A ZONAL ROOM MODEL IN COMBINED SIMULATION WITH A PHYSIOLOGICAL HUMAN RESPONSE MODEL TO QUANTIFY INDOOR HEAT STRESS RISKS

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ABSTRACT

The proposed paper presents a simulation-based approach to study indoor heat stress that has been developed in the DFG Research Unit 1736. To be able to identify heat stress effects on human beings and to test adaptation or mitigation strategies during a heat wave by computer simulations, we present the 3D zonal room model. It is implemented in the object-oriented modelling language Modelica and will be connected to dynamic methods of heat stress risk assessment.

For the purpose of parameterization and validation we simulate a model room. We use CFD-calculations to cross-validate the zonal model and compare all simulation outcomes to findings based on measured data. As a case study, we apply the zonal approach to a living-/bedroom under everyday conditions in combined simulation with the selected assessment model. This provides a sketch of the approach to quantify heat stress risks and shows the strengths and weaknesses of this simulation model.

INTRODUCTION

Heat stress is a well known phenomenon in mid-latitude cities during summertime. The DFG Research Unit 1736 “Urban Climate and Heat Stress in mid-latitude cities in view of climate change” (UCaHS) addresses a wide range of scientific questions related to heat stress in mid-latitude cities by a multi- and interdisciplinary approach involving climatologists, urban geographers and hydrologists, physicians, architects, physicists and engineers, urban planners and social scientists. The research project “Indoor Simulations”, located at the University of the Arts Berlin, is responsible for the development of a simulation-based approach to study indoor heat stress.

Studies have shown that 5 percent of all death in Berlin (Germany) are statistically correlated with high air temperature (Scherer et al. 2014). Besides that it is known that inhabitants of a city spend most of their time at indoor locations, e.g. at work places or at home (Jantunen 1998). As the most affected persons by heat stress are vulnerable groups (vulnerable by age or illness) the time periods spent indoor are even more important. Comprehensive knowledge of indoor climate is therefore necessary to study heat stress risks.

To be able to identify heat stress effects on human beings and to test (local) adaptation or mitigation strategies during heat waves by computer simulation, two basic criteria must be fulfilled. It is necessary to know the spatial resolved distribution of temperature and radiation. Furthermore it is crucial to perform transient calculations, which are capable to cover the whole duration of a heat wave. As heat waves could be defined as five days or more with high temperature (Tinz et al. 2008) the required computation time is an important factor.

With the intend to find a compromise between fast methods of building energy simulation which are too simplified, and highly detailed but time consuming methods of computer fluid dynamics (CFD), the zonal approach could be used (Griffith & Chen 2003; Haghighat et al. 2000; Henson 1999; Musy et al. 2000). The development of a zonal room model enables us to do spatial resolved simulations covering medium time periods up to several days. In contrast to CFD calculations, the results are much less spatially resolved but seem to be suitable to analyze indoor heat stress risks. Regarding the aspect of assessment, different room configurations like closed and tilted windows should be realizable and any location of the indoor room should be connectable to a suitable assessment model.

In this context, we apply Fanger’s commonly known PMV/PPD model (Fanger 1970) to assess indoor thermal sensation and comfort. The model itself is regarded suitable for uniform morphologies and steady-state conditions near thermal neutrality. However, the highly dynamic ambient conditions treated within the context of this work, require alternative indices for the assessment of heat stress risk. (Wölki et al. 2014) suggested to replace the rudimentary human core model of Fanger by the more sophisticated dynamic two-node Pierce model of (Gagge 1973). The latter includes realistic thermoregulatory mechanisms like vasomotion, shivering and sweating in order to defend the body against hypo-/hyperthermia. Corresponding modifications expand the original PMV/PPD index by appropriate dynamic components, which lead to the indices Transient Predicted Mean Vote (TPMV)
and Transient Predicted Percentage of Dissatisfied (TPPD).

The proposed paper presents two application of the zonal simulation approach. As a first application, a model room (Aachen Model Room AMoR1) is simulated. With adjustable air inlets and heat sources this room meets the same demands of the zonal model as a typical living-, sleeping- or office room. As there are measurement data for the model room available and stationary or short time CFD calculations for cross-validation are possible this application is mainly done for a parameterization study concerning the impulse equations and validation purpose.

Secondly, the zonal approach is applied to an actual used living-/bedroom under everyday conditions in combined simulation with the assessment model. This shows the ability of the zonal approach to simulate time periods up to several days in a reasonable amount of time. The comparison of simulated and measured air temperature values show the need to improve the model by the integration of user behaviour. The results of the assessment model show the added value of using dynamic indices for heat stress risk assessment.

THE ZONAL MODEL

The zonal approach has been developed and implemented in the object-oriented modeling language Modelica. This approach distinguishes air volumes and flow elements and follows altogether the mathematical approach of the finite volume method. The indoor room can be divided into 150 - 350 air volumes of various sizes. Similar to (Norrefieldt 2011), inside every air volume a thermodynamic state is calculated by solving energy-, mass- and humidity balance equations and additional equations for temperature and pressure. All inner air volumes are connected to six neighbouring air volumes by flow elements. To calculate the velocity distribution within every flow element, a simplified one-dimensional form of the impulse equation is solved. The resulting mass flows are distributed to the air volume to determine a characteristic velocity. In order to compensate neglected modelling of turbulences and boundary layers, the impulse equations are parameterized.

Outer air volumes are connected to indoor walls, furniture, outdoor walls or openings. The thermal storage capacity of solids has a great impact on the indoor climate and needs to be considered. Outdoor walls and potential openings like windows are connected to outdoor climate data, which drives the simulation model.

Further functionalities, which are needed to create an suitable indoor simulation, are the calculation of long wave radiation and the implementation of certain room configurations regarding passive ventilation and shading. For heat stress assessment arbitrary air volumes can be connected to an assessment model.

First validations on the base of measured values and CFD calculations had been done by the simulation of a thermal model house (Jänische et al. 2011). The results are described in (Mucha et al. 2014) and include the validation of temperature changes in a heating process and a first estimation of air velocities in the context of CFD-comparisons.

PARAMETERIZATION

The next step is the application to real size rooms to adjust the parameterization of the impulse equations. Basically the impulse equation is simplified and one-dimensional, adding pressure force ($F_p$), momentum force ($F_M$), in case of the z-direction gravity force ($F_g$), and an opposing force ($F_O$) to the right side of the derivation of the velocity component. Figure 1 shows the impulse equation for the velocity component $u$ in $x$-direction.

![Figure 1: AirVolume-FlowElement connection](image)

As described in (Norrefieldt 2011; Norrefieldt et al. 2012) the pressure force and momentum force between two air volume elements of the size $dx \cdot dy \cdot dz$ could be written as

$$F_p = -A \cdot (p_j - p_i)$$

$$F_M = -\rho \cdot A \cdot (u_j^2 - u_i^2)$$

The opposing force could be represented by viscous forces or a singular loss model. For inside-lying connections between two air elements the viscous force (see equation 3) is proposed.

$$F_O = F_v = \mu_n \cdot 0.5 \cdot$$

$$\left( \left( \frac{\Delta u}{\Delta y} \right)_{y_2} - \left( \frac{\Delta u}{\Delta y} \right)_{y_1} \right) \cdot A_{yz} + \left( \frac{\Delta u}{\Delta z} \right)_{z_2} - \left( \frac{\Delta u}{\Delta z} \right)_{z_1} \cdot A_{zx}$$

$$+ \left( \frac{\Delta u}{\Delta y} \right)_{y_2} - \left( \frac{\Delta u}{\Delta y} \right)_{y_1} \right) \cdot A_{zy} + \left( \frac{\Delta u}{\Delta z} \right)_{z_2} - \left( \frac{\Delta u}{\Delta z} \right)_{z_1} \cdot A_{zy} \right)$$

1 Further information is available at: www.ebc.eonerc.rwth-aachen.de/go/id/fdqk/lidx/1

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or almost two-dimensional flow and therefore change the flow structure.

Another option to reduce the velocity is to introduce the known loss factor model, which is proposed for openings like doors or windows. It could be written as

\[ F_0 = F_{\text{loss}} = f_{\text{loss}} \cdot A \cdot \text{sign}(u) \cdot u^2 \]  

A loss factor model could be applied to inside flow connections as well. While \( F_{\text{loss}} \) should be very small in the middle of a room, near to boundary layers it could be increased for flow elements calculating velocity components parallel to the boundary in order to consider boundary layers.

\[ F_0 = F_{\text{loss,lay}} = f_{\text{lay}} \cdot f_{\text{loss}} \cdot A \cdot \text{sign}(u) \cdot u^2 \]  

We propose the combination of both approaches and to use an increased viscosity as a tune factor, which is supported by the loss factor model. The resulting impulse equation could be written as:

\[ \Delta x_{ij} \cdot \rho \frac{du}{dt} = F_P + F_M + \frac{1}{2} (F_V + F_{\text{loss,lay}}) \]  

Equation 6 provides three parameters \( f_{\text{pv}} \), \( f_{\text{loss}} \) and \( f_{\text{lay}} \) to parameterize the impulse equations. In contrast to CFD calculations the zonal approach does not intend to be spatially resolved as high as possible or to take almost every effect into account. Nevertheless, to obtain a realistic velocity distribution, a parameterization is mandatory. An initial approach in this direction will be shown in the next section.

**AACHENER MODELROOM (AMoR)**

In the Aachen Model Room (AMoR) basic experiments on room airflow structures and thermal comfort can be conducted. It shows an idealized case of a typical ventilation situation like in a meeting room, a plane or a train cabin. The supply air is introduced close to the ceiling and the heat sources are positioned at the floor. The exhausted air leaves the model room at the bottom zone. The supply and exhaust air openings as well as the heating loads are introduced into the model room over the whole length (see Figure 2) (Kandzia 2013).

By various combinations of supplied air and internal heat loads, different air flow structures like free convection, mixed convection with dominant forced convection or mixed convection with neither of the two forces is dominant can be created. In our first validation case, we use the benchmark test, in which mixed convection with dominant forced convection (inlet velocity of 1.5 m/s and heating loads of 2 kW) is created (Kandzia & Müller 2015).

The simulation model consists of 232 air volumes (see Figure 2). Supplied air is implemented by given mass flow values, internal heat loads are taken into account by surface temperatures, which were obtained from measurements. The same measurements are used for the validation of velocity values. The sensors are positioned automatically in the model room by using a traverse system. The measurements had been done in three different planes (0.9, 2.5 and 4.1 m) and three different heights (1.1, 1.9 and 2.7 m).

![Figure 2: left: Sketch of the model room AMoR (Kandzia 2013), right: zonal simulation model.](image)

To find the optimal parameterization, equation (3) and equation (5) were used separately to find in each case the best parameters. The best results could be achieved with the parameterization:

\[ f_{\text{pv}} = 345, \quad f_{\text{loss}} = 0.01 \quad \text{and} \quad f_{\text{lay}} = 3.25. \]

A further increased viscosity slows the velocity more down but tends to change the flow structure. A lower loss-factor has no effect at all, while a higher loss factor smoothes and eliminates side movements.

![Figure 3: Comparison of measured velocity data at the 0.9m-plane at the height of 2.7 m (top) and 1.9 m (bottom) with simulation results at the corresponding finite volume centres.](image)
The combination of both approaches like equation (6) fits the measurement data best (see Figure 3, where measured and simulated velocity profiles in the height of 1.9m and 2.7m at the plane 0.9m are plotted across the room width).

To ensure realistic flow movements, the zonal results have been compared to CFD\(^2\) results. This is difficult, because of the highly transient character of the flow structure and limited possibilities of visualisation in Modelica.

Figure 4: Comparison of CFD results and zonal modelling results: magnitude of velocity in a balanced state on the scale of 0 - 1.5 m/s.

Figure 4 shows the velocity magnitudes at the chosen plane of interest (0.9m). The comparison of the contour plots show similar flow structures with significant discrepancies. The circle movements above the heat sources could not be found in the zonal results. Whether this is only caused by the coarse zonal division of the room, or whether this is an effect of the parameterization of the impulse equations need to be analyzed. Further validation need to be done to check dependencies of the parameterization on the underlying flow structure. Therefore it is necessary to extend the estimation of optimal parameters to test cases in which free convection is dominant, forced convection is dominant or neither of them. Our aim is to create a model which could be used without knowledge about the flow structures that are going to come up.

CASE STUDY SLEEPING ROOM

As an application to the real world, the simulation of an actual used living-/bedroom within the nursing home Lazarus under everyday conditions for a test period of 8 days has been done.

The zonal simulation model consists of 303 air volumes. The non-rectangular shape of the room and furniture (compare to Figure 5: view through outer wall with window in the front (not shown), narrow corridor at the back, table and chairs on the left, two beds and bedside tables on the right) is grossly done by omission of the related air volumes. We distinguish between indoor and outdoor walls. Indoor walls assume that neighbouring rooms have the same temperature as the observed rooms. The outdoor wall of the room consists of wall elements and a window.

Corresponding settings are listed in Table 1. Long-wave radiation interchange is implemented, using the net method of (Glück 1997). The required view factors of all surface elements are calculated previously with the command-line tool View3D\(^3\). The impulse equations are set according to the results of the parameterization tests.

<table>
<thead>
<tr>
<th></th>
<th>$U$ [W/m(^2)K]</th>
<th>Thickness [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Outside</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Wall Inside</td>
<td>1.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Window</td>
<td>1.7</td>
<td>0.006</td>
</tr>
</tbody>
</table>

The model is driven by measured outdoor climate data. The used outdoor observations consists of air temperature and relative humidity sensors (DK390 HumiLog GP "rugged", EU-325 ±0.3 °C and RFT-325 ±2 %) implemented by Technical University of Berlin, Department of Ecology. The sensors are ventilated when sunlit by means of solar panels and mounted at the building façade at floors 3 and 5.

The simulation of 8 days was performed employing Dymola 2015, on an Intel(R) Core(TM) i7-3770 CPU with 3.4GHz and 32 GB RAM. Using the solver CVODE from SUNDIALS the simulation took approximately 5 hours. For a first assessment of the simulation results they are compared to measurement data. Indoor air temperature and relative humidity were measured by Humboldt University of Berlin, Geography Department, using three Testo 174H loggers (accuracy of ± 0.5 °C and ± 3% RH, respectively). To estimate the average conditions per room, it was avoided to place sensors at locations where they might be influenced by direct solar irradiation. Both outdoor and indoor observations are part of the UCaHS observation network of Berlin\(^4\), described in more detail in (Walikewitz et al. 2015).

\(^2\) All CFD calculations are performed using ANSYS CFD version 14.

\(^3\) Further information is available at: http://view3d.sourceforge.net/

\(^4\) Further information about the observation network: http://www.ucahs.org/index.php?page=observations
A first comparison between simulation results (window continuously closed, window continuously tilted) and indoor measurement values shows some deviations (see Figure 6). We assume a huge impact of user caused room configurations and conclude that more information about user behaviour patterns are absolutely necessary to improve the results of the simulations.

However, the simulation results with tilted window reproduce the trend of measured indoor air temperature, if the heat wave lasts several days. The results will be used to analyze the application with respect to its ability of heat stress risk assessment.

ASSESSMENT MODEL

The introduction of a dynamic global thermal comfort index, applicable to transient changes in ambient conditions, is part of the research work of the Insitute of Energy Efficiency and Sustainable Building (E3D) of RWTH Aachen. In this regard, the researchers introduced the transient indices TPMV/TPPD, which incorporate the dynamic human core model of (Gagge 1973). Generally, the TPMV/TPPD model is based on the same idea as Fanger’s PMV/PPD approach. Both models are calculating the energy balance of the human body via similar thermal expressions. In contrast to Fanger’s static human core model, the two-node Pierce model of Gagge contains realistic human thermoregulatory mechanisms like shivering, sweating, vasoconstriction and vasodilatation, thus affecting the human heat balance in a more realistic and dynamic manner. Both models, Fanger’s PMV/PPD (ISO7730 2005) and the corresponding TPMV/TPPD are implemented in the object-oriented programming language Modelica/Dymola.

COMBINED SIMULATION

One of the advantages of the modular structure of the chosen language Modelica is the easy integration of various modules that can be developed independently. As the room model and the assessment model are both implemented in the object orientated language Modelica there is no extra work to perform a combined simulation. At the moment it is an one-direction exchange as the climate parameter of the room are used to drive the assessment model. One of the next steps will be to extend the exchange to both directions, as the feedback of a human body to the room climate (heat load, humidity) should be considered as well.

HEAT STRESS RISK ASSESSMENT

The target application of the zonal approach is to improve the ability of heat stress assessment in indoor locations. Most of the needed values (air velocity, air temperature, operative temperature) of indoor climate could be derived from the current simulation model. As the calculation of indoor air humidity has not yet been validated, measurement data was used instead. Thermal indices like PMV could be calculated easily.

Regarding the requested heat stress risk assessment for vulnerable (ill and/or old) groups the static indices assessment will be enhanced. Dynamic indices, appropriate for transient ambient conditions, will be used too. The obvious difference between static and dynamic indices is shown in Figure 7 and Figure 8.
Due to human thermoregulatory reactions, which are taken into account, the actual resulting TPMV and TPPD seems quite unspectacular. But, given that the human body has to do the work to keep this “positive neutral” state of thermal comfort, precisely this performance has to be considered to judge the heat stress risk. The heat loss by evaporation (perspiration) is considered as a significant factor for this. Comparing Figure 7, Figure 8 and Figure 9, it can be concluded, that the reduction of heat load, which leads to an acceptable TPMV/TPPD, is governed by perspiration.

**CONCLUSIONS**

The development of a simulation-based approach to study indoor heat stress addresses two issues: the development of an indoor climate simulation environment at room level and the development/application of appropriate models for heat stress risk assessment. The zonal model is suitable for heat stress risk assessment of medium time periods. First validations on the base of test rooms show good agreement with measurement data and possibilities for optimisation by parameterization. The simulation model could be applied to real sized rooms and used to perform indoor climate simulations over time periods of heat waves. The simulation can be carried out in a reasonable amount of time so that alternative room configurations could be tested. The simulation results provide all data needed for the calculation of thermal indices. The use of dynamic indices extend the possibilities of heat stress risk assessment. They provide information about the work, a body has to perform to avoid heat stress. As an example the heat loss by evaporation is shown. This may give a new impetus to assess indoor heat stress risks tailored for special demands of older people or people with health restrictions.

**OUTLOOK**

Further validation of the zonal model in particular of the parameterization need to be done including different cases of flow structures. The application of the simulation model to an actual used room, showed the importance of user behaviour patterns, which are insufficiently considered so far. This needs to be implemented, organized and validated. In addition to user behaviour, reducing the room configuration (window, curtains, HVAC) to a single room is a strong simplification regarding heat stress analysis. More complex and realistic indoor heat stress scenarios including the possibility of room changes motivates an even more extended dynamic heat stress risk assessment from the point of view of human beings.

Taking thermoregulatory reactions like perspiration into account emphasizes the importance of calculating indoor air humidity. A calculation of indoor air humidity depending on outside air humidity, building construction and last but not least perspiring people as moisture gains must therefore be accelerated.

The assessment model developed at the Institute of Energy Efficiency and Sustainable Building (E3D) of RWTH Aachen add value and improve heat stress risk assessment done by indices. For an interpretation of the calculated human thermoregulatory reactions, in particular in the context of heat stress assessment for vulnerable groups, further work needs to be done.

**NOMENCLATURE**

- **PMV**: Predicted Mean Vote
- **PPD**: Predicted Percentage Dissatisfied
- **TPMV**: Transient Predicted Mean Vote
- **TPPD**: Transient Predicted Percentage Dissatisfied
- **F_p**: Pressure Force
- **F_M**: Momentum Force
- **F_G**: Gravity Force
- **F_o**: Opposing Force (e.g. F_v, F_loss)
- **u_i**: velocity in i-direction in air volume
- **A, A_xz, A_xy**: Contact surface between two neighbouring air volumes
- **X1, X2, Z2**: Referring to the direction of a connection
- **Δx, Δy, Δz**: Distance between two volume-centers
- **Δu, Δv, Δw**: Velocity delta between two volume-centers in x-, y- and z-direction
- **ρ**: Density
- **p**: Pressure
- **μ**: Dynamic Viscosity
- **F_V**: Viscous Force
- **F_loss**: Loss model Force
- **f_loss, f_lay, f_pv**: Introduced parameters to fit the impulse equation
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