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Research on Thermal Comfort Models for Naturally Ventilated Buildings

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Abstract. Aiming at the insufficiency of thermal comfort standards of naturally ventilated buildings, the domestic existing thermal comfort evaluation models are introduced, including revised PMV models, climate adaptive models and its revised models. The results show that building energy saving potential can be well exerted by the use of thermal comfort models for naturally ventilated buildings to guide architectural design and the operation of air conditioning equipment. Chinese thermal comfort study samples are abundant, but have not yet established complete human thermal comfort research database. Therefore, it is difficult to form a standardized thermal comfort evaluation system. Various models have advantages and disadvantages when used to evaluate the indoor thermal comfort of naturally ventilated buildings. The follow-up studies should consider the error correction and focus on the combination of PMV model and adaptive model, and finally form a more comprehensive lumped parameter evaluation model which can combine the theories of human body heat balance and human body adaptability.

Introduction

Thermal comfort models are used to guide thermal comfort standards, which in turn affect the design of the buildings and the operation of the heating and ventilation system. The existing thermal comfort models mainly include the PMV model, the thermal adaptive model and the revised models of the two. More and more studies have shown that the PMV model neglects the human body's ability to the environment, the measurement error of the four environmental parameters such as air temperature, relative humidity, air flow rate and average radiation temperature, and the inaccurate estimation of the metabolic rate. So, it usually makes a serious deviation when predicting thermal sensation of the human body in the actual buildings by thermal comfort standard basing on the PMV model. The more the temperature deviates from the thermal neutral temperature, the more obvious the scissors phenomenon" is [1]. Therefore, worldwide scholars have actively discussed the way to revise classical PMV model and also carried out field study of naturally ventilated buildings. They established various climate adaptive models at the same time.

Naturally ventilated building doesn't use artificial hot and cold heat source (such as air conditioning equipment). It only relies on natural cold and heat sources, such as wind pressure and hot pressing to promote indoor and outdoor air exchange. Therefore, the natural ventilation effect is closely related to outdoor weather conditions. Mining the energy-saving potential of naturally ventilated building and establishing calculation and design indicators based on population, region, climate characteristics can help to play the role of passive design in energy conservation and sustainable development. This paper systematically introduces thermal comfort evaluation models of naturally ventilated building, and focuses on the related research results of Chinese scholars in the field.

Revised PMV Model

PMVe model

Fanger believes that there are two reasons for the fact that the PMV model overestimates the actual human body's thermal sensation. The first point is the estimation of human body's metabolic rate in the hot environment. The second point is inhabitants' low expectation of the living environment in the non-air-conditioned environment [2, 3]. Therefore, Fanger chose human's "lower expectation" as the entry point for the correction of PMV, and thought that the two key factors that affect the heat expectation are the climate and architecture. When the metabolic rate is small, the calculated PMV value is multiplied by the *expected factor e* of 0.5 to 1.0, and the resulting PMVe value is used to predict the thermal comfort of the human body in a naturally ventilated building [3]. Table 1 shows the values of the *expected factor e* in different cases.

Table 1 The values of *expectation factor e* in non air-conditioned buildings in warm region [1,2]

expectation	building Type	the values of *expectation factor e*
high	air-conditioned buildings are here where naturally ventilated buildings are also common. Hot period appears shortly in summer.	0.9～1.0
medium	air-conditioned buildings are in the area where there are also some naturally ventilated buildings. The summer is very hot.	0.7～0.9
low	air-conditioned buildings are here where there are few naturally ventilated buildings. Hot weather runs through all seasons.	0.5～0.7

Many scholars have validated the applicability of PMVe model in China. The results show that the calculated results are satisfactory in some areas [4, 5], but PMV values obtained by the recommended *expectation factor e* in some other areas are greatly different from the actual human body thermal sensation [6,7]. And the PMVe model can't correct the thermal neutrality.

aPMV model

In order to fully explain the difference between the PMV model and the adaptive model, some scholars have made a new attempt. Yao Runming considered various factors influencing the human body's thermal sensation and established aPMV model basing on the engineering control theory [8]. She revised the PMV model by the *adaptive coefficient λ*, which has different meanings from the *expectation factor e*. The model is described as Eq. 1[8]:

$$aPMV = \frac{PMV}{1+\lambda \times PMV} \tag{1}$$

Where λ is greater than zero under warm conditions, and is less than zero under cold conditions.

Chinese GB/T 50785-2012"Evaluation standard for indoor thermal environment in civil buildings" [9]is based on the aPMV model, and establishes the thermal comfort evaluation standard for naturally ventilated buildings. It made the provisions of the *adaptive coefficient λ*. See Table 2.

Table 2 Values of λ in GB/T 50785-2012"Evaluation standard for indoor thermal environment in civil buildings" [9]

climate zone	PMV value	residential buildings, store buildings, hotel buildings and offices	education buildings
severe cold area and cold area	PMV≥0	0.24	0.21
	PMV＜0	-0.50	-0.29
hot summer and cold winter area, hot summer and warm winter area, temperate areas	PMV≥0	0.21	0.17
	PMV＜0	-0.49	-0.28

Zheng Wuxing, Yang Liu et al find that there are significant differences of the body's thermal sensation with the temperature change in the cold climate area [10]. In autumn and winter, the human body has a low level of adaptation, while higher in spring and summer. And the *adaptive coefficients λ* for four seasons are: -1.24(spring), 0.45(summer), -0.38(autumn), -0.23(winter). This is different from the value of λ in the above standard. Therefore, subsequent researches should further clarify the value of the *adaptive coefficients* λ.

Revised PMV model by Tsinghua University

Zhou Xiang of Tsinghua University studied the causes of bias through a series of artificial climate laboratory test to explain why it generated deviation when PMV model was used to predict human thermal sensation in a non-air-conditioned overheated environment. The study finds that in an overheated environment, the average daily outdoor temperature $t_{out,\ d}$, indoor operating temperature t_{op}, the average wind speed v will cause a deviation between the predicted thermal sensation and the actual thermal sensation. By the way of multiple linear regression, he proposed revised PMV model which contains these factors. The model is described as Eq. 2 and Eq. 3 [11]:

$$PMV^{*} = PMV - \Delta PMV \quad (2)$$

$$\Delta PMV = 6.961 - 0.26\times t_{op} - 0.262\times t_{out,d} - 5.104\times v + 0.01\times t_{op}\times t_{out,d} + 0.21\times t_{op}\times v \quad (3)$$

The applicable scope of revised PMV model: non-air-conditioned partial heat environment, outdoor average temperature of 10 ~ 32 ℃, indoor operating temperature of 26 ~ 32 ℃, the average wind speed less than 1.4 m/s.

PMV linear revised model

In view of the fact that the PMVe model proposed by Professor Fanger are not universally applicable, Zhang Jianbo proposed a PMV linear revised model [7]. He thinks that there is a linear relationship between TSV and PMV. This model uses the *correction factor k* to adjust the direction angle of the original PMV regression curve, and *l* to adjust the intercept of the equation to the vertical axis. See in Eq. 4:

$$TSV = PMVe = k * PMV + l \quad (4)$$

The premise of using the PMV linear revised model is to obtain abundant and effective TSV values. He validated the PMV linear revised model by the data of Liu Jing's research [4]. The results show that the PMV values corrected by the PMV linear revised model are closer to the TSV and MTS values, and the original PMV values are smaller than the MTS values in almost all the temperature ranges of the research area. The PMV linear revised model of Chongqing obtained by this algorithm is $PMV_{(k,l)}$~(0.72，0.08).

Summary of Revised PMV Model

The above four models are the development of PMV model, but their correction mechanisms are very different. For most areas, the results of *expectation factor e* given by Professor Fanger are satisfactory. However, the PMVe model is applicable only for warm climates. The aPMV model uses the *adaptive coefficient* λ to revise the PMV model, which is a bold attempt to combine the theory of human body heat balance with human adaptive theory. Further study is still needed to ultimately form a more comprehensive lumped parameter model combined the human body factors with environmental factors. The revised PMV model by Tsinghua University takes various factors into account. PMV linear revised model is more perfect than PMVe model, which needs to be further verified with the measured data.

Adaptive Model

Adaptability theory

Adaptability theory thinks that human body has three basic adaptation models. Namely, physiological adaptation, behavior adaptation and psychological adaptation to the thermal environment. When the actual ambient temperature deviates from the comfort zone, people will take self-regulation to improve their own thermal state, and adapt to the environment by physical and psychological adjustments.

Research on foreign adaptive model

Two large-scale adaptive thermal comfort field researches carried out abroad. In 1998, Brager and De Dear carried out the famous ASHRAE RP-884 project on, acquiring 21000 sets of data from 160 natural ventilated buildings on four continents, and established the ASHRAE field research database. They firstly proposed a climate adaptive model for naturally ventilated buildings. Between 1996 and 2000, Nicol and Mc Cartney launched the SCAT project, acquiring 31939 sets of data from 26 free-run buildings in five European countries and established control algorithm of European thermal adaptive model. And they firstly took time as an important factor in describing the feedback cycle of adaptive behavior and determining the thermal comfort temperature. The two large-scale field research successfully contributed to implementation of adaptive thermal comfort standards ASHRAE55-2004 and EN15251-2007 and has greatly promoted the worldwide research on thermal comfort of naturally ventilated buildings.

Research on domestic adaptive model

Chinese thermal comfort research has covered all the building thermal divisions. Scholars on the one hand study a single factor on the human body thermal comfort by artificial climate laboratory. On the other hand, they conducted field researches of naturally ventilated buildings adaptive model with statistical methods. At present, the main work of thermal comfort of naturally ventilation buildings are: (1) thermal environment and thermal comfort survey; (2) thermal comfort factors analysis; (3) adaptive model research; (4) building energy efficiency research.

On the base of the survey data of Yang Liu, Mao Yan conducted a field investigation on the naturally ventilated buildings' indoor thermal environment and thermal comfort of 12 representative city in four typical climate zones in China. For the first time, the model of human adaptability in different climatic zones was established [12]. See in Eq. 5 to Eq. 8:

Severe cold region: $t_c=0.121t_{out}+21.488(16.3\le t_c\le 26.2^{\circ}C)$ (5)

Cold region: $t_c=0.27t_{out}+20.014(15.8\le t_c\le 29.1^{\circ}C)$ (6)

Hot summer and cold winter region: $t_c=0.326t_{out}+16.862(16.5\le t_c\le 27.8^{\circ}C)$ (7)

Hot summer and warm winter region: $t_c=0.554t_{out}+10.578(16.2\le t_c\le 28.3^{\circ}C)$ (8)

It can be seen that the slope of the regression equation in the severe cold region is the smallest, while the hot summer and warm winter region' is the largest, indicating that the sensitivity of the southerners to the temperature is higher than that of the northerners.However, the thermal neutral temperature ranges of each model is very close, which shows that people in different climates have some similarities to climate adaptability.

Han Jie has obtained seven factors that influence the thermal comfort of the human body in the naturally ventilated environment [13]. And he established the adaptive model of urban and rural areas in hot summer and cold winter regions.Yang Qian of Xi'an University of Architecture and Technology also established the adaptive model of natural ventilated buildings in urban and rural areas in cold regions [14]. The comparison of the two models is shown in Table 3.

Table 3 A comparison of the models established by Han Jie [13]and Yang Qian [14]

researcher	Yang Qian	Han Jie
climate zone	cold region	hot summer and cold winter region
adaptive model of urban area	$t_c=0.2125t_{out}+20.477$（$16\le t_c\le 28.2^{\circ}C$）	$t_c=0.67t_{out}+10.32$（$14\le t_c\le 32.75^{\circ}C$）
adaptive model of rural area	$t_c=0.6301t_{out}+9.7972$（$10.1\le t_c\le 29.9^{\circ}C$）	$t_c=0.44t_{out}+9.17$（$8.41\le t_c\le 30.14^{\circ}C$）

Both have concluded that the comfortable temperature range of the villagers is wider than that of the city, indicating that the extreme tolerance of the rural residents to the environment is stronger than that of the urban residents. However, the thermal comfort temperature of the rural residents in the cold area is greatly affected by the outdoor temperature, while the urban residents is more sensitive to the temperature than the villagers in the hot summer and cold winter area.Two very different results confirmed that adaptive thermal comfort studies should be carried out separately for building thermal design partitions, rural and urban residential housing.

GB/T 50785-2012 “Evaluation standard for indoor thermal environment in civil buildings” [9] adopted the thermal comfort model established by Jin Zhenxing of the Chongqing University in naturally ventilated residential buildings of nine typical cities in different climate zones. Taking non-artificial cold and heat source environment II as the object being compared, the thermal neutral adaptive model is different from those in the international standard ASHRAE55-2013 and EN15251-2007. See Table 4.

Table 4 Comparison of thermal neutral adaptive models in different standards

different standards	applicable area	thermal neutral adaptive model	applicable scope
GB/T 50785-2012 “Evaluation standard for indoor thermal environment in civil buildings”	severe cold and cold region	$t_c=0.82t_{rm}+7.4$	$10.5 \le t_{rm} \le 27.6$ ºC
	hot summer and cold winter region, hot summer and warm winter region and moderate area	$t_c=0.82t_{rm}+4.515$	$14 \le t_{rm} \le 31.1$ ºC℃
ASHRAE55-2013	all areas	$t_c=0.31t_{m,out\_av}+17.8$	$10 \le t_{a,out\_av} \le 34$ ºC
EN15251-2007	all areas	$t_c=0.33t_{out\_av}+18.8$	$10 \le t_{a,out\_av} \le 30$ ºC

Note: t_c is the thermal neutral temperature (operating temperature), t_{rm} is the outdoor smoothing week average temperature, t_{m,out_av} is the outdoor monthly mean air temperature, and t_{out_av} is the continuous average outdoor air temperature.

From the slope of the adaptive model in Table 4, it can be seen that Chinese population is more sensitive to temperature changes than foreign populations.Through the applicable scope of the models, further calculation can be drawn:The thermal neutral temperature range of Southern China and Northern China is roughly the same, that is, 16 to30 ºC,which is wider than that of ASHRAE55-2013 and EN15251-2007 (20.9 to 28.3 °C and 22.1 to 28.7°C, respectively).The thermal neutral temperature range of Europeans specified in EN15251-2007 is the narrowest. This also reflects that the adaptability of foreign population models in China's applicability should be verified.

The results of field researches on the thermal comfort of naturally ventilated buildings in different climate zones are summarized in Table 5.

Table 5 Comparison of climate adaptive models of different climate zones in China

city surveyed	climate zone	research time	building Type	regression formula
Harbin [15]	severe cold region	autumn	urban residential building	$t_c=0.486t_{out}+11.802$
Harbin [16]	severe cold region	spring, autumn	student dormitory	$t_c=0.25t_{out}+18.4$
Jiaozuo [17]	cold region	winter	urban residential building	$t_c=0.317t_{out}+18.19$
Changsha [18]	hot summer and cold winter region	summer	urban residential building	$t_c=0.32t_{out}+17.5$
Changsha [19]	hot summer and cold winter region	autumn, winter	College classrooms	$t_c=0.384\ 24t_{out}+17.593\ 43$
Hangzhou [20]	hot summer and cold winter region	winter	urban residential building	$t_c=0.634t_{out}+9.001$
Hefei [20]	hot summer and cold winter region	winter	urban residential building	$t_c=0.621t_{out}+12.91$
Huanggang [21]	hot summer and cold winter region	summer, winter	rural residential building	$t_c=0.81t_{out}+6.14$
Kunming [22]	temperate area	Summer, winter	Urban residential building	$t_c=0.498t_{out}+11.573$

As can be seen from Table 5, the adaptive models obtained in different cities is not exactly the same, as well as those obtained in different types of buildings in the same city (as in [15-16], [18-19]).This is mainly because subjects in the university are usually young students, while the subject of residential buildings usually contain different ages of the residents. Secondly, adaptive models of rural and urban areas in the same climate zone are also different (as in [20-21]). This is mainly due to the different living background of rural and urban population and their long-term ability to the living environment. Moreover, the adaptive models established in different seasons are also different. This is mainly because people's adaptive behaviors are different in different seasons. In the cold winter, people will find ways to enhance the warmth. But in the hot summer, people will naturally try to enhance the heat dissipation. Therefore, in addition to climate, architectural forms, subject background and season are also the factors that adaptive model research should be considered.

Summary of adaptive model

In China, the development of each building thermal design division is uneven.In severe cold region and cold region, thermal comfort research carried out earlier, and the majority of the buildings are heating buildings. In the hot summer and cold winter areas, climate changes quickly, and people's adaptive behaviors are complex. So, the adaptive models established by each researcher are quite different. The research in hot summer and warm winter areas is mainly artificial climate laboratory research. The related research in temperate areas is the least. Due to the lack of attention to the rural residents and the difficulties in rural research, the study on the thermal comfort of rural naturally ventilated buildings is generally partial less.

In the adaptive model, the thermal neutral temperature increases (decreases) with the increase (decrease) of the outdoor temperature. This adaptability reduces the indoor and outdoor temperature difference and helps to tap the energy-saving potential of the naturally ventilated buildings. However, there is very little adaptive thermal comfort research results of naturally ventilated buildings can form the standards in the region.This reflects that the thermal comfort study samples and conclusions are abundant, but the research results lack the systematic induction. At the same time, adaptive model is affected not only by climate, building type, personnel background, seasons, but also greatly influenced by error measurements of environmental parameters, clothing thermal resistance and metabolic rate estimation error. So even for the same building thermal design partition, the same building type and the same season on field research, the adaptive models may be also different (as the results in [33] in Hangzhou and Hefei). Therefore, how to reduce the measurement error and correct the error are also the key issues to solve on thermal comfort research.

Revised Adaptive Model

In the adaptive model, the outdoor air temperature is the only factor considered when we calculate the indoor thermal neutral temperature. Other factors influencing the body's physiological heat balance are not manifested in most of the models. Therefore, some scholars have proposed to revise the adaptive model,mainly considering the correction of the wind speed and humidity .

Yang Wei finds that the higher the temperature is, the higher are people's requirements on the indoor air flow rate when she analyzes the relationship between people's vote values of the wind speed and the indoor air flow rate in different temperature ranges. Su Xing revised adaptive model by the reference of Gong Bo's conclusion that how air flow velocity and relative humidity influence human body's thermal comfort. See in Eq. 9 [23]:

$$t_c = 19.7 + 0.30 t_o - 4(\varphi - 70\%) + \frac{0.55}{0.15} v (t_c > 28℃, \varphi > 70\%) \quad (9)$$

Where: t_o is the indoor temperature, φ is the indoor relative humidity, v is the human face velocity.

When the indoor temperature is lower than 28 ℃and the relative humidity has little effect on the thermal comfort of human body, then the Eq. 9 can be simplified as the Eq. 10[23]:

$$t_c = 19.7 + 0.30 t_o + \frac{0.55}{0.15} v \ (t_c \le 28℃) \quad (10)$$

Tan Meilan of Chongqing University proposed that *SET* can be used to revise the influence of relative humidity and wind speed on thermal sense, and e_{RH} and e_v can be used to revise δSET_{RH} and δSET_v respectively. On the basis of the naturally ventilated thermal comfort model established by Liu Hong [24], Zhang Minfei and Zhang Hualing established the thermal comfort evaluation model considering both the temperature and humidity [25]. They are compared in Table 6.

Table 6 80% acceptable range of the corresponding regression equation and revised regression equation

80% upper and lower limits	regression equation [24]	revised regression equation [25]
80% upper limits	t_c=0.40t_{out}+16.8 (14 ºC≤t_c≤30 ºC, φ＞70%)	t_c=0.40t_{out}+16.8-(φ－70%)/10%×0.4 (14 ºC≤t_c≤30 ºC,φ＞70%)
80% lower limits	t_c=0.59t_{out}+4.0 (14 ºC≤t_c≤30 ºC)	t_c=0.59t_{out}+4.0 (14 ºC≤t_c≤30 ºC)

The above correction of the adaptive model reflects the impact of single factors such as wind speed and humidity on the thermal comfort of the human body can not be ignored in hot and humid regions.Therefore, the follow-up study should combine the theory of human body heat balance with the theory of thermal adaptability, and comprehensively correct the existing thermal comfort evaluation model to form a comprehensive, reasonable and applicable lumped parameter model to guide the indoor thermal environment assessment and architecture design.

Application of Adaptive Model

ASHRAE 55 standard and GB/T 50785-2012"Evaluation standard for indoor thermal environment in civil buildings" both show how to establish comfort zone of naturally ventilated buildings. That is, taking the thermal medium temperature as the center, then 90% and 80% of the population is satisfied with the temperature range corresponding to the PMV ±0.5 and ±0.85. Correspondingly, the acceptable temperature range for the 90% of the population is 5 °C, ie a width of ±2.5 °C, and the acceptable temperature range for 80% of the population is 7 °C, ie a width of ±3.5 °C. At the design stage of the building, the simulated natural room temperature values can be compared with the thermal comfort zones determined by the adaptive model to determine whether natural ventilation can meet comfort requirements or whether air conditioning systems is required.

Conclusions

The following conclusions can be got through the whole paper：

1. PMV (revised) model, climate adaptive (revised) model each have their own advantages and disadvantages in the practical use, the follow-up studies should combine them organically aPMV model is the only try at present. Subsequent studies should further improve the PMV (revised) model and the climate adaptive (revised) model, and also should focus on the combination of human body heat balance and human fitness theories to finally form a more comprehensive lumped parameter evaluation model.

2. The practicality of thermal comfort evaluation model. The conclusions lack systematic induction and it is difficult to form a thermal comfort evaluation system or establish a comprehensive database of human thermal comfort.The development of thermal comfort in each district is not balanced. There are few studies on naturally ventilated buildings in rural areas, and it is imminent to establish a thermal comfort standard for rural residential homes.

3. Error correction can not be ignored. Adaptive model is greatly influenced by the uncontrollable factors in the field. Therefore, future research should consider the factors that affect the thermal comfort of the human body, and also should consider how to reduce the measurement error and error correction.

4. Comprehensive correction of adaptive model. In the adaptive model, the effect of outdoor air temperature is the only factor considered when we calculate the indoor thermal neutral temperature . Other factors influencing the body's physiological heat balance, such as humidity, wind speed, radiation, heat adaptability, are not manifested in most of the models. How to improve the mechanism of the existing adaptive model for the above factors, is still worthy of our discussion.

5. The study of thermal comfort evaluation model for naturally ventilated buildings is of great significance. China's vast territory, complex and changeable climate give buildings huge energy-saving potential.The use of naturally ventilated building thermal comfort model to guide architecture design and operation air conditioning equipment can greatly reduce the energy consumption. This is one of the future direction of green building development.

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