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Coupling a Thermal Comfort Model with Building Simulation for User Comfort and Energy Efficiency

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Abstract

This paper describes a methodology for coupling an advanced model of the thermo-regulatory system of the human body that describes its physiological processes, a comfort model that evaluates thermal sensation and comfort, and the ESP-r building simulation software that computes the transient thermal response of a building model. The objective of this study was to utilise the physiology and comfort models to dynamically modify the heating and cooling temperature set points of a zone controller in ESP-r, in accordance with the computed human thermal sensation and achieve realtime thermal comfort management. The comunication between the software is managed by the ESP-r controller, which at each simulation time step prints the building states on text files. The building states are then used by the physiology and comfort models to compute the perceived sensation and comfort metrics. These metrics are utilised by a logic in the controller of the indoor conditions to calculate the temperature set point corrections for the next time step. Simulation results were generated for a single zone model, using UK climate, over five winter and five summer days. Both winter and summer tests showed the expected behaviour in set point modification. The integration of the comfort model during the simulation of the case study building shows promising results in adjusting the set point by maintaining a relatively wide temperature range that ensures the building does not utilise excessive energy to maintain a narrow comfort band and at the same time that local thermal comfort requirements are satisfied.

Keywords

energy, user, simulation, efficiency, building, coupling, model, comfort, thermal

Disciplines

Engineering | Science and Technology Studies

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COUPLING A THERMAL COMFORT MODEL WITH BUILDING SIMULATION FOR USER COMFORT AND ENERGY EFFICIENCY

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ABSTRACT

This paper describes a methodology for coupling an advanced model of the thermo-regulatory system of the human body that describes its physiological processes, a comfort model that evaluates thermal sensation and comfort, and the ESP-r building simulation software that computes the transient thermal response of a building model.

The objective of this study was to utilise the physiology and comfort models to dynamically modify the heating and cooling temperature set points of a zone controller in ESP-r, in accordance with the computed human thermal sensation and achieve real-time thermal comfort management.

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1 INTRODUCTION

Over the past 25 years, research in the realm of thermal comfort has evolved significantly. Fanger's PPD (predicted percentage of dissatisfied) curve already showed that there is no ambient condition in which all individuals feel comfortable. (Fanger 1970). Based on this knowledge and in the search for energy efficient solutions, researchers started developping devices which provide local comfort while a broader dead band can be maintained in the central HVAC system (Brager et al. 2015, Pasut et al. 2015, Hoffmann et al. 2016). Such devices target a local area of the body or a specific body part which itself is particularly sensitive to warm or cold conditions. Convective heat transfer through fans is used for local cooling, and radiative or conductive heat transfer is used for heating the core region (chest, back, pelvis) and feet (Zhang et al. 2015). If comfort is provided through a local device, the central HVAC system can be operated at lower temperatures during the heating period and at higher temperatures during the cooling period.

Nowadays, we know how to model and predict thermal comfort with respect not only to ambient conditions, but also to age, gender, height, weight, body fat, activity and clothing (Völker et al. 2009). At the same time, building simulation has become a state-of-the art tool to estimate temperature distribution and energy consumption of buildings.

As a logical next step, we have coupled a physiology model and a thermal comfort model with a building simulation software in order to be able to understand and predict the effictiveness of local comfort devices under a variety of building types and climates.

2 THE SINGLE SOFTWARE PARTS

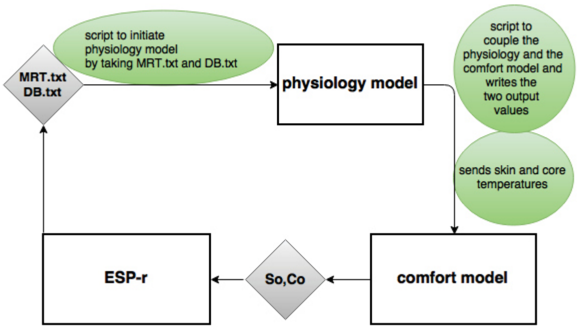

Figure 1: Coupling of the software parts

Figure 1 shows the individual programs which are externally coupled with each other (white boxes): 1) the building simulation software ESP-r (ESP-r 2016), 2) a physiology model written in C++ (Huizenga et al. 2001), 3) a spreadsheet based thermal comfort model. The three green boxes represent two scripts which enable the coupling between the programs. The first script automates the following steps that are required for the physiology model to run at every time step: it reads surrounding conditions from ESP-r; it runs the physiology simulation, and; it writes body temperatures as output. The second script reads the body temperatures from the output of the physiology model and runs the comfort model, which in turn produces thermal sensation and comfort values. The sensation and comfort values are then read by ESP-r which actuates a heating or a cooling system to adjust the indoor conditions for the next time step.

In the following, we describe the individual programs and the underlying algorithms in more detail.

2.1 The physiology model

The physiology model of this study is based on the Stolwijk 25-node model (Stolwijk 1971). The model discretises the body in four layers (core, muscle, fat, skin) for each body segment (head, chest etc.). For each compartment, the model calculates a temperature and compares it to a reference temperature. The difference between the calculated temperatures and the set point temperatures determines the signals that are constitutive for the following four regulative mechanisms: sweating, shivering, vasodilation, vasoconstriction.

The 65-node model that we are using is based on important experimental and numerical work in the field of thermo-regulatory models of the human body over the last 50 years from (Stolwijk 1971), (Tanabe et al. 2002), (Huizenga et al. 2001) and others. It describes the physiological processes through a complex set of equations in which the human body is represented through 16 body parts, each of them consisting of a core layer, a muscle layer, a fat layer and a skin layer and a blood flow node (see Figure 2). Layers are connected to each other through conduction while body segments are linked via the blood flow model.

The core temperatures of the human body are maintained in a narrow range and are regulated mainly through the skin (sensible and latent heat transfer) and through shivering and breathing. To achieve the thermal heat balance, heat sources from inside and outside (metabolic heat production, solar load, longwave radiation) are considered as well as heat sinks (breathing, sensible and latent heat transfer at the skin) within the body.

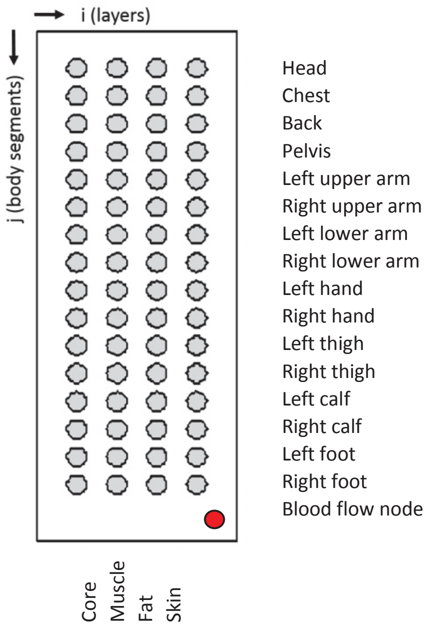

Figure 2: 64 nodes to represent 64 compartments of the human body and one blood flow node

2.2 The thermal comfort model

Several human subject tests have shown that there is a strong relation between skin and core temperatures and thermal sensation (Zhang 2003).

The relationship between skin and core temperatures and thermal sensation is included into the comfort model of this study and the necessary inputs for the skin and core temperatures are taken from the physiology model that has been described in Section 2.1. The empirical comfort equations in the comfort model were developed at the UC Berkeley (Zhang et al. 2010a, 2010b, 2010c).

The outputs of the thermal comfort model are thermal sensation in terms of being warm or cold, and thermal comfort in terms of feeling comfortable or uncomfortable. Both metrics range from -4 (very cold or very uncomfortable) to +4 (very hot or very comfortable). The sensation and comfort metrics are given for each of the 16 body segments (local sensation / local comfort) as well as for the whole body (overall sensation / overall comfort).

The local sensation output for one body segment depends on the calculated skin temperature; with high skin temperatures leading to warm or hot local sensations and low skin temperatures leading to a cool or cold sensation. The definition of high or low skin temperatures refers to set point values implemented in the program. Some body parts are more susceptible to heat than others, e.g. the head. Other body parts on the other hand are particularly sensitive to cold, e.g. back, chest and pelvis. The relationship between the local sensation for the 16 body parts and the overall sensation is complex and is described in Zhang et al. (Zhang et al. 2010a, 2010b, 2010c).

The further the local sensation metric is from neutral (neutral conditions equal 0 for the sensation metric), the less comfortable one perceives the thermal conditions for that specific body part. The body parts with the highest or lowest thermal sensation value (i.e. most uncomfortable cases) determine the overall perception of thermal conditions. For example, if the model calculates that the head and one upper body part have high skin temperatures and therefore high values for sensation, the conditions for these body parts are perceived as very uncomfortable and the person will overall feel very uncomfortable.

2.2.1 Sensation

According to Zhang et al. (Zhang et al. 2010a), static local sensation for different body parts can be predicted by a logistic function where the main inputs are local skin temperatures and the mean skin temperature. For transient local sensation, time derivatives of skin and core temperature are considered.

Some body parts, like chest, back and head, have a small temperature change range and they are more sensitive to temperature changes than other body parts. This means for example that if there is a small decrease in skin temperature for these sensitive body parts, the body would feel much cooler than if the same decrease of skin temperature occurred for less sensitive body parts.

Overall sensation (S_o) is influenced by strong local sensations, which dominate the overall sensation. In Zhang's human comfort model, body parts have different weighting factors for warm and cool sensations.

Zhang et al. (Zhang et al. 2010a) found that a weighted average of the most extreme sensation plus the third-most-extreme sensation determines the overal sensation value S_o.

2.2.2 Comfort

If sensation decreases or increases with regard to the neutral sensation point, the comfort level decreases. The dependency of local comfort on the local and overall sensation are described in detail in (Zhang et al. 2010b). In this study overall comfort (C_o) is calculated with the two most uncomfortable body part votes and also with the most comfortable vote, because in transient environments the most comfortable feeling could sometimes be the dominant feeling that is perceived by a person according to (Zhang et al. 2010c).

2.3 ESP-r building simulation program

The ESP-r program (2016) was selected as the building simulation platform for this study because of its flexible open source structure that allows internal and external coupling with new models at a time step level. ESP-r is a finite volume dynamic whole building simulation program, in which the built environment (building, plant systems, controls, etc.) is discretised into a number of control volumes. Conservation of energy and mass principles are applied for each control volume and numerical simultaneous solution techniques are used to solve the set of energy and mass balance equations that are derived from all control volumes. A detailed description of the discretisation process and the numerical techniques used in ESP-r is given by Clarke (2001). The open source nature of ESP-r was also necessary for the development of the control logic that would respond to the output of a local thermal comfort model in a way that will be described in Section 3 of this paper.

As with most building simulation programs, ESP-r includes the well-discussed in the literature Fanger's PMV model (Fanger, 1970) that calculates average zone thermal comfort metrics. An adaptive comfort control algorithm is also available in ESP-r where comfort bands are updated at each time step based on the running mean comfort temperature that is calculated with the process described in EN 15251 Standard (EN 15251, 2007)

In addition to the average zone comfort calculations, a user in ESP-r could define Mean Radiant Temperature (MRT) sensors that have a specific geometry and position in a thermal zone and by using ray tracing calculations, the view factors can be produced at the specific locations and for each side of the MRT sensors. However, analytical local comfort and physiology models have not hitherto been implemented within ESP-r or within the majority of the state-of-the-art building simulation programs.

3 COUPLING THE SOFTWARE

The objective of this study was to utilise the physiology and comfort models described in Section 2 to dynamically modify the heating and cooling temperature set points, in accordance with the human thermal perception computed by the combination of the physiology and comfort models. To simulate the effect of this correction on the set points, the two models were coupled with the ESP-r building simulation software. The ESP-r model is required to simulate the indoor building conditions and passes the necessary information (so far: mean radiant temperatures and air temperatures) to the comfort and physiology models at each simulation time step. The ESP-r simulation will then pause at each time step until the comfort and physiology models compute the S_o and C_o metrics, which are then used by ESP-r to modify indoor conditions in a way that suits better the indoor local comfort requirements of the occupant.

Figure 3 shows the details of the coupling between the software tools of this study.

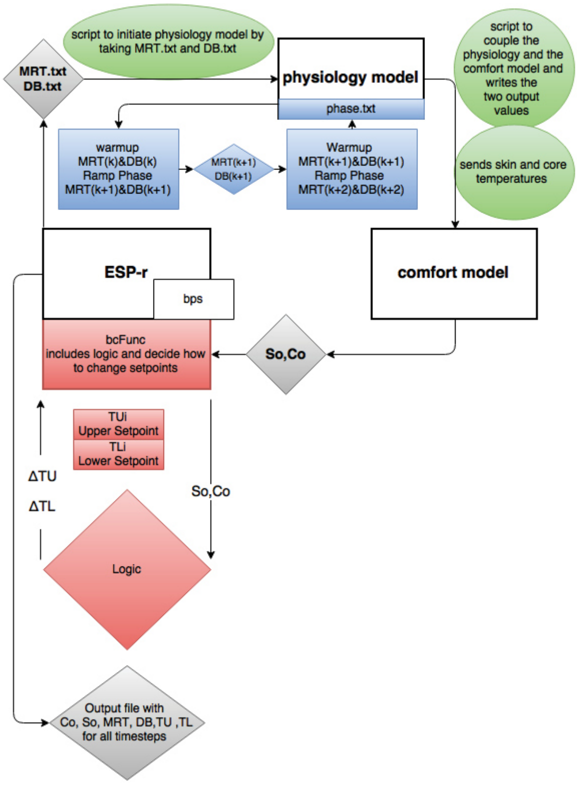

Figure 3. Information flow within the coupled system

3.1 ESP-r controller

Since the integration of the physiology and comfort models has to be achieved at each time step of the simulation in ESP-r, and since it involves exchange of information on sensed variables and set-point variations, the coupling was implemented inside a controller routine of ESP-r. Specifically, the general ideal controller *BCL00* subroutine, located in the *bcfunc.F* of ESP-r, was modified to utilize the set points defined in the standard controller for the warm-up period, and then activate the coupling with the physiology and comfort models to calculate and increment or decrement of the heating and cooling set-points for the next time step (Equation 1) based on the values of S_o and C_o.

$$\text{if } k < n\_warmupsteps \quad \begin{cases} TL(k) = TL_i \\ TU(k) = TU_i \end{cases} \qquad (1)$$

$$else, \quad \begin{cases} TL(k) = TL(k) + \Delta TL(k) \\ TU(k) = TU(k) + \Delta TU(k) \end{cases}$$

Where k is the current time step, *n_warmupsteps* represents the number of time steps of the warm up period in ESP-r, TL and TU are the heating (lower) and cooling (upper) temperature set points respectively, TL_i and TU_i are the initial temperature set points for heating and cooling respectively, ΔTL and ΔTU are the increments of the lower and upper set points that are derived from the calculations of the comfort and physiology models.

The sensor selected in the ESP-r controller uses a routine that provides the area weighted mean radiant temperature as a result of the calculated inside surface temperatures from the surface energy balances. While the sensor obtains information for the mean radiant temperature of the zone in order to pass it to the physiology and comfort model, it senses the inside air temperature of the zone (convective component). The air and mean radiant temperatures are printed in two text files at each time step, and these files are the input to the physiology and comfort models (Figure 1). The physiology model computes the skin temperatures of the 16 body parts and the core temperatures for back, chest and pelvis. Based on this information, the S_o and C_o values are computed by the comfort model and are printed in a third text file. This third text file with the S_o and C_o values is then read by ESP-r on the following time step to calculate ΔTL and ΔTU according to the rules that will be presented in Section 3.2. Once the physiology and comfort models provide feedback (S_o and C_o) to ESP-r the controller in ESP-r will actuate convective heat fluxes that will be imposed on the air of the zone.

3.2 Set point increment levels

The physiology and comfort models provide values to the ESP-r controller for the current time step: the thermal sensation S_o and thermal comfort C_o as described in section 2.2.

A positive and negative value of S_o means that a person is feeling hot or cold respectively. Neutral thermal sensation should lead to positive comfort values. If the sensation deviates strongly from 0 (neutral thermal sensation) in either direction, it will result in a negative value of C_o.

As an example, a negative C_o and a positive S_o would identify a situation where a person is feeling uncomfortable because the space is too warm. On the other hand, if C_o is positive and S_o is negative the person is comfortable, but would at the same time feel slightly cold.

It should be mentioned here that while the above stated example is always true for steady state conditions, in transient conditions there might be situations where a non-neutral sensation is desired. In the case of previous overheating, entering a cool to cold environment ($S_o < 0$) can lead to high comfort values, up to $C_o > 2$).

The temperature set point adjustments that have been used as a trial to evaluate the benefits from coupling the different models in this study are presented in Table 1. It should be noted that such adjustments are also sensitive to the thermal inertia of the building and functionality that is adaptive to the specific building case should become part of the future developments of this study.

Table 1:
Set points increments and decrements

Co	***So***	***ΔTL***	***ΔTU***
Co <0	0< So≤0.5	0	-0.1
	0.5< So≤1	0	-0.2
	1< So≤2	0	-0.5
	2< So≤3	0	-0.8
	So>3	0	-1.0
	-0.5≤ So<0	+0.1	0
	-1≤ So<-0.5	+0.2	0
	-2≤ So<-1	+0.5	0
	-3≤ So<-2	+0.8	0
	So<-3	+1.0	0
0≤ Co≤0.5		0	0
0.5< Co		0	0
reset to:		TLi	TUi

Starting with a broader than usual dead band, a negative comfort value (C_o) will provoque a narrowing of the dead by either increasing the heating set point or decreasing the cooling set point. When the comfort value (C_o) is greater than 0.5, the set point temperatures are set back to the initial value. For comfort values between 0 and 0.5, no change of set point temperatures takes place. This allows for a stabilization of thermal conditions in the room as well as for the human body and avoids excessive oscillation.

Section 4 demonstrates some of the results that were produced for a trial case where the above coupling has been achieved.

4 RESULTS

Figure 4 and 5 show simulation results after coupling the physiology and comfort model with ESP-r. The results were generated for a single zone model where an ideal controller is used to match the energy requirements for heating and cooling. The input parameters of the physiology model were set to an air velocity of 0.1 m/s, clothing level of 0.6 clo and a metabolic rate of 1 met. Solar radiation on the body was neglected. Indoor air temperature and MRT were exchanged between ESP-r and the physiology model as explained in section 3.

Figure 4 shows five days during summer in a moderate climate (UK test climate). Sensation and comfort values are shown on the secondary axis in the lower part, while setpoint temperatures and indoor air temperature are shown on the primary axis. Tu (upper set point) was set to 28 °C and Tl was set to 20 °C. During morning, evening and night hours, Co values greater than 0 (i.e. just comfortable) could be maintained without a change of set point temperature. Around 10 am, sensation values start raising and in consequence, comfort values are dropping. This causes the upper set point temperature Tu to be lowered. When the comfort value raises again above 0.5, Tu is reset to its initial value. This causes an oscillation of indoor temperature which results in a subsequent oscillation of sensation and comfort values.

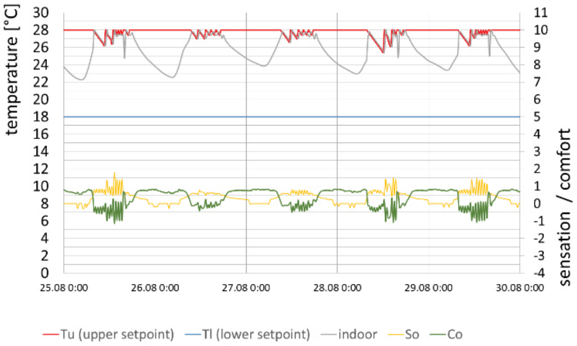

Figure 4. Adjusting the upper set point temperature

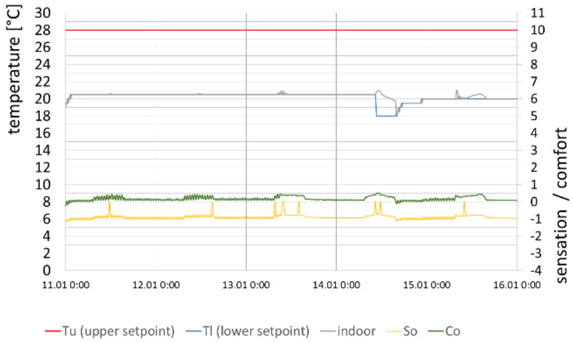

Figure 5. Adjusting the lower set point temperature

In Figure 5 five days in the heating period are shown with initial limits of Tl = 18 °C and Tu = 28 °C again. Immediately after the warm-up period when the sensation and comfort models are called, the lower set point is raised to 20.5 °C due to the cool sensation of So = -1 and the just uncomfortable comfort value of Co = -0.5. At day 4, a sudden increase of overall sensation to So = 0 leads to an increase of Co to Co ≥ 0.5, and consequently the set point is lowered again to the initial value (Tl = 18 °C). No comfortable condition can be maintained at a room temperatur of 18 °C, so the set point is raised to 20 °C for the remaining time.

5 DISCUSSION

The simulations shown in section 4 were run with a dead band from 18 to 28 °C. For conventional HVAC systems, controls are usually set to a narrow temperature range from 21 to 25 °C (these values can differ slightly depending on climate and expectations). Using the comfort model, we found room temperatures up to 26 °C still providing acceptable comfort under hot conditions. For the heating period, indoor air temperatures of 20 °C were necessary to satisfy thermal comfort conditions. These simulation results justify the conventional dead band and show that the detailed physiology and comfort model confirms simpler comfort approaches such as Fanger's PMV.

However, the great opportunity of using the more complex approach of modeling human thermal comfort lies in the application of local devices which can provide thermal comfort independently from the central system. For desk fans, foot warmers or heated/cooled chairs, the sensation and comfort values can be calculated according to the heat transfer of the body with the local devices, and the dead band of the central system can be adjusted according to the comfort values from the detailed physiology and sensation model.

6 CONCLUSION

It could be shown that the described method allows to adjust the dead band for cooling and heating according to the predicted sensation and comfort metrics. The presented approach is promising for further investigation for several reasons:

- A broader dead band of HVAC systems will lead to potentially significant reductions of energy consumption. For example, in cooling conditions and for specific types of cooling systems, a 1K reduction of set point temperature can lead to a 10 - 15% of reduction in energy consumption (Ward & White, 2007; Hoyt et al. 2009). With the development and implementation of local low-energy systems (personal control systems), an extension of the dead bands will be possible.

- If simulation methods are used to develop and implement controls, the coupling with a detailed local thermal comfort model allows radiative heating and cooling systems to be controlled with higher precision since the long-wave radiative heat transfer is taken into account for specific locations in the room and for single body parts. Thermal comfort research has shown that with radiant floors and ceilings, air temperatures can be kept beyond typical indoor air temperatures (Wang et al., 2009).

- The physiology model can be adjusted to individuals, i.e. to their body fat, age, gender and metabolic activities. Heating and cooling of a kinder garden requires different indoor (surrounding body) conditions than those suited for a home for elderly people. While this has not yet been in the focus of our current research, it will be included in further studies.

However, the current state of the coupling as described in this paper needs to be further tested, adjusted and extended in the following ways:

- Some significant input is missing in the physiology model in order to predict the actual thermal sensation and comfort. Currently, the variables that are exchanged between ESP-r and the physiology model are limited to dry bulb room air temperature and mean radiant temperature. Important variables such as solar load onto body parts and air speed at the body parts are not yet taken into account. In the future, we will include the effect of solar radiation on the specific body parts by implementing the SoLoCalc tool developed by Hoffmann (Hoffmann et al., 2012) into the physiology model.

  Additionally, the knowledge of the directional air speed around single body parts is indispensable to predict thermal comfort. Convection governs about half of the sensible heat transfer and most of the latent heat transfer at the skin. Air velocity needs to be either measured or calculated with computational fluid dynamic solvers and coupled with the physiology and comfort model (Völker 2011).

- The temperature curves shown in Figure 4 and 5 are generated with an ideal controller and an instantaneous heating/cooling system. While an ideal controller can give representative results in simulations, in reality the thermal response time of a building can be relatively slow, causing unnecessary oscillations of the temperature set points if the control step and change rates are not selected properly. It is anticipated to further test the coupling between the software tools of this paper by testing the control logic with a more realistic controller (e.g. with dead band and a PID controller for the heating and cooling delivery).

Overall, thermal comfort modelling in combination with building simulation will help us to better understand human thermal comfort and the opportunities for energy savings when using local devices for heating and cooling and adjusting the dead band for central HVAC systems.

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REFERENCES

Brager G., Zhang H., Arens E. 2015. Evolving opportunities for providing thermal comfort. Building Research & Information, 43(3), pp. 274-287.

Clarke J. Energy Simulation in Building Design, Elsevier; 2001. doi:10.1016/B978-075065082-3/50001-2.

EN 15251, 2007. Indoor environmental criteria for design and calculation of energy performance of buildings. CEN. Brussels, Belgium.

ESP-r. 2016. Open source building simulation program: https://github.com/ESP-rCommunity/ESP-rSource

Fanger P.O. 1970. Thermal Comfort: Analysis and applications in environmental engineering, New York: McGraw-Hill.

Hoffmann S., Jedek C., Arens E. 2012. Assessing Thermal Comfort Near Glass Facades, Conference proceedings, BEST3, Building Science and Technology, Atlanta, USA, April 2012

Hoffmann S., Boudier K. 2016. A new approach to provide thermal comfort in office buildings – a field study with heated and cooled chairs, IAQVEC 2016, Seoul, Republic of Korea, October 2016.

Hoyt T., Lee K.H., Zhang H., Arens E. & Webster T. 2009. Energy savings from extended air temperature setpoints and reductions in room air mixing. International Conference on Environmental Ergonomics 2009, August 2-7, Boston. available at:

http://escholarship.org/uc/item/28x9d7xj (accessed April 15 2016)

Huizenga C., Zhang H. & Arens E. 2001. A model of human physiology and comfort for assessing complex thermal environments, Building and Environmental Performance Simulation: Current State and Future Issues, Building and Environment 36: 691–699.

Pasut W., Hui Z., Arens E., Zhai Y. 2015. Energy-efficient comfort with a heated/cooled chair. Results from human subject tests, Building and Environment, 84, pp. 10-21.

Stolwijk, J. 1971. A mathematical model of physiological temperature regulation in man, NASA Contractor report, NASA CR-1855, Washington, D.C.

Tanabe S., Kobayashi K., Nakano J., Ozeki Y. & Konishi M. 2002. Evaluation of thermal comfort using combined multi-node thermoregulation (65MN) and radiation models and computational fluid dynamics (CFD), Special Issue on Thermal Comfort Standards 34, pp. 637–646.

Voelker C., Hoffmann S., Arens E., Huizenga C., Zhang H. 2009. Heat and moisture transfer through clothing, Eleventh International IBPSA Conference, Glasgow, Scotland, July 27-30, 2009

Voelker, C. 2011. Entwicklung und messtechnische Validierung der Kopplung von CFD-Simulation mit einem thermophysiologischen Modell zur Bestimmung der thermischen Behaglichkeit, PhD. Thesis, Bauhaus-Universität Weimar, Germany

Wang Z., Zhang H., Lehrer D., Arens E., Huizenga C., Yu T., Hoffmann S. 2009. Evaluating Thermal Comfort of Radiant Floors and Ceilings, 4th International Building Physics Conference; Istanbul, June 2009.

Ward J., White S. 2007. Smart Thermostats Trial, ET/IR 970/R, Prepared for Sustainability Victoria, 29 pages.

Zhang H. 2003. Human thermal sensation and comfort in transient and non-uniform thermal environments, Ph.D. Thesis, University of California, Berkeley (USA), 435 pages.

Zhang H., Arens E., Huizenga C., Han T. 2010a. Thermal sensation and comfort models for non-uniform and transient environments: Part I: local sensation of individual body parts. Building and Environment, 45(2), pp. 380-388.

Zhang H., Arens E., Huizenga C., Han T. 2010b. Thermal sensation and comfort models for non-uniform and transient environments: Part II: local comfort of individual body parts. Building and Environment, 45(2), pp. 389-398.

Zhang H., Arens E., Huizenga C., et al. 2010c. Thermal sensation and comfort models for non-uniform and transient environments: Part III: whole-body sensation and comfort. Building and Environment, 45(2), pp. 399-410.

Zhang H., Arens E., Taub M., Dickerhoff D., Bauman F., Fountain M., Pasut Wilmer., Fannon D., Zhai Y., Pigman M. 2015. Using footwarmers in offices for thermal comfort and energy savings, Energy and Buildings, 104, pp. 233-243.