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ON THE COUPLING OF A ZONAL MODEL WITH A BES MODEL FOR PREDICTING VERTICAL TEMPERATURE DISTRIBUTION

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ABSTRACT

The airflow in one zone is often treaded as ‘fully mixed’ in Building Energy Simulation programs (BES) e.g. TRNSYS. On the other hand Computational Fluid Dynamics (CFD) are too complex and time-consuming to predict temperature and relative humidity in a building for a longer time-period, such as one year. Nevertheless several building applications require a prediction of the vertical distribution of the indoor relative humidity and temperature. This paper presents the development and possibilities of a coupled TRNSYS-zonal model, which allows accounting the stratification in a room. The zonal model is based on the block-model proposed by Togari [1] and describes a one dimensional heat and mass transfer between horizontal layers. The goal of this preliminary study is to examine the effect of parameters such as the number of layers, the value of the heat convection coefficient and the choses time step. To validate the implemented TRNSYS-model, the case of natural convection in a test room (3m x 3m x2,55m) described by Arai [2] and Togari [1] has been used.

INTRODUCTION

In large indoor spaces such as churches, stratification occurs during heating. In many cases this causes difficulties in preserving the many valuable artworks, e.g. panel paintings and organs. Thus in the early planning stages, when designing a heating system, there is need for accurate prediction of the vertical temperature distribution. So in order to make a correct assessment of the stratification caused by the heating, next to the calculation of the energy exchange, also the calculation of the airflow in the space is necessary. To predict the temperature and humidity distribution, different modelling approaches have been used: namely computational fluid dynamics (CFD) and zonal airflow models.

The CFD-method is a widespread approach to model the airflow with a computational simulation. This method predicts the temperature, velocity and other flow parameters by the Navier-Stokes equations with a high degree of accuracy. However, in order to assess the risk on damage at art works like wooden panel paintings, the fluctuations in temperature and humidity over a longer time period are of interest. To simulate longer time periods, the mentioned CFD models are less suitable for their need for powerful computers with a large amount of memory. In reality, these requirements are often not available. So to be able to predict the airflow in a building in a fast way and for a longer time period, the use of a macroscopic airflow model offers a solution. The zonal models is an intermediate approach between the CFD and the multizone models used in BES, which consider the air as perfectly mixed. The zonal airflow models give faster results than the CFD-method and are more accurate that the multizone models.

In literature several macroscopic airflow models can be found. An overview of these models is given by Megri and Haghighat [3] and Griffith [4] . Different types of models had been reported: the pressure-based and the temperature-based. Griffith [5] added a third type: the so-called momentum-based model. These different macroscopic airflow models differentiate themselves by the simplifications they make in the conservation equations. Much work has been applied to the pressure-based zonal models which uses the power-law equations to solve the pressure field to predict the airflow in a room. Song(sec [6]) found that these models failed to predict the temperate gradient due to the fact that the pressure difference based on the power law poorly represents the airflow driven by thermal effects in buildings like atria. To predict the temperature gradient is large rooms, Togari et al. [1] presented the temperature-based zonal model without pressure drop. This temperature-based zonal model uses correlations based on the theory of wall streams. The model has less unknowns than the pressure-based one and is a good alternative to the pressure-based one to predict indoor thermal environment when thermal gradient exist [6]. The goal of this paper is to develop a suitable dynamic simulation tool to predict the temperature and humidity distribution in a church building. To this end the authors implemented a zonal model in the BES-software TRNSYS, based on the former thermal zonal model described by Togari et al. [1].

NOMENCLATURE

A_b	[m²]	Cross section area of the top or bottom layer
A_w	[m²]	Area of the wall
C	[J/kgK]	Heat capacity
C_b	[W/m²°C]	the value obtained when a stable (2.3W/m²°C) or unstable (112W/m²°C) temperature stratification is formed
G_{cur}	[kg/s]	Vapour flow from the wall current of wall K adjacent to layer i
G_{lay}	[kg/s]	Vapour flow from layer i-1 to layer i
G_s	[kg/s]	Vapour flow produced by people, systems, activities such as washing,…
m	[kg/s]	Air mass flow between layer i and layer i+1
m_{in}	[kg/s]	Air mass flow from wall k to layer i
m_m	[kg/s]	Air mass flow of wall current
m_{md}	[kg/s]	Air mass flow of wall current from layer I to layer i+1
m_{out}	[kg/s]	Air mass flow from layer i to wall k
Q_b	[W]	the heat flow from inversion between layers
Q_{cur}	[W]	the heat flow from or to the wall currents
Q_{lay}	[W]	the heat flow due to mass transport from layer i with layer i-1 and layer i+1
Q_s	[W]	heat sources or sinks
RH	[%]	Relative humidity
T	[°C]	Zone temperature
T_D	[°C]	Film temperature
T_m	[°C]	Temperature of the wall current
T_w	[°C]	Wall temperature
V	[m³]	Volume
Y	[kg/kg]	Humidity ratio of layer i
Y_m	[kg/kg]	Humidity ratio of wall current i,k

Special characters

α_c	[W/m²K]	Heat convection coefficient
ρ_a	[kg/m³]	Density of the air

Subscripts and superscripts

i	Number of the layer
k	Number of the wall
m	Number of iteration steps

METHOD

The model selected for this work was first proposed by Togari et al.[1] and has been used by others [2, 7-9]. The model is a simplified model for calculating the vertical temperature distribution in a large space building. To calculate the temperature distribution in the room the model starts from a given inside wall temperature. The airflows along the vertical wall surfaces and supply airstreams are assumed to be the main components of the air movement in a large space. Further it was also assumed that the horizontal temperature was uniform, except for the regions affected by supply air jet ventilation. This temperature-zonal model would be more useful when it could be used in an energy simulation, starting from other boundary conditions than the wall temperature. Therefore the zonal model is implemented in the existing BES-software TRNSYS [10] is used.

Governing equations of the model

In the zonal model, the space is divided into a finite number of horizontal layers or blocks. Each layer consists of a core cell and wall cells, as displayed in Figure 1. The core cell represents a horizontal layer and when the layer is bounded by a wall, a wall cell is defined which accounts for the mass flow along the wall.

Flows are defined as positive in the upward direction and from the wall cells to the layers. Between a “wall cell” and a “zone cell” there is an exchange of mass and energy, but because the velocity in the “zone cell “ is assumed to be very low, the conservation of momentum in the zone is not considered [11].

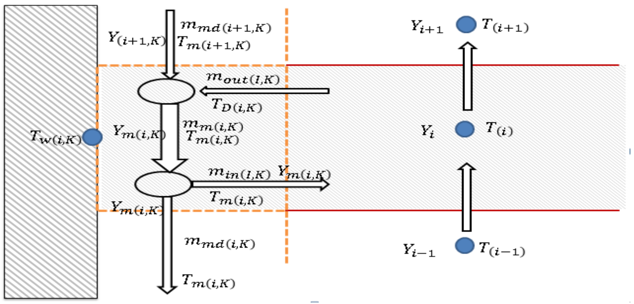

Figure 1: Schematic representation of the wall currents and air mass flows in one layer

When the air in a space is warmed up, it becomes cooled at the colder walls. By consequence an airflow along the vertical walls is induced. To account the heat gain or loss in a zone by this convective flow the model of Togari was used. This model assumes that heat convection drives mass flow $m_{out(I,K)}$ with an average temperature $T_{D(i,K)}$ from layer I to its related boundary layer. To calculate $m_{out(I,K)}$ with temperature $T_{D(i,K)}$ following equations were used:

$$T_{D(i,K)} = 0.75T_{(i)} + 0.25T_{w(i,K)} \tag{1}$$

$$m_{out(I,K)} = 4\,\frac{\alpha_{C(i,K)} \cdot A_{w(I,K)}}{C} \tag{2}$$

The current flow from layer i will combine with the current flow $m_{md(i+1,K)}$ from layer i+1, to form a total air mass flow with mass $m_{m(i,K)}$ and an average temperature $T_{m(i,K)}$, yielding:

$$m_{m(i,K)} = m_{out(i,K)} + m_{md(i+1,K)} \tag{3}$$

$$T_{m(i,K)} = \frac{m_{out(i,K)}T_{D(i,K)} + m_{md(i-1,K)}T_{m(i-1,K)}}{m_{m(i,K)}} \tag{4}$$

Some of the air of this current flow returns to the air layer i ($m_{in(i,K)}$) and some air of the current continues to the current flow of the cell down or up($m_{md(i,K)}$), depending on the direction of the current flow. The splitting of the mass $m_{m(i,K)}$ into $m_{in(i,K)}$ and $m_{md(i,K)}$ is calculated by the ratio P(i,K):

Flow direction	Temperature conditions	$P_{i,K}$
Descending	$T_{m(i,K)} \geq T_{(i)}$	0
	$T_{(i)} > T_{m(i,K)} > T_{(i-1)}$	$\frac{T_{(i)} - T_{m(i,K)}}{T_{(i)} - T_{(i-1)}}$
	$T_{m(i,K)} \leq T_{(i-1)}$	1

Ascending	$T_{m(i,K)} \leq T_{(i)}$	0
	$T_{(i)} < T_{m(i,K)} < T_{(i+1)}$	$\frac{T_{m(i,K)} - T_{(i)}}{T_{(i+1)} - T_{(i)}}$
	$T_{m(i,K)} \geq T_{(i+1)}$	1

To calculate the mass balance in every zone, there was started from the lowermost zone. Flows are defined as positive in the upward direction and from the wall cells to the layers. The mass balance for a layer i is calculated by:

$$0 = m_{si(i)} + \sum_{k=1}^{m} m_{in(i,K)} - \sum_{k=1}^{m} m_{out(i,K)} + m_{(i-1)} - m_{(i)} \tag{5}$$

The moisture balance equation for a layer i can be expressed as:

$$\rho_a V_i \frac{(Y_i{}^{t+\Delta t,m} - Y_i{}^{t})}{\Delta t} = G_{lay} + G_{cur} + G_s \tag{6}$$

In the air the heat transfer equation can be written as:

$$V_i \frac{(\rho C)^{t+\Delta t,m} T_i{}^{t+\Delta t,m} - (\rho C)^{t} T_i{}^{t}}{\Delta t} = Q_s + Q_{lay} + Q_{cur} + Q_b \tag{7}$$

In this equation Q_b expresses the heat transfer between the layers due to thermal stability, yielding:

$$q_{b(i)} = C_{b(i)} A_b \left(T_{(i-1)} - T_{(i)}\right) \tag{8}$$

Coupling of the zonal model with TRNSYS

TRNSYS [10] is a TRaNsient SYStems Simulation program with a modular structure. Next to its own library of components, this software allows for implementing an own written component as a dynamic link library in the simulation environment, which is called 'the Simulation Studio'[10]. The multizone building model of TRNSYS is represented by 'Type 56' and calculates the heat and moisture balance of a building for given boundary conditions such as temperature, solar radiation, heat and moisture gains. The building can contain different zones. Each zone represents one or more rooms in which T and RH is typically assumed to be well-mixed.

The zonal model is written as a new component for TRNSYS v17. This version of TRNSYS has the possibility to divide one zone into several air nodes [12], but to be able to study the effect on stratification in the room, there is need of an airflow model. For that the thermal-zonal model of Togari was used. Each air node of this building model must be connected with a layer in the zonal model. Figure 2 shows a schematic overview of the procedure used to couple the thermal zonal model with the building energy simulation program TRNSYS. The interior surface temperature and the heat transfer coefficient act as boundary conditions for the zonal model. Initial values of the temperature and relative humidity from each air node are used as an input of the zonal model, together with the vapour mass flux of the walls. This can be done by the implementation of a HAM-model for TRNSYS[13] or by using a simplified model provided by TRNSYS.

Once the boundary conditions were given to the zonal model, the latter calculates the wall currents and the heat and mass conservation equations for all the layers until convergence is reached. As a convergence criterion, the maximum temperature difference in the layers between successive iterations is chosen. Afterwards, the net heat and moisture gain for every layer is passed on to the multizone building model (TRNBuild). In other words, the coupling of the BES-software with the zonal model consists of a convective heat and water vapour gain for every air node in TRNSYS, calculated by the zonal model. Looking closer to the heat conservation in TRNSYS, TRNSYS calculates in every air node a convective heat gain. To avoid to include twice this heat gain - one by the wall currents in the zonal model and one by TRNSYS itself-, the convective surface heat flows calculated by TRNSYS may not be taken into account. Therefore, this value also has to be passed to the zonal model, in which it will be taken into account. The radiative heat gain, which is decoupled of the convective heat gain, will be calculated by TRNSYS.

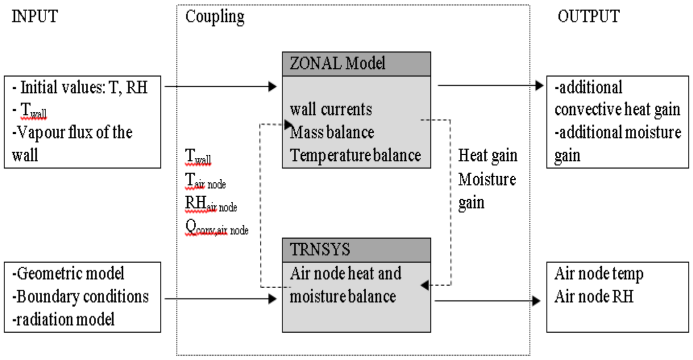

Figure 2: Schematic overview of the coupling between the multizone building model in TRNSYS and the developed new type based on the thermal zonal model proposed by Togari.

INITIAL RESULTS

Description of the test case

The case studied in this paper is the case that can be found in the report of Togari et al. [1] and that of Arai et al.[2] which was used for evaluating the implemented model. The geometrically simple test room had a ground plane of 3m x 3m and measures 2,5m in height. The room consisted of insulated boards (three vertical walls, a ceiling and a floor) and one glass wall. In the wall opposite to the glass wall, two openings were made in the symmetry plane: a supply inlet at 0,625 m above the floor and a return outlet at 0,250m above the floor. Several configurations were measured in this test room e.g. heating or cooling and natural convection.

To validate the calculated results of the newly implemented model, the natural convection case (N10) has been used in this paper. In this case, the temperature outside the room was kept at about 12°C and was then raised to 42°C, while 24 hours later it was again lowered to 12°C.

Steady-state calculation

The first calculation with the zonal model was a steady-state calculation of the layers temperature using the measured interior surface temperatures at two hours of testing as boundary conditions. The reason for the steady-state calculation was that the result presented by Togari were also calculated steady-state. The measured surface temperatures described by Togari [1] were used together with constant heat transfer coefficients. The coefficient was 3.5 W/m²K for the glass wall and the insulated wall. For the floor and the ceiling, the coefficient was 4.6W/m²°K when heat flow was upward, and 2.3W/m²K when the heat flow was downward.

The calculated temperatures are displayed on Figure 3. These results show that the model overpredicted the room temperature. This could be due to the constant heat transfer coefficients and the use of a C_b coefficient to implement the effect of stable or unstable stratification.

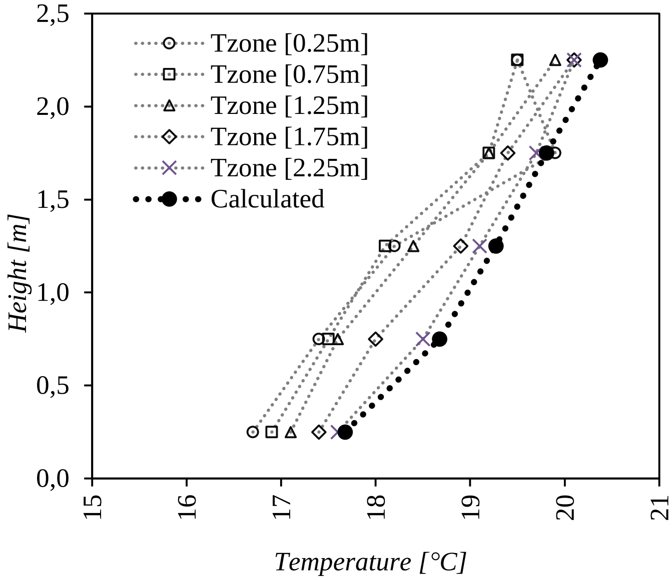

Figure 3: Comparison of the measured temperature at different locations in the room of the test case and the calculated temperature in the thermal-zonal model

Dynamic calculation: implementation in TRNSYS

The next step was to perform a dynamic calculation taking the transient terms from equation 6 and equation 7 into account. In this calculation, 48 hours were simulated with the coupled TRNSYS – zonal model. The goal of this study was to examine the effect of physical and numerical parameters such as the thermal resistance of the walls, the value of the heat convection coefficient, the number of layers and the value for the time step. In this case, the full test room was modelled in TRNBuild, the building model of TRNSYS.

Because material parameters were unknown, several compositions for the walls were tested. Good agreement was found for the thermal resistance R=1.6 m²K/W for the insulated walls and with the glass wall as a massless layer. However, the surface temperature of glass was slightly underpredicted.

On Figure 4, results were depicted for the first seven hours where outdoor temperature was raised from 12 to 42°C. The measured outdoor temperature acted as boundary condition, while the temperatures for the insulated walls and the glass surface were calculated by TRNSYS. This was opposite to the calculated results of Togari in which all interior surface temperatures at each time step (one hour) were given by the experiment (steady state calculation for every hour). The calculated results were compared to the measurements and the calculations of Togari. From Figure 4 can be concluded that the temperatures for the layers were lower than was seen in the calculations of Togari. This was probably due to the lower surface temperatures of glass and due to the dynamic character of the calculation (Togari adapted the boundary conditions every hour based on his measured results).

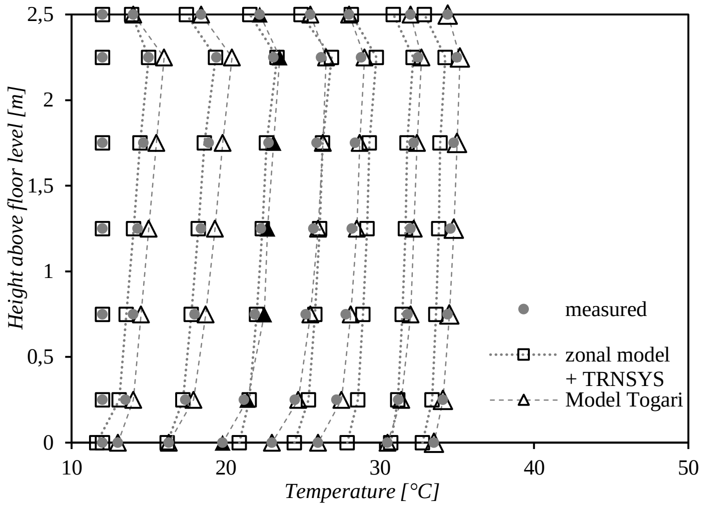

Figure 4: Comparisons between the calculated values, the measured values and the calculations performed by Togari in the case that there was heated outside. Results are given for every hour , during the first seven hours (case N10).

On Figure 5 the progress of the temperature after two hours of heating was compared for a different number of layers . On the figure can be seen that the more the room was divided into layers, the more the stratification became detailed. In the middle layers, the stratification had a quite linear progress, whereas the slope of the stratification cure for the layers close to the floor and the ceiling became less steep. Further, it can also be noticed that the number of layers had an impact on the surface temperature of the floor. Also, the more layers, the more the temperature curves moved to the right and thus the higher the temperature became. In future, further research will be done on the allowed maximal number of layers.

On Figure 6 the effect of the number of layers on the relative humidity distributions was visualised. Because the absolute humidity remained the same, the relative humidity curves were in agreement with the temperature on Figure 5.

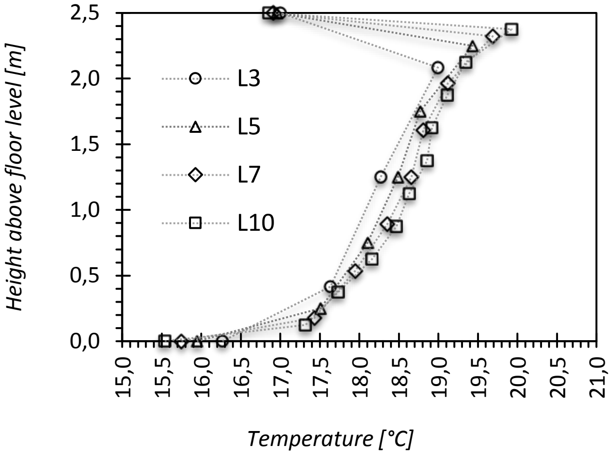

Figure 5: The progress of the temperature after two hours of heating. These results are compared for different number of layers (3,5,7 or 10 layers)

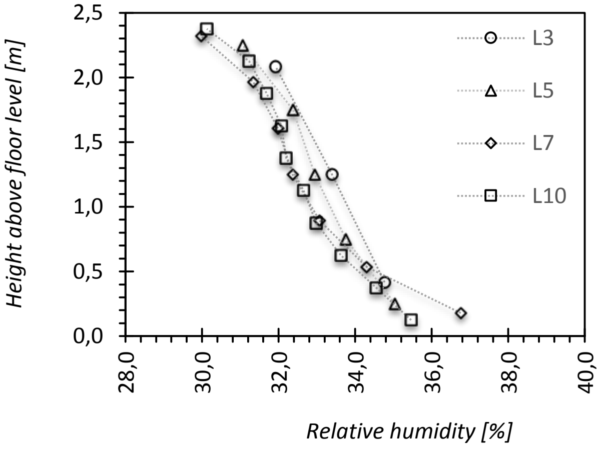

Figure 6: The progress of the relative humidity after two hours of heating. These results are compared for different number of layers (3,5,7 or 10 layers)

Next, the effect of the time step had also been investigated. Whit a time step of 0,01s or 0,05s convergence was reached. Larger time steps resulted in fluctuations. It is obvious that the choice for such a small time step in TRNSYS leaded to longer computational times.

Further there was looked at the value of the heat transfer coefficients. In the first calculation heat transfer coefficients were considered as simple constant values as described earlier. In the second and third calculation, heat transfer coefficients were adapted for every time step based on the temperature in the layer. In the second calculation the equations for natural convection proposed by TRNSYS were used. The internal convection coefficient is expressed as :

$$\alpha = K(T_{surf} - T_{air})^n \tag{9}$$

Values for K and n are 1,5 and 0,25 for vertical surfaces. For horizontal surfaces K and n are 2,11 and 0,31 if the surface temperature is higher than the surrounding air temperature and 1,87 and 0,25 if this is not the case. In the third calculation the equations presented by Alamdari and Hammond [14] were used. . For vertical surfaces, and horizontal surfaces for which the convective heat flow is upward, the Alamdari and Hammond expression is:

$$= \left[\left\{a\left(\frac{T_{air} - T_{surf}}{L}\right)^{1/4}\right\}^6 + \left\{b(T_{air} - T_{surf})^{1/3}\right\}^6\right]^{1/6} \tag{10}$$

Where L is the characteristic length of the surface and a and b are coefficients. These are set 1,5 and1,23 for vertical surfaces and 1,4 and 1,63 for horizontal surfaces (upward het flow). For horizontal surfaces for which the convective heat flow is downward, the expression becomes:

$$= \alpha = 0{,}6\left(\frac{T_{surf} - T_{air}}{L^2}\right)^{1/5} \tag{11}$$

All values of α were subject to a minimum of 1.0 W/m²K. The results for the second and third calculation were very similar and using these algorithms led to a slower heating up and a slower cooling down, compared to the use of fixed heat transfer coefficients as proposed by Togari (Figure 7).

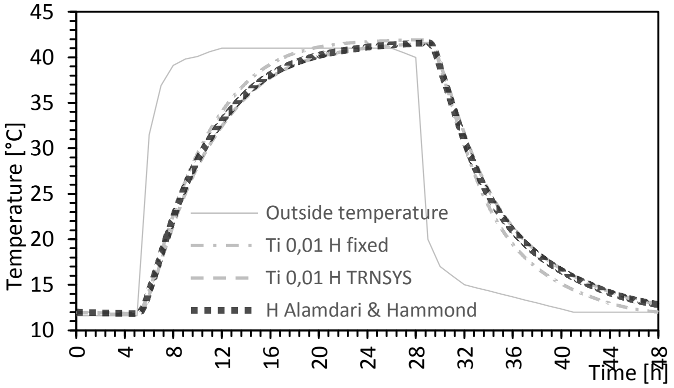

Figure 7: Effect of the choice of heat transfer coefficient of the progress of the temperature. Results are shown for the temperature in zone 3.

CONCLUSION AND FURTHER WORK

Currently the thermal-zonal model, based on the model of Togari, is operational in the version of the BES-software TRNSYS v17. Without the use of the thermal-zonal model in a BES-software like TRNSYS, the air is considered to be perfectly mixed. This includes one temperature and relative humidity for the whole room. In TRNSYS v17 there is the possibility to divide one room into different air nodes. However, some kind of linking is needed between these air nodes to implement the effect of the airflow in the room. For this a thermal zonal model, based on the model of Togari[1] was linked in TRSYS. To study the effect of stratification in one room, the zonal model defines for each air node a convective heat gain and a gain in vapour mass. To validate the zonal model the case of natural convection described by Togari was used. The initial testing has been positive for the prediction of the temperature stratification. However, some fundamental work still needs to be done. As shown the results are dependent of the choice of heat transfer coefficient and the number of layers. The choice for the Cb coefficients will also have an impact. For these parameters a more detailed sensitivity analysis will be done. Further it must be kept in mind that the model is a simplification, in which some assumptions were made such as the value of the Cb coefficient. Also, if the number of layers increase, one can question the physical background accepted in the simplifications. So the allowable number of layers and the choice of the Cb coefficient need further study.

In the next stage the model will also be further developed. The equations for the jet flows will be implemented and there will also be looked at the possibility to combine the model with the airflow network model TRNFLOW in order to make more complex models.

REFERENCES

[1] S. Togari, Y. Arai, K. Milura, A Simplified Model for Predicting Vertical Temperature Distribution in a Large Space, *ASHRAE Transaction*, Vol. 99,1993, pp. 84-90.

[2] Y. Arai, S. Togari, K. Miura, Unsteady-state thermal analysis of a large space with vertical temperature distribution, *ASHRAE Transactions*, Vol.100, 1994, pp. 396-411.

[3] A.C. Megri, F. Haghighat, Zonal Modeling for Simulating Indoor Environment of Buildings: Review, Recent Developments, and Applications, *HVAC&R Research*, Vol.13, 2007, pp. 887-905.

[4] B.T. Griffith, Incorporating Nodal and Zonal Room Air Models into Building Energy Calculation Procedures, *Mechanical engineering*, Massachusetts Institute of Technology, 2002.

[5] B. Griffith, Q.Y. Chen, A Momentum-Zonal Model for Predicting Zone Airflow and Temperature Distributions to Enhance Building Load and Energy Simulations, *HVAC&R Research*, Vol.9, 2003, pp. 309-325.

[6] J. Gao, X. Zhang, J.N. Zhao, F.S. Gao, A heat transfer parameter at air interfaces in the BLOCK model for building thermal environment, *International Journal of Thermal Sciences*, Vol. 49, 2010, pp. 463-470.

[7] X. Wang, C. Huang, W. Cao, Mathematical modeling and experimental study on vertical temperature distribution of hybrid ventilation in an atrium building, *Energy and Buildings*, Vol.41 ,2009, pp. 907-914.

[8] Y. Takemasa, S. Togari, Y. Arai, Application of an unsteady-state model for predicting vertical temperature distributions to an existing atrium, *ASHRAE Transaction*, Vol.102, 1996, pp. 239-247.

[9] J. Gao, J.-n. Zhao, X.-d. Li, F.-s. Gao, A Zonal Model for Large Enclosures With Combined Stratification Cooling and Natural Ventilation: Part 1—Model Generation and its Procedure, *Journal of Solar Energy Engineering*, Vol. 128, 2005, pp.367-375.

[10] University of Wisconsin-Madison. Solar Energy Laboratory, TRNSYS 17: A Transient System Simulation Program, University of Wisconsin-Madison, USA, 2010.

[11] H. Schlichting, K. Gersten, Boundary-Layer Theory, Seventh Edition ed., MacGraw-Hill, New York and London, 1979.

[12] University of Wisconsin-Madison. Solar Energy Laboratory, Multizone Building modeling with Type56 and TRNBuild, in: TRNSYS 17, Solar Energy Laboratory, University of Wisconsin-Madison, 2012.

[13] M. Steeman, Hygrothermal modelling for building energy simulation applications, Thesis, Ghent University, Ghent, 2010.

[14] F. Alamdari, G.P. Hammond, Improved data correlations for buoyancy-driven convection in rooms, *BSER&T*, Vol. 4, 1983.