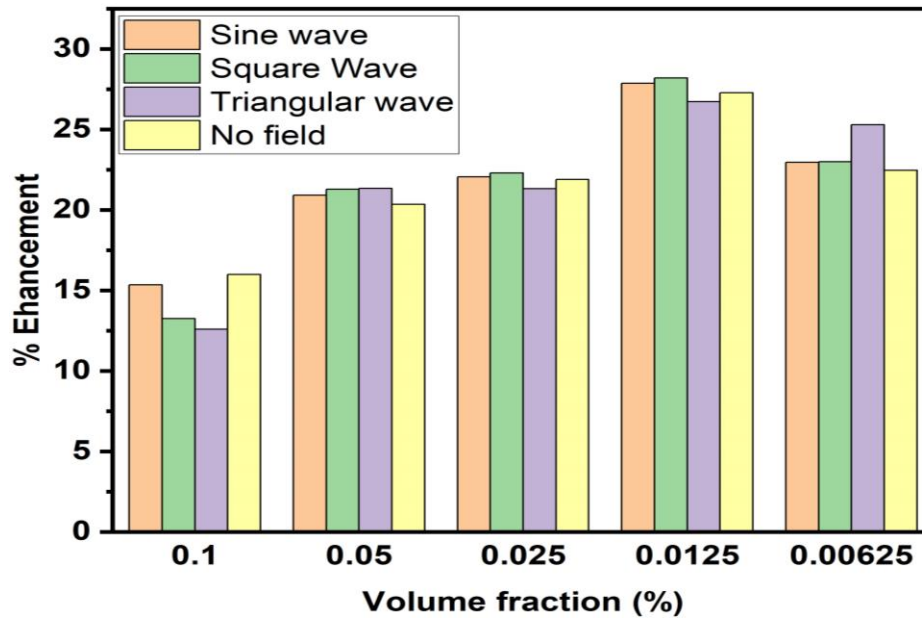


Figure 6. 21 Comparison of heat transfer improvement percentage across different magnetic field waveforms and volumetric ratio.

6.3.8 Effect of volume fraction and magnetic field waveforms vs flow rate on CHT coefficient of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ MHNFs

In **Figure 6.23a, b, and c** illustrate the combined influence of volumetric ratio and the comparisons of the average heat transfer coefficient for $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluid with the three waveforms, triangular, square, and sine. The results are also contrasted with a control scenario that does not utilize a magnetic field, as well as DIW for reference. Across the different volumetric ratio of the MHNFs, a consistent reduction in the average CHT coefficient is noted as the volumetric ratio fraction increases. This trend highlights the impact of NPs concentration on CHT performance, suggesting that higher concentrations may hinder the argumentation of heat exchange.

The observed enhancement is most pronounced at optimal volume fractions where the interplay between magnetic field strength and nanoparticle concentration achieves maximum effectiveness. Conversely, at higher volume fractions, the viscosity increase may counterbalance the benefits of the magnetic field, moderating the extent of enhancement.

These findings underscore the critical influence of magnetic fields on heat transfer dynamics and align with previous studies that highlight the efficacy of magnetic fields in improving convective

heat exchange in ferrofluids. Furthermore, comparison with DIW, the CHT coefficient offers critical insights into the nanofluid's performance in improving heat exchange. These findings highlight the complex interplay between flow rate, volumetric ratio, waveforms, and the heat exchange coefficient, providing valuable insights for enhancing thermal performance in practical applications.

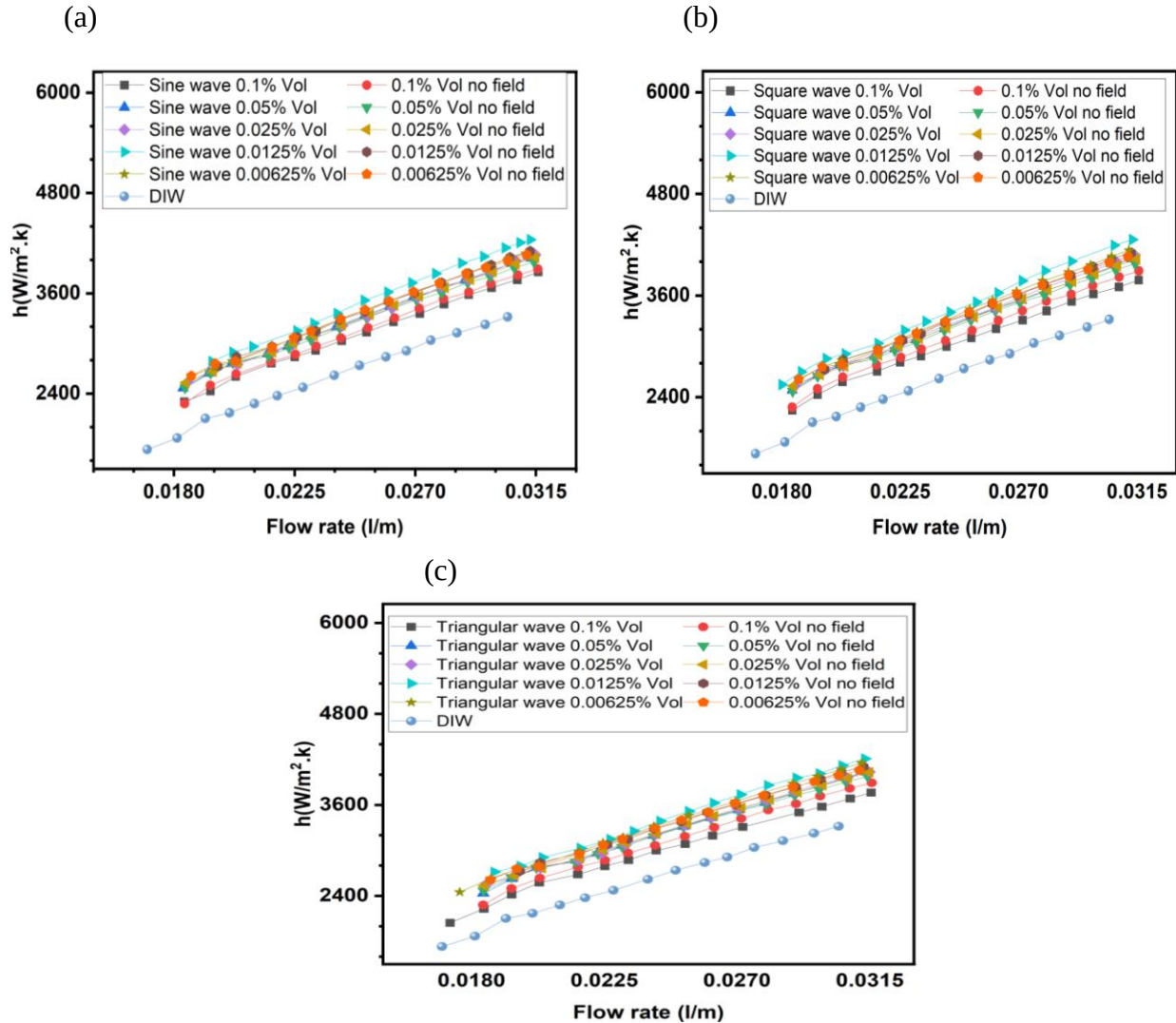


Figure 6. 22 Impact of volume fractions on average CHT coefficient MHNFs with triangular wave vs flow rates, with no magnetic field.

6.3.9 Analysing pressure drop behavior in MHNFs under magnetic waves.

In **Figures 16.23a, b, and c**, pressure drops are plotted against flow rate for various volumetric ratio with the effect of magnetic waves. The experimental data sheds light on the behavior of

$\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids within the turbulent regime of forced convection, influenced by factors such as concentration, the viscous drag effect of the nanofluids, and flow rate dynamics. The results indicate that higher concentrations of nanofluids correspond to increased pressure drops, suggesting a concentration-dependent effect on hydraulic resistance, especially pronounced at elevated concentrations. Additionally, The connection between Δp and flow rates across various volumetric ratio shows a steady decline. Remarkably, this linear pattern mirrors the behavior observed in DIW at lower volumetric ratio (0.00625 and 0.0125 vol), implying that while flow rate remains the primary influence, the rise in NPs concentration exacerbates the Δp . These results align with previous studies conducted by Sundar et al [228] and Emad et al.[32], [225] and.

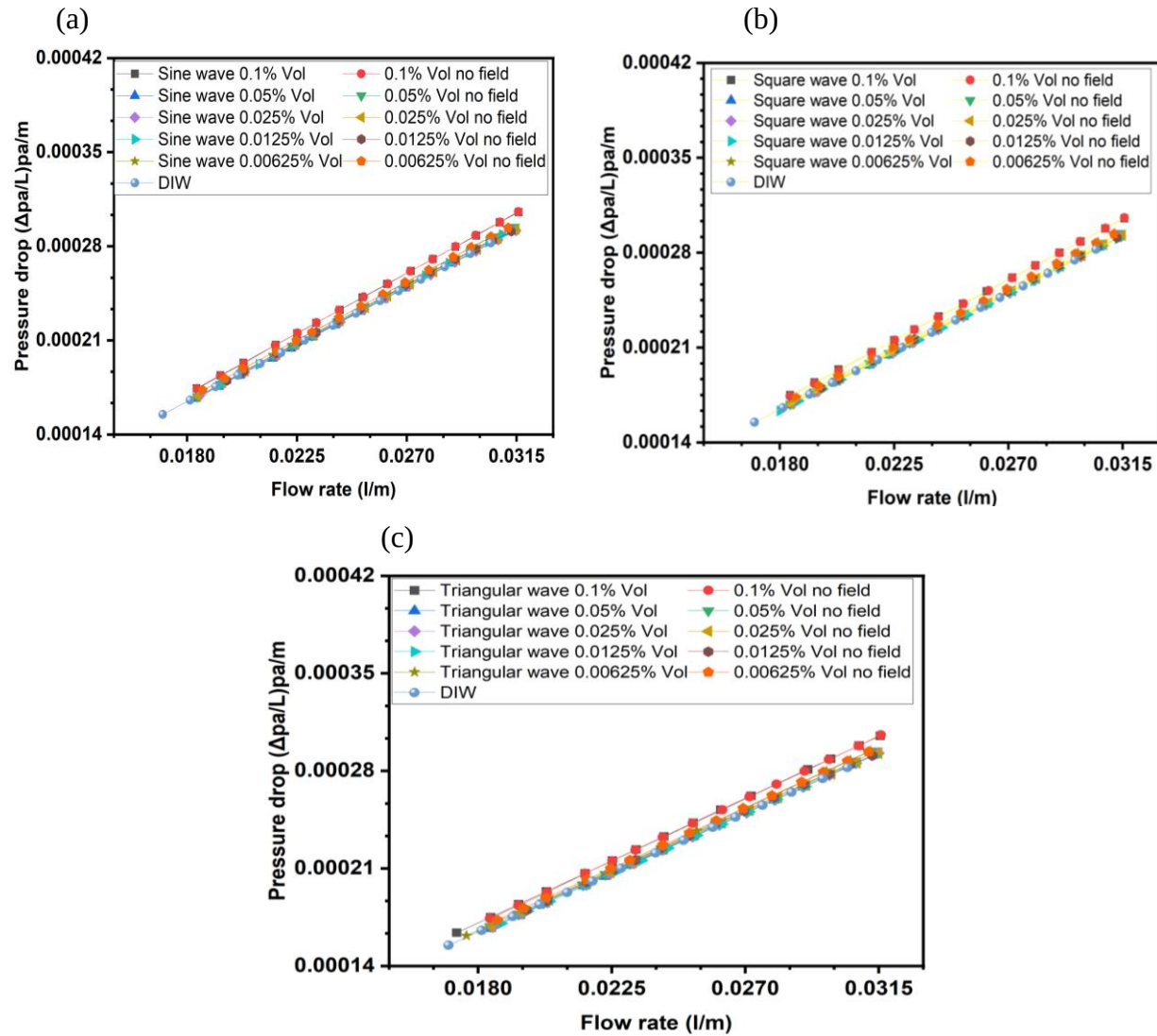


Figure 6. 23 Understanding pressure drop variation in MHNFs under difference magnetic wave effect across different flow rates.

6.3.10 Analysing thermal performance of MHNFs under difference magnetic wave conditions and volume fractions.

Evaluating the thermal efficiency index (TEI) is essential for determining the performance of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids in heat transfer systems under varying waveform conditions. TEI serves as an indicator of how efficiently energy is transferred, helping optimize heat transfer processes in systems exposed to different magnetic waveforms. This analysis discusses the behavior of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids when subjected to sine, square, and triangular waves, as well as in a no-field condition, as illustrated in **Figures 16.24 a, b, and c**. **Figure 16.24d** provides a comparison of the waveforms with the absence of a magnetic field.

Across various flow rates, the TEI consistently shows that higher concentrations of nanofluids, specifically 0.1% and 0.05% by volume, exhibit lower thermal efficiency compared to the smaller concentrations of 0.025%, 0.0125%, and 0.00625%. This suggests that higher nanoparticle concentrations may introduce challenges, such as uneven particle distribution and increased thermal resistance, reducing overall efficiency.

The data in **Table 6.4** provides valuable insights into the impact of waveform type on thermal performance, particularly at the minimal flow rate. The analysis reveals those different waveforms lead to varying degrees of enhancement in thermal efficiency juxtaposed to the with no magnetic field.

At a 0.1% volumetric ratio, sine waves enhance thermal efficiency by 8.76%, while square and triangular waves provide 5.07% and 2.76% improvements, respectively. This suggests that sine waves are more effective at enhancing thermal performance at higher nanoparticle concentrations, although overall efficiency remains lower than at smaller concentrations.

As the volume fraction decreases to 0.05%, the enhancements become more pronounced. Sine waves increase thermal efficiency by 15.06%, with square waves and triangular waves showing even higher improvements of 15.40% and 16.62%, respectively. This pattern continues with the 0.025% volume fraction, where triangular waves lead to a 15.35% enhancement, slightly outperforming sine and square waves, which show 14.08% and 14.16% improvements, respectively.

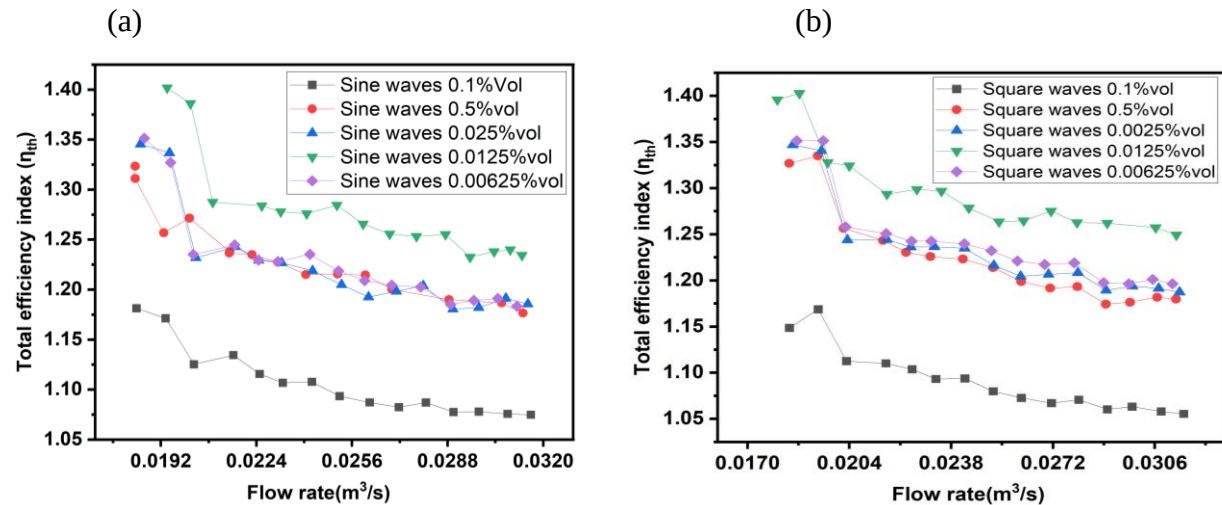
At the 0.0125% volume fraction, which offers the optimal thermal efficiency, both square and triangular waves yield significant enhancements of 17.48%, while sine waves follow closely with a 15.50% improvement. Finally, at the lowest concentration of 0.0065%, sine waves show a

13.53% improvement, while square and triangular waves both provide an 18.99% boost in thermal efficiency.

Overall, the data clearly indicates that as the volume fraction decreases, the effectiveness of the waveforms in enhancing thermal efficiency increases, with triangular waves consistently offering the highest improvements. This highlights the critical role that waveform type and nanoparticle concentration play in optimizing heat exchange performance in MHNFs, particularly at lower flow rates.

Table 6. 4 Thermal performance of different volume fractions under square, triangular, and sine waves and no magnetic field at the minimal flow rate

Vol %	Thermal efficiency no magnetic field	Thermal efficiency Sine	Thermal efficiency of Square	Thermal efficiency Triangular
0.1	1.085	1.180	1.140	1.115
0.05	1.149	1.322	1.326	1.340
0.025	1.179	1.345	1.346	1.360
0.0125	1.213	1.401	1.425	1.425
0.0065	1.190	1.351	1.416	1.416



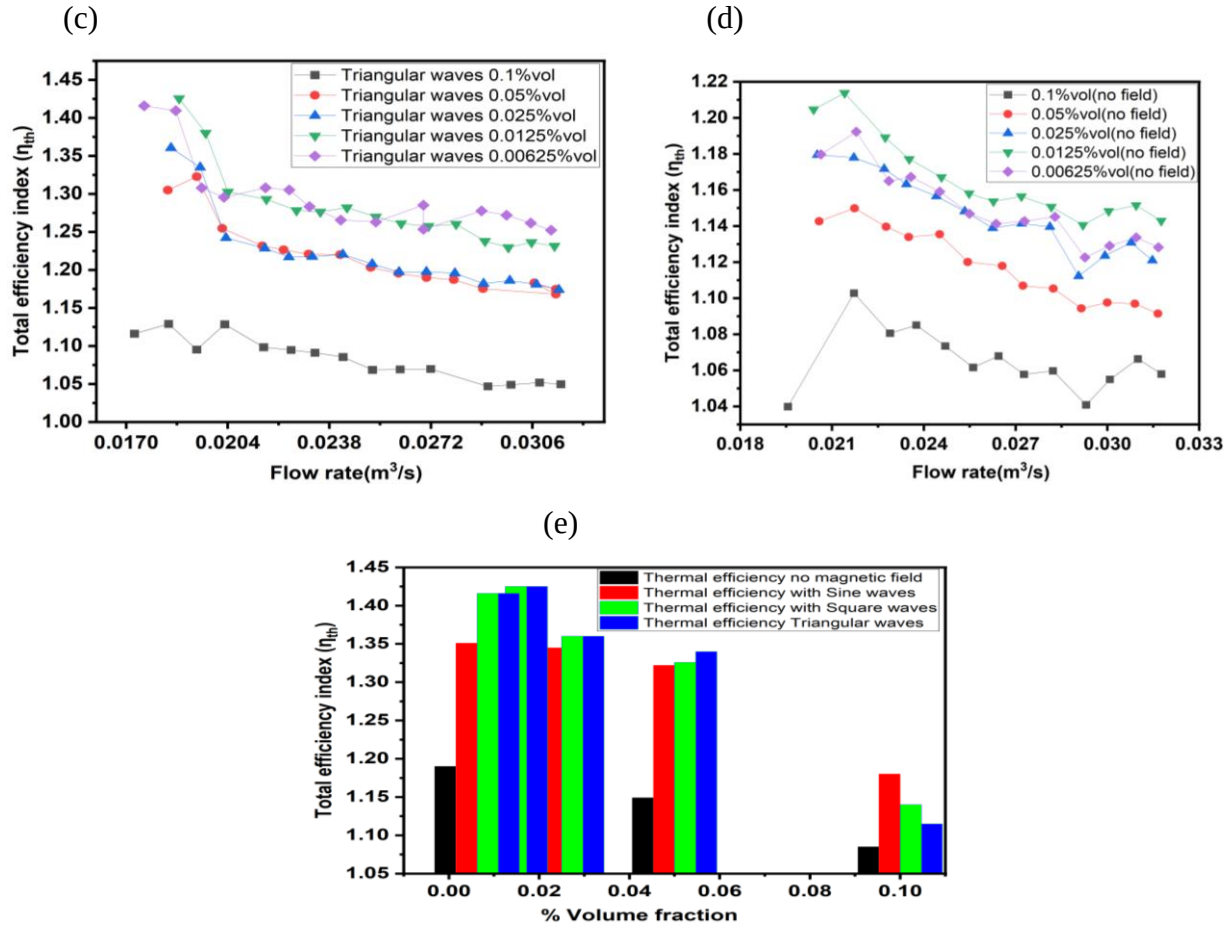
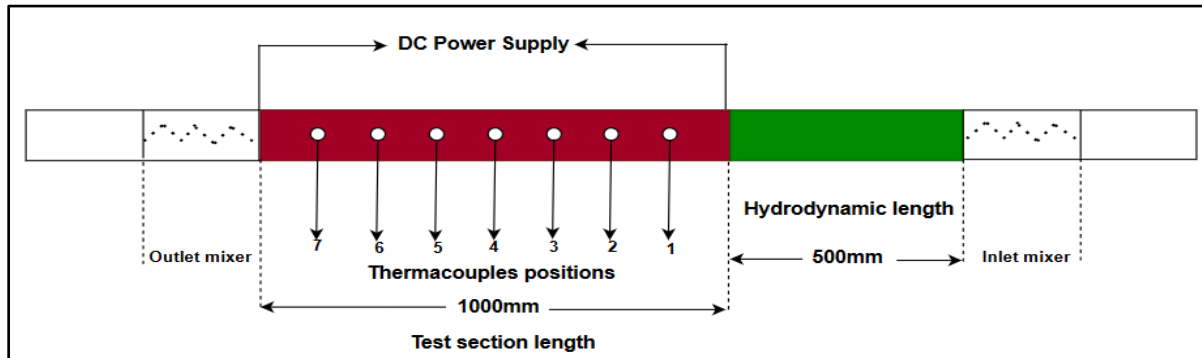


Figure 6. 24 Thermal performance of MHNFs under different magnetic wave conditions and volume fractions, with comparison to no magnetic field scenario, vs. flow rate (a) sine waveform (b) square waveform (C) triangular waveform (d) No magnetic field (e) Comparison of all the thermal efficiency.

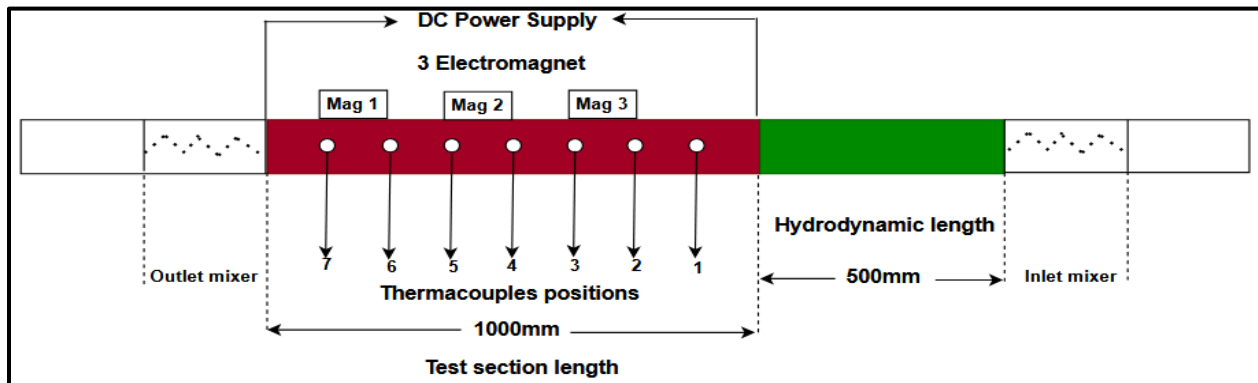
6.5 Influence of magnetic waveform positioning on heat transfer, entropy generation, and thermal performance factor in turbulent regime

The positioning of magnetic waveform along the test section may significantly influence heat transfer enhancement, entropy generation, and thermal performance factors in turbulent regimes. Through strategic placement, researchers can optimize these processes. in **Figure 6.25** shows the different cases , **Case I**, without a magnetic field, serves as a baseline for comparison. **Cases II** to **IV** involve different magnetic field configurations, demonstrating the varying impact on heat transfer, entropy generation, and thermal performance factors. Understanding and manipulating

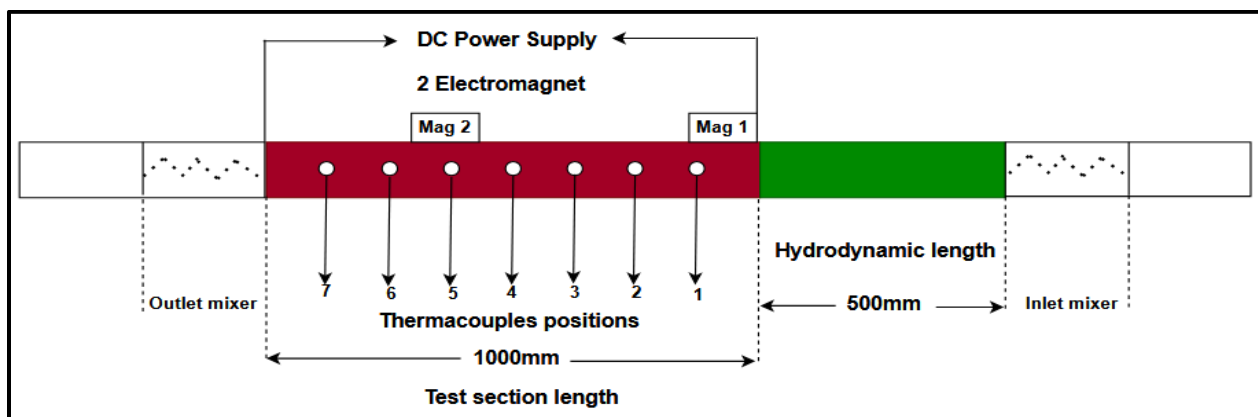
magnetic waveform positioning are crucial for achieving desired heat transfer outcomes in practical applications



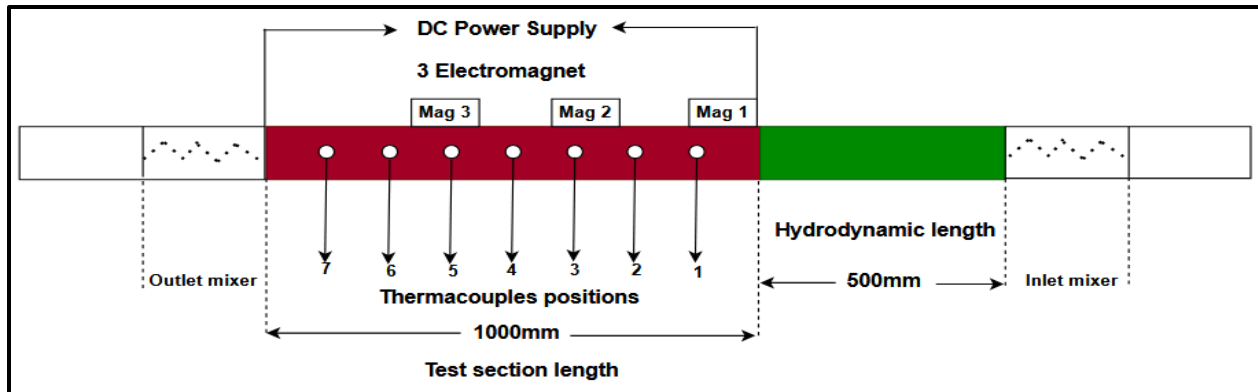
Case (I) No magnetic field



Case (II)



Case (III)



Case (IV)

Figure 6. 25 Visualization of various magnetic field positions along the test section

6.5.1 Comparison of heat exchange improvement with different magnetic field positions along the test section

The sensitivity of the magnetic field's effects to wave concentration is demonstrated by the pronounced differences in heat enhancement across the tested volume fractions, particularly at lower concentrations such as 0.0125% and 0.00625%. The results in **Figure 6.26a, b, and c** for Case (II) clearly show that the magnetic field, whether applied via sine, square, or triangular waves, significantly boosts heat transfer compared to the absence of a field. Among these, the 0.0125% volume fraction achieves the pick improvement across all waveform types. This suggests that at this specific volume fraction, the balance between nanoparticle dispersion, alignment under the magnetic field, and fluid flow dynamics is optimal, leading to superior heat transfer performance. The term "sensitivity" in this context refers to how variations in volume fraction influence the interaction between the magnetic field and the nanoparticles, thereby affecting heat enhancement. Lower concentrations appear more responsive to the magnetic field's influence, likely due to reduced particle-particle interactions and better nanoparticle alignment under the applied waveforms. Additionally, when compared to DIW, all volume fraction, with and without a magnetic field, show greater heat improvement juxtaposed to DIW alone. This steady trend indicates that incorporating magnetic waves, even at low volumetric ratio, plays a pivotal role in improving fluid flow dynamics.

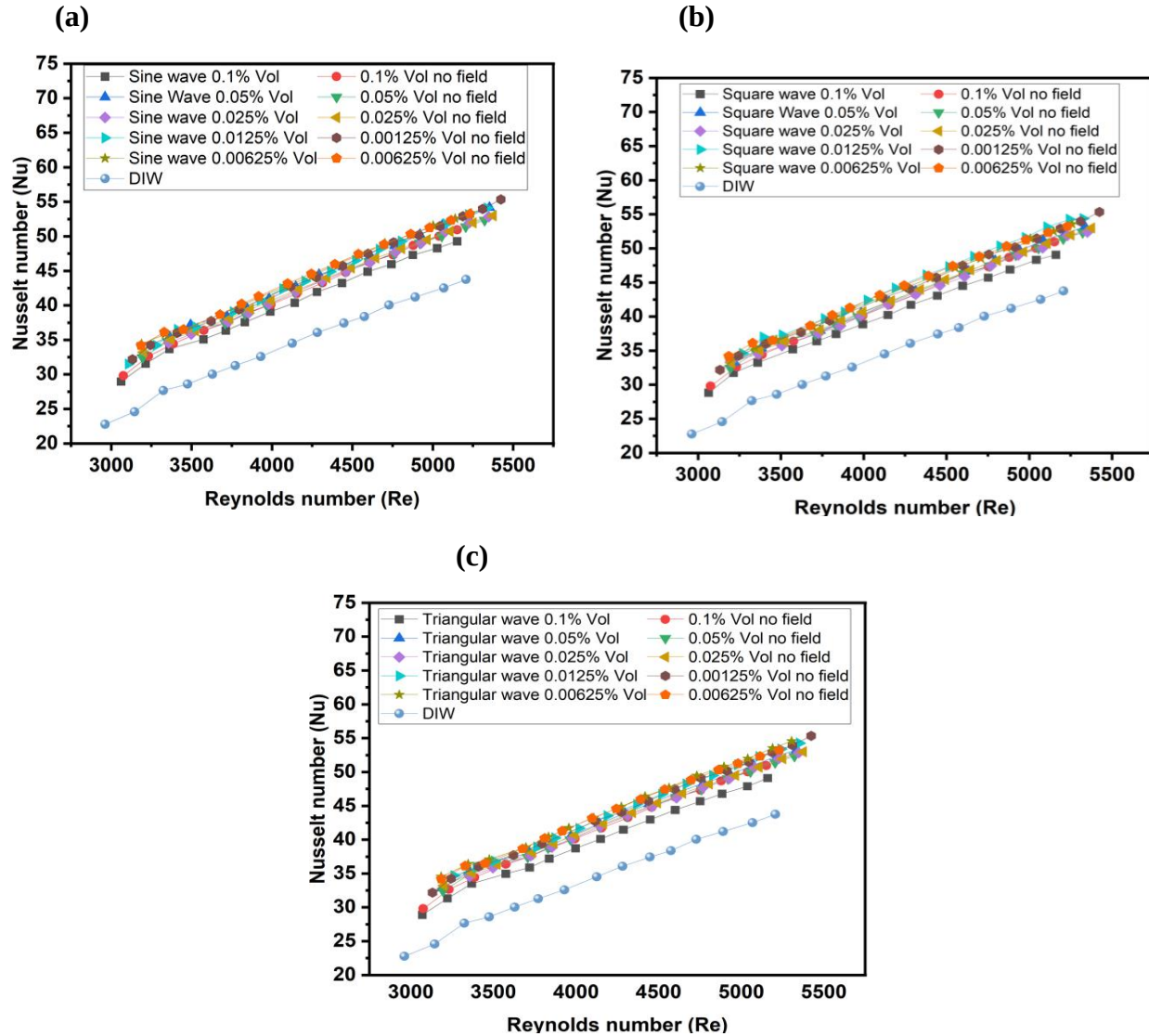
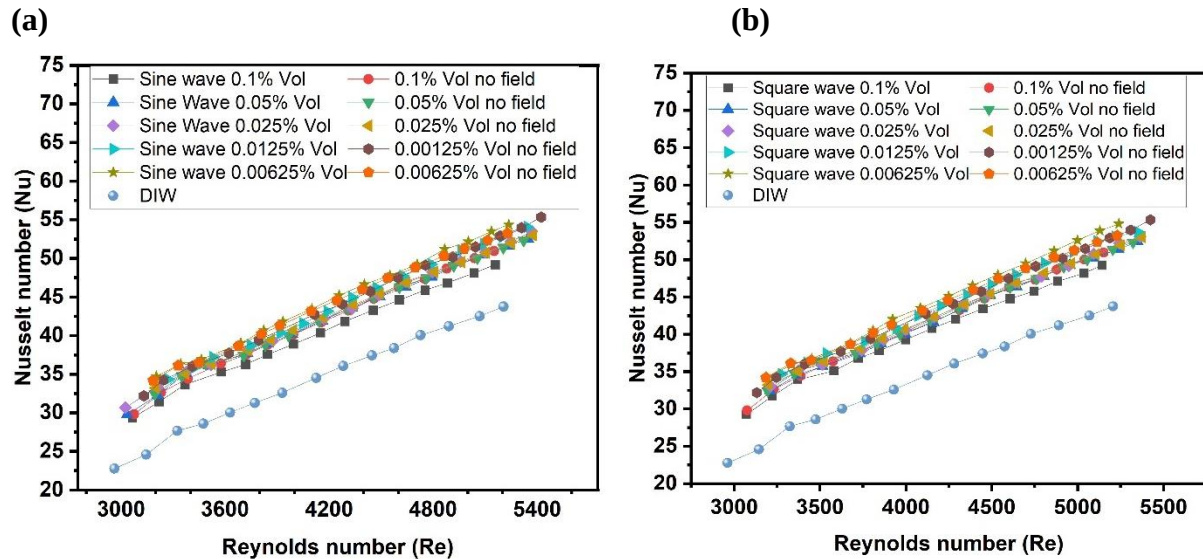


Figure 6. 26 Heat transfer enhancement with case (II) magnetic field Influence (a) sine waves (b) square waves and (c)triangular waves at various volume fractions

While in **Figure 6.27 a, b, and c**, along with **Case (III)**, collectively demonstrate the significant impact of magnetic field waves on enhancing heat exchange in the fluid. When waves are applied at different volumetric ratio, an intriguing observation arises when comparing conditions with and without a magnetic field at the same volume fraction with a magnetic field, there is a consistent enhancement of heat transfer. The observed phenomenon at lower volume fractions, like 0.00625%, can be attributed to the interaction between the NPs and the applied magnetic field. At lower concentrations, the nanoparticles are more evenly dispersed, reducing the likelihood of particle agglomeration. This dispersion allows the magnetic field to exert a stronger influence on

the nanoparticles, aligning them more effectively along the field lines and enhancing thermal conductivity. Consequently, this leads to improved convective heat transfer in the test section. The placement of the magnetic field at the beginning of the thermally developed region further amplifies this effect. In this position, the field can directly influence the fluid's behavior as it enters the critical heat transfer zone. However, the distance between successive magnetic field sources, as mentioned for Case (III), may result in partial demagnetization, causing fluctuations in heat augmentation. This indicates a complex interplay between magnetic field positioning, nanoparticle concentration, and fluid flow dynamics, particularly at lower volume fractions where the effect of the magnetic field is more pronounced. Furthermore, the comparison with DIW alone underscores the substantial contribution of magnetic field waves to improving fluid flow dynamics and improving heat transfer efficiency across all volume fractions.



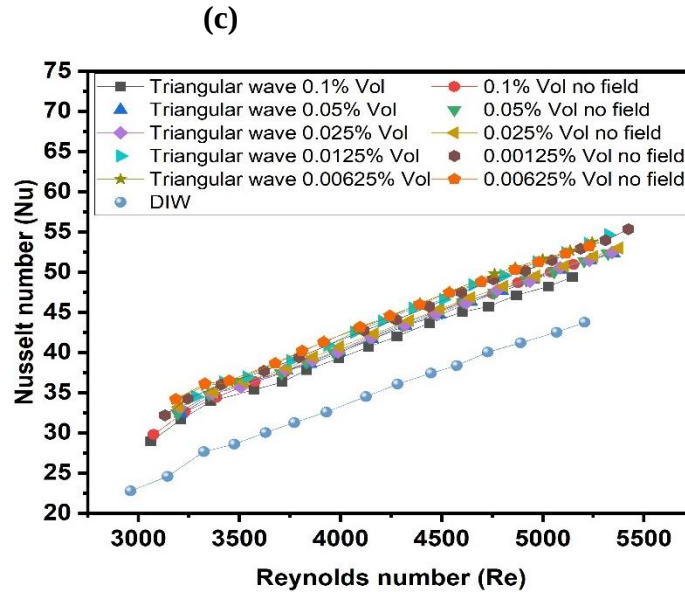


Figure 6. 27 Heat transfer enhancement with case (III) magnetic field Influence (a) sine waves (b) square waves and (c)triangular waves at various volume fractions

Figure 6.28a, b, and c, along with Case (IV), collectively demonstrate the significant impact of magnetic field waves on enhancing heat transfer in the fluid. When the waves are applied at different volume fractions. In **Case IV**, depicted in **Figure 9**, the thermocouple is positioned at the end of the thermally developed region where the electromagnetic field is applied, allowing us to observe the effect on the heat transfer coefficient specifically in this region. However, an intriguing observation arises when comparing conditions with and with no magnetic field at the same volumetric ratio. Interestingly, the highest enhancement under this case was observed at volumetric fractions of 0.1 vol, 0.0125 vol, and 0.00625 vol without a magnetic field across all waveform types. However, at a volumetric ratio of 0.025 vol, enhancement was noticed across all waveform types, more than in the case of no magnetic field. This behavior could be attributed to several factors. One possible explanation is that at lower volume fractions, the presence of the magnetic field induces more significant changes in the fluid dynamics and heat transfer characteristics, leading to improved heat exchange. Furthermore, the behavior observed at 0.05 vol and 0.025 vol could be due to a specific interaction between the magnetic field and the nanofluid at this volumetric ratio, resulting in improved heat exchange despite the magnetic field.

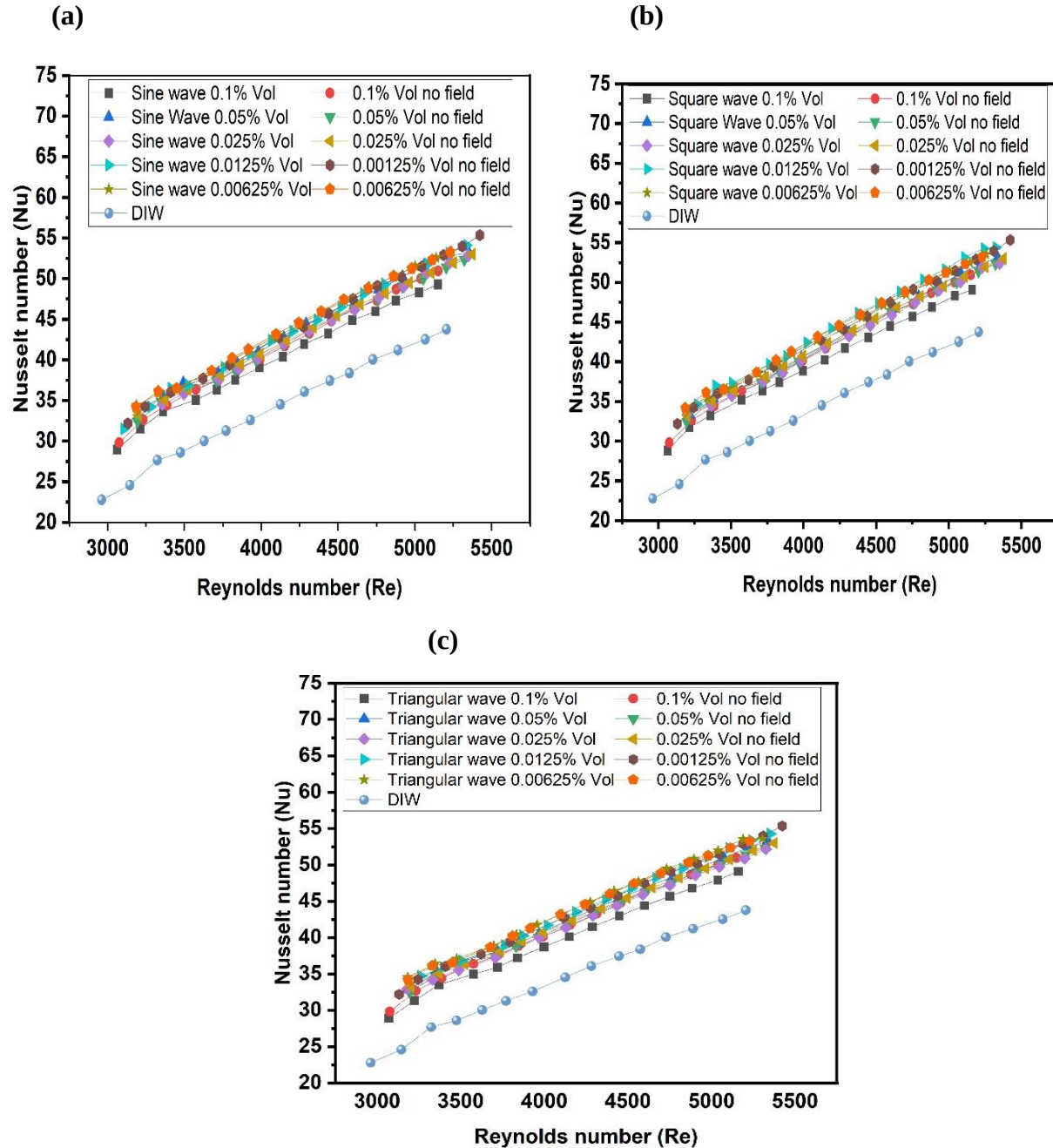


Figure 6. 28 Heat transfer enhancement with case (III) magnetic field Influence (a) sine waves (b) square waves and (c)triangular waves at various volume fractions

6.5.2 Comparative analysis of CHT coefficient enhancement different waveforms and volumetric ratio in various cases

Figure 6.29 illustrates significant variations in the CHT coefficient enhancement different volume fractions, waveforms, and cases of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluid. A rise in concentration leads to a

reduction in enhancement in the CHT coefficient, with notable improvements observed particularly at lower volume fractions. For instance, at 0.00625 Vol, the CHT coefficients for Sine wave **case IV**, square wave **case IV**, and triangular wave case IV are 22.97%, 25.28%, and 22.44%, respectively, compared to the base case value of 22.4%. However, **case IV** generally exhibits lower enhancement compared to other cases in all waveforms, possibly due to the positioning of the magnetic field along the test section, as depicted in **case (IV)**. Conversely, in **case III**, $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluid without a magnetic field shows more enhancement from 0.1 Vol to 0.0125 Vol, except for at 0.00625 Vol where square waves demonstrate the highest enhancement at 25.28%, followed by sine waves at 24.21% and triangular waves at 22.81% over no magnetic field. This could be attributed to the influence of the magnetic field positioning at the beginning of the thermally developed area of the test section, followed by demagnetization due to the distance between the first and second magnetic fields, likely contributing to fluctuations in heat augmentation. Among the waveform cases, square wave cases demonstrate the highest enhancement percentages, consistently outperforming sine and triangular wave cases. For instance, at 0.0125 Vol, the enhancement percentages for square wave **case II** are 28.21%, while for sine wave **case II**, it's 27.87%. This could be attributed to the influence of the magnetic field positioning from the beginning of the thermally developed area of the test section to almost the end of the test section, as illustrated in **case (II)**, showing that the magnetic particles are homogeneously suspended within the fluid during the flow, thereby causing improved enhancement along the test section. Moreover, at higher volume fractions, Square Wave cases exhibit substantial enhancement compared to other waveforms. For example, at 0.1 Vol, the CHT coefficients for square wave **case III** and triangular wave **case III** are 12.58 and 12.95, respectively, while for sine wave **case III**, it's 12.42. However, at higher volume fractions (0.1% Vol), the percentage enhancement in heat transfer generally decreases across all waveform types compared to the control condition without a magnetic field. This suggests a concentration-dependent behavior of the nanofluid, potentially influenced by factors such as particle distribution and agglomeration that the applied magnetic field helps to amplify. Consequently, increasing the volume fraction beyond a certain threshold may not lead to significant improvements in heat transfer enhancement, even with the application of a magnetic field. The choice of waveform also impacts the enhancement, with Square Wave cases generally yielding the best results. However, square wave **case III** also presents competitive enhancement values, showcasing its effectiveness in certain scenarios. Overall, the selection of the optimal case

for maximizing heat transfer enhancement depends on various factors such as volume fraction, waveform characteristics, and specific application requirements. Therefore, a comprehensive understanding of each case's performance is essential for optimizing thermal management systems and fluid-based heat transfer processes.

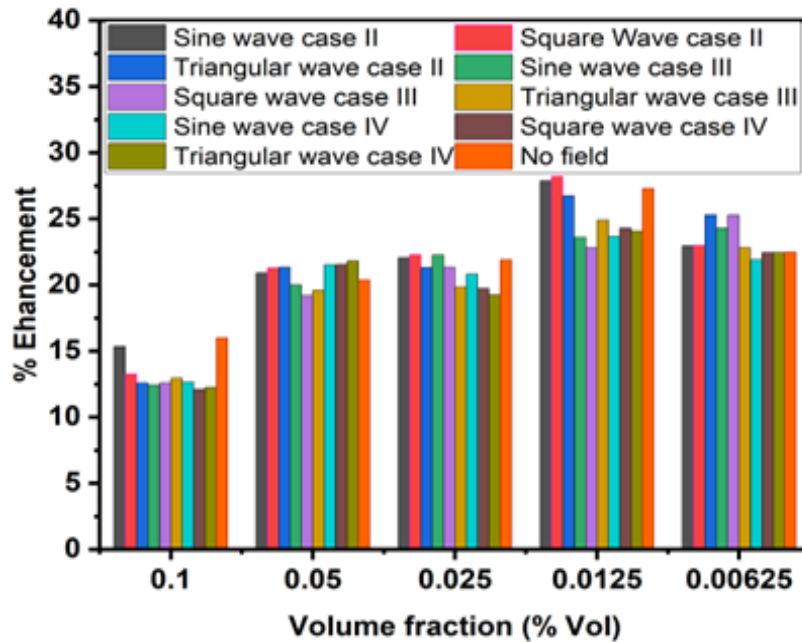


Figure 6. 29 Examination of heat transfer enhancement considering different magnetic field positions and waveforms across diverse volume fractions

In **Figures 6.31(a), (b), and (c)**, **Figures 6.32(a), (b), and (c)**, **Figures 6.33(a), (b), and (c)** depict **case II, case III, and case IV**, respectively, while **Figure 6.30**, represents case I without a magnetic field, for magnetic hybrid nanofluids across varying conditions with concentrations ranging from 0.1 wt% to 0.000625 wt% and different waveforms at different velocities, illustrating the CHT behavior. Comparing the CHT (h_{avg}) values under the impact of sine waves, square waves, and triangular waves for **case II, case III, and case IV**, as well as in the absence of a magnetic field across different volume fractions and velocities, reveals intriguing patterns. At a volume fraction of 0.1%, the heat exchange coefficient remains relatively stable under sine waves for all cases, ranging from 3754.7 W/m² K to 3855.068 W/m² K at a velocity of 0.63 m/s, while without a magnetic field at the same velocity, the h_{avg} is higher at 3889.478 W/m² K. This trend is consistent across square and triangular waves for all cases. The disparity in heat exchange coefficients between cases with and without the magnetic field at a volumetric ratio of 0.1% can be attributed

to factors such as nanoparticle alignment, agglomeration, alterations in fluid dynamics, and changes in suspension stability induced by the magnetic field. Similarly, at lower volumetric ratio of 0.05% and 0.025%, h_{avg} values fluctuate within a narrow range for both conditions, indicating minimal impact from the application of magnetic waves. As we move to lower volumetric ratio of 0.0125vol% and 0.00625vol%, a slight deviation in h_{avg} values is observed between sine, square, and triangular waves for the three cases, with higher h_{avg} values consistently under sine wave conditions compared to no magnetic field conditions. This observed deviation suggests a significant influence of the magnetic field on Fe_3O_4/TiO_2 nanoparticle suspension at these lower volume fractions, potentially due to enhanced nanoparticle alignment, dispersion, and alterations in fluid flow induced by the magnetic field. Overall, While nanoparticle volume fraction and dispersion are foundational factors in determining heat transfer efficiency, the application of magnetic waves serves as an important enhancement mechanism. Magnetic waves optimize the alignment and mobility of nanoparticles, thereby augmenting thermal conductivity and convective heat transfer. This interplay is particularly effective in systems designed to leverage the dynamic influence of magnetic fields, highlighting their complementary role in maximizing overall heat transfer performance. These results highlight the complex correlation between nanoparticle concentration, fluid dynamics, and external stimuli in heat exchange processes, showing the necessity for further research to optimize such systems.

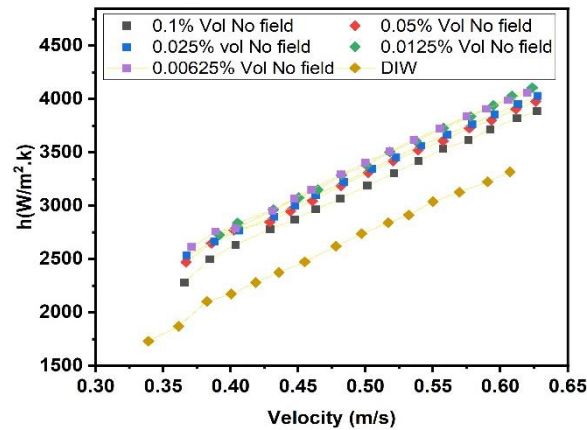


Figure 6. 30 Impact of MHNFs concentration and flow velocity on heat transfer efficiency and absence of magnetic fields (Case I).

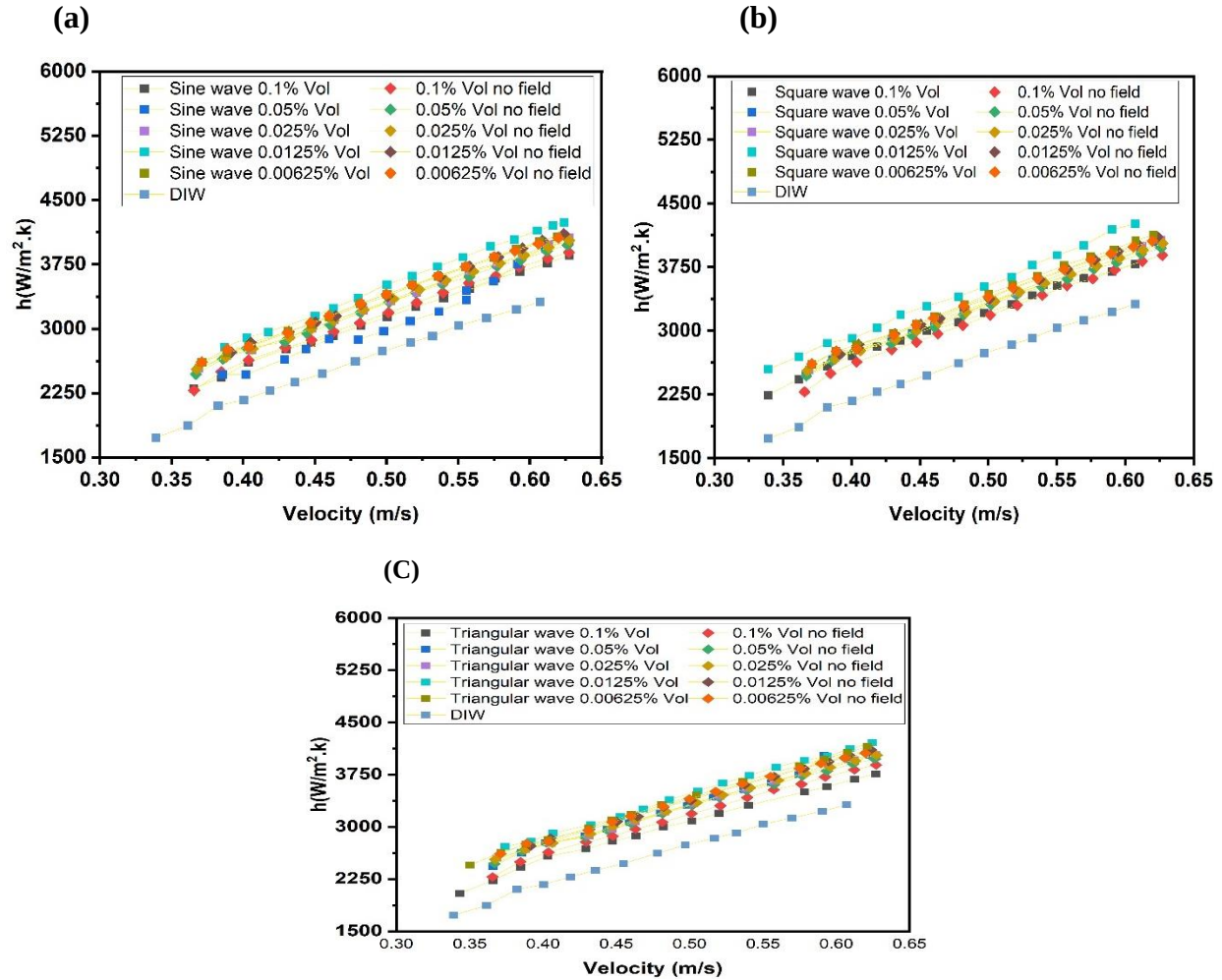
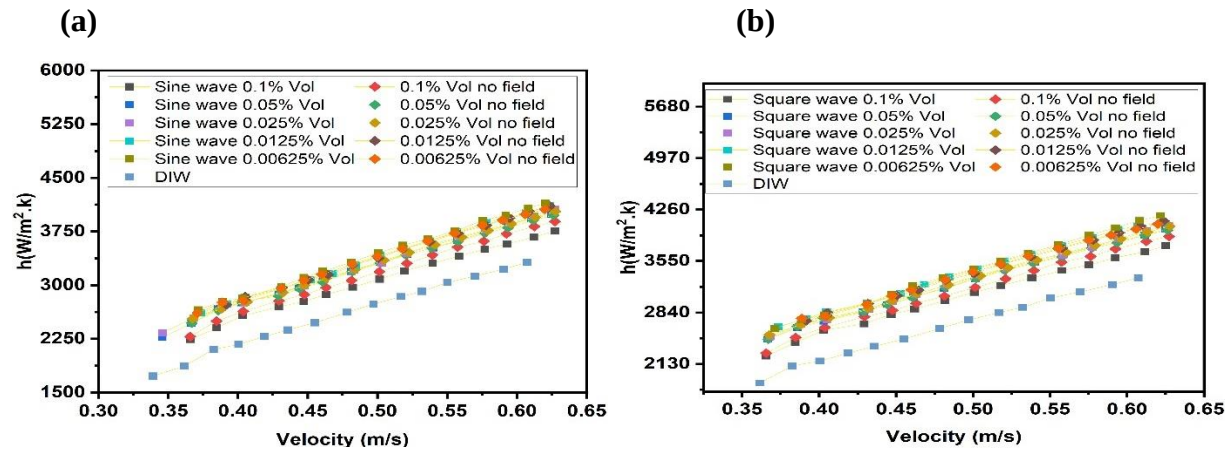


Figure 6. 31 Impact of MHNFs concentration and flow velocity on heat transfer efficiency and absence of magnetic fields (Case I)



(c)

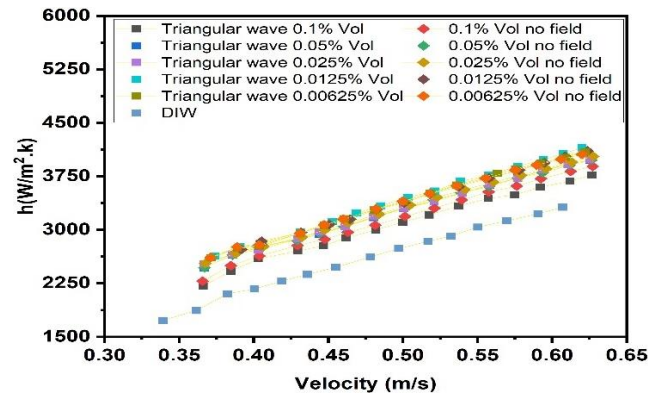
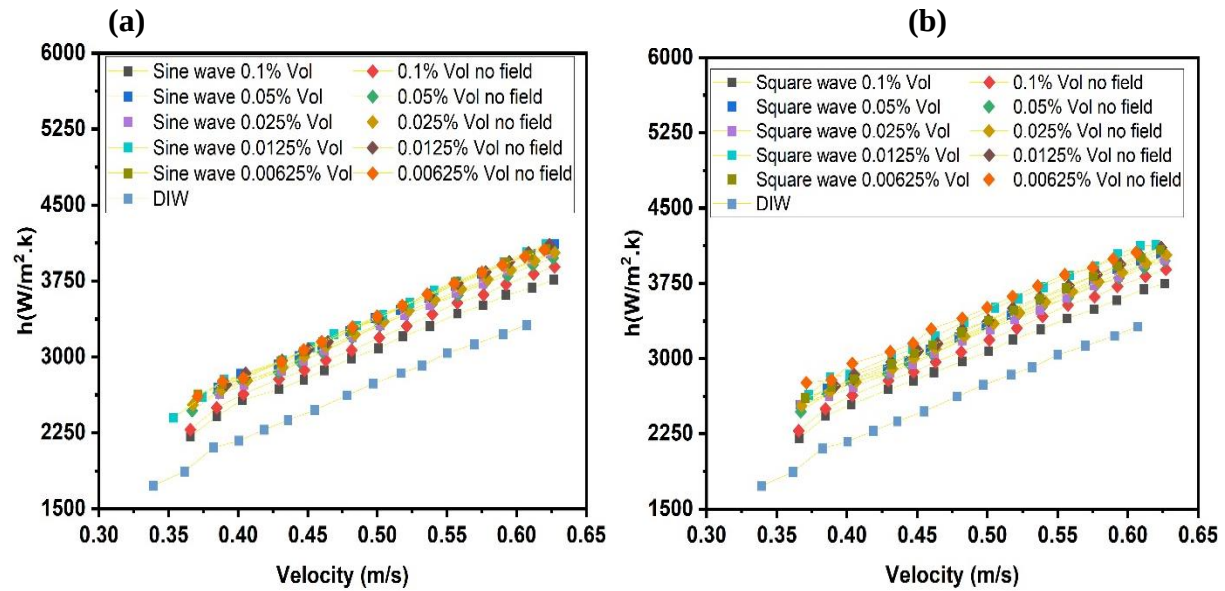


Figure 6. 32 Comparative analysis of MHNFs vs DIW, flow velocity on heat transfer efficiency and concentrations with magnetic waves and in the absence of magnetic fields Case III (a) sine waves (b) square waves (c) triangular waves.



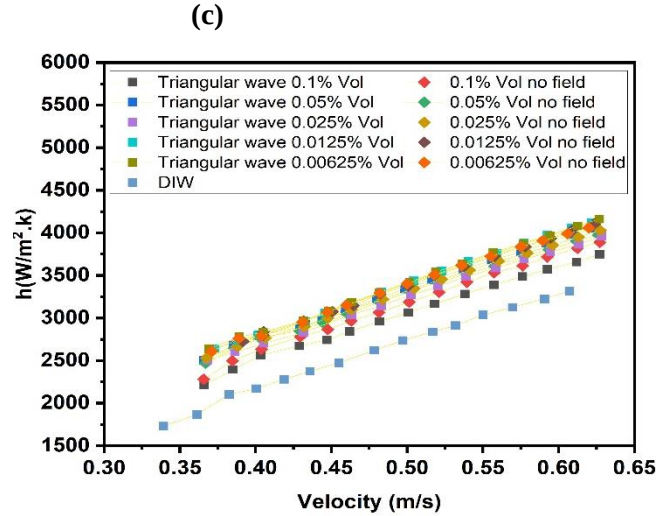


Figure 6. 33 Comparative analysis of MHNFs vs DIW, flow velocity on heat transfer efficiency and concentrations with magnetic waves and in the absence of magnetic fields Case IV (a) sine waves (b) square waves (c) triangular waves

6.5.3 Assessment of effect of magnetic field positioning on pressure drop MHNFs

The evaluation of the friction factor for MHNFs nanofluids passing through the test section is conducted across various concentrations and flow velocities. In the absence of a magnetic field (referred to as **Case I**) as shown in **Figure 6.34**, the calculated friction factor for the MHNFs nanofluids is analysed. As per theoretical expectations derived from pressure drop equations, the friction factor of MHNFs nanofluids is anticipated to increase due to viscous drag and density gradient. The observed results align with these expectations, indicating an increase in the friction factor with higher MHNFs nanoparticle concentrations and a decrease with increasing flow velocity, a typical behavior for fluid flow in straight tubes.

In **Case II, III, and Case IV** (illustrated in **Figures 6.35a, b, and c, Figures 6.36a, b, and c, and Figures 6.37a, b, and c, respectively**), with sine, square, and triangular waves, the pressure drops are depicted as a function of velocity flow rate with different volumetric ratio under the impact of waves. The experimental results reveal the behavior of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids within the turbulent region, influenced by factors including volumetric ratio, viscous drag effects of the nanofluids, and dynamics of the flow rate.

The outcomes indicate that as the volumetric ratio of nanofluids increases, there is a corresponding rise in Δp , particularly noticeable at higher concentrations, indicating a heightened influence of nanofluids on hydraulic resistance. Additionally, the relationship between Δp and velocity rate

across all volumetric ratio exhibits a linear decline, the pattern consistent across all cases. Notably, this linear pattern is similar to the behavior seen in DIW at the minimal volumetric ratio (0.00625 and 0.0125 vol), indicating that although flow velocity is the primary factor, an increase in NPs concentration intensifies the Δp . This results is consistent with earlier studies conducted by Emad et al.,[32], [225] and Sundar [228].

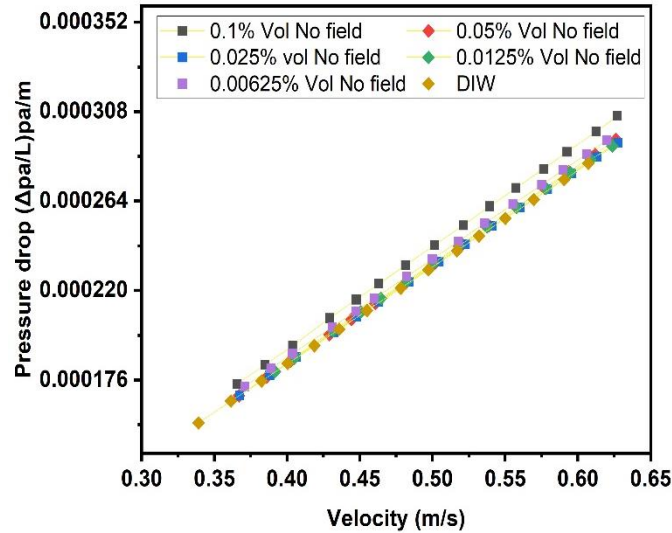
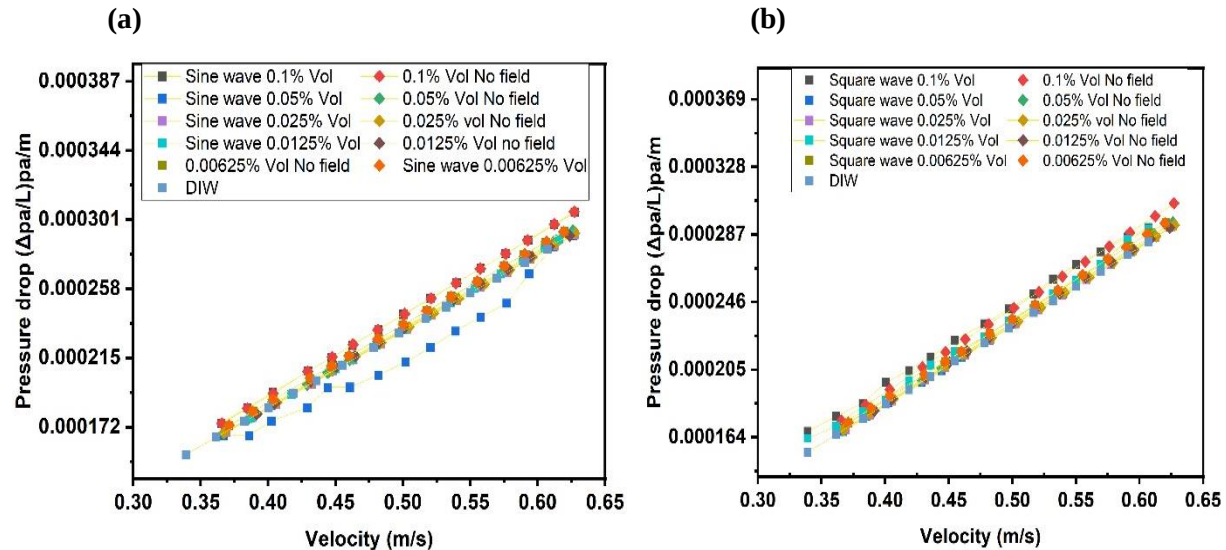


Figure 6. 34 Comparison of pressure drop between DIW and MHNFs with no field at various concentrations with varied velocities case I



(c)

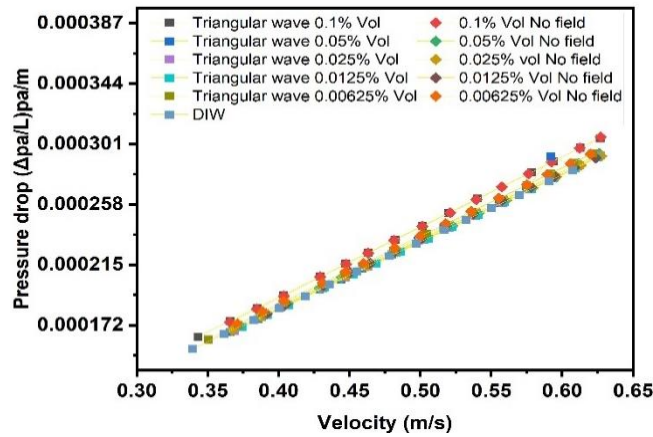
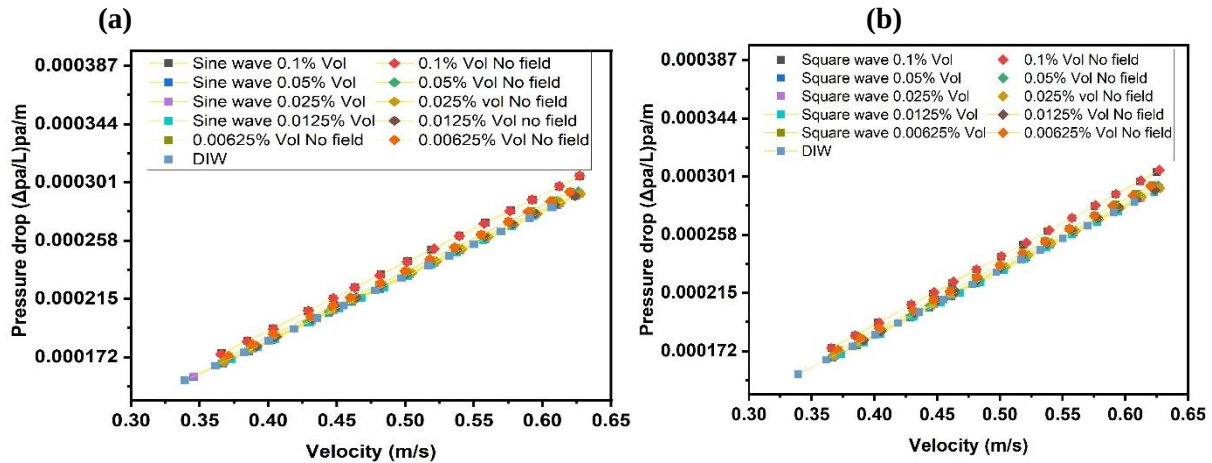


Figure 6. 35 Comparison of pressure drop between DIW and MHNFs with magnetic field at various concentrations with varied velocities case II. (a) sine waves (b) square waves and (c) triangular waves.



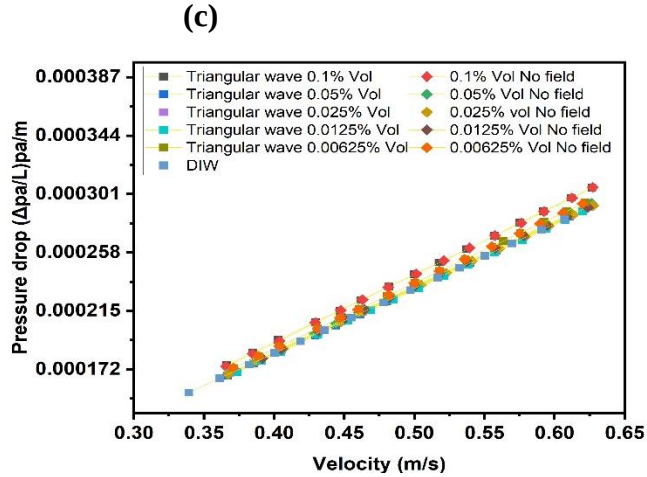
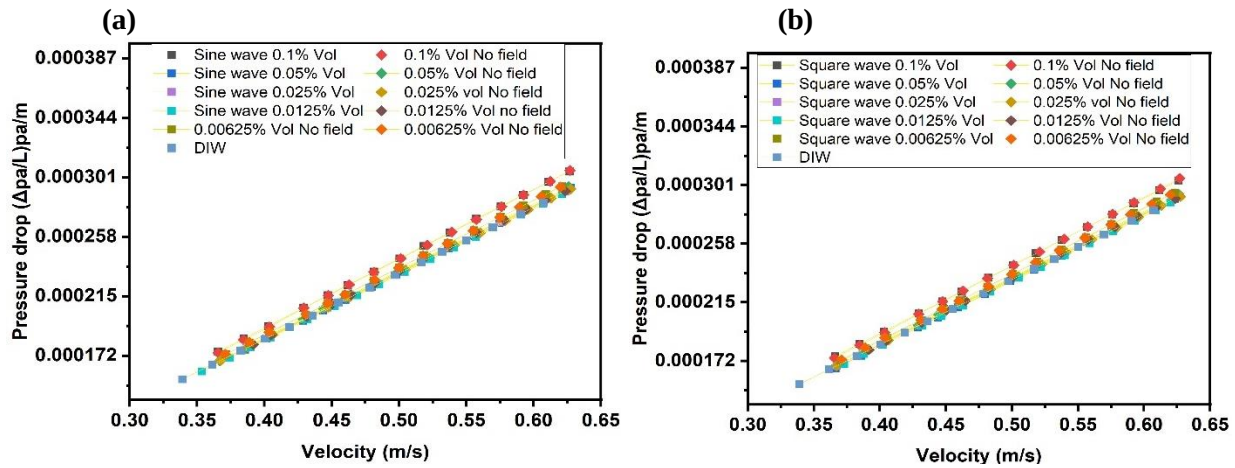


Figure 6. 36 Comparison of pressure drop between DIW and MHNFs with magnetic field at various concentrations with varied velocities case II. (a) sine waves (b) square waves and (c) triangular waves.



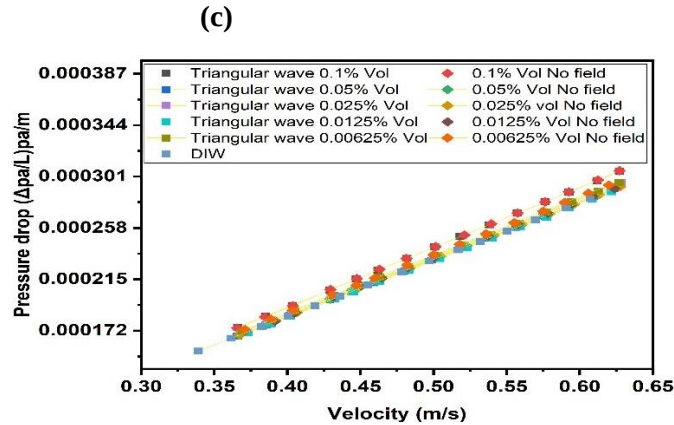


Figure 6. 37 Comparison of pressure drop between DIW and MHNFs with magnetic field at various concentrations with varied velocities case IV. (a) sine waves (b) square waves and (c) triangular waves.

6.5.4 Hypothesis on the differential effects of magnetic waveforms on Δp and a comparative evaluation.

A possible reason for the differing impacts of magnetic waveforms on pressure drop lies in how the waves impact the alignment and behavior of NPs inside the fluid. Sine waves, with their smooth, gradual magnetic variations, may facilitate a more controlled reorientation of nanoparticles, potentially reducing sharp fluctuations in resistance to flow. On the other hand, square waves, characterized by abrupt shifts, could lead to more significant disruptions in nanoparticle arrangement, possibly resulting in either enhanced or obstructed flow, depending on the nanoparticle concentration. Triangular waves, which combine aspects of both sine and square waveforms, might produce moderate effects on pressure drop. The results are in consistent with earlier reports, such as those by Emad et al. [225], who suggested that magnetic fields can both support and hinder fluid flow, influenced by the waveform behaviours. Ashjaee et al. [32]also observed that the turbulence induced by magnetic fields could either improve or decline flow resistance, echoing similar trends in pressure drop in this study. Additionally, Sundar [228]noted the dual effect of magnetic fields on NPs arrangement and fluid flow.

The complex relationship between magnetic field effects, fluid dynamics, and pressure drop underscores the importance of comprehending these interactions, particularly in systems using magnetic hybrid nanofluids for heat transfer. By fine-tuning the application of different magnetic waveforms, it may be possible to optimize Δp control and improv thermal performance in advanced heat transfer systems.

6.5.4 Analysing the influence of MHNFs concentration on thermal performance factor (TPF)

To precisely evaluate the CHT and Nu within a system, it's crucial to determine the thermophysical properties of the nanofluid. These properties, combined with empirical information on frictional losses, enable the calculation of a thermal efficiency parameter for the system. The thermal efficiency parameter (η) is formulated following established protocols [294]

$$\eta = \left(\frac{Nu_{nf}}{Nu_{bf}} \right) \left(\frac{f_{nf}}{f_{bf}} \right)^{\frac{1}{3}} \quad 6.3$$

Figure 6.38 depicts the TPF across different concentrations of magnetic hybrid nanofluids in the absence of a magnetic field. Notably, at volume fractions of 0.00625 wt.% and 0.1 wt.%, the thermal performance factor of Fe_3O_4/TiO_2 nanofluids stands out. Surprisingly, the data reveal that a volume fraction of 0.0125% leads to the most efficient heat transfer performance, contrary to the anticipated trend where higher volume fractions would result in superior thermal performance [41]. This unexpected discovery suggests that even a lower concentration of nanoparticles in the fluid can significantly enhance heat transfer. It indicates that the increased thermal conductivity associated with higher volume fractions does not necessarily translate to a higher thermal performance factor. Furthermore, the trend indicates a decrease in the thermal performance factor ratio with increasing velocity across all volume fractions. This finding holds profound implications for thermal management, underscoring the critical importance of optimizing nanoparticle volume fractions to achieve maximal thermal performance. In practical applications prioritizing heat transfer efficiency, such as in heat exchangers or cooling systems, leveraging this optimal volume fraction can strategically enhance performance and increase energy efficiency. However, attaining this optimal volume fraction requires careful consideration of various factors, including particle agglomeration, viscosity effects, interfacial resistance, thermal conductivity saturation, and nanoparticle distribution. Through meticulous adjustment of nanoparticle volume fractions, engineers and researchers can unlock enhanced thermal performance and optimize thermal management systems for improved efficiency and effectiveness.

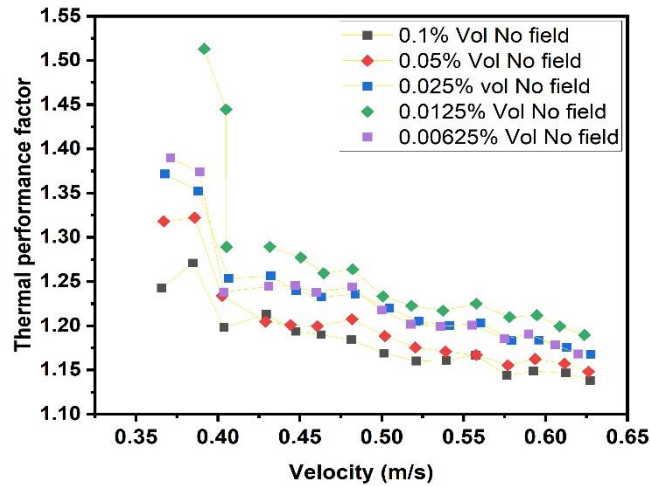


Figure 6. 38 Analysis of TPF variation with velocity across different volume concentrations of MHNFs

6.5.5. Influence of magnetic field positioning and waveforms on TPF in MHNFs

Evaluation of the TPF and its correlation with magnetic field positioning focused on concentrations of 0.00625 wt.% and 0.1 wt.%. Remarkably, the TPF peaked at a concentration of 0.0125%, indicating promising potential for further exploration in optimizing magnetic field positioning and assessing the impact of different waveforms on fluid performance. **Figures 6.39a, b, and c** compared various waveforms for **case II**, **case III**, and **case IV**, respectively. Results highlighted that for **case II** waveform, sine waves outperformed square waves and triangular waves along the flow velocity. Conversely, for **case III**, triangular waves exhibited superior performance compared to sine waves and square waves. Lastly, in **case IV**, square waves showed the highest performance along the flow velocity. These insights underscore the significance of magnetic field positioning and waveform selection in influencing fluid thermal performance factors. Optimizing thermal performance for practical applications hinges on tailored considerations of these factors, reflecting the complex interplay between magnetic field dynamics and fluid behavior in enhancing heat transfer efficiency in magnetic hybrid nanofluids across diverse applications.

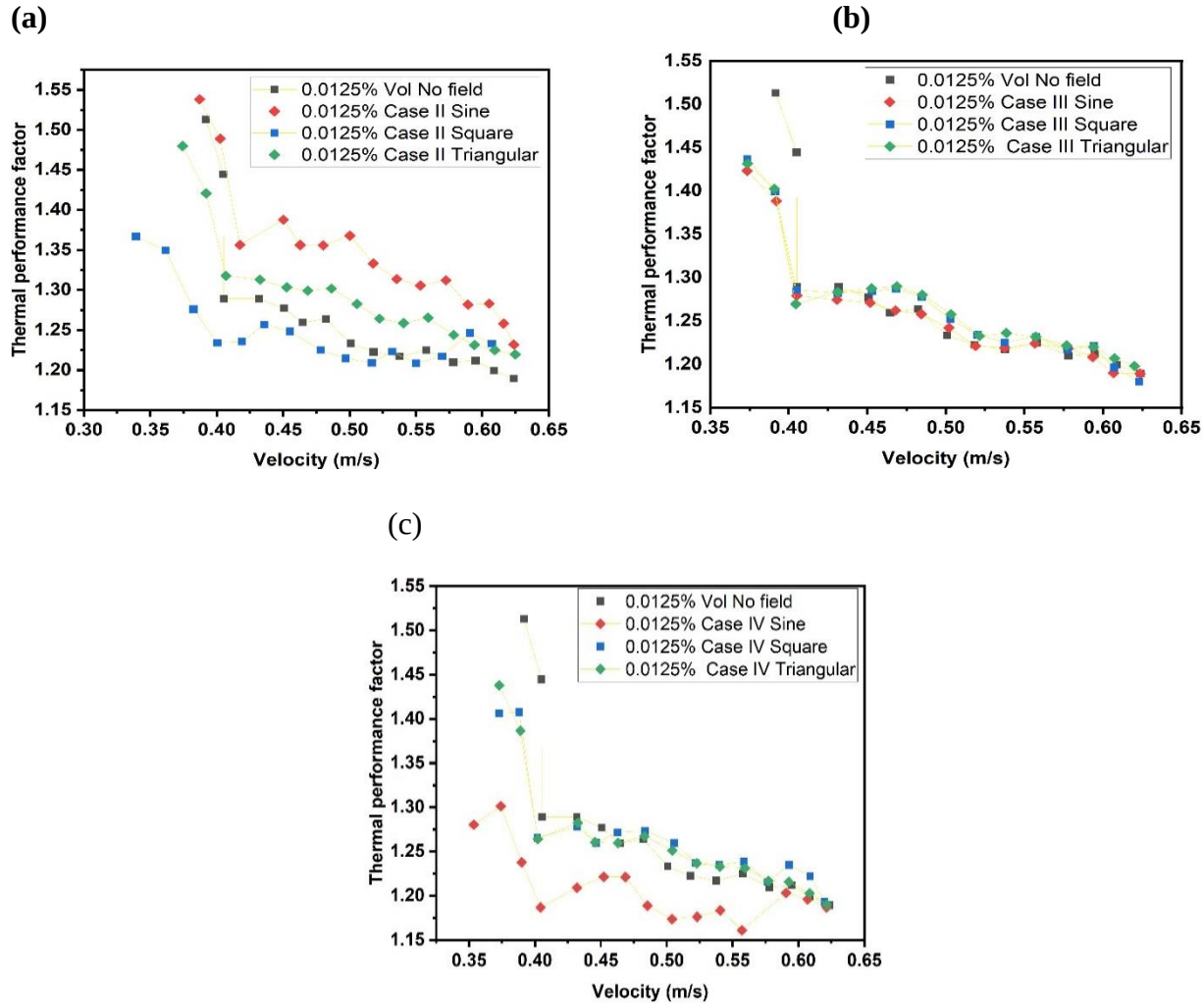


Figure 6. 39 Comparative analysis of TPF with various magnetic field positions and waveforms in MHNFs. (a)Comparing case II waveform (b) Comparing case III waveform and (c) Comparing case IV waveform.

The comparison of TPF for different magnetic hybrid nanofluid cases using sine waveforms at 0.0125% volume fraction (**Figure 6.40a**) reveals that **Case II** demonstrates the highest thermal performance among the tested cases. Across various velocities, Case II consistently exhibits higher thermal performance factors compared to **Cases III** and **IV**. For example, at a velocity of 0.623 m/s, the thermal performance factor for **Case II** ranges from approximately 1.189 to 1.231, while for **Case III** and **Case IV**, the values range from approximately 1.187 to 1.190 and 1.161 to 1.203, respectively. Several factors likely contribute to the superior performance of **Case II** with sine waves. Firstly, **Case II** may have optimized parameters or conditions that enhance convective heat

transfer efficiency. Additionally, the smoother oscillations of sine waveforms may promote better fluid mixing and heat transfer compared to other waveforms like square or triangular waves. Moreover, the arrangement or positioning of the magnetic field in **Case II** might be more conducive to enhancing heat transfer within the nanofluid, potentially leading to improved thermal performance factors. Furthermore, the interaction between the magnetic field and nanoparticles in **Case II** under sine wave conditions could result in more favourable nanoparticle dispersion and alignment, further enhancing convective heat transfer. Overall, the combination of optimized parameters, waveform characteristics, and magnetic field positioning likely contributes to the superior thermal performance observed in **Case II** with sine waves compared to **Cases III** and **IV**. In the comparison using square waveforms at 0.0125% volume fraction (**Figure 6.40b**), **Case IV** demonstrates the highest thermal performance factor among the cases. Analysing the velocities and corresponding thermal performance factor values reveals that **Case IV** with square waves generally exhibits higher values compared to **Cases II** and **III**. This superiority in thermal performance can be attributed to the specific characteristics of the square wave magnetic field, which may induce optimal fluid flow patterns and enhance convective heat transfer within the nanofluid. Additionally, the interaction between the square wave magnetic field and the $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanoparticles may lead to improved dispersion and alignment of nanoparticles, resulting in enhanced thermal conductivity and heat transfer efficiency. In summary, the unique characteristics of the square wave magnetic field likely contribute to the observed superior thermal performance in **Case IV** compared to **Cases II** and **III**.

Lastly, the comparison using triangular waveforms at 0.0125% volume fraction (**Figure 6.40c**) demonstrates that **Case II** exhibits the highest thermal performance factor among the cases. Across various velocities, **Case II** consistently shows higher thermal performance factors compared to **Cases III** and **IV**. The superior thermal performance in **Case II** with triangular waves can be attributed to the specific characteristics of the triangular wave magnetic field, which may induce optimal fluid flow patterns and enhance convective heat transfer within the nanofluid. Additionally, the interaction between the triangular wave magnetic field and the $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanoparticles may lead to improved dispersion and alignment of nanoparticles, resulting in enhanced thermal conductivity and heat transfer efficiency. Overall, the unique characteristics of the triangular wave magnetic field likely contribute to the observed superior thermal performance in **Case II** compared to **Cases III** and **IV**.

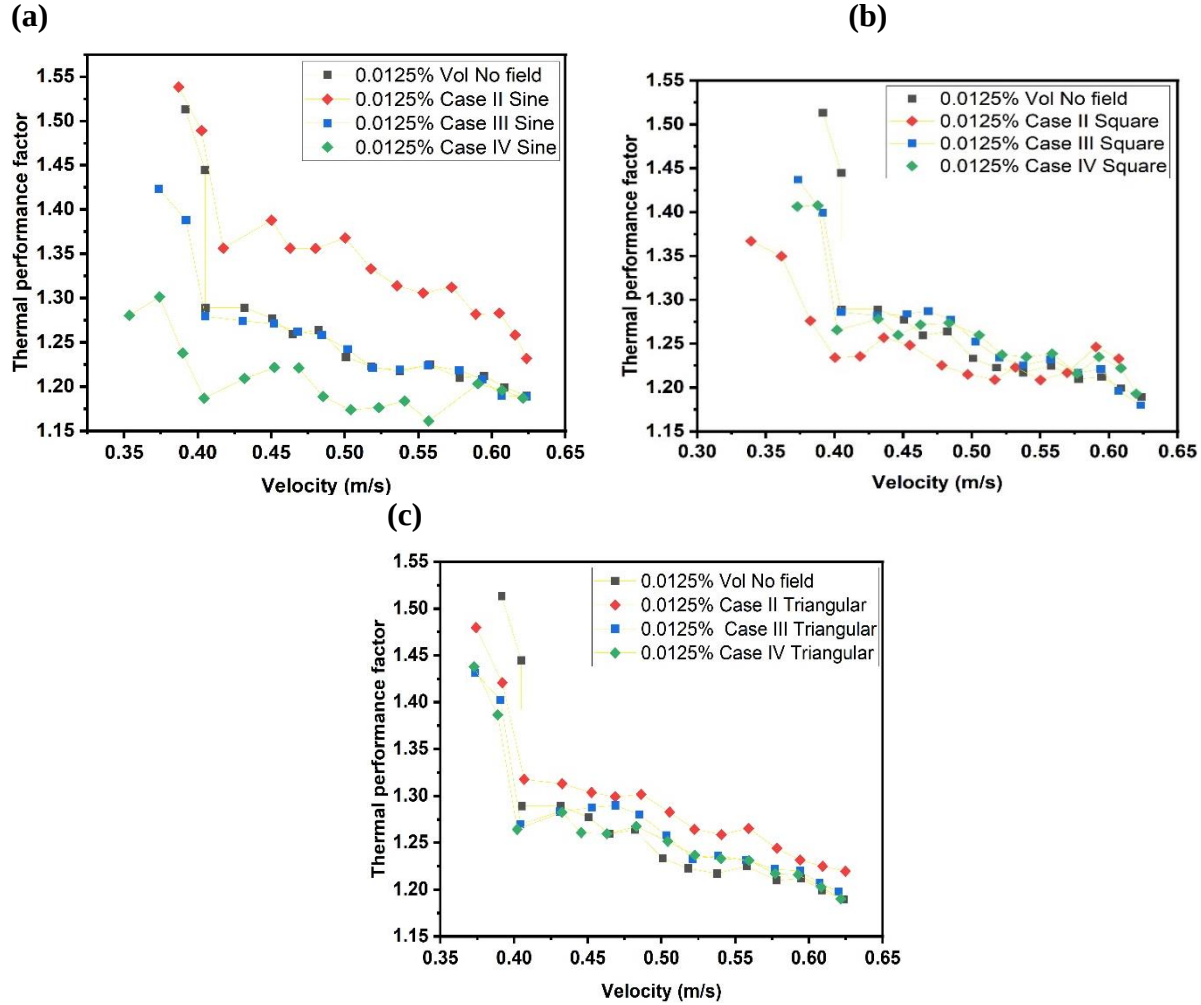


Figure 6. 40 Comparative analysis of TPF with various magnetic field positions and waveforms in MHNFs. (a)Comparing case II waveform (b) Comparing case III waveform and (c) Comparing case IV waveform

6.5.6 Thermal entropy generation assessment in MHNFs impact of nanoparticle concentration and flow velocity

The total entropy generation rate ($\dot{E}_{gen}$) in a cylindrical tube of length L encompasses both the thermal entropy generation rate ($\dot{E}_{gen,Th}$) and the frictional entropy generation rate ($\dot{E}_{gen,fl}$). This combined entropy generation rate is determined by the summation of these two components, as described in the following equations [294].

$$\dot{E}_{gen} = \dot{E}_{gen,Th} + \dot{E}_{gen,fl} \quad 6.4$$

$$\dot{E}_{gen,Th} = \frac{\pi d^2 L q^{-2}}{K_{nf} Nu T_{av}} \quad 6.5$$

$$E_{gen.fl} = \frac{32\dot{m}^2 fl}{\rho_{nf}^2 \pi^2 d^5 T_{av}} \quad 6.6$$

$$T_{avg} = \frac{(T_{in}-T_{out})}{\ln\left(\frac{T_{in}}{T_{out}}\right)} \quad 6.7$$

The analysis presented in **Figures 6.41a** demonstrates the impact of nanoparticle concentration on entropy generation in MHNFs. A decrease in nanoparticle concentration correlates with a reduction in total entropy generation $E_{gen.Th}$. Moreover, as velocity increases, both total and $E_{gen.Th}$ decrease. For instance, at a velocity of 0.431 m/s and a nanoparticle concentration of 0.00125% vol, the $E_{gen.Th}$ is determined to be 27.666. Interestingly, at this velocity, the $E_{gen.Th}$ is lower compared to 0.05% vol and 0.025% vol, which exhibit $E_{gen.Th}$ of 28.3 at a velocity of 0.429 m/s and 27.82 at a velocity of 0.432 m/s, respectively.

The analysis suggests that lower velocities generally result in higher $E_{gen.Th}$ rates across all concentrations. This phenomenon arises due to reduced convective heat transfer rates and slower fluid motion at lower velocities, leading to higher temperature gradients and consequently higher entropy generation within the system. Conversely, higher velocities promote more efficient heat transfer by enhancing fluid mixing and reducing temperature gradients, thereby resulting in lower entropy generation rates. Therefore, optimizing velocity conditions is crucial for minimizing thermal losses and enhancing the efficiency of heat transfer processes involving MHNFs. By controlling velocity parameters, it is possible to enhance heat transfer efficiency and reduce total entropy generation in MHNF systems, ultimately improving their overall performance.

Figure 6.41b illustrates an increase in $E_{gen.fl}$ with higher concentrations of MHNFs nanofluids. Conversely, a decrease in MHNFs concentration corresponds to a decrease in $E_{gen.fl}$ accordingly. For instance, at a velocity of 0.623 m/s, the $E_{gen.fl}$ decreases from approximately 1.69532E-09 for a concentration of 0.1% to 5.51537E-10 for a concentration of 0.00625%. This pattern indicates that lower concentrations of MHNFs lead to improved hydrodynamic efficiency, resulting in lower frictional losses within the heat transfer system. Additionally, the analysis reveals that higher velocities generally result in higher $E_{gen.fl}$ rates across all concentrations, although these values are extremely low and negligible. For instance, at a concentration of 0.0125%, the $E_{gen.fl}$

increases from approximately $1.55641\text{E-}09$ at a velocity of 0.623 m/s to $7.10846\text{E-}10$ at a velocity of 0.391609769 m/s .

These findings highlight the significance of optimizing flow conditions to minimize frictional losses and enhance the efficiency of heat transfer processes involving MHNFs. Furthermore, the results suggest that lower concentrations of MHNFs nanofluids can be effectively utilized as working fluids in thermal energy systems. Since they show negligible effects from increases in fluid viscosity and pressure drop, these observations suggest the possibility of improving forced convective heat transfer while simultaneously reducing entropy generation by lowering the concentration of MHNFs nanoparticles.

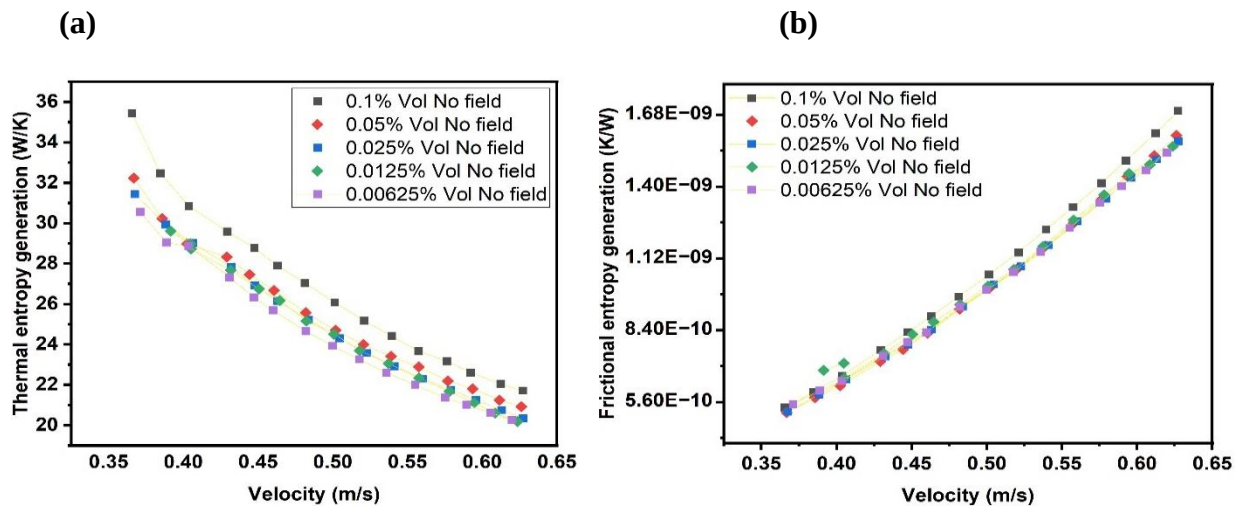


Figure 6. 41 Influence of velocity and concentration on entropy generation rate components in magnetic hybrid nanofluids without external magnetic fields (a) thermal entropy generation and (b) frictional entropy generation components.

6.5.7 Analysing entropy generation in MHNFs heat transfer systems and influence of magnetic field positioning and waveforms.

Figures 6.42a, c, and e present Case II, Case III, and Case IV, respectively, illustrating the positioning of the magnetic field along the test section and its effect on the thermal entropy generation $E_{\text{gen.Th}}$ rate in the magnetic nanofluid. These figures demonstrate that the application of a magnetic field results in a decrease in $E_{\text{gen.Th}}$, with thermal entropy generation decreasing with increasing velocity. Specifically, in Figure 6.42 (a), it is evident that magnetic forces

contribute to enhancing heat transfer, with **Case II** exhibiting the most significant enhancement, particularly with square waves at a fluid velocity of 0.375 m/s. Furthermore, the total entropy generation rate is reduced by up to 4.28% compared to the absence of a magnetic field, with reductions of 2.2% for sine waves and 2.73% for triangular waves. Conversely, **Case III** shows less enhancement in heat transfer compared to other cases, with a total entropy generation rate reduction of up to 1.79% at a fluid velocity of 0.375 m/s. **Case IV** demonstrates enhanced heat transfer with the best performance observed with triangular waves, resulting in a reduction of up to 1.65% at a fluid velocity of 0.375 m/s.

Several factors contribute to the observed improvement in heat transfer following the application of different magnetic waveforms. Specifically, the accumulation of magnetic particles near the inner wall surface enhances thermal conductivity and viscosity, leading to modifications in the thickness of the thermal boundary layer [17]. Additionally, the migration of magnetic particles towards the tube wall due to the influence of the magnetic field further amplifies heat transfer properties[41].

Figure 6.42d, and f depict Case II, Case III, and Case IV, respectively, representing the magnetic field position along the test section. These figures show that the frictional entropy generation rate increases with velocity, albeit with negligible enhancement. Furthermore, the findings suggest that lower concentrations of MHNFs can serve as efficient working fluids in thermal energy systems, demonstrating limited sensitivity to rises in fluid viscosity and pressure drop. These observations imply the potential for improving forced convective heat transfer while simultaneously reducing total entropy generation by decreasing the concentration of MHNFs nanoparticles

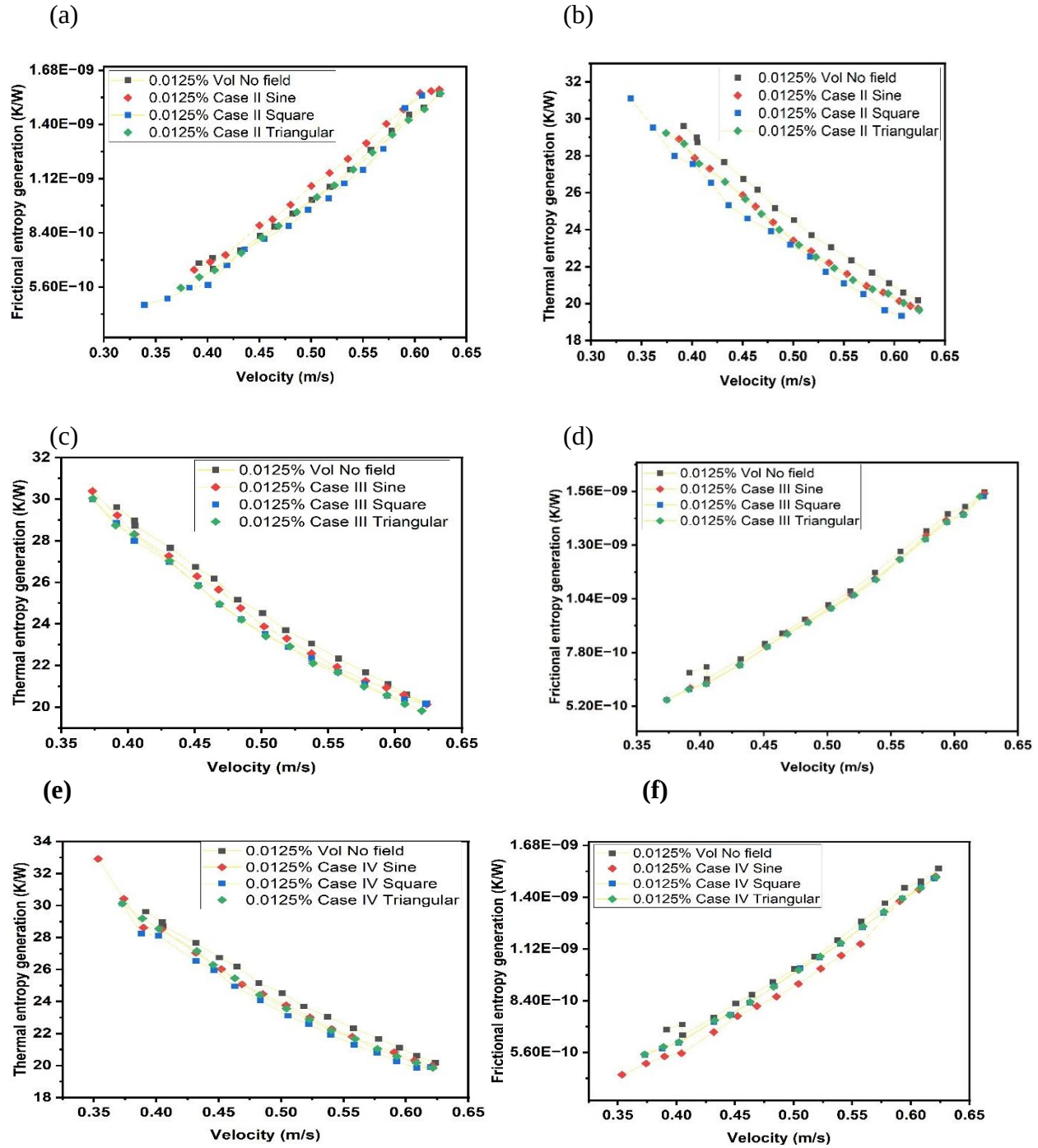


Figure 6. 42 Influence of velocity and concentration on entropy generation in magnetic hybrid nanofluids: comparative analysis of thermal and frictional entropy generation components for different magnetic field cases (a) case II (c) case III and (e) case IV on thermal entropy generation and (b) case II (d) case III and (f) case IV

Figure 6.43. Presents a visual representation of each waveform utilized in this study.

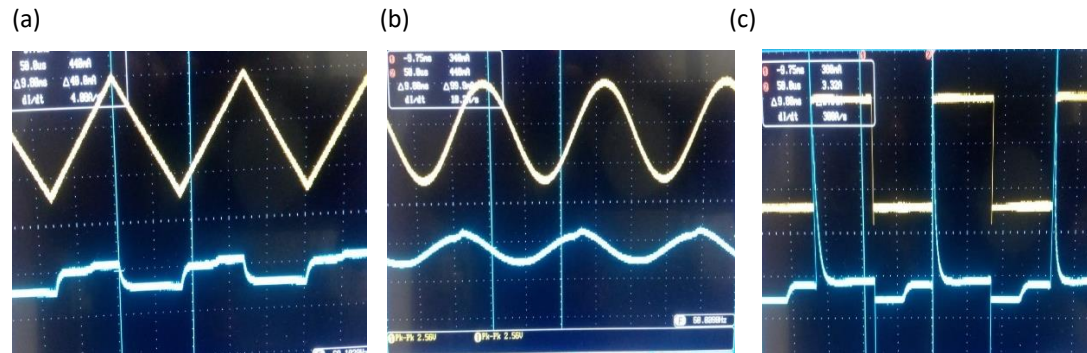


Figure 6.43 The picture of wave type used (a) Triangle wave, (b) Sine wave and (c) Square wave

6.6 Conclusion

This study presents a comprehensive investigation into the heat transfer characteristics, hydraulic resistance, and thermal efficiency of magnetic hybrid nanofluids (MHNFs) under various flow conditions, nanoparticle concentrations, and magnetic field influences.

The first study explored the behavior of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids across Reynolds numbers and volume fractions, revealing optimal heat transfer enhancements at lower nanoparticle concentrations, particularly at 0.0125% vol attains the highest CHT, with an impressive enhancement of approximately 26.33%

The second part of the study delved into the influence of $\text{Fe}_3\text{O}_4/\text{MgO}$ MHNFs on heat transfer characteristics across laminar, transition, and turbulent flow regimes. Interestingly, the transition regime for MHNFs was found to occur at higher Re juxtaposed to DIW, which contradicted prior research findings. This discrepancy could be attributed to the distinct properties of MHNFs, including changes in viscosity, thermal conductivity, and density due to nanoparticle dispersion. Additionally, variations in nanoparticle dispersion, size, shape, and concentration might affect flow dynamics and transition behavior. Heat exchange comparisons between the transition and turbulent flow regimes revealed superior heat transfer performance in the transition regime. For MHNFs, the average heat transfer enhancements were 30.2% at 0.00625 vol%, 31.6% at 0.0125 vol%, 25.6% at 0.025 vol%, 17.9% at 0.05 vol%, 25.7% at 0.1 vol%, 25.8% at 0.2 vol%, and 26% at 0.3 vol%. Additionally, an increase in pressure drop was noted with higher MHNF volume fractions, highlighting the intricate relationship between nanofluid characteristics and flow behavior. Overall, the findings suggest that MHNFs offer significant improvements in thermal

efficiency, attributed to factors such as Brownian motion of nanoparticles, enhanced fluid mixing, and suppression of turbulence.

The third study investigated the thermal and hydraulic characteristics of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids under the impact of magnetic field intensity across different waveforms. Optimization of NPs volumetric ratio and magnetic field was found crucial for achieving desired thermal and hydraulic performance. Magnetic field application reduced thermal entropy generation rate and enhanced thermal performance factors, with differences observed across waveform types and magnetic field positioning.

Lastly, utilizing magnetic fields to control flow in MHNFs emerged as a promising strategy for improving heat exchange within thermal systems. Comparative analysis demonstrated significant enhancements in convective heat transfer coefficients, with square waveforms consistently outperforming sine and triangular waveforms. Lower concentrations of MHNFs showed promise as efficient working fluids in thermal energy systems.

In conclusion, the studies collectively emphasize the complex interplay between nanoparticle properties, flow dynamics, and external stimuli in determining heat exchange efficiency and hydraulic performance in MHNF systems. The findings provide valuable insights for maximizing thermal processes impact by magnetic fields, nanoparticle concentrations, and flow conditions, with implications for various practical applications requiring enhanced heat transfer and thermal management.

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

7.1 Overview

This study extensively investigates the heat transfer performance of MHNFs, particularly focusing on transitional and turbulent flow regimes with hybrid nanofluids due to limited literature in this area. Additionally, it explores the TC, viscosity, and thermal expansion coefficient (TEC) of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ -DIW, $\text{Fe}_3\text{O}_4/\text{MgO}$ -DIW, and $\text{Fe}_3\text{O}_4/\text{ZnO}$ -DIW MHNFs, analysing the influence of temperature, hybridization mixing ratio (HMR), and nanoparticle type on their thermophysical properties. Notably, MHNFs with an HMR of 80:20 consistently demonstrate superior stability and thermal conductivity, especially when incorporating TiO_2 , MgO , and ZnO nanoparticles. Key findings include the temperature-dependent behavior of thermal and electrical conductivity, with $\text{Fe}_3\text{O}_4/\text{ZnO}$ -DIW MHNFs exhibiting superior thermal conductivity. The study highlights the significant impact of temperature, HMR, and nanoparticle characteristics on MHNF stability and thermophysical properties, offering implications for industrial and energy system applications.

Furthermore, an experimental investigation aims to optimize heat transfer in MHNFs through electromagnetic field application. Parameters influencing the magnetic field are examined, including strength, direction, and strategies for aligning it with fluid flow. Various magnetic field waveforms, such as sine, triangular, and square waves, are explored for their effects on nanoparticle alignment and heat transfer properties, considering optimum waveform frequency and voltage for energy-efficient heat transfer enhancement in MHNFs under magnetic field influence. Additionally, the study investigates the optimal volume fraction of MHNFs across a range of concentrations, from 0.00625% to 0.3%vol for $\text{Fe}_3\text{O}_4/\text{MgO}$ -DIW and $\text{Fe}_3\text{O}_4/\text{TiO}_2$ -DIW to determine the most effective concentration for heat transfer applications in transition and turbulent flow regimes respectively.

7.2 Conclusion

7.2.1 Conclusions on MHNFs $\text{Fe}_3\text{O}_4/\text{TiO}_2$ -DIW

This research examines the performance of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluids in terms of heat exchange and hydraulic resistance over a Reynolds number range of 3200 to 5300, with volumetric ratio varying from 0.3vol%-0.00625vol%. The following key findings were observed:

- The convective CHT shows a marked trend, with higher percentage improvements observed at lower volume fractions. A notable increase of about 26.33% is seen at a volumetric ratio of 0.0125vol%, highlighting its effectiveness in enhancing heat transfer.
- At a Reynolds number of 5200, the $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluid consistently demonstrates positive percentage improvements at different points along the tube (x/d) for volumetric ratio of 0.3vol%-0.00625vol%. The maximum enhancements, around 46.24vol% and 45.07vol%, are typically found at x/d 96.25 for 0.00625vol% and 0.0125vol%, respectively, while the lowest improvements, approximately 6.24%, occur at x/d 80 for 0.3vol%.
- The greatest pressure drop, about 21%, occurs at a Re of 5018 for a volumetric ratio of 0.3vol%, representing the highest pressure loss under these conditions. A reduction in volumetric ratio generally results in a lower pressure drop, with values ranging from approximately 13.10% to 10.29% for concentrations from 0.2vol% to 0.00625vol%. This suggests a potential trade-off between nanoparticle concentration and pressure loss.
- Higher volumetric ratio of solid particles in the nanofluids (0.3vol% , 0.2vol% , 0.1vol% , and 0.05vol%) negatively impact thermal efficiency. The increased solid content disrupts fluid flow, leading to higher resistance to heat transfer and, consequently, a decrease in thermal efficiency.

7.2.2 Conclusions on MHNFs $\text{Fe}_3\text{O}_4/\text{TiO}_2$ -DIW with impact of electromagnetic waves form

- The introduction of magnetic field waveforms waves consistently enhances heat transfer across various volume fractions (0.1%, 0.05%, 0.025%, 0.0125%, and 0.00625%). At 0.0125% volume fraction, significantly higher heat enhancement values are observed for all three waveforms compared to with no magnetic field, indicating the responsiveness of the waves volumetric ratio. Specifically, the heat enhancement values for Sine wave, Square wave, and Triangular wave at 0.0125% volume fraction are 27.87%, 28.21%, and 26.74%, respectively.

- Frequency variations from 40Hz to 1000Hz result in a direct increase in total magnetic field strength across Sine, Square, and Triangular wave configurations. While sine waves consistently generate stronger magnetic fields juxtaposed to square and triangular waves, with convergence points observed at approximately 6.0 and 17.11 Tesla at 40 Hz and 60 Hz, respectively, this does not necessarily translate into greater heat transfer enhancement. The square wave, despite generating a weaker magnetic field, results in more significant heat transfer improvements. This highlights that the magnetic field strength alone does not solely determine heat exchange efficiency, and the specific characteristics of the waveform, such as its frequency and shape, play a crucial role in enhancing the performance of magnetic hybrid nanofluids. This result carries significant importance for fine-tuning magnetic field parameters, especially in analysing how variations in magnetic field strength influence improvements in heat transfer.
- Optimization of magnetic field frequency occurs at 60Hz for different waveforms, exhibiting favourable heat transfer properties juxtaposed to other frequencies across various Reynolds numbers. This indicates enhanced thermal performance, particularly notable at 4V for all waveform configurations.
- Additionally, at 0.0125% volume fraction, notably higher heat enhancement values are consistently observed across all three waveforms compared to with no magnetic field, emphasizing the important of the impact of magnetic field on fluid flow dynamics and heat transfer efficiency across different volume fractions.

7.2.3 Examining the influence of magnetic waveform positioning in turbulent regime on heat transfer, entropy generation, and thermal performance of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ magnetic hybrid nanofluids.

The examination of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluid involved varying magnetic field positions along the test section: Case I denoted the absence of a magnetic field, whereas Case II, Case III, and Case IV represented different magnetic positions and pulsating parameters, affect heat exchange, entropy generation, and thermal performance of $\text{Fe}_3\text{O}_4/\text{TiO}_2$ under turbulent conditions. Experiments were conducted with different waveform configurations, yielding the following deductions.

- Findings indicate that higher volumetric ratio lead to increased Δp , reducing thermal efficiency, while lower volumetric ratio improve thermal performance.

- Application of magnetic fields decreases thermal entropy generation rate and enhances thermal performance factors.
- Frictional entropy generation rises with velocity but has minimal impact.
- Analysis reveals that CHT coefficient enhancement varies significantly across volume fractions, waveforms, and magnetic field positioning cases.
- Increasing volume fraction decreases CHT coefficient augmentation, with better performance at lower fractions.
- At higher fractions (0.1% Vol), heat transfer enhancement decreases across all waveform types compared to no field.
- Square Wave cases consistently outperform Sine and Triangular Wave cases, with Square Wave **Case II** exhibiting the highest enhancement percentages, such as 28.21% at 0.0125 Vol.
- **Case IV** generally shows lower enhancement, possibly due to magnetic field positioning.
- Conversely, $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluid without a magnetic field (**Case III**) shows more enhancement from 0.1 Vol to 0.0125 Vol, except for at 0.00625 Vol, where Square Waves demonstrate the highest enhancement at 25.28%.

7.2.4 Heat exchange and thermal performance, Δp , and magnetic hybrid nanofluids $\text{Fe}_3\text{O}_4\text{-MgO}$ in transitional flow region

This research examines the heat transfer characteristics of $\text{Fe}_3\text{O}_4/\text{MgO}/\text{DIW}$ MHNFs in comparison to deionized water across laminar, transition, and turbulent flow region.

- Contrary to previous findings, the transition of magnetic hybrid nanofluids occurs at notably higher Re compared to deionized water, potentially due to altered viscosity, thermal conductivity, and density caused by nanoparticle dispersion, along with variations in nanoparticle characteristics.
- Comparing heat exchange enhancements between turbulent and transition flow region reveals more pronounced improvements in the transition regime.
- Across different MHNF concentrations, average heat transfer enhancements range from 17.9% to 31.6%, with optimum enhancement observed at volumetric ratio of 0.0125 vol% and 0.00625 vol%.

- Higher volumetric ratio of MHNFs result in increased Δp , highlighting a intricate interaction between fluid dynamics and MHNFs characteristic.
- The results underscore significant improvements in thermal performance across transition and laminar flow region, attributed to factors such as Brownian motion of nanoparticles, enhanced fluid mixing, and turbulence suppression.

7.3 Recommendations

- Optimizing Nanoparticle Concentration: Further investigation into the optimal volumetric ratio for MHNFs to achieve highest heat exchange enhancement while reducing Δp .
- Understanding Transition Regime Behavior: Deeper exploration into the transition regime behavior of MHNFs, including the factors influencing the transition onset and its impact on heat transfer characteristics.
- Characterization of Nanoparticle Properties: Detailed analysis of the properties of NPs, such as size, shape, and dispersion, to understand their influence on flow dynamics and heat transfer performance.
- Enhancing Nanoparticle Dispersion: Developing methods to improve the dispersion of nanoparticles within the fluid to ensure uniformity and maximize their effectiveness in enhancing heat transfer.
- Practical Applications: Exploring practical applications of MHNFs in thermal energy systems, considering their potential benefits in terms of improved heat transfer efficiency and thermal management.
- Experimental Validation: Conducting additional experimental validation to confirm the observed trends and behaviours of MHNFs under various flow conditions and magnetic field influences.
- Modelling and Simulation Studies: Utilizing computational modelling and simulation techniques to complement experimental findings and gain insights into the underlying mechanisms governing heat transfer in MHNFs.
- Scale-Up and Industrial Applications: Investigating the scalability of MHNF production processes and assessing their feasibility for industrial-scale applications, considering factors such as cost-effectiveness and scalability.

- **Environmental Impact Assessment:** Conducting an assessment of the environmental impact of using MHNFs, including their potential toxicity and ecological implications, to ensure their safe and sustainable use in various applications.

7.4 Challenges

The challenges associated with the use of Magnetic Hybrid Nanofluids (MHNFs) for heat transfer applications:

- **Nanoparticle Dispersion:** Achieving homogeneous dispersion of nanoparticles poses a significant hurdle, given their tendency to aggregate and potentially cause equipment blockages.
- **Viscosity Increase:** Incorporating nanoparticles can elevate fluid viscosity, necessitating higher energy inputs for pumping and potentially impacting system efficiency.
- **Pressure Drop:** Higher nanoparticle concentrations may result in increased fluid resistance, demanding system modifications to mitigate pressure drop effects.

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Appendix A

Error assessment and uncertainty analysis in experimental measurements

A.1 Introduction

In any experimental endeavor, the analysis of uncertainty and errors is indispensable. This study undertakes the calculation of uncertainty in pressure drop and heat transfer parameters to assess the reliability of the measurements, forming the foundation of the present investigation. The error associated with each measured value (x) encompasses two components: (i) bias error, a constant attributed to sensor calibration or initial fixed operating conditions, and (ii) random error, induced by sensor sensitivity and commonly referred to as accuracy. The uncertainty in the measurement of a variable represents the disparity between the true value of that variable and the mean measured value of the same variable.

A.2 Background

compute the uncertainties u_x associated with both the measured and evaluated parameters. These uncertainties were assessed at a 95% confidence level as shown in Equation.

$$u_x = \sqrt{u_B^2 + U_P^2}, P\% \quad (A.2)$$

where u_B represents bias error and u_p represents precision error in x with a probability of $P\%$. The calculation of parameter uncertainty based on measured variables can be accomplished using a series of equations as outlined below.

$$R(x) = f(x_1, x_2, \dots, x_n),$$

For a given variable x_i , the uncertainty in the parameter R , with respect to both its mean value $\bar{R}$ and its true (actual) value R_{actual} , can be expressed as follows.,

$$R_{actual} = \bar{R} + \delta R$$

where δR is the uncertainty in R can be expressed as follows,

$$\delta R = \sqrt{\left(\delta_{x1} \frac{\partial R}{\partial x_1}\right)^2 + \left(\delta_{x2} \frac{\partial R}{\partial x_2}\right)^2 + \dots + \left(\delta_{x_n} \frac{\partial R}{\partial x_n}\right)^2} \quad (A.3)$$

Where δ_{x_i} represent the uncertainty of the evaluated variable x_i

The measured temperature data using the established relationship between heat transfer rate, temperature gradient, and surface area. Typically, it is determined by applying the equation:

$$h_x = \frac{\dot{q}_s}{T_{s(x)} - T_{m(x)}} \quad (A.4)$$

with its uncertainty is determined by

$$\begin{aligned} \partial h(x) &= \sqrt{\left(\frac{\partial h(x)}{\partial \dot{q}} \delta \dot{q}\right)^2 + \left(\frac{\partial h(x)}{\partial T_s} \delta T_s\right)^2 + \left(\frac{\partial h(x)}{\partial T_m} \delta T_m\right)^2} \\ \delta h(x) &= \sqrt{\left(\frac{\partial \dot{q}}{T_{(wi)} - T_m}\right)^2 + \left(\frac{-\dot{q}}{(T_{(wi)} - T_m)^2} \delta T_{(wi)}\right)^2 + \left(\frac{-\dot{q}}{(T_{(wi)} - T_m)^2} \delta T_m\right)^2} \\ \frac{\delta h(x)}{h(x)} &= \sqrt{\left(\frac{\partial \dot{q}}{\dot{q}}\right)^2 + \left(\frac{\partial T_{(wi)}}{T_{(wi)} - T_m}\right)^2 + \left(\frac{\partial T_m}{T_{(wi)} - T_m}\right)^2} \end{aligned} \quad (A.5)$$

For the average heat transfer

$$\begin{aligned} h_{avg} &= \frac{h_{(x1)} + \dots \dots \dots h_{(xn)}}{n} \\ \delta_{h_{avg}} &= \sqrt{\left(\frac{\partial h_{avg}}{\partial h_{(x_1)}}\right)^2 \delta h_{(x_1)} \dots \dots + \left(\frac{\partial h_{avg}}{\partial h_{(x_n)}}\right)^2 \delta h_{(x_n)}} \\ \frac{\partial h_{avg}}{h_{avg}} &= \sqrt{\frac{1}{n} \left(\left(\frac{\partial h_{(x_1)}}{h_{(x_1)}}\right)^2 + \left(\frac{\partial h_{(x_2)}}{h_{(x_2)}}\right)^2 + \dots + \left(\frac{\partial h_{(x_n)}}{h_{(x_n)}}\right)^2 \right)} \end{aligned} \quad (A.6)$$

Fluid means temperature

$$T_m(x) = T_i + \frac{q \cdot \dot{x} \cdot p}{\dot{m} C_p}$$

$$\delta T_m(x) = \sqrt{\left(\frac{\partial T_m(x)}{\partial T_i} \delta T_i\right)^2 + \left(\frac{\partial T_m(x)}{\partial \dot{q}} \delta \dot{q}\right)^2 + \left(\frac{\partial T_m(x)}{\partial x} \delta x\right)^2 + \left(\frac{\partial T_m(x)}{\partial p} \delta p\right)^2 + \left(\frac{\partial T_m(x)}{\partial \dot{m}} \delta \dot{m}\right)^2 + \left(\frac{\partial T_m(x)}{\partial C_p} \delta C_p\right)^2}$$

$$\delta T_m(x)$$

$$= \sqrt{(\delta T_i)^2 + \left(\frac{x \cdot p}{\dot{m} C_p} \delta \dot{q}\right)^2 + \left(\frac{\dot{q} \cdot p}{\dot{m} C_p} \delta x\right)^2 + \left(\frac{\dot{q} \cdot x}{\dot{m} C_p} \delta p\right)^2 + \left(\frac{\dot{q} x p}{\dot{m}^2 C_p} \delta \dot{m}\right)^2 + \left(\frac{\dot{q} x p}{\dot{m} C_p^2} \delta C_p\right)^2}$$

$$\frac{\delta T_m(x)}{T_m(x)}$$

$$= \sqrt{\left(\frac{\dot{m} C_p}{\dot{m} C_p T_i + \dot{q} x p} \cdot \delta T_i\right)^2 + \left(\frac{x \cdot p}{\dot{m} C_p T_i + \dot{q} x p} \cdot \delta \dot{q}\right)^2 + \left(\frac{\dot{q} \cdot p}{\dot{m} C_p T_i + \dot{q} x p} \cdot \delta x\right)^2 + \left(\frac{\dot{q} \cdot x}{\dot{m} C_p T_i + \dot{q} x p} \cdot \delta p\right)^2 + \left(\frac{\dot{q} x p}{\dot{m} C_p T_i + \dot{q} x p} \cdot \frac{\delta \dot{m}}{\dot{m}}\right)^2 + \left(\frac{\dot{q} x p}{\dot{m} C_p T_i + \dot{q} x p} \cdot \frac{\delta C_p}{C_p}\right)^2} \quad (A.7)$$

Heat flux

$$\dot{q} = \frac{Q_w}{A_s}$$

$$\delta \dot{q} = \sqrt{\left(\frac{\partial \dot{q}}{\partial Q_w} \delta Q_w\right)^2 + \left(\frac{\partial \dot{q}}{\partial A_s} \delta A_s\right)^2}$$

$$\delta \dot{q} = \sqrt{\left(\frac{1}{A_s} \delta Q_w\right)^2 + \left(\frac{Q_w}{A_s^2} \delta A_s\right)^2}$$

$$\frac{\delta \dot{q}}{\dot{q}} = \sqrt{\left(\frac{\partial Q_w}{Q_w}\right)^2 + \left(\frac{\partial A_s}{A_s}\right)^2} \quad (A.8)$$

Heat transfer input to the test section

$$\dot{Q} = V \cdot I$$

$$\delta \dot{Q} = \sqrt{\left(\frac{\partial \dot{Q}}{\partial V} \delta V\right)^2 + \left(\frac{\partial \dot{Q}}{\partial I} \delta I\right)^2}$$

$$\delta \dot{Q} = \sqrt{(I \cdot \delta V)^2 + (V \cdot \delta I)^2 +} \quad (A.9)$$

Perimeter of test section

$$P = \pi \cdot D$$

$$\partial P = \sqrt{\left(\frac{\delta P}{\delta D} \cdot \delta D\right)^2}$$

$$\partial P = \pi \cdot \delta D \quad (A.10)$$

Heat transfer area

$$A_s = \pi \cdot D \cdot L$$

$$\delta A_s = \sqrt{\left(\frac{\partial A_s}{\partial D} \cdot \delta D\right)^2 + \left(\frac{\partial A_s}{\partial L} \cdot \delta L\right)^2}$$

$$\delta A_s = \sqrt{(\pi \cdot L \cdot \delta D)^2 + (\pi \cdot D \cdot \delta L)^2} \quad (A.11)$$

Reynolds number

$$Re = \frac{\rho V D_h}{\mu}$$

$$\delta Re = \sqrt{\left(\frac{\partial Re}{\partial \rho} \cdot \delta \rho\right)^2 + \left(\frac{\partial Re}{\partial V} \cdot \delta V\right)^2 + \left(\frac{\partial Re}{\partial D_h} \cdot \delta D_h\right)^2 + \left(\frac{\partial Re}{\partial \mu} \cdot \delta \mu\right)^2}$$

$$\delta Re = \sqrt{\left(\frac{V D_h}{\mu} \cdot \delta \rho\right)^2 + \left(\frac{\rho D_h}{\mu} \cdot \delta V\right)^2 + \left(\frac{\rho V}{\mu} \cdot \delta D_h\right)^2 + \left(-\frac{\rho V D_h}{\mu^2} \cdot \delta \mu\right)^2}$$

$$\frac{\delta Re}{Re} = \sqrt{\left(\frac{\partial \rho}{\rho}\right)^2 + \left(\frac{\partial V}{V}\right)^2 + \left(\frac{\partial D_h}{D_h}\right)^2 + \left(\frac{\partial \mu}{\mu}\right)^2} \quad (A.12)$$

Friction coefficient

$$f = \frac{2\Delta P D_h}{\rho L V^2}$$

$$\delta f = \sqrt{\left(\frac{\partial f}{\partial \Delta p} \cdot \delta \Delta p\right)^2 + \left(\frac{\partial f}{\partial D_h} \cdot \delta D_h\right)^2 + \left(\frac{\partial f}{\partial \rho} \cdot \delta \rho\right)^2 + \left(\frac{\partial f}{\partial L} \cdot \delta L\right)^2 + \left(\frac{\partial f}{\partial V} \cdot \delta V\right)^2}$$

$$\delta f = \sqrt{\left(\frac{2D_h}{\rho L V^2} \cdot \delta \Delta p\right)^2 + \left(\frac{2\Delta p}{\rho L V^2} \cdot \delta D_h\right)^2 + \left(\frac{-2\Delta p D_h L V^2}{(\rho L V^2)^2} \cdot \delta \rho\right)^2 + \left(\frac{-2\Delta p D_h \rho V^2}{(\rho L V^2)^2} \cdot \delta L\right)^2 + \left(\frac{-4\Delta p D_h \rho L V}{(\rho L V^2)^2} \cdot \delta V\right)^2}$$

$$\frac{\delta f}{f} = \sqrt{\left(\frac{\partial \Delta p}{\Delta p}\right)^2 + \left(\frac{\partial D_h}{D_h}\right)^2 + \left(\frac{\partial \rho}{\rho}\right)^2 + \left(\frac{\partial L}{L}\right)^2 + \left(\frac{2\partial V}{V}\right)^2} \quad (A.13)$$

Nusselt number

$$Nu = \frac{h_{avg} D_h}{k}$$

$$\delta Nu = \sqrt{\left(\frac{\partial Nu}{\partial h_{avg}} \cdot \delta h_{avg}\right)^2 + \left(\frac{\partial Nu}{\partial D_h} \cdot \delta D_h\right)^2 + \left(\frac{\partial Nu}{\partial k} \cdot \delta k\right)^2}$$

$$\delta Nu = \sqrt{\left(\frac{D_h}{k} \cdot \delta h_{avg}\right)^2 + \left(\frac{h_{avg}}{k} \cdot \delta D_h\right)^2 + \left(\frac{-h_{avg} \cdot D_h}{k^2} \cdot \delta k\right)^2}$$

$$\frac{\delta Nu}{Nu} = \sqrt{\left(\frac{\partial h_{avg}}{h_{avg}}\right)^2 + \left(\frac{\partial D_h}{D_h}\right)^2 + \left(\frac{\partial k}{k}\right)^2} \quad (A.14)$$

Prandtl number

$$Pr = \frac{\mu c_p}{k}$$

$$\delta pr = \sqrt{\left(\frac{\partial pr}{\partial \mu} \cdot \delta \mu\right)^2 + \left(\frac{\partial pr}{\partial c_p} \cdot \delta c_p\right)^2 + \left(\frac{\partial pr}{\partial k} \cdot \delta k\right)^2}$$

$$\delta pr = \sqrt{\left(\frac{c_p}{k} \cdot \delta \mu\right)^2 + \left(\frac{\mu}{k} \cdot \delta c_p\right)^2 + \left(\frac{-\mu c_p}{k^2} \cdot \delta k\right)^2}$$

$$\frac{\delta pr}{pr} = \sqrt{\left(\frac{\partial \mu}{\mu}\right)^2 + \left(\frac{\partial c_p}{c_p}\right)^2 + \left(\frac{\partial k}{k}\right)^2} \quad (A.16)$$

A.3 Uncertainty results

Table A.1: instruments used for the study uncertainty

Instrument	Rang	Uncertainty
Power supply Current Voltage	0–12.5 A	0.04A
	0–320 V	0.33V
Thermocouples	-200–350 °C	0.1 °C
Flow meter	0–252 L/h	0.1%
Pressure transducer	0–17 kPa	0.21%

Table A.2: Uncertainty of DI water properties

Instrument	Uncertainty
Thermal conductivity	2%
Density	0.1
Viscosity	1%
Specific heat	0.1%

Table A.3: Heat transfer and pressure for DIW for low Reynolds number and High Reynolds number.

Properties	Re	ΔP	f	h	Nu	Bulk temperature	$\dot{q}$	$\dot{m}$
High Re	2.145%	1.15%	18%	2.49%	3.69%	0.727	3.49%	0.20%
Low Re	1.09%	0.3%	2.0%	1.35%	2.45%	0.437	3.49%	1.97%

APPENDIX B

Heat transfer characteristics of the working fluids

Popiel and Wojtkowiak polynomial equation was used to determine the properties of the water.

B.1 Properties of water

B.1.1 Saturated liquid water density

$$\rho = a + bT + cT^2 + dT^{2.5}eT^3 \quad (B.1)$$

Where

$a = 999.79684$, $b = 0.068317355$, $c = -0.010740248$, $d = 0.00082140905$ and $e = -2.3030988 \times 10^{-5}$. The Equation uncertainty is estimated C.1 is $\pm 0.004\%$.

B.1.2 Specific heat of water at constant pressure

$$\rho = a + bT + cT^{1.5} + dT^2eT^{2.5} \quad (B.2)$$

$a = 4.2174356$, $b = -0.0056181625$, $c = 0.0012992528$, $d = -0.00011535353$ and $e = 4.14964 \times 10^{-6}$. The Equation uncertainty is estimated C.2 is $\pm 0.04\%$.

B.1.3 Thermal conductivity of water

$$k = a + bT + cT^{1.5} + dT^2eT^{0.5} \quad (B.3)$$

Where

$a = 0.5650285$, $b = 0.0026363895$, $c = -0.00012516934$, $d = -1.5154918 \times 10^{-6}$. and $e = -0.0009412945$. The Equation uncertainty is estimated C.3 is $\pm 2\%$.

B.1.4 Dynamic viscosity of water

$$\mu = \frac{1}{a + bT + cT^2 + dT^3} \quad (B.4)$$

Where

$a = 557.82468$, $b = 19.408782$, $c = 0.1360459$, $d = -3.1160832 \times 10^{-4}$. The Equation uncertainty is estimated C.4 is $\pm 1\%$.

B2 Nanofluid properties

In this segment, the provided correlations are sourced from existing literature. The density and specific heat relationships are universally applicable to any nanofluid type, while the determination of thermal conductivity and viscosity requires experimental assessment and is contingent on the specific nanofluid type. The viscosity of the nanofluids subjected to testing underwent direct measurement, whereas the density and specific heat were computed utilizing the mixture theory,

which remains valid for any amalgamation of two or more fluids. The anticipation of thermal conductivity relies on utilizing correlations from existing literature tailored to analogous nanofluid types and concentrations.

B.2.1 Density of the Nanofluids

The density of the nanofluids are determined from the equation used in the literature.

$$\rho_{MHNFs} = \varphi \times \rho_p + (1 - \varphi) \cdot \rho_{bf} \quad (B.5)$$

B.2.3 Specific heat of the nanofluid

The specific heat is determined from the equation used in the literature.

$$C_{PMHNFs} = \varphi \cdot \rho_p + (1 - \varphi) \cdot C_{bf} \quad (B.6)$$

B.2.3 Thermal conductivity of the nanofluid

The examination of thermal conductivity in $\text{Fe}_3\text{O}_4/\text{TiO}_2$ nanofluid, particularly at a 0.3% volume fraction, encompasses a correlation that holds validity for concentrations up to 10.4%. The correlation utilized is derived from the work of Pack and Cho, as documented in the existing literature.

$$K_{nf} = \left(K_{bf}(1 + 7.47\varphi) \right) \quad (B.7)$$