THE ROLE OF ENVIRONMENTAL AND PERSONAL VARIABLES IN INFLUENCING THERMAL COMFORT INDICES USED IN BUILDING SIMULATION

Stephanie Gauthier[1]
[1]UCL Energy Institute, London, United-Kingdom

ABSTRACT

The need to identify variables, which influence human behaviour, has become one of the priorities in the quest to reduce energy demand. Environmental and personal variables, as set out in the thermal comfort models, have long been associated with people's behaviour by predicting their state of thermal comfort or rather discomfort. The aim of this paper is to explore and to report on the influences of these variables on thermal discomfort indices used in building simulation models. Surprisingly, the results of the sensitivity analysis show that different indices are most sensitives to different variables.

INTRODUCTION

One application of building simulation is to assess the design and associated energy consumption of buildings while maintaining an acceptable level of occupants' thermal comfort. This paper aims to review thermal comfort assumptions of building simulation. The current thermal comfort models used in building simulation are of two types: adaptive and predictive models.

Adaptive models are derived from empirical studies, and assume that occupant's preferred indoor temperature varies with external weather conditions. Therefore people's behaviour may vary according to the different seasons; summer, autumn, winter, and spring. Also occupants are given time and opportunity to adapt, through:

- opening and closing of windows and/or doors,
- modifying their activity,
- modifying their food and liquid intake,
- modifying their level of clothing insulation,
- using a local device: hot-water bottle, warm-hand pads, local fan as mechanical ventilation with unconditioned air, shutters, etc.

Intended for naturally ventilated buildings, these models are part of the ASHRAE 55 and the EN15251.

The second type of thermal comfort model is based on physical and physiological properties. The most notable model are: Fanger model (one-node) (Fanger, 1970), Pierce model (two-nodes) (Gagge et al. 1986), and Kansas State University model (two-nodes) (Azer and Hsu, 1977). These differ in the physiological models employed and the criteria used to predict thermal sensation. Described in ASHRAE 55, EN15251, and ISO 7730, these models are applied to mechanically conditioned buildings (heated and cooled), which aim to provide a uniform environment. While seeking to reduce energy demand, this suggests that where possible buildings should be designed to deliver comfortable indoor-conditions without the use of mechanical systems.

This paper first reviews the thermal comfort models used in building simulation software and identifies their different input and output variables. Then, it reports on an evaluation of the global sensitivity of these models models, as described in the standards and guidelines. This sensitivity analysis seeks to identify the dependant and independent variables and their relationships. In light of the results of this analysis, this paper suggest a methodological framework to determine occupants' activity and thermal insulation levels in free-living environments. One of the key issues is to gather accurate measurements while using 'discreet' observatory methods to have minimum impact on people's behaviour. These methods could potentially be used to validate and to inform building simulation with behaviour components focusing on energy efficiency and personal wellbeing.

REVIEW OF THE CURRENT THERMAL COMFORT MODELS AND ASSOCIATED INDICES

Thermal comfort models are representations of physical and physiological systems, and have resulted in a great number of thermal comfort indices (Auliciems and Szokolay, 2007). The first type of models, called 'adaptive', are based on field study results. The second type of models, called 'predictive', are built on the principles set by heat balance of the human body. This section will give an outline of the principles behind the most common models used by building simulation software, including commercially available ones such as Thermal Analysis Simulation (TAS) and Integrated Environmental Solutions (IES), and open-source tools such as EnergyPlus.

Adaptive model: ASHRAE 55:2010

As thermal adaptation is by nature a dynamic process, an occupant may be accustomed to a range of comfortable indoor temperatures that will change in time and through different space within a building. In a recent review, Humphreys et al. (2010) reported that the indoor temperature was associated to outdoor temperature, and that this relationship was linear. In the ASHRAE 55 this relationship is stated as:

$$T_{ot} = 0.31 \times (T_o + 17.8) \quad (1)$$

Where: T_{ot} is the operative temperature (°C).

T_o is the running mean outdoor air dry-bulb temperature over the previous thirty days (°C).

For the assessment of buildings, the limits of the comfort zones are given by the following two categories:

Cat. I	90% acceptability	$T_{ot} = 0.31 \times (T_o + 17.8) \pm 2.5$
Cat.II	80% acceptability	$T_{ot} = 0.31 \times (T_o + 17.8) \pm 3.5$

This model is only applicable for the following conditions:

- Occupants engaged in near sedentary physical activities (1 to 1.3met).
- T_o ranging from 10°C to 33.5°C.

It is essential that the occupants have the opportunity to adapt by adjusting their clothing, opening/closing windows, or by other means. Although the model accounts for local thermal discomfort effects, these may be reviewed through the building simulation process and included: radiant temperature asymmetry, vertical air temperature difference, and draft.

Adaptive model: EN 15251:2007

In Europe, extensive surveys in offices were conducted, and equations for optimum comfort where developed from the SCATs project (Nicol and Mc Cartney, 2001), giving:

$$T_{ot} = 0.33 \times (T_o + 18.8) \quad (2)$$

Where: T_{ot} is the operative temperature (°C).

T_o is the running mean outdoor air dry-bulb temperature over the previous seven days (°C).

Limits of the comfort zones are given by the following three categories:

Cat. I	90% acceptability	$T_{ot} = 0.33 \times (T_o + 18.8) \pm 2$
Cat.II	80% acceptability	$T_{ot} = 0.33 \times (T_o + 18.8) \pm 3$
Cat.III	65% acceptability	$T_{ot} = 0.33 \times (T_o + 18.8) \pm 4$

This model is only applicable for the following conditions:

- Occupants engaged in near sedentary physical activities (1 to 1.3met).
- T_o upper-marging, from 10°C to 30°C.
- T_o lower-marging, from 15°C to 30°C.

For example in the UK, the running outdoor mean temperature over thirty days in winter is likely to be below the degree day, set at 15.5°C (Carbon Trust, 2012). Therefore assessment of buildings in winter may use the second type of models - predictive models.

Predictive model: Fanger single-node model, EN ISO 7730:2005

This single-node comfort model is based on the heat balance of the human body. Fanger (1970) proposes that thermal comfort is achieved if the heat flowing to and from the human body is balanced, this could be summarised in the following equations:

$$H = L \quad (3)$$

Where: H is the internal heat production rate per unit area (W/m2).

L represents all modes of energy loss from body (W/m2).

In this model, the human body exchanges energy with the environment through:

- Evaporation of sweat and/or water vapor diffusion through the skin.
- Respiration.
- Skin exchanges energy by convection and radiation.

These heat exchanges are represented in the following equation:

$$M = E_{sk} + Q_{res} + Q_{dry} + W \quad (4)$$

Where: M is the metabolic rate per unit area (W/m^2).

E_{sk} is the total evaporative heat loss from skin (W/m^2).

Q_{res} is the rate of respiratory heat loss (W/m^2).

Q_{dry} is the sensible heat flow from skin (W/m^2).

W is the rate of heat loss due to the performance of work (W/m^2); in steady state condition W is equal to 0 (CIBSE guide A, section 1.3.2).

The first term, evaporative heat loss from skin (E_{sk}) is defined as:

$$E_{sk} = E_{rsw} + E_{diff} \quad (5)$$

Where: E_{rsw} is the rate of heat loss from the evaporation of regulatory sweating at the state of comfort (W/m^2).

E_{diff} is the rate of heat loss from the diffusion of water vapor through the skin (W/m^2).

The second term, rate of respiratory heat loss (*Qres*) is defined as:

$$Q_{res} = E_{res} + C_{res} \quad (6)$$

Where: E_{res} is the rate of latent respiratory heat loss (W/m^2).
C_{res} is the rate of dry respiratory heat loss (W/m^2).

The third term, sensible heat flow from skin (Q_{dry}) is denifed as:

$$Q_{dry} = Q_c + Q_r \quad (7)$$

Where: Q_c is the rate of convective heat loss (W/m^2).
Q_r is the rate of radiative heat loss (W/m^2).

These flows depend on six variables which vary over time:

- Two personal variables: clothing insulation level (I_{cl}) as described in EN ISO 9920, and activity level (*M*) as described in EN ISO 8996.
- Four environmental variables as descrived in EN ISO 7726, with (*Ta*) air dry-bulb temperature, (*Tr*) mean radiant temperature, (*Va*) relative air velocity, and (*RH*) relative humidity.

As a measure of thermal comfort, the indices of this single-node model predict the mean comfort vote of a group of people, defined as the Predicted Mean Vote (*PMV*), and Predicted Percentage of Dissatisfied (*PPD*), where:

$$PMV = (0.028 + 0.303e^{-0.036M})\times(H - L) \quad (8)$$

$$PPD = 100 - 95e^{(-0.03353PMV^4 - 0.2179PMV^2)} \quad (9)$$

A seven-point thermal comfort scale is used to describe PMV, ranging from (-3) cold to (+3) hot. The recommended categories for design of mechanical heated and cooled buildings are as follow (EN ISO 7730:2005, Annex A):

Cat. A	PPD<6%	-0.2 < PMV < +0.2
Cat. B	PPD<10%	-0.5 < PMV < +0.5
Cat. C	PPD<15%	-0.7 < PMV < +0.7

Generally predictive models should be used to assess occupants level of thermal comfort when a building is mechanicaly heated, or cooled. It has been recognised that the single-node model is an good idicator but holds formulation and evaluation errors (Humphreys and Nicol, 2000). First, the model only takes into account four environmental parameters, and does not account for adaptive opportunities, or habits. Moreover it has been shown that the model overestimates the thermal sensation response, with a mean error of 1.29 units. Also the accurary of this model decreases as metabolic rate and effective temperature increase (Doherty and Arens, 1988). The global sensitivity analysis carried-out in the following section may provide futher insights on this last point.

Predictive model: Pierce two-node model

The most recent version of the Pierce two-node model was published in 1986 (Gagge, et al., 1986). The human body is modeled as three sections: (1) the core, (2) the skin, and (3) the environment. The heat loss from the skin surface is itself divided into two parts: (2a) the sensible part - including: conduction through clothing, radiation, and convection from the body surface, and (2b) the insensible part - including: evaporation of perspiration on the skin surface. The heat flows between the three main elements are determined on a minute per minute basis, where the initial state is set at T = 0min, then the model iterates until reaching equilibrium. This should occur within one hour. The two-nodes allow the model to account for heat conduction from the core to the skin. The heat balance equation reads as:

$$M = E_{sk} + Q_{res} + Q_{dry} + Q_{crsk} + W \quad (10)$$

Where: M, E_{sk}, Q_{res}, Q_{dry}, and W as per equation 4.
Q_{dry} is the heat flow from core to skin (W/m^2).

This two-node model has six indices. The first one *ET**, stands for New Effective Temperature, this index accounts for the radiative and latent heat transfers. Using *ET**, the second index *PMVET** is determined by the following equation:

$$PMVET^* = (0.028 + 0.303e^{-0.036M})\times(H - L_{ET^*}) \quad (11)$$

The third index, Standard Effective Temperature, *SET* relates to the conditions that would give the same physiological response in people with clothing level set at 0.5clo, metabolic rate set at 1met, and relative humidity set at 50%. Using *SET*, the fouth index *PMVSE*T is determined by the following equation:

$$PMVSET = (0.028 + 0.303e^{-0.036M})\times(H - L_{SET}) \quad (12)$$

The fifth index, the Thermal Sensation Index (*TSENS*) is defined in term of mean body temperature. *PMVET**, *PMVSET*, and *TSENS* using an 11-point scale, ranging from (-5) intolerably cold, to (+5) intolerably hot (Doherty and Arens, 1988). Finally the Discomfort Index (*DISC*) determines the level of discomfort based on the skin temperature and the skin wetness.. It also uses an 11-point scale, ranging from (-5) to (+5), where comfortable and pleasant (0), slightly uncomfortable but acceptable (±1), uncomfortable and unpleasant (2), very uncomfortable (3), limited tolerance (4), and intolerable (5).

Similar to the single-node approch, this model was calibrated in a climate chamber, and in steady state conditons. This might be one of the reason for its evaluation errors, in particular during exercise simulations (Doherty and Arens, 1988). This model was part of the past editions of ASHRAE 55, but recent editions have used *PMV*. However building simulation software such as EnergyPlus have included the six indices of the two-node model in its output.

GLOBAL SENSITIVITY ANALYSIS OF THE THERMAL COMFORT MODELS

To follow the review of the current thermal comfort models, this section reports on evaluations of the sensitivity of those models. This analysis provides insights into how the models dependant variables respond to changes in the independent variables, and which of those have the greatest level of influence. Using global sensitivity analysis, this method allows the interaction among variables to be determined, while not making any assumption on the additive effects of the inputs.

The adaptive models are based on linear relationships between in input (T_o) and the output (T_{ot}). In this instance the correlation coefficient will be 1, both variables are completely depentant of each other.

On the other hand, the two predictive models have six independent variables and five associated indices, as *PMV, PMVET*, PMVSET, DISC* and *TSENS*. Using Saltelli's fremework (2000), the first step in the analysis was to select the ranges and the values of the input variables, as described in Table 1.

Table 1. Characteristics of the independent variables of the predictive models.

Independent variables				Selected ranges [2]	Increment values [3]	No. of possible inputs values
Environmental variables (EV)	**Air dry-bulb temperature**	(T_a)	^oC	[10,30]	0.5	41
	Mean radiant temperature	(T_r)	^oC	[10,40]	2	16
	Water vapour partial pressure	(P_a)	*Pa*	[0,2700]	150	-
	Relative humidity [1]	(*RH*)	%	[0,100]	5	21
	Relative air velocity	(V_a)	*m/s*	[0,1]	0.05+0.05Va	16
Personal variables (PV)	**Metabolic rate** With 1 met = 58.2 W/m2	(*M*)	*met*	[0.8,4]	0.1	33
	Effective mechanical power	(*W*)	W/m^2	[0]	0	1
	Thermal insulation of clothing With 1 clo = 0.155 m^2.K/W	(I_{cl})	*clo*	[0,2]	0.1	21

(1) *RH is a function of (Ta) and (Pa), as per the Antoine equation (Gagge, et al., 1976).*
(2) *ISO:7730, section 4.1.*
(3) *ISO:7726 for the environmental variables, and ISO:7730 Annex B and C for the personal variables.*

The analysis of the predictive model was taken from the relevant standards and guideline, and did not assumed any prior distribution of the input variables. Therefore uniform distributions of its input variables were assumed. Then a sample of 10,000 combinations of inputs were drawn randomly from the selected input values. This large sample size was chosen to strengthen the power of the analysis and increase precision when estimating correlation coefficients. The random sampling process estimates unbiased mean and variance of the independent variables. Finally the output sensitivity to the six indendent varibles is summarised in Table 2, as a Pearson product moment correlation coefficients are quantified.

With regards to the adaptive model, the only independent variable is the external air temperature, which implies that this environmental variable is the main influencing factor in determining occupants response to thermal discomfort.

For the predictive models, the results vary. The single-node model shows that *PMV* appeared to be most sensitive to the personal variables, as metabolic rate (*M*), and thermal insulation of clothing (I_{cl}). In current practice of building simulations, these two variables are often given constant values (Schiavon, 2013). These model assumptions might have a great effect on the estimation of occupants comfort.

Table 2. Summary of the correlation coefficients between the thermal comfort indices and their independent variables.

Independent variables			Adaptive models		Predictive models				
			ASHRAE 55:2010	**EN 15251:2007**	**ISO 7730:2005**	**Pierce model**			
			T_{ot} (°C)	T_{ot} (°C)	PMV(1)	PMV ET	PMV SET	DISC	TSENS
EV	**Monthly mean outdoor air dry-bulb temperature**	(T_o)	**1**	**1**	-	-	-	-	-
EV	**Air dry-bulb temperature**	(T_a)	-	-	0.21	**0.47**	**0.51**	**0.21**	**0.21**
EV	**Mean radiant temperature**	(T_r)	-	-	0.19	0.18	0.19	0.07	0.07
EV	**Relative humidity**	*(RH)*	-	-	0.01	**0.52**	**0.56**	0.20	0.20
EV	**Relative air velocity**	(V_a)	-	-	-0.04	-0.02	0.01	-0.002	0.01
PV	**Metabolic rate**	*(M)*	-	-	**0.37**	0.22	0.11	**-0.92**	**-0.90**
PV	**Thermal insulation of clothing**	(I_{cl})	-	-	**0.31**	0.37	0.10	0.03	0.02

(1) ISO:7730, section 4.1. the index has been used only for values of *PMV* beteen (-2) and (+2).

With regards to the two-node models, the sensitivity of the indices, seems to be divided into two groups. First *PMVET** and *PMVSET* appeared to both be most sensitive to environmental variables, such as air dry-bulb temperature (T_a), and relative humidity (*RH*). However *DISC* and *TSENS* are mostly influenced by metabolic rate (*M*). These results are surprising as different indices are most sensitives to different variables, yet they all aim to predict a person's level of thermal comfort.

DISCUSSION AND CONCLUSION

This short introduction to indoor comfort models, and the results of the sensitivity analysis of these models, suggest that the existing standards and associated indices might only give a general indication of the state of occupants' comfort. To complement this sensitivity analysis, it will be interesting to carry out an error analysis to each index. This should be complemented by large field study results, in order to assess the under/over estimation of the indices.

As three of the five indices are most influenced by personal variables, these should be assessed thoroughly, and determined with high accuracy. However (*M*) and (I_{cl}) are often given as constant values in building energy simulation. For example, (I_{cl}) will be set at 0.5 clo during summer and 1 clo during winter (Schiavon, 2013). Concurrently, most field studies only estimate these two personal variables. With regard to (*M*), the protocols are described by 'Level 1: Screening' or by 'Level 2: Observation' in ISO 8996. In the best case 'Level 2' the accuracy of the results is estimated to be within ±20%. Considering that the personal variables are the most influential variables within three indices, there high level of inaccuracy that will undoubtedly undermine the results on the models.

In order to address these issue wearable sensors, may be able to provide a robust and durable approach to measure those variables (Gauthier and Shipworth, 2013). Monitoring systems should be designed to have minimum influence on the occupants while measuring each factor accurately. Then the output of those sensors may be able to provide probability distributions to these personal variables. Providing the representativeness of the sample, these distributions could be part of building simulation input files.

While thermal comfort remains an essential requirement of building standards, this paper suggest that it is essential to introduce new methods to better estimate and assess its variables.

ACKNOWLEDGEMENT

The author would like to thank the reviewers and to acknowledge UK EPSRC support for the London-Loughborough Centre for Doctoral Research in Energy Demand, grant number EP/H009612/1.

REFERENCES

ASHRAE. 2010. Standard 55-2010 - Thermal Environmental Conditions for Human

Occupancy (ANSI approved), American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA.

Auliciems, A., Szokolay, S.V. 2007. Thermal Comfort (2nd ed.). London: Passive and Low Energy Architecture (PLEA).

Azer, N.Z., Hsu, S. 1977. The prediction of Thermal Sensation from Simple model of Human Physiological Regulatory Response, ASHRAE Trans., Vol.83, Pt. 1.

Carbon Trust, 2012. Degree days for energy management. A practical introduction. CTG075. London.

CEN. 2007. Standard EN15251 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Bruxelles: European committee for Standardisation.

Doherty, T.J., Arens, E. 1988. Evaluation of the Physiological Bases of Thermal Comfort Models. ASHRAE Trans., Vol.94, Pt. 1.

Fanger, P.O. 1970. Thermal comfort. Danish Technical Press, Copenhagen.

Gagge, A.P., Nishi, Y., Nevins R. G. 1976. The role of clothing in meeting energy conservationguidelines, ASHRAE Trans. 82, 234-247.

Gagge, A.P., Fobelets, A.P., Berglund, L. G. 1986. A Standard Predictive Index of Human Response to the Thermal Environment, ASHRAE Trans., Vol.92, Pt 2.

Gauthier, S., Shipworth, D. 2013. Review of Methods to Map People's Daily Activity – Application for Smart Homes. In A. Hakansson et al., eds. Sustainability in Energy and Buildings SE - 38. Springer Berlin Heidelberg, pp. 401-411.

Humphreys, M.A., Fergus Nicol, J. 2000. The effect of measurement and formulation error on thermal comfort indices in ASHRAE database of field studies. ASHRAE Trans., Vol.106, Pt 2.

Humphreys, M.A., Fergus Nicol, J. 2002. The validity of ISO-PMV for predicting comfort votes in everyday thermal environments. Energy and Buildings, 34, pp.667_684.

Humphreys, M.A., Rijal, H.B., Nicol, J.F. 2010. Examining and developing the adaptive relation between climate and thermal comfort indoors. Proceedings of Conference on Adapting to Change: New Thinking on Comfort, Cumberland Lodge, Windsor, UK, 9-11 April 2010. London: Network for comfort and Energy Use in Buildings.

ISO 2001. Ergonomics of the thermal environment - Instruments for measuring physical quantities. BS EN ISO 7726:2001.

ISO 2005. Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. BS EN ISO 7730:2005.

ISO 2004. Ergonomics of the thermal environment - Determination of metabolic rate. BS EN ISO 8996:2004.

ISO 2009. Ergonomics of the thermal environment - Estimation of thermal insulation and water vapour resistance of a clothing ensemble (ISO 9920: 2007, Corrected version 2008-11-01). BS EN ISO 9920:2009.

Nicol, F. McCartney, K. 2001. Final Report Smart Controls and Thermal Comfort (SCATs). Report to the European Commission of Smart Controls and Thermal Comfort project. Oxford: Oxford Brookes University.

Saltelli, A., Chan, K., Scott, E.M. 2000. Sensitivity analysis. John Wiley & Sons, Chichester, UK.

Schiavon, S., Lee, K.H. 2013. Influence Of Three Dynamic Predictive Clothing Insulation Models On Building Energy Use, HVAC Sizing And Thermal Comfort. UC Berkeley: Center for the Built Environment.