Topic A7: Thermal comfort

PREDICT THERMAL SENSATION OF CHINESE PEOPLE USING A THERMOPHYSIOLOGICAL AND COMFORT MODEL

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SUMMARY

INTRODUCTION: Currently most thermal sensation models were developed based on the physiological and comfort studies of western people, ethnic and culture differences have not been taken into account. Chinese may present different thermal response from western people.

MODEL DEVELOPMENT: UCB thermal sensation model developed by Zhang has the structure which allows for changes of its coefficients to fit the model to various types of populations. The model coefficients were modified based on experimental data of Chinese people for a better prediction.

MODEL VALIDATIONS: Better predications were achieved with the modified Chinese model comparing with the western models, the differences in thermal sensation between predictions and laboratory and field study results are less than 0.5 scale unit.

CONCLUSIONS: A thermal sensation model was developed to provide better predictions of overall thermal sensation for Chinese people, with discrepancies less than 0.5 scale.

INTRODUCTION

Satisfying the thermal requirement of occupants is one of the most important tasks for Heating, Ventilation and Air Conditioning (HVAC) systems. Thermal sensation and comfort are the two most widely used indicators to evaluate occupants' satisfaction. Thermal comfort is defined as "that condition of mind that expresses satisfaction with the thermal environment" in ASHRAE standard 55-2010. The "condition of mind" or "satisfaction," is influenced by physical, physiological, psychological and other factors (ASHRAE 2010). To develop a universal thermal comfort model for all people in all types of buildings may lead to discomfort of occupants or energy dissipation (Van Hoof 2008). On the other hand, we express thermal sensation more than comfort in daily life, e.g. we usually say it is warm or cool today other than presenting a comfort level. Thermal sensation is a feeling that we perceive a certain thermal environment, which is closely related to and also can be predicted by skin and core temperatures (Zhang, Arens et al. 2010, Takada, Matsumoto et al. 2013). Predicting thermal sensation is more convincing and practical than predicting thermal comfort. Accurate thermal sensation model applied in design phases could be helpful to maximum occupants' satisfaction with less energy consumption (Schellen, Loomans et al. 2013). There are various models to predict thermal sensation, and the most widely used one is the PMV model (Fanger 1970). However, using PMV model may encounter limitations. PMV model can only be used in uniform stable environment (typical HVAC environment, Van Hoof 2008). Recently studies showed that higher levels of thermal comfort could be achieved under asymmetrical thermal environments in comparison to uniform environments (Zhang, Arens et al. 2010, Zhang, Arens et al. 2010). Many energy efficient technologies produce non-uniform environments, such as radiant, displacement ventilation, and underfloor systems.

Individual differences in physiological and psychological were not taken into consideration in PMV model (Kingma, Schellen et al. 2012). Studies had found discrepancies between PMV and Actual Mean Vote (AMV) due to the regardless of individual information (like age, gender, body composition) (Van Hoof 2008, Schellen, Van Marken Lichtenbelt et al. 2010, Karjalainen 2012). Considering the limitations of the PMV model, several thermophysiological and comfort models based on thermoregulation and bioheat transfer were established. Fiala's comfort model (Dynamic Thermal Sensation, DTS) was based on the human subject experiments conducted earlier by other researchers, e.g. the studies in KSU, and simulated skin temperatures by his physiology model (Fiala, Lomas et al. 1999). Based on physiological responses (i.e. mean skin temperature, local skin temperatures, and rate of change in these parameters) and subjective sensation and comfort responses, UCB model (Zhang, Arens et al. 2010) predicts thermal sensation and comfort for 16 individual body parts and for the whole body, and is widely used for thermal sensation prediction worldwide (Foda, Almesri et al. 2011, Cheng, Niu et al. 2012, Schellen, Loomans et al. 2013). However, most of the above models were built based on the experiment studies of western people (mainly white people), ethnic differences were not considered, and only different short-wave absorption rate for different skin color was considered in the UCB model. People from different ethnic groups or climates may experience different thermal sensation in the same environment (Nakano, Tanabe et al. 2002). If using the same existed models to predict the thermal sensation of Chinese people, we may end up with malperformance of HVAC system or thermal discomfort for occupants. When taking care of the ethnical difference, both the physiological and psychological aspects should be considered. As differences had been found in body composition, age and sex (Havenith 2001, van Marken Lichtenbelt, Frijns et al. 2004, van Marken Lichtenbelt, Frijns et al. 2007) between subpopulations, a Chinese thermoregulation model which is more accurate in skin temperature prediction for Chinese people was developed (Zhou, Lian et al. 2013). For thermal sensation prediction, a thermal sensation model developed for Chinese people coupling with the thermoregulation model is indispensable.

In this paper, we compared the existed models' predictions with results on Chinese subjects, and built a Chinese thermal sensation model. Coupling this sensation model with the Chinese thermoregulation model, we can predict thermal sensation for Chinese people using environmental inputs and human parameters.

CHINESE MODEL ESTABLISHMENT

UCB model, because it has been widely accepted and used (Foda, Almesri et al. 2011, Cheng, Niu et al. 2012, Schellen, Loomans et al. 2013), was introduced in this study. The UCB model consists of two independent parts: thermoregulation model (Huizenga, Hui et al. 2001) and thermal sensation model (Zhang, Arens et al. 2010). First part can be replaced by the Chinese thermoregulation model (Zhou, Lian et al. 2013). With environmental inputs and human parameters, the Chinese thermoregulation model can output local skin temperatures for thermal sensation prediction. For the second part - the thermal sensation model, the CBE model provides rational structure with regression coefficients that can be easily adjusted. Thus the inherent advantage of UCB model in thermal sensation prediction and flexibility in structure provide a possible way to build a Chinese thermal sensation model.

In the UCB sensation model, local thermal sensation was firstly calculated by the local and mean skin temperatures, and then overall thermal sensation was predicted by a rational approach using local sensations. Local sensation was predicted by the corresponding local skin temperature and mean skin temperature, as we can see in equation 1 (Zhang, Arens et al. 2010):

$$\text{Local Sensation}_{\text{static}} = 4\left(\frac{2}{1+e^{-C_1\left(T_{skin,local}-T_{skin,local,set}\right)-K_1\left[T_{skin,local}-T_{skin,local,set}\right)-\left(\bar{T}_{skin}-\bar{T}_{skin,set}\right)]}}-1\right) \quad (1)$$

UCB sensation model not only includes the local skin temperature ($T_{skin,local}$) of corresponding segment and its setpoint in a neutral environment ($T_{skin,local,set}$), but also the influence of mean skin temperature on local thermal sensation.

To evaluate UCB model predictions, laboratory studies by Yu (2011) and Jin, Li et al (2012) were used to compare the predictions and the real votes. The environment conditions are from cold to hot (Table 1). PMV and PPD values were listed here as a reference.

Table 1. Environmental conditions for the modification of UCB models

Ambient air temperature (℃)[1]	18	20	23	26	29	32	34
PMV	-2.58	-1.88	-0.84	0.19	1.24	2.31	3.04
PPD	95%	71%	20%	6%	37%	89%	99%
Sensation	Cold	Cool	Slight Cool	Neutral	Slight Warm	Warm	Hot

[1]All the other environment parameters were kept the same: Relative Humidity=50%, air speed= 0.1m/s, mean radiation temperature is the same as ambient air temperature. Subjects wear 0.61 clo clothes and with metabolic rate of 1.

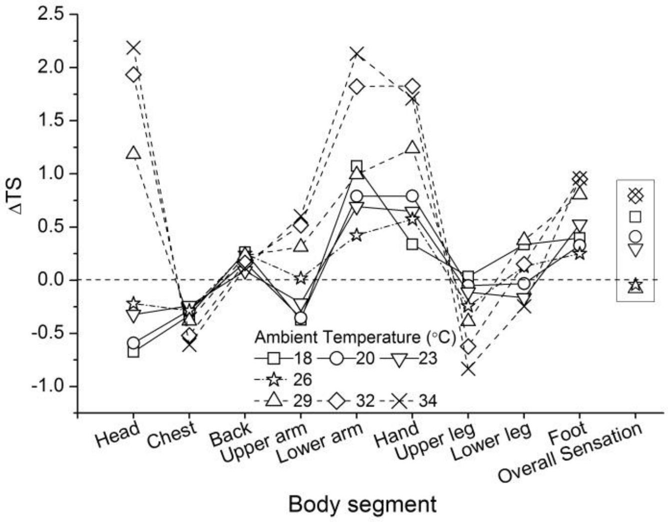

Figure 1. Difference in local thermal sensation between Chinese and UCB model

Figure 1 shows the differences in local and overall thermal sensation between the predictions and the real votes. ΔTS is the value of UCB model prediction minus experiment result. All the thermal sensation are evaluated according to ASHRAE 7 point scale (ASHRAE 2010). The differences mostly happen in warm conditions (29, 32, 34 ℃). In general, the model overestimates thermal sensation especially when under warm and hot environment. Head, lower arm and hand overestimates the most, which can be as large as 2 scale unit. The model underestimates sensation for upper leg at 29, 32, and 34 ℃ conditions. Discrepancies was found when comparing the thermal sensation distribution of different body parts between Chinese and western people, these discrepancies require a modification on UCB local sensation model.

The structure of UCB local thermal sensation model was kept the same whereas the coefficients (C_1 and K_1) for each body segment will be modified. Skin temperature set value ($\ddot{T}_{skin,set}$) will also be changed according to experiments on Chinese people. Three major human body parts: core, distal and intermediate, was defined for the designation of the coefficients. The core part includes head, chest and back. They are more easily affected by the body core temperature. Their skin temperature are relatively stable, thus was designated with larger C_1 and K_1 values. Distal part includes lower arm (leg), hand and foot. Distal parts are more easily influenced by ambient temperature comparing with the core parts. They can easily sense a cold or warm feeling with more fluctuant skin temperatures, even when the mean skin temperature is stable, thus their C_1 and K_1 value are the lowest among the three body parts. The intermediate part includes the upper arm and leg, and their coefficients are designated values between the core and distal parts.

The coefficients of local sensation model were further adjusted segment by segment using trial-and-error to minimize the sum of squared residuals under all the temperatures. The modified coefficients and the original ones in the UCB model are shown in Table 2, ΔT equals the skin temperature minus the skin temperature set value. Most coefficients were modified when ΔT>0, because model overestimates real votes in warm environments. The modifications for ΔT<0 is small. The UCB sensation model was smoothed and gave the concept of moving neutral temperature set-point (Zhao, Zhang et al. 2014), thus $\ddot{T}_{skin,set}$ values listed in Table 2 are only validated for people in 1 met and wearing 0.6 clo clothes. $\ddot{T}_{skin,set}$ value as a input will be influenced by the combination of clothes wearing and metabolic rate.

Table 2. Modified coefficients of local thermal sensation prediction for Chinese people

	ΔT<0		ΔT>0		
	C1	K1	C1	K1	$\ddot{T}_{skin,set}$
Head	0.50 (0.40) *	0.20	0.90 (1.30)	0.20	34.7
Chest	0.40 (0.35)	0.10	0.90 (0.60)	0.20 (0.10)	34.2
Back	0.35	0.10	0.90 (0.70)	0.20 (0.10)	34.5
Upper arm	0.35 (0.30)	0.10	0.60 (0.40)	0.15 (0.10)	32.9
Lower arm	0.30	0.10	0.50 (0.70)	0.15 (0.10)	32.6
Hand	0.35(0.20)	0.15	0.40 (0.45)	0.10 (0.15)	33.6
Upper leg	0.35 (0.20)	0.10	0.60 (0.30)	0.20 (0.10)	33.5
Lower leg	0.30	0.10	0.5 (0.40)	0.15 (0.10)	32.4
Foot	0.30 (0.25)	0.15	0.30 (0.25)	0.10 (0.15)	32.0

* Numbers in the round brackets are the original value in the UCB model.

Overall sensation predication based on local sensation in the UCB model was given (Zhang, Arens et al. 2010). For the cold and warm environments, the overall thermal sensation was determined by the coldest (warmest) and third coldest (warmest) body segment with certain coefficients; for an intermediate environment, average value of thermal sensation in all body segments was designated as the overall thermal sensation. The strategy of overall thermal sensation prediction used in UCB model is simple and mostly validated (Schellen, Loomans et al. 2013), thus was kept unchanged in the Chinese model.

MODEL VALIDATIONS

Named as UCB-Chinese sensation model, the modified UCB sensation model based on Chinese experiments was evaluated. As we can see in Figure 2, thermal sensation prediction results of PMV and UCB model are nearly the same, but the discrepancies between these two models and experiment study on Chinese people could be as large as 1 scale unit in the cold and hot environments. Difference between the model prediction and experiment prediction is less than 0.5 scale unit. The prediction of thermal sensation was improved into a more acceptable level after modifications.

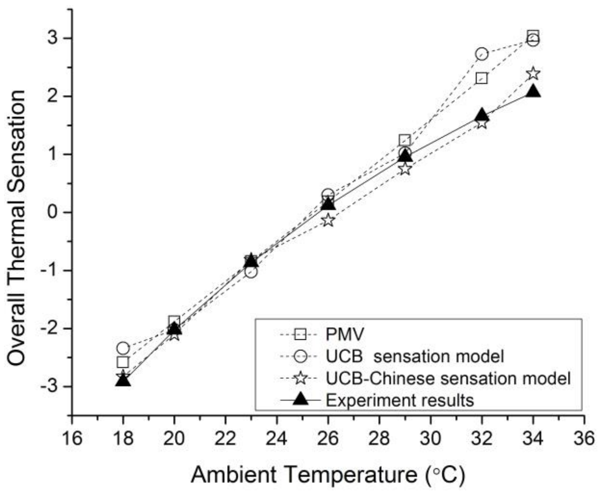

Figure 2. Examination of UCB-Chinese model in thermal sensation prediction.

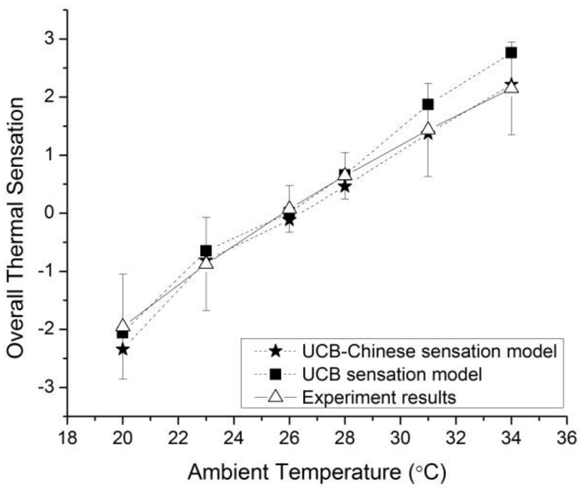

Figure 3. Prediction of thermal sensation input with the measured Chinese skin temperature.

The first validation is for the thermal sensation model only, using the measured skin temperatures as inputs to predict sensations. A different set of human subject test by Yu (2011) is used. Figure 3 shows the validation of the UCB-Chinese thermal sensation model. The tested environment temperatures were 20℃, 23℃, 26℃, 28℃, 31℃ and 34℃. Tested subjects were all young male, with 1.0 met metabolic rate and wearing 0.5 clo clothes. The Chinese thermal sensation model agree well with the experiment results, the difference is less than 0.5 scale, whereas the prediction of UCB sensation model in warm environment could be as large as 0.5 scale. An improvement in prediction of Chinese people sensation was observed after the modification of coefficients in the UCB model.

Till now a complete thermophysiological and sensation model for predicting Chinese people thermal sensation has been built, which will be further referred as SJTU model. It consists of two independent parts: a thermoregulation model (calculating skin temperature) and a thermal sensation model (based on skin temperature). Model inputs include air temperature, velocity, mean radiation temperature (MRT) and relative humidity (environmental parameters), together with metabolic rate, thermal resistance and individual characters (height, weight, age and sex) for occupants.

The following two validations are for SJTU model. The SJTU model was validated with environment inputs and human parameters, comparing with the existed PMV, DTS and UCB model. Experiments on Chinese people carried out by Chen (Chen, Zhang et al. 2010) were employed to validation the performance of these models in thermal sensation predicting of Chinese people. Table 3 shows the prediction results with different thermal sensation models. PMV, DTS and UCB model, all based on western people, have nearly the same thermal sensation prediction values. They all predict warmer thermal sensation than the real votes, the difference can be as large as 0.8. The Chinese model predictions agree better than the other three models, which has a difference of less than 0.25 scale when compare with the experiment results.

Table 3. Prediction of thermal sensation with different models

Ambient temperature (℃)*	20	23	26	29	32
PMV model	-1.88	-0.84	0.19	1.24	2.31
DTS model	-2.29	-1.65	-0.82	0.10	1.97
UCB model	-1.61	-0.56	0.08	0.88	2.45
SJTU model	-2.07	-1.22	0.10	0.89	1.92
Experiment results	-2.25±1.12	-1.05±1.04	-0.17±0.82	0.49±0.79	1.84±1.17

* All the other environment parameters were kept the same: Relative Humidity=50%, air speed= 0.1m/s, mean radiation temperature is the same as ambient temperature. Subjects wear 0.57 clo clothes and with metabolic rate of 1.

The SJTU model was further validated with a field study on Chinese people (Zhang, Wang et al. 2010), which was carried out in natural ventilated buildings in Guangzhou, China in spring and autumn. Detailed information was shown in Table 4.

Table 4. Environmental conditions and human parameters in the field study

Environmental input	Ambient temperature (℃)	18.0	19.6	21.1	22.0	23.0	23.6	26.1	26.9
	MRT (℃)	19.2	21.5	22.2	24.4	24.1	24.6	27.4	28.2
	Air speed (m/s)	0.3	0.6	0.2	0.3	0.2	0.2	0.2	0.3
	Relative humidity (%)	50.1	33.8	41.3	47.4	60.6	54.1	73.4	68.4
Human input	Metabolic rate (met)	1.0	1.0	1.0	1.0	1.1	1.1	1.0	1.0
	Thermal resistance (clo)	0.7	0.7	0.8	0.7	0.7	0.5	0.4	0.4
	Sex	Male	Male	Male	Male	Male	Male	Male	Male
	Average height (m)	1.71	1.70	1.71	1.70	1.69	1.68	1.70	1.70
	Average weight (kg)	61.1	60.5	62.1	60.1	59.6	59.6	60.3	60.1
	Average age (year)	22.0	22.0	22.1	22.3	22.0	22.1	22.3	22.2

Validation results with field study can be seen in Figure 4. The difference between experiment results and model prediction is also less than 0.5 scale unit according to ASHRAE 7-point thermal sensation scale. The model was thus validated to be applicable for thermal sensation prediction in field study carried out in nature ventilation buildings. . Further validation may need to be done throughout China, with difference in ambient environments, social cultures and climate zones.

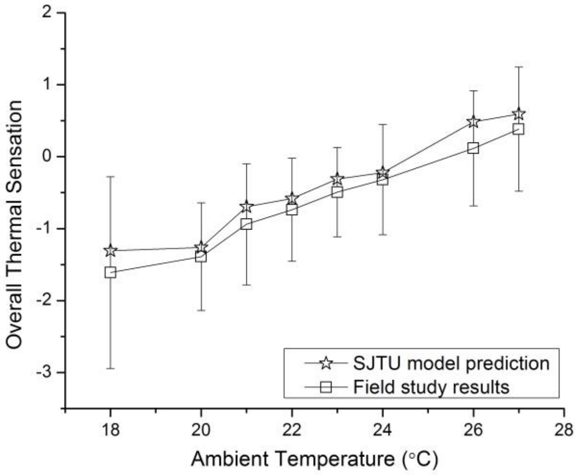

Figure 4. Validation of the SJTU model with field studies

CONCLUSIONS

1. Thermal sensation model based on western physiological data may be inadequate to predict thermal sensation of Chinese people, discrepancies between prediction and experiment for local parts could be as large as 2 scale unit.
2. A Chinese thermal sensation model was built based on the experiment of Chinese people, the model predictions agree well with the experiment results when using skin temperature as input, the discrepancies are less than 0.5 scale unit.
3. Together with thermoregulation model, input with environmental and human parameters, the prediction of the SJTU model was validated with both laboratory and field studies, the differences between prediction and experiment are within ±0.5 scale unit.

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