THERMOPHYSIOLOGICAL MODELS: A FIRST COMPARISON

K. Katic[1], W. Zeiler[2], G. Boxem[2]
[1,2]University of Technology Eindhoven, Department of the Built Environment
Den Dolech 2, Eindhoven
Netherlands

ABSTRACT

Modeling the thermal response of the human body under various personal and environmental conditions is needed for designing HVAC systems and their control systems for buildings. Many human thermal response models have been developed based on the energy balance equations for the human body since 1970.

Fanger's steady-state model and Gagge's two-node transient model were used to evaluate thermal sensation. The first multi-segmented model was developed by Stolwijk and it became one of the most influential multi-node models. In recent years, various thermophysiological models were developed. Several improved multi-segment models have been developed including the models discussed by Tanabe, Fiala, Yi and Fengzhi, the Berkeley Comfort Model and ThermoSEM.

There are many thermal physiological models to predict the mean skin temperatures of each body segment. In the paper the most commonly used and recent developed thermophysiological models are briefly explained and evaluated. The modified Kesselring method was used to evaluate the models.

INTRODUCTION

Nowadays there is a great focus on the reduction of energy and sustainable development across all sectors. There is a lot of attention for net zero energy buildings, since buildings are currently responsible for 40% of primary energy consumption in most countries and are a significant source of CO_2 emissions. Consequently the thermal comfort of the buildings occupants is compromised (Schellen et al., 2010). For human existence and health it is essential to provide thermal comfort in indoor environment (Parsons et al., 2003; Baughman and Arens et al., 1996). When observing Heating, Ventilation and Air Conditioning (HVAC) system performance, energy consumption and thermal comfort are factors that should be taken into account (Freire et al., 2008; Zhou et al.,2013). The successful application of low-energy HVAC systems are determined with the thermal contentment of the building occupants. A lot of research was aimed towards developing models for the prediction of thermal comfort.

In recent years there is an ongoing interest in studying physiological response of the human body to different environment conditions. In order to provide thermal comfort and thermal satisfaction to the occupants in buildings, various thermophysiological models were developed. The goal of this paper is to evaluate and discuss the most recent and most common used thermophysiological models.

THERMOPHYSIOLOGICAL MODELS

One of the most important examples of homeostasis is the regulation of body temperature. A constant core body temperature at 36.5 °C (Choi and Loftness et al., 2012) is maintained under adequate conditions within narrow ranges. Thermoregulation reactions are the result of the deviation in the core temperature (Ivanov et al., 2006). In humans, body temperature is primary controlled by the thermoregulatory center in the hypothalamus. Simplified thermoregulatory system is shown in Figure 1. The change of the brain temperature above the set point results in vasodilation and sweating, and the vasoconstriction and shivering are result of the reduction in the skin temperatue. Warm and cold systems are coupled with crossed inhibitory connections (Parsons et al., 2003).

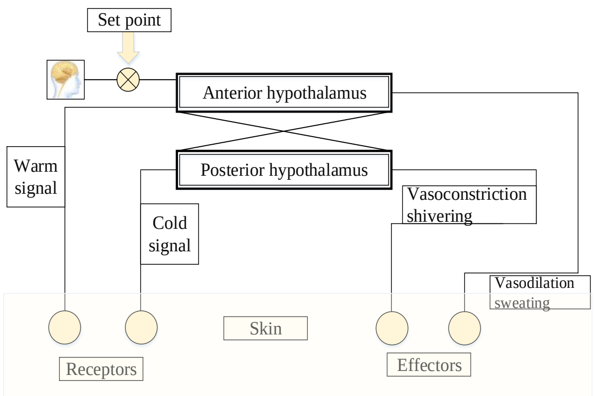

Figure 1: Diagram of the thermoregulatory system (Parsons et al.,2003) modified from (McIntyreal et al .,1980)

The human organism can be divided into two interacting systems of thermoregulation, hence the thermophysiological models mainly consist of a controlling active system and the controlled passive system (Fiala et al., 1999).

The passive system simulates the physical human body and it models heat transfer within the human body and between the human body and its environment (Van Oeffelen et al., 2008).

Within the human body metabolic heat is produced and distributed over the body areas by blood circulation. For internal heat transfer and body heat exchange thermal properties of blood, muscle fat, bone are important (Parsons et al., 2003). Through the body tissue layers the heat is carried to the clothing insulated body surface by conduction (Fiala et al., 1999).

The passive system must be controlled by a dynamic system of thermoregulation in order to regulate temperature in a changing environment (Parsons et al., 2003).

Thermoregulatory system is presented as the active system that simulates the human body's regulatory responses of shivering, sweating and vasomotion (Fiala et al., 2001). The mean skin temperature, core temperature and the rate of the change in skin temperature are the main signals for the active system (Van Oeffelen et al., 2008). Since 1970. many different human thermal respons models have been developed (Figure 2).

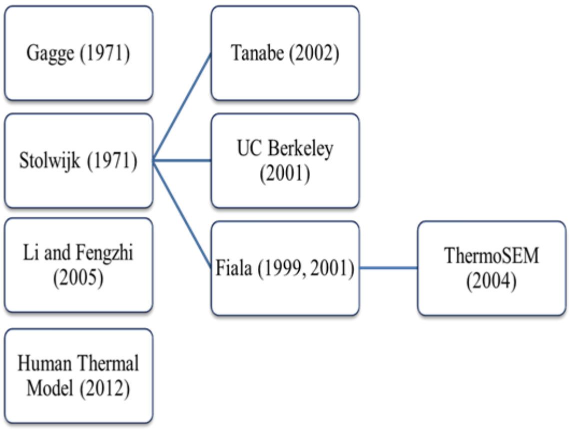

Figure 2: Development of thermophysiological models trough years

To evaluate thermal sensation Fanger's model and Gagge's two-node model have been generally used. Fanger's empirical model is capable to predict the overall thermal sensation (Schellen et al., 2013). The model includes prediciton of the mean thermal sensation vote (predicted mean vote-PMV) and the results are expressed on the 7-point ASHRAE thermal sensation scale that is widely accepted and used (ASHRAE et al., 2010).

Gagge developed a simple two-node model that is capable to predict thermal sensation under transient environmental conditions (Zolfaghari & Maerefat et al., 2010). The body is simulated as a two concentric cylinders; outer layer of skin and the inner cylinder that presents body skeleton, muscles and internal organs. Skin and core temperatures are simulated by a physiological model of the heat transfers between core, skin and the environment, using dynamic thermoregulatory control functions for sweating, vasodilatation and constriction, and shivering (Zolfaghari and Maerefat et al., 2010).

Stolwijk model

The most influential multi-node model that paved the foundations for many human thermal-modeling studies was developed by Stolwijk. The 25-node thermoregulation model was developed for the NASA in order to create a mathematical model of human thermoregulation (Stolwijk et al., 1971).

The passive part of the Stolwijk model consists of six segments (head, trunk, arms, legs, hands and feet) and each segment is divided into four layers: the core, fat, muscles and skin (Stolwijk and Hardy et al., 1966). Also the model includes a central blood compartment that is thermally connected to all the other nodes. The effects of counter-current heat exchange in the blood flow and the blood flow characteristics in local tissue are not included in the Stolwijk model. The re-evaluation suggests that the Stolwijk model accurately predicts both the absolute and the tendency in transient mean skin temperature of an "average" person under low activity conditions (Munir et al., 2009).

Tanabe model

Based on the Stolwijk model, a 65-node thermoregulation model was developed by Tanabe. The Tanabe model is able to predict the variation of physiological conditions for various parts of the body (16 segments). The whole body is divided into head, chest, back, pelvis, right shoulder, left shoulder, right arm, left arm, right hand, left arm, right thigh, left thigh, right leg, left leg, right foot and left foot. The body segments consist of core, muscle, fat and skin layers (Tanabe et al., 2002).

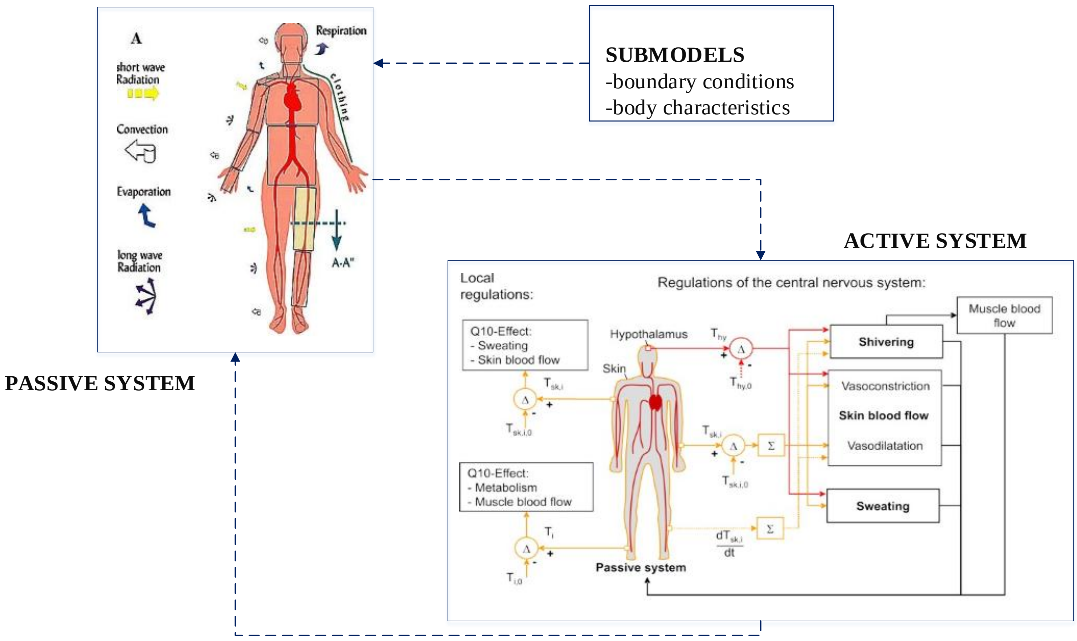

Figure 3: Schematic diagram of the thermophysiological models modified from (Fiala et al., 2012)

The last 65th node in the model represents the central blood compartment and all the body segments have artery and vein blood pools. Also superficial veins and arteriovenous anastomoses (AVA) are included in the vascular system of the limbs. Vasoconstriction, vasodilation, perspiration and shivering are also included into the model. As the heat characteristics of the human body depend on height, weight, sex, age, body fat percentage, basal metabolic rate and cardiac index these physical parameters in this model can be changed (Kobayashi & Tanabe al., 2013)

Fiala model

The Fiala model is a multi-node model that extensively simulates the human body including the predictions of overall and local physiological responses. The original Fiala model has represented an average human (body surface area of 1.85 m^2, body weight of 73.4 kg, and body fat content of 14%) and the body was idealized as 15 cylindrical or spherical elements (Fiala et al., 1999). Model consists of annular concentric tissue layers and seven different tissue materials (brain, bone, muscle, lung, fat, skin and viscera) are used. The environmental heat exchange was modelled including local heat losses from the body by free and forced convection, solar irradiation, long-wave radiation, evaporation of moisture from the skin and insulation effect of the clothing (Fiala et al., 1999) . For the purpose of creating a new Universal Thermal Climate Index (UTCI) the Fiala model was selected. The original Fiala model was adapted and expanded into new UTCI-Fiala model. The adapted model is formed as a 12 spherical or cylindrical compartment, 187-node model. The left and right extremities are joined and each extremity is presented as a unity (Fiala et al., 2012). In the model thermoregulatory responses of the central nervous system; shivering, sweating and peripheral vasomotion. One of the new implementations in the new model is adaptive clothing model that combines outdoor environmental factors, clothing permeability and behavioral adaptation of the clothing insulation (Fiala et al., 2012).

UC Berkeley model

The UC Berkeley multi-node comfort model is based on the Stolwijk model of human thermal regulation and the Tanabe model, however it includes several significant improvements. Physiological mechanisms like vasomotion, sweating and metabolic heat production are explicitly considered (Huizenga and Zhang et al., 2001). The Berkeley model can simulate an arbitrary number of segments. For developing the model, 16 body segments were used (head, chest, back, pelvis, right and left upper arms, right and left lower arms, right and left hands, right and left thighs, right and left lower legs, and right and left feet). Each segment consists of four body layers (core, muscle, fat, and skin tissues) and a clothing layer. The blood compartments are represented with a separate series of nodes (Huizenga and Zhang et al., 2001). Although many of the models are capable of considering physiological differences between individuals, in practice most of them are using a single set of physiological data to represent an average person.

The UC Berkeley model incorporates set of physiological parameters which may be used to predict variations in thermal response between individuals. The model has incorporated the body builder function and Figure 4 shows the relationships between the model inputs and the predicted physiological data (Zhang et al., 2001). Apart from ability to model unlimited number of body segments there are more improvements that have been made compared with the Stolwijk model : improved blood flow model, including counter-current heat exchange in the extremities, improved convection and radiation heat transfer coefficients, incorporation of a radiation heat flux model. Also clothing heat and moisture transfers, heat loss by conduction to surfaces in contact with the body are considered and explicit radiation heat transfer calculation using angle factors are considered(Huizenga and Zhang et al., 2001)

ThermoSEM model

The mathematical thermoregulation model (ThermoSEM) is a dynamic thermo-sensation model that is based on the Fiala model (Schellen et al., 2013). Like other models that are suitable to simulate transient condition ThermoSEM is also consisted of passive and active components. In the ThermoSEM, the difference from the Fiala model is that the extremities have been split in upper and lower parts and that the skin perfusion is corrected for tissue volume (Severens et al., 2008). The human body is modelled of 18 concentric cylinders for body parts and one sphere representing the head. In addition, there is a spatial subdivision into three sectors. The cylinders are divided into anterior, posterior and interior sector (Kingma et al., 2012). Within the model individual characteristics as height, weight and fat percentage can be taken into account as well as the asymmetric boundary conditions (Van Marken Lichtenbelt et al., 2004). The main difference between the Fiala model and ThermoSEM is in the active part of the model. Looking at the neurophysiological concepts for thermoregulation in the active part, a model for skin blood flow based on neurophysiological concepts was developed and included in the model. At this time equations that define shivering or sweating are still obtained from Fiala's active model. Figure 5 shows the neurophysiological skin blood flow model that simulates five phases of the thermoregulatory tract.

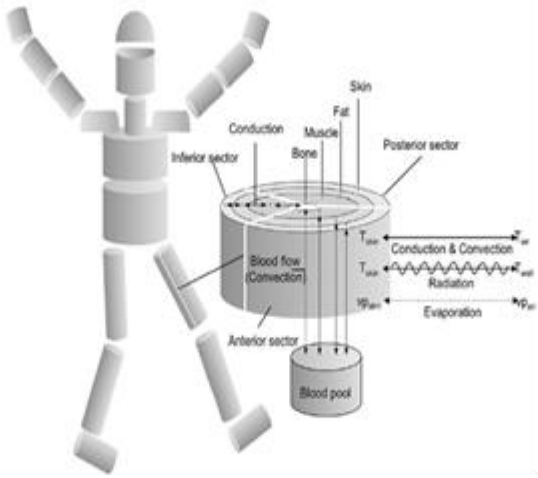

Figure 4: Schematic diagram of the ThermoSEM model (Kingma et al., 2012)

In the first phase local skin temperatures are transduced into the dynamic fire rates of warm and cold temperature sensitive neurons. Following the first phase, in accordance with the neurophysiological pathways the skin neuron fire rates are integrated. Third, the integrated peripheral warm and cold sensing pathways project to the medial pre-optic area (MPO) of the hypothalamus where local warm sensitive neurons are inhibited. The fourth phase represents the inhibition of the ventromedial medulla neurons. In the last phase, from the ventromedial medulla skin blood flow is controlled with efferent neurons (Kingma et al., 2012).

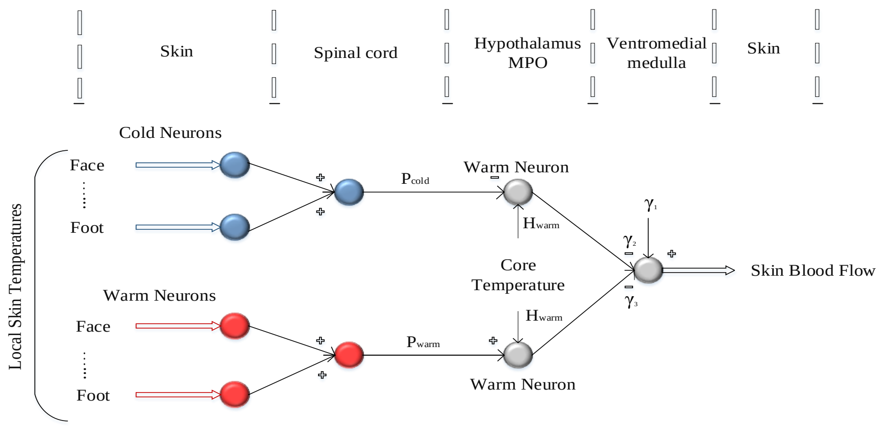

Figure 5: Schematic of neuronal model for control of skin blood flow (Kingma et al., 2012)

To better understand and evaluate different thermoregulation models the modified Kesselring method was used. Kesselring developed a simple and effective decision support method with which different variants can be compared with each other. The method incorporates two criteria for the requirements, a category for realization and a category for functionality. Evaluation is conducted in terms of each criterion separately. The values determined are aggregated into a score. The evaluation criteria are given scores on the individually basis. The obtained evaluation scores are marked in the Stärke diagram (Zeiler et al., 2007).

The thermoregulation models were compared and evaluated using the modified Kesselring method. The evaluation scores are given according to the authors individual understanding of models based on the literature review.

The evaluating criteria were separated into two categories, critical body parts and human body systems vs. building systems analogy.

Figure 6 shows a table of how each group of criteria is divided into sub-requirements that are evaluated and supplementary to the total score of each group of criteria. The total score of the criteria are expressed as a percentage of the maximum score to gain.

In the diagram shown in Figure 7 the percentage of the human body systems criteria group is set out on the y- axis and the percentage of the critical body parts criteria group on the x-axis. The best variants lie near the diagonal and have high scores. In the Kesselring diagram it is easy to see on what side of criteria the improvements must take place. This evaluation method shows that models can be improved mainly on the critical body parts aspect by improving vascular system and thermoregulatory mechanisms as vasodilatation and vasoconstriction of critical body parts. Also the degree of neurophysiological concepts for thermoregulation should be increased and implemented into the models.

MODEL			**Stolwijk**	**Tanabe**	**Fiala**	**UC Berkeley**	**ThermoSEM**	**HTM**	**Yi & Fengzhi**
DESCRIPTION			25-node	65-node	187-node	Multi-node model (arbitary number of segments)	Multi-node model(arbitary number of segments)	Human thermal modelling & thermal sensation and comfort model	Thermoregulation model combined with clothing model
FUCTIONALITY / HUMAN BODY SYSTEMS VERSUS BUILDING SYSTEMS ANALOGY		Ideal	Stolwijk	Tanabe	Fiala	UC Berkeley	ThermoSEM	HTM	Yi & Fengzhi
Human body system automotation (thermoreception) vs. Building system automotation	Skin blood flow based on neurophisiology	4	1	1	1	1	4	1	1
	Shivering and sweating based on neurophisiology	4	1	1	1	1	1	1	1
Vascular system vs. Hydronic piping	Arteries and veins	4	2	3	2,5	3,5	3	3	2
Environmental conditions vs. Air quality in the building	Transient conditions	4	3	3,5	3,5	4	3,5	3	3
	Non-uniform conditions	4	1	3,5	1	4	3,5	3	1
	Total points (-)	20	8	12	9	13,5	15	11	8
	Total percentage (%)	100%	40%	60%	45%	68%	75%	55%	40%
REALIZATION / CRITICAL BODY PARTS		Ideal	Stolwijk	Tanabe	Fiala	UC Berkeley	ThermoSEM	HTM	Yi & Fengzhi
Detailed vascular system	Vascular system, ArterioVenous Anastomosis	4	1	3,5	2,5	3	2	2,5	2
Active system	Local vasoconstriction and vasodilatation model	4	1	1	1	1	1	1	1
Flexibility	Gender	4	1	3,5	1	4	1	1	1
	Different climate area	4	1	1	1	1	1	1	1
	Height, weight, fat percantage…	4	1	3,5	1	4	3,5	1	1
	Total points (-)	20	5	12,5	6,5	13	8,5	6,5	6
	Total percentage (%)	100%	25%	63%	33%	65%	43%	33%	30%

Figure 6: Categories used for evaluating thermoregulation models using modified Kesselring method

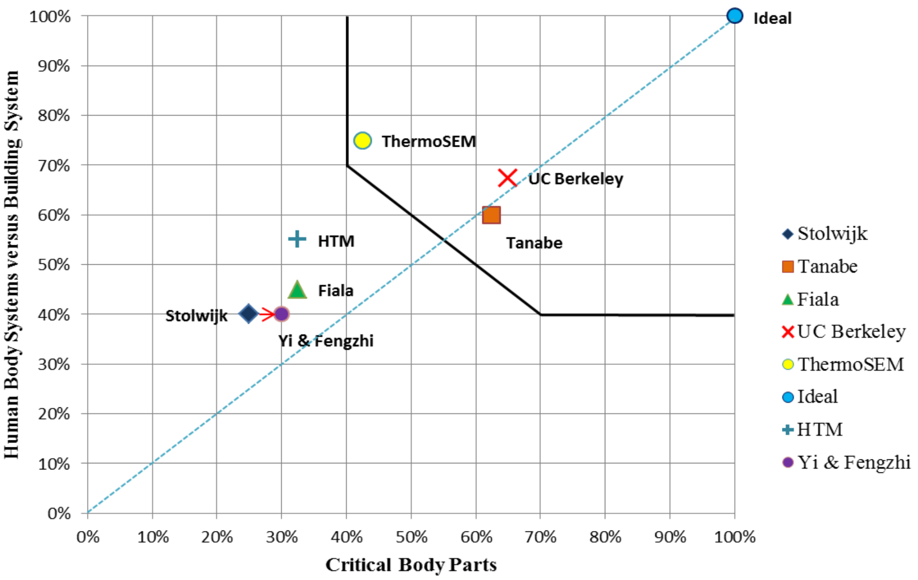

Figure 7. S-diagram of modified Kesselring showing the evaluated thermoregulation model

Other models

Yi and Fengzhi developed the model that combines a modified 25-nodes thermoregulation model from Stolwijk with a dynamic clothing model that describes the dynamic coupled heat and moisture transfer in clothing (Fengzhi and Yi et al., 2005). The influence of clothing material on thermal responses of the human body are investigated by using an integrated model of a clothed thermoregulatory human body. The model seems able to predict dynamic heat and moisture transfer between the human body and the clothing system. The model results show that during environmental transients that the human thermoregulation process is effected by the hygroscopicity of clothing materials (Fengzhi and Yi et al., 2005).

The Human Thermal Model (HTM) was developed for the non-commercial building simulation environment VTT House. The model is combining the human thermal modelling with a thermal sensation and comfort model inside of a building simulation program. The Zhang's method (Zhang et al., 2003) is used for the thermal sensation and thermal comfort calculations. The HTM models the human body physical interaction with the surrounding area and the physiological response of the human body (Holopainen et al., 2012).

CONCLUSIONS

Thermal comfort is an imperative indicator of building performance and inline of that important for human wellbeing and health. With the constant demand for the energy reduction the comfort of the occupants is compromised as well as their health. Thermoregulation model is a valuable tool used for

prediction of the thermal response of the human body under different environmental conditions. Therefor, there is a great necessity to start the building design process from the human perspective and thermoregulation models could be very useful in the design of new high performance buildings.

In this paper several thermoregulation models were reviewed and compared. The multi-node models take into account the anatomical and thermal-physiological properties of the human body to simulate the human heat transfer inside the body and at its surface. Compared with the simplified two-node Gagge's model where the temperature within each compartment is assumed to be uniform, multi-node models consider the inhomogeneous distribution of temperature and thermoregulatory responses over all segments of human body. For the thermal comfort evaluation Gagge modeled the human body as two nodes: the skin and the core. Multi-segmental models with advanced vasomotion models are capable to predict local skin temperatures of individual body parts.

It is also observed that in some of the models physiological differences between humans are not considered. The human thermal response to the environment is considerably influenced by the variations in physiology between individuals. More advenced thermoregulation models as ThermoSEM and Berkeley model use a set of physiological data to represent an individual person. However, there is a question how to develope a feasible system in the building that will recognize personal physiological charachteristics of every occupant in the building.

It is noted that existing thermoregulation models don't include a clothing characteristics in an extensive way. Fengzhi & Yi et al. (2005) proved that the hygroscopicity of clothing materials influences the human thermoregulation process significantly during environment transients. It is material to incorporate a dynamic clothing model into a thermal regulatory model.

The thermal environments where humans carry out their daily activities are often asymmetrical (non-uniform or transient). Thermal environmental asymmetry can be more pleasurable than the conventional uniformity and under these environmental conditions the reduction of required energy for conditioning systems is possible. In recent years, more progressive models that can predict transient behavior were developed. Over the last few years at the UC Berkeley, the model's ability to predict human reaction to non-uniform thermal environments during transient processes has been researched. The Berkeley model is used to predict the thermal sensation of local body parts and overall thermal sensation under non-uniform conditions.

Meanwhile, there is a question whether a thermophysiological models can be used in the built environment for the prediction of thermal sensation. As stated by Schellen et al. (2013) thermal comfort can be assessed on a more individualized level under complex, daily encountered thermal environments by using a thermophysiological model in combination with a thermal sensation model. Even though more advanced models were developed over last few years, there is a need for further research, development and improvement before the models can be used under more daily encountered conditions in daily building design practice.

FUTURE RESEARCH

In order to satisfy different needs of building occupants and to improve thermal comfort it is essential that individual approach is implemented and that the individual comfort within the control loop is included.

Personalized conditioning systems have been proved to positively impact the thermal comfort and along with that to have the ability of energy reductions with the proper control strategy (Zhang et al. 2010; Schiavon et al. 2010; Schiavon & Melikov et al. 2009; Veselý & Zeiler et al. 2014). Our research is focused on the development of new comfort process control strategies and personalized conditioning system. We think that the required thermal comfort level should be seen from a neurophysiological perspective (Kingma et al. 2012). We already used the outcome of one of our experiments to test and to apply the neuro-physiological model (Vissers et al. 2014). In the future, the use of the thermoregulation models to predict overall and local thermal comfort in non-uniform environmental conditions will be evaluated with the outcome of experiments of localized conditioning by individual controlled heating of specific body parts.

REFERENCE

ASHRAE, S., 2010. Thermal Environmental Conditions for Human Occupancy. , 2010.

Baughman, A. V & Arens, E.A., 1996. Indoor Humidity and Human Health Part-I: Literature Review of Health Effects of Humidity-Influenced Indoor Pollutants. *ASHRAE TRANSACTION*, 102.

Choi, J.-H; Loftness, V; 2012. Investigation of human body skin temperatures as a bio-signal to indicate overall thermal sensations. *Building and Environment*, 58:258–269.

Fengzhi, L; Yi, L; 2005. Effect of clothing material on thermal responses of the human body. *Modelling and Simulation in Materials Science and Engineering*, 13(6): 809–827.

Fiala, D. 2012. UTCI-Fiala multi-node model of human heat transfer and temperature regulation. *International journal of biometeorology*, 56:429–41.

Fiala, D; Lomas, K.J; Stohrer, M; 2001. Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions. *International journal of biometeorology*, 45(3):143–59.

Fiala, D; Lomas, K.J; Stohrer, M; 1999. A computer model of human thermoregulation for a wide range of environmental conditions:the passive system. *Journal of Applied Physiology*, 87:1957-1972

Freire, R.Z; Oliveira, G.H.C; Mendes, N; 2008. Predictive controllers for thermal comfort optimization and energy savings. *Energy and Buildings*, 40(7):1353–1365.

Holopainen, R; 2012. *A human thermal model for improved thermal comfort* , Aalto University.

Huizenga, C; Zhang, H; Arens, E, 2001. A model of human physiology and comfort for assessing complex thermal environments. *Building and Environment*, 36: 691–699.

Ivanov, K.P; 2006. The development of the concepts of homeothermy and thermoregulation. *Journal of Thermal Biology*, 31(1-2):24–29.

Kingma, B; 2012. *Human Thermoregulation - A synergy between physiology and mathematical modelling*. Maastricht University.

Kobayashi, Y; Tanabe, S; 2013. Development of JOS-2 human thermoregulation model with detailed vascular system. *Building and Environment*, 66:1–10.

McIntyre, D.A., 1980. *Indoor Climate*, London: Applied Science.

Munir, A; Takada, S; Matsushita, T; 2009. Re-evaluation of Stolwijk's 25-node human thermal model under thermal-transient conditions: Prediction of skin temperature in low-activity conditions. *Building and Environment*, 44(9):1777–1787.

Parsons, K; 2003. *Human Thermal Environments: The effects of hot, moderate and cold environments on human health, comfort and performance* Second Edi; London & New York: Taylor & Francis.

Schellen, L; Loomans, M; Van Marken Lichtenbelt, W.D; Frijns, A; De Wit, M.H; 2010. Assessment of thermal comfort in relation to applied low exergy systems. In *Adapting to Change: New Thinking on Comfort*. Cumberland Lodge, Windsor

Schellen, L; Loomans, M.G.L.C; Kingma , B.R.M.; De Wit, M.H; Frijns, A.J.H; van Marken Lichtenbelt, W.D;2013. The use of a thermophysiological model in the built environment to predict thermal sensation. *Building and Environment*, 59:10–22.

Schiavon, S; Melikov, A.K; 2009. Energy-saving strategies with personalized ventilation in cold climates. *Energy and Buildings*, 41(5):543–550.

Schiavon, S; Melikov, A.K; Sekhar, C; 2010. Energy analysis of the personalized ventilation system in hot and humid climates. *Energy and Buildings*, 42(5): 699–707.

Severens, N.M.W; 2008. *Modelling Hypothermia in Patients Undergoing Surgery*. Eindhoven University of Technology.

Stolwijk, J., 1971. *A mathematical model of physiological temperature regulation*, New Haven, Connecticut 06510.

Stolwijk, J; Hardy, J.D; 1966. Temperature regulation in man--a theoretical study. *Pflügers Archiv für die gesamte Physiologie des Menschen und der Tiere*, 291(2):129–62.

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). 34:637-646.

Van Marken Lichtenbelt, W.D. et al., 2004. Effect of individual characteristics on a mathematical model of human thermoregulation. *Journal of Thermal Biology*, 29(7-8):577–581.

Van Oeffelen, E C.M; Loomans, M; De Wit, M.H; Van Marken Lichtenbelt, W.D; Frijns, A; 2008. Application of a thermophysiological model for assessing non-uniform thermal environments. In *The 11th International Conference on Indoor Air Quality and Climate*. Copenhagen.

Veselý, M; Zeiler, W; 2014. Personalized conditioning and its impact on thermal comfort and energy performance – A review. *Renewable and Sustainable Energy Reviews*, 34:401–408.

Vissers, D; Zeiler, W; Boxem, G; Vesely, M; Verhaart, J; 2014. Neuron fire rates simulations of cold thermal sensations validated by measurements. In *Counting the Cost of Comfort in a changing world*. Cumberland Lodge, Windsor, UK.

Zeiler, W; Savanovic, P; Quanjel, E; 2007. Design decision support for the conceptual phase of the design process; *International association of societies of design research*; The Hong Kong Polytechnic University

Zhang, H; Arens, E; Kim, D; Buchberger, E; Bauman, F; Huizenga C; 2010. Comfort, perceived air quality, and work performance in a low-power task–ambient conditioning system. *Building and Environment*, 45(1): 29–39.

Zhang, H; Huizenga, C; Arens, E; Yu; T; 2001. Considering individual physiological differences in a human thermal model. *Journal of Thermal Biology*, 26(4-5):401–408.

Zhou, X; Lian, Z; Lan, L; 2013. An individualized human thermoregulation model for Chinese adults. *Building and Environment*, 70:257–265.

Zolfaghari, A; Maerefat, M; 2010. A new simplified thermoregulatory bioheat model for evaluating thermal response of the human body to transient environments. *Building and Environment*, 45(10):2068–2076.