A DYNAMIC INDEX FOR TRANSIENT THERMAL COMFORT PREDICTION

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ABSTRACT
The aim of this paper is to introduce a new modelling approach for global thermal comfort prediction, including transient ambient conditions and to show its necessity concerning energy performance simulations. The new model is based on Fanger’s original PMV/PPD-model (Fanger, 1970) whose core-model is replaced by the well known Pierce-model (Gagge, 1973; Gagge et al., 1970). The resulting thermal sensation/thermal comfort indexes are termed TPMV (transient predicted mean vote) and TPPD (transient predicted percentage dissatisfied) respectively. The model has been implemented in the object-oriented programming language Modelica/Dymola and was transferred to NMF (Neutral Model Format) used by IDA ICE (EQUA Solutions AG, SE). A first theoretical study, investigating the energy demand of an ideal cooling device of an office room during an eight hour office day in summer, is shown (IDA ICE). The corresponding device is controlled for PMV as well as the newly invented TPMV.

INTRODUCTION
Today it is common practice to use powerful simulation tools for the design of human centred indoor environments, satisfying the requirements of thermal comfort. In this context, the most commonly used approach is Fanger’s PMV/PPD index (Fanger, 1970), which uses a rudimentary human core model, expressed as a static energetic term, to calculate the energy exchange between the human being and its surrounding microclimate. This energy balance calculation allows for the direct correlation of ambient conditions and global thermal comfort. In general, the model is regarded suitable for uniform morphologies and steady state conditions near thermal neutrality (Schellen, 2012), but is inappropriate for transient ambient conditions, because of its missing dynamics. Hence, our research approach is focussed on the introduction of a new global thermal comfort index, applicable to transient ambient conditions. The resulting index is termed TPPD (transient predicted percentage dissatisfied) and is based on the substitution of the original static human core model of Fanger by the more sophisticated dynamic 2-node Pierce model (Gagge, 1973). The latter contains realistic human thermoregulatory reactions like sweating, shivering and vasomotion, thus influencing the human heat balance in a more realistic and dynamic way. However, the energetic terms of the energy balance calculation of both models are quite similar (Doherty et al., 1988). The additional degrees of freedom embedded in the mathematical structure of the Pierce model, allow for the adaptation of the model to other morphological groups. This can be of great interest regarding the invention of control strategies for customizable HVAC systems.

Fanger’s PMV/PPD (DIN EN ISO 7730:2005), our Pierce model and the corresponding TPMV/TPPD have been implemented in the object-oriented programming language Modelica/Dymola and serve as the fundamental code structure for the equivalent NMF-implementation. A comparative study concerning the energy demand of an ideal cooling/heating device, controlled for PMV and TPMV using IDA ICE, is introduced.
SIMULATION AND EXPERIMENT

Fanger’s core model
The idea of Fanger (1970) is to calculate the energy balance between the ambient climate and the human body to be able to estimate the appropriate thermal discomfort based on its energetic state (Eq. 1).

\[ L = M - W - S_D - E_{sw} - (R_D + R_W) - (C + R) \]  

(1)

In this context, the heat stored by the human body \( L \) is calculated as the difference between the metabolic heat produced \( M \), the heat lost to the environment through the skin and the respiratory tract and the energy needed for the heating of muscles due to mechanical work \( W \) (Table 1).

Table 1: Additional expressions of the energy balance calculation

<table>
<thead>
<tr>
<th>EXPRESSION</th>
<th>DESCRIPTION</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_D )</td>
<td>Water vapor diffusion through skin (insensible)</td>
<td>W/m²</td>
</tr>
<tr>
<td>( E_{sw} )</td>
<td>Evaporative heat loss due to sweating (sensible)</td>
<td>W/m²</td>
</tr>
<tr>
<td>( R_D )</td>
<td>Dry heat loss of respiratory tract</td>
<td>W/m²</td>
</tr>
<tr>
<td>( R_W )</td>
<td>Wet heat loss of respiratory tract</td>
<td>W/m²</td>
</tr>
<tr>
<td>( C )</td>
<td>Heat loss due to convection</td>
<td>W/m²</td>
</tr>
<tr>
<td>( R )</td>
<td>Radiative heat loss</td>
<td>W/m²</td>
</tr>
</tbody>
</table>

\( M \) and \( W \) are representing Fanger’s human core model. Regarding this, \( M \) is the most important parameter inside the model structure, because it is involved in nearly all the expressions used for the energy balance calculation (Eq. 2-5) and the estimation of important physiological parameters like mean skin temperature \( \theta_{skm} \) and sweating \( E_{sw} \).

\[ S_D = 0.00305 \times (5733 - 6.99 \times M - p_a) \]  

(2)

\[ E_{sw} = 0.42 \times (M - 58.15) \]  

(3)

\[ R_D = 0.0014 \times M \times (34 - \theta_a) \]  

(4)

\[ R_W = 0.00017 \times M \times (5867 - p_a) \]  

(5)

\[ \theta_{skm} = 35.7 - 0.0275 \times M \]  

(6)

\( p_a \) (Eq. 2) is representing the partial water vapor pressure and \( \theta_a \) (Eq. 4) the ambient air temperature.

\[ C = h_c \times f_d \times (\theta_d - \theta_a) \]  

(7)

The convective heat loss \( C \) from the body surface to its surrounding can be calculated from Eq. 7 where \( h_c \) represents the convective heat transfer coefficient, \( f_d \) the dimensionless clothing area factor and \( \theta_d \) the resultant surface temperature of the clothing combination.

\[ R = f_d \times \sigma \times \varepsilon \times (\theta_d + 273)^4 + (\theta_a + 273)^4 \]  

(8)

Eq. 8 describes the radiant heat loss from the body surface to the environment according to Stefan-Boltzmann’s law, involving the terms \( \theta_d \) as the mean radiant wall temperature, \( \varepsilon \) as the dimensionless skin emissivity and \( \sigma \) as the Stefan-Boltzmann constant \((5.67 \times 10^{-8} \text{W/m}^2\text{K}^4)\). \( R \) and \( C \) can be combined to form the dry heat loss of the human body \( DRY \). Dynamic reactions of the human thermoregulatory system like shivering, sweating and vasomotion are not considered explicitly.

Pierce model
Gage’s two-node Pierce model (Gage, 1973) is based on the same idea as Fanger’s model. It also calculates the energy balance of the human body according to the same basic equation (Eq. 1), but additionally considers dynamic physiological reactions of the human thermoregulatory system, evoked by changes in ambient climate. Appropriate reactions are mainly reflected in changes of skin- and core body temperature (Doherty et al., 1988; Fiala et al. 1999, 2001). In this context, the human physiology is geometrically approximated by two concentric cylinders, representing the body core and the skin shell (Passive System). The latter varies in thickness with respect to adaptations of skin blood flow \( SKBF \), caused by changes in ambient microclimate. The accompanying shift in total body mass from core to skin and vice versa, is expressed through the parameter \( ALPHA \).

\[ ALPHA = 0.0442 + (0.3509 \times SKBF - 0.01386) \]  

(9)

\( SKBF \) is influenced by vasomotive reactions like vasoconstriction \( STRIC \) (Eq. 11) and vasodilatation \( DILAT \) (Eq. 12).

\[ SKBF = (6.3 + DILAT)/(1 + STRIC) \]  

(10)

\[ STRIC = 0.5 \times COLDS \]  

(11)

\[ DILAT = 150 \times WARMC \]  

(12)

Regarding this, \( COLDS \) represents the afferent cold signal from the peripheral skin surface, calculated as the difference between the actual mean skin temperature \( TSKM \) and the setpoint temperature \( TSETSKIN \) (Eq. 13).

\[ COLDS = - (TSKM - TSETSKIN) \]  

(13)

\( WARMC \) is the afferent warmth signal from the body core and can be calculated as the difference between the setpoint temperature of the body core \( TSETCORE \) and the actual body core temperature \( TCR \) (Eq. 14).

\[ WARMC = (TCR - TSETCORE) \]  

(14)

Protection from cold is achieved by an increase in basal metabolic rate \( MBAS \) (Eq. 15) due to shivering reactions \( SH \) (Eq. 16).

\[ ALPHA = 0.0442 + (0.3509 \times SKBF - 0.01386) \]  

(9)
MBAS = MBAS + SH  \tag{15}

SH = 19.4 \cdot \text{COLD} \cdot \text{COLD}  \tag{16}
The afferent signal \text{COLD} from the peripheral skin surface can be calculated according to Eq. 17.

\text{COLD} = -(\text{TCR} - \text{TSETCORE})  \tag{17}

To avoid hyperthermia in hot climatic conditions, an additional sweating term \text{SW} (Eq. 18) is considered.

\text{SW} = 150 \cdot (\text{ALPHA} \cdot \text{WARMS}) + (1 - \text{ALPHA}) \cdot \text{WARMC} \cdot e^{\text{WARMS}/10.7}  \tag{18}
The afferent warmth signal from the skin surface \text{WARMS} can be calculated by Eq. 19.

\text{WARMS} = (\text{TSKM} - \text{TSETSKIN})  \tag{19}

For the sake of completeness, the single energetic terms for the calculation of the energy balance implemented within the Pierce model are listed below (Eq. 20-23).

\text{CRES} = 0.0012 \cdot \text{MBAS} \cdot (34 - \delta_o)  \tag{20}

\text{ERES} = 0.0023 \cdot \text{MBAS} \cdot (44 - \rho_o)  \tag{21}

\text{ERSW} = 0.68 \cdot \text{SW}  \tag{22}

\text{EDIF} = \text{PWET} \cdot \text{EMAX} - \text{ERSW}  \tag{23}

In this connection \delta_o describes the operative temperature of the ambient microclimate, \rho_o the partial water vapor pressure (see Eq. 2), \text{PWET} the dimensionless skin wettedness factor and \text{EMAX} the maximum evaporative heat loss from skin surface.

\text{DRY} = \text{CTC} \cdot \text{FCL} \cdot (\text{TSKM} - \delta_o)  \tag{24}

\text{CTC} = \text{CHR} + \text{CHC}  \tag{25}

In Eq. 24 \text{FCL} is the so called clothing thermal efficiency factor. Eq. 25 describes the calculation of the combined heat transfer coefficient \text{CTC}, consisting of the radiant heat transfer coefficient \text{CHR} and the convective heat transfer coefficient \text{CHC}. In contrast to the original Pierce model, which considers a static value for \text{CHC} depending on the person’s corresponding posture, our model uses the equation suggested in DIN EN ISO 7730 (Appendix D), involving the air velocity \text{VAIR} of the surroundings.

**Transient Predicted Mean Vote (TPMV)**

Eq. 26 shows the connection between Fanger’s empirical thermal sensation index \text{PMV} and the energy balance of the human body described in Eq. 1.

\text{PMV} = (0.303 \cdot e^{(0.036 + 0.028)} \cdot L  \tag{26}

In this context, Fanger’s original core model, used for the calculation of the heat storage \text{L} (Eq. 2-Eq. 5), has been replaced by the corresponding dynamic Pierce model (Eq. 15-Eq. 23). This consequently leads to the transient predicted mean vote \text{TPMV} (Eq. 27).

\text{TPMV} = (0.303 \cdot e^{(0.036 + 0.028)} \cdot \text{L}_{\text{Pierce}}  \tag{27}

Table 2 contains the comparison of the energy balance expressions of Fanger’s original core model and the equivalent expressions of the Pierce model in order to illustrate the analogy between both of them.

**Table 2: Comparison of energy balance expressions**

<table>
<thead>
<tr>
<th>FANGER MODEL</th>
<th>PIERCE MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_D</td>
<td>\text{CRES}</td>
</tr>
<tr>
<td>R_RW</td>
<td>\text{ERES}</td>
</tr>
<tr>
<td>\text{E}_{\text{SW}}</td>
<td>\text{ERSW}</td>
</tr>
<tr>
<td>\text{S}_{\text{SW}}</td>
<td>\text{EDIF}</td>
</tr>
<tr>
<td>\text{M}</td>
<td>\text{MBAS}</td>
</tr>
</tbody>
</table>

**Transient predicted percentage dissatisfied (TPPD)**

For the quantitative evaluation of the thermal sensation vote \text{PMV}, Fanger (1970) invented the index \text{PPD}, which enables the estimation of the percentage of people probably being dissatisfied with the actual climatic conditions (Eq. 28).

\text{PPD} = 100 - 95 \cdot e^{-0.03353 \cdot \text{TPMV}^{-0.2179} \cdot \text{TPMV}^2}  \tag{28}

The derived transient equivalent, based on our \text{TPMV}, is called \text{TPPD} and can be calculated according to Eq. 29.

\text{TPPD} = 100 - 95 \cdot e^{-0.03353 \cdot \text{TPMV}^{-0.2179} \cdot \text{TPMV}^2}  \tag{29}

**Model implementation of TPMV and TPPD**

Figure 1 shows the Modelica/Dymola structure of the described Pierce model, coupled with the newly invented \text{TPMV}/\text{TPPD}-model.

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**Figure 1: Modelica/Dymola implementation of the Pierce model coupled with TPMV/TPPD model**

The model itself consists of two interacting systems, representing the virtual human physiology (Passive System) and the appropriate central nervous system (Active System). The latter contains the thermoregulatory reactions necessary for keeping the
body core temperature $TCR$ on a constant level of about 37 °C. The Passive System calculates the energy balance $L$ based on the input data of the ambient climate ($\vartheta_O$, $VAIR$, relative humidity $RH$) and provides the appropriate parameters for $TPMV$ and $TPPD$. Figure 2 illustrates the equivalent IDA ICE model implemented in NMF.

Figure 2: NMF/IDA ICE implementation of the Pierce model coupled with $TPMV$ and $TPPD$

Validation of the human core models
To ensure the correct implementation of the Pierce model, transferred from Modelica/Dymola to NMF/IDA ICE, a model validation was performed. In this context the measurement data of the before mentioned office room, recorded by the equipment listed in Table 3 during an 8-hour office day, serves as inputs for the appropriate procedure.

The zonal model
IDA ICE is a software tool, developed for the analysis of the energy consumption of entire buildings and indoor climatic effects.

Depending on the scope of application, different zonal models are recommended. Energy performance calculations can be carried out, using the provided Simplified Zone Model (SZM). However, investigations concerning indoor climatic effects require a more detailed model, called the Detailed Zone Model (DZM). The latter allows for the study of displacement ventilation, thermal comfort assessment and day light levels at arbitrary room locations. In addition, moisture and heat of people present in the corresponding zone is modeled according to DIN EN ISO 7730.

The DZM consists of two main heat balance equations, one referring to the air volume, the other one to the enclosing surfaces. Convective heat fluxes, caused by air exchange and internal loads, originating from equipment and occupants, are considered in Eq. 30.

The heat balance of the enclosing surfaces is calculated according to Eq. 31 and considers the following physical processes:

- conduction through the wall
- convection
- longwave/shortwave radiation

The radiative heatfluxes are calculated by the law of Stefan-Boltzmann and geometric dependencies are treated by view factors, respectively.

$$0 = Q_{\text{Cond from Surf}} + \alpha A_{\text{Surf}} (\vartheta_{\text{Air Surf}} - \vartheta_{\text{Surf}}) + Q_{\text{Longwave}} + Q_{\text{Shortwave}}$$

Validation of the zonal model
The above described $DZM$, has been applied to a real office room replicated in IDA ICE (Figure 3).

![Figure 3: Geometrical model of an office room replicated with IDA ICE](image)

In order to model the internal gains of the $DZM$ close to reality, two occupants, two notebooks and the related monitors are considered. The emitted energy of the electrical devices within the zonal model is estimated to be 75 W/person.

Additional internal heat sources like desks, boards and other equipment are approximated by an internal wall, possessing a mass of 435 kg and a specific heat capacity of 920 J/(kg K). Occupants’ behavior

Table 3: Components of the Comfort Index Measurement Device

<table>
<thead>
<tr>
<th>DEVICE</th>
<th>AHLBORN TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data logger</td>
<td>2690 8A</td>
</tr>
<tr>
<td>Globe thermometer</td>
<td>ZA 9030-FS2</td>
</tr>
<tr>
<td>Humidity/temperature sensor</td>
<td>FH A646-E1</td>
</tr>
<tr>
<td>Thermo-anemometer</td>
<td>FVA605-TA10</td>
</tr>
</tbody>
</table>

In order to model the internal gains of the $DZM$ close to reality, two occupants, two notebooks and the related monitors are considered. The emitted energy of the electrical devices within the zonal model is estimated to be 75 W/person.
concerning the opening and closing of windows/doors and their physical presence is considered by the use of realistic schedules.

Local weather data (Schneider, 2014), including solar radiation, air velocity and relative humidity for the appropriate office day, were set as boundary conditions at the outer surfaces of the replicated office room and deliver the resulting operative temperature \( \vartheta_O \) of the corresponding air volume.

The building construction of the replicated office room (Figure 3) can be extracted from Table 5.

### Performance simulation of the office room

The office room depicted in Figure 3 serves as the base model for our performance simulation study. Parameters like geometrical structure, building construction, internal gains and occupant behavior are described in the section before.

The scope of the study is to investigate the effect of the application of the Pierce model (Figure 2) on the energy demand of an ideal cooling device, embedded inside the air zone of a DZM. The maximum power dissipation is limited to 1800 W.

By applying the prescribed thermal sensation index \((PMV \text{ or } TPMV)\), a PI-controller adjusts the power of the mentioned cooling device until the operative temperature \( \vartheta_O \) of the mentioned air zone satisfies the desired thermal sensation index. In this context, the PI-unit is only triggered, if occupants are present in the corresponding room. To avoid numerical instabilities, a minimum value of 0.01 was set for \( PMV \) as well as \( TPMV \). The corresponding IDA ICE model is depicted in Figure 4.

Regarding the reference values of the PI-controller, the \( TPMV \)-index is reflecting the dynamic activity of the thermoregulatory system of a human being, exposed to the prevailing climatic conditions. Necessary input parameters defined for the calculation of \( PMV/TPMV \) are depicted in Table 6.

### Table 6: Input parameters for PMV and TPMV model

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESCRIPTION</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v_{AIR} )</td>
<td>Air velocity</td>
<td>0.15 m/s</td>
</tr>
<tr>
<td>Met</td>
<td>Activity</td>
<td>1.2 act</td>
</tr>
<tr>
<td>W</td>
<td>Mechanical work</td>
<td>0.0 act</td>
</tr>
<tr>
<td>Icl</td>
<td>Clothing insulation</td>
<td>0.38 clo</td>
</tr>
</tbody>
</table>
The simulation setup for the performance simulation of the office room is shown in Table 4.

RESULTS

Comparison of human models

Figure 5 shows the calculated heat storage $L$ of the different human core models implemented in Modelica/Dymola and NMF. As mentioned before, the results are based on real input data recorded during an eight-hour office day.

The Pierce model implementations show good agreement. The total heat storage $L$, calculated by the Fanger model, is constantly exceeding the results of the Pierce models, resulting in a final difference in amplitude of about 39 W/m².

The comparison of the sensible heat loss of the human models, caused by water vapor diffusion through the skin, is depicted in Figure 6.

Again, the different Pierce model implementations show good agreement. Their highly dynamic behavior is reflected in amplitudes between 7.02 W/m² and 26.85 W/m². In contrast to that, the simulation results of the Fanger model are almost constant (from 10.02 W/m² to 10.13 W/m²).

Figure 6: Insensible heat loss through the skin surface

The sensible heat loss, caused by regulatory sweating, is illustrated in Figure 7. The results show a constant sweating rate ESW calculated by the Fanger model (4.88 W/m²) and increasing sweating rates ERSW for both of the Pierce implementations, leading to a difference in amplitude of about 34.37 W/m².

For a comparison of the total dry heat loss through the respiratory tract see Figure 8. A constant offset of about 0.04 W/m² can be obtained from the comparison of the different Pierce models and the corresponding Fanger model.

Figure 7: Sensible heat loss by regulatory sweating

The latter shows an elevated heat loss throughout the whole simulation cycle. However, the behavior of the models looks similar.

Figure 8: Dry heat loss through respiratory tract

Again, the different Pierce model implementations show similar model behavior. In this case the results of the Pierce models exceed the simulation results of the Fanger model. The difference in amplitude is about 0.07 W/m².
The total dry heat loss $\text{DRY}$ of the different human models, depicted in Figure 10, is composed of convective and radiative processes on the body surface.

Once again, the models show similar behavior. However, the amplitudes of the Pierce models exceed the appropriate amplitude of the Fanger model, leading to a final difference of about 8.19 W/m².

**Thermal Sensation**

Figure 11 shows the effect of the Pierce model on the prediction of the thermal sensation.

It is obvious, that the $\text{PMV}$-index predicted by the Fanger model ($\text{PMV}$ between $+0.9$ and $+2.22$), constantly exceeds the $\text{TPMV}$ of the Pierce model ($\text{TPMV}$ between $-1.26$ and $+0.95$).

**Thermal Discomfort**

The prediction of thermal discomfort ($\text{PMV/TPMV}$) is illustrated in Figure 12.

A constantly growing percentage of dissatisfied ($\text{PPD}$) can be obtained for the Fanger model. This is reflected in increasing $\text{PPD}$-amplitudes, starting at 36.3 % and reaching a maximum value of about 85.24 %. In contrast to that, the $\text{TPPD}$-values of the Pierce models are fluctuating between 5 % and 36.3 %, constantly remaining below the amplitudes of the Fanger model.

**Validation of the zonal model**

Figure 13 shows the comparison of the simulated operative temperature $\theta_o$ predicted by the $\text{DZM}$ and the real measurement data recorded by the equipment listed in Table 3.

The results show good agreement. The maximum difference in amplitude (2760 s) between the measured and simulated data is 0.7 °C.
Performance simulation of an office room

The effect of the different control strategies on the power demand of the above mentioned cooling device is depicted in Figure 14.

![Figure 14: Power of cooling device controlled by PMV and TPMV](image)

A difference of 1335 W (about 75%) in maximum amplitude between the PMV-/TPMV-controlled unit becomes apparent.

Operative temperatures $\theta_O$ of the appropriate air zone are depicted in Figure 15. The TPMV-controlled $\theta_O$ (between 27.1 °C and 30.95 °C) exceeds the PMV-controlled $\theta_O$ (between 26.08 °C and 26.7 °C) throughout the whole simulation period.

![Figure 15: Operative temperatures $\theta_O$ of the appropriate air zone](image)

The heat loss of the TPMV-model, caused by regulatory sweating, can be extracted from Figure 16. It is shown, that the corresponding amplitude is constantly increasing, resulting in a maximum value of 31.95 W/m².

![Figure 16: Evaporative heat loss due to sweating, TPMV controlled](image)

For the comparison of the predicted percentage of dissatisfied (PPD vs. TPPD) see Figure 17.

![Figure 17: PPD vs. TPPD](image)

A small difference in amplitude of 0.75 % is present at the time the occupants enter the office room (TPMV-controlled PPD=5 %, PMV-controlled PPD=5.75 %).

**DISCUSSION**

The simulation results of the different Pierce-model implementations (Figure 5-10) show good agreement. This indicates the correct transfer of the model structure from Modelica/Dymola to the NMF/IDA ICE. The fluctuating amplitudes are the consequence of the dynamic simulation-inputs, originating from the measurement data recorded by the equipment of Table 3 during an 8-hour office day.

In Figure 5 the comparison of the simulated total heat storage $L$ between the Fanger model and the different Pierce model implementations is shown. As described in Eq. 1 the parameter $L$ comprises the total energetic processes involved in the calculation of the total human heat balance. Between the start of the simulation and the first 2600 seconds, an increase in $L$ can be obtained for the Fanger model. In contrast to that, the Pierce models show a decrease in amplitude from 23.29 W/m² down to 3.33 W/m². This is in...
In accordance with Figure 7, showing an increase in heat loss by regulatory sweating for the Pierce models (from 2.88 W/m² to 26.79 W/m²), caused by the dynamic thermoregulatory reactions of the Active System, resulting from the steep rise in operative temperature $\theta_O$ (Figure 13).

It is obvious, that the corresponding heat loss of Fanger’s core model remains at a constant level of 4.88 W/m², based on the correlation between the static metabolic heat production $M$ and the evaporative heat loss $E_{sw}$ (Eq. 3).

Regarding the Pierce model, the final amplitude of $L$ converges to 0 W/m², indicating the accomplishment of thermal neutrality. However, the Fanger model remains at a significantly higher level (39.42 W/m²) thus reflecting a disequilibrium in the total human heat balance. The corresponding thermal sensation results are illustrated in Figure 11.

A direct correlation between the heat storage $L$ and $PMV/TPMV$ becomes apparent (Eq. 26 and Eq. 27). The starting value of $PMV$ as well as $TMPV$ adds up to +1.22 for each model, indicating a similar energetic initial state (Figure 5). As mentioned before, the total heat load of the surrounding microclimate on the Pierce model is compensated by regulatory sweating. This dynamic component finally leads to the thermal neutrality statement $TPMV=0$. Based on the missing dynamic of Fanger’s regulatory sweating rate $E_{sw}$ (Eq. 3), the human core model gets heated up, expressed by a $PMV=+2.08$. The corresponding thermal comfort statements ($PPD=80\%$, $TPPD=5\%$) are depicted in Figure 12.

For our investigation on the power demand of an ideal cooling device, embedded inside the re-modeled office room from Figure 3, a validation of the corresponding air zone (Figure 4) was necessary. In this connection, the governing state variable of the $DZM$ is represented by the operative temperature $\theta_O$ (Figure 13). In general, the results show good agreement. The average deviation of $\theta_O$ adds up to 0.5 °C and is originating from theidealization of occupant behavior and internal thermal loads (Eq. 30). As a consequence, the $DZM$ is regarded suitable for our investigations. The power demand of the ideal cooling device, necessary for adapting $\theta_O$ to the prescribed thermal sensation index $PMV/TPMV$, is illustrated in Figure 14.

A maximum reduction of power demand (75\%) can be reached, using the realistic human Pierce model, represented by the $TPMV$-index, as reference value for the PI-controller unit. The corresponding Active System control mechanisms (Figure 1) cause an increase in heat loss due to regulatory sweating (Figure 16). The operative temperatures $\theta_O$ of the corresponding air zone still remains on a higher level (Figure 15), leading to a reduction in power demand of the appropriate cooling device. The resulting influence on thermal comfort can be extracted from Figure 17. Even though the operative temperature is beyond the normal comfort range, the predicted percentage of dissatisfied is still on a comfortable level ($TPPD=5\%$).

However, the influence of sweating on the thermal dissatisfaction level of individuals is currently unclear and has to be considered in future work. The adjustment of Eq. 27 and Eq. 29 is inevitable for the prediction of reliable comfort statements.

**CONCLUSION**

This study shows the need for realistic human models regarding energy performance simulations, involving thermal comfort models. Based on Gagge’s 2-node Pierce model, we invented a dynamic thermal sensation index ($TPMV$) and showed its potential regarding the invention of energy saving control strategies, satisfying the requirements of thermal comfort ($TPPD$). Such kind of controllers, involving the energy balance of the human body for the control of HVAC systems are state of the art (VDI/VDE 3512-1:2009).

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>DZM</td>
<td>Detailed Zone Model</td>
</tr>
<tr>
<td>NMF</td>
<td>Neutral Model Format</td>
</tr>
<tr>
<td>PMV</td>
<td>Predicted Mean Vote</td>
</tr>
<tr>
<td>PPD</td>
<td>Predicted Percentage Dissatisfied</td>
</tr>
<tr>
<td>SZM</td>
<td>Simplified Zone Model</td>
</tr>
<tr>
<td>TPMV</td>
<td>Transient Predicted Mean Vote</td>
</tr>
<tr>
<td>TPPD</td>
<td>Transient Predicted Percentage Dissatisfied</td>
</tr>
</tbody>
</table>

**REFERENCES**


Schneider, C., Ketzler, G. 2014. [Hrsg.]: Klimamessstation Aachen-Hönn - <01/13 till 12/13>, RWTH Aachen, Geographisches Institut, Lehr- und Forschungsgebiet Physische Geographie und Klimatologie, ISSN 1861-4000.