Field study of a thermal environment and adaptive model in Shanghai

A long-term field investigation was carried out in naturally ventilated residential buildings in Shanghai from April 2003 to November 2004. A total of 1.768 returned questionnaires were collected in the study. This study deals with the thermal sensation of occupants in naturally ventilated buildings and the change in thermal neutral temperature with season. The range of accepted temperature in naturally ventilated buildings is between 14.7 °C Top and 29.8 °C Top. The results also report the findings of the adaptive comfort model in Shanghai that determines the adaptive relationship of neutral temperature with outdoor air temperature.

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The study of thermal comfort is very important because it is correlated not only with occupants' comfort, but also with energy consumption. For example, there are about five million homes in Shanghai. About 260.000 kWh per hour power load could be saved if air-conditioning temperature increases by 1 °C in each home [25]. Thermal comfort standards in China are in accordance with some international standards, such as ASHRAE 55-1992 (ASHRAE, 1992) and ISO 7730 (ISO, 1994). However, these standards are based almost exclusively on data from climate chamber experiments and they are suitable for static and uniformly thermal conditions. The indoor design temperatures as described by these standards take no account of climatic variations and adaptive behavior of people. For any task and use of the building, there is a recommended temperature that is assumed to apply irrespective of climate and social convention, way of life and kind of clothing, although with some recognition of difference between summer and winter [7; 11; 16]. Studies suggest that thermal comfort standards based on laboratory studies are not representative of real conditions [7; 11; 16]. With the development of the thermal comfort study, researchers found that a subject's thermal
sensation was different according to individual, race, climate, habits and customs, etc. [17; 23].
Researchers have carried out adaptive thermal comfort studies in different countries or areas (Cardinale and Stefanizzi, 1996; Tsilingiridis and Sotiropoulos, 1998), believing that thermal comfort standards should conform to local climate and comfortable temperature could be variable according to outdoor temperature, thereby improving the degree of thermal comfort and saving energy.

The adaptive model is defined as a linear regression model that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters [6]. The adaptive approach to thermal comfort, based on field study data, can be used to develop better standards that would result in more energy efficiency and encourage building designers to give occupants ≠ The rate of change of comfort temperature can be characterized by the running mean of the outdoor temperature. This means that an adaptive algorithm can be formulated which can be used to calculate a variable indoor set-point, related to the outdoor temperature [30].

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AIMS

The current study was performed in Shanghai and the aims of this project are as follows:

- The article describes a 'climatically adaptive' environment in residential buildings in order to provide thermal comfort with a minimal expenditure of energy.
- To develop a database of the thermal environments and subjective responses of occupants in Shanghai with long-term thermal comfort surveys.
- To determine the neutral temperature for occupants and study the relationship between neutral temperature and relative humidity in existing residential buildings in Shanghai.
- To provide an adaptive model for setting comfortable indoor temperatures for residential buildings in Shanghai.

Scale	Thermal sensation	Air quality vote	Comfort level
+3	Hot	Very pleasant	Very comfortable
+2	Warm	Moderately pleasant	Moderately comfortable
+1	Slightly warm	Slightly pleasant	Slightly comfortable
0	Neutral	Neutral	Common
-1	Slightly cool	Slightly unpleasant	Slightly uncomfortable
-2	Cool	Moderately unpleasant	Moderately uncomfortable
-3	Cold	Very unpleasant	Very uncomfortable

Scale used for environmental evaluation in the survey.

- *Table 1* -

METHODS AND BACKGROUND DESCRIPTIONS

Instruments

Air temperature, globe temperature, air velocity and relative humidity were measured in this study. The locations of measurements were conducted at representative points in the building. Air temperature was measured with a digital thermometer (TESTO 110, Testo AG, Lenzkirch, Germany), with an accuracy of ±0.2 °C within the range of)25 to +75 °C. Air velocity was measured with a hot wire anemometer (EY3-2A, with an accuracy of ±2 % within the range of 0.05–1 m/s, Tianjin Meteorologic & Instrument Co., Tianjin, China). Relative humidity was measured with a dry and wet bulb thermometer (WS508D, Xinhua Laboratory Instrument Co., Haimen City, China), with an accuracy of ±0.5 °C. The mean radiant temperature was measured with a 150 mm diameter black globe thermometer, with an accuracy of ±0.1 °C. Measurements were taken with the instruments placed 1,1 m above the floor. The accuracy of the instrument conformed to ASHRAE Standard 55-1992 (ASHRAE, 1992) and ISO 7726 (ISO, 1985). Measurements of environmental data were taken while the subjects were completing their questionnaires.

Questionnaire

The questionnaire was divided into two parts – environmental parameters and sensation vote. The background included demography and health. The sensation vote questionnaire mainly included thermal sensation, indoor air quality and personal comfort. The scope and format of the questionnaire was based on a conventional questionnaire [27; 31; 34; 35]. The details of the sensation vote in this study are listed in table 1. Subjects were asked to complete a thermal questionnaire while the field measurements were taken.

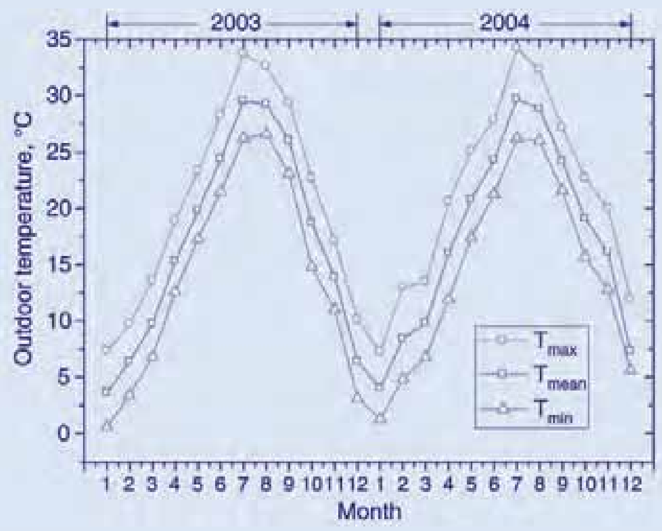
Building selection and background data

The long-term field investigation was carried out in five naturally ventilated residential buildings in Shanghai. The selected buildings included both four old style (built more than 15 years) and one modern style (built less than 5 years) buildings, and they were divided into two groups – one private organization building and four educational organization buildings. Two of them are located in the central part of Shanghai, one in the south-west, one in the west, one in the north. The size of the window is 1.1 m x·1.6 m or 1.4 m x 1.6 m. The windows of all buildings are single, and occupants can open or close it freely. More information is shown in table 2. The surveys were spread over a period of 20

Building	A	B	C	D	E
Orientation	NS	NE	NE	E	SW
Construction	Brick wall	Shell frame	Shell frame	Brick wall	Brick wall
Floors	7	18	18	7	5
Property	Private	University	University	University	University
Type	Residential House	Apartment	Apartment	Apartment	Apartment
Density (persons/m^2)	1/8,2	1/3,8	1/7,6	1/5,8	1/6,2
Sample size	224	704	311	255	274

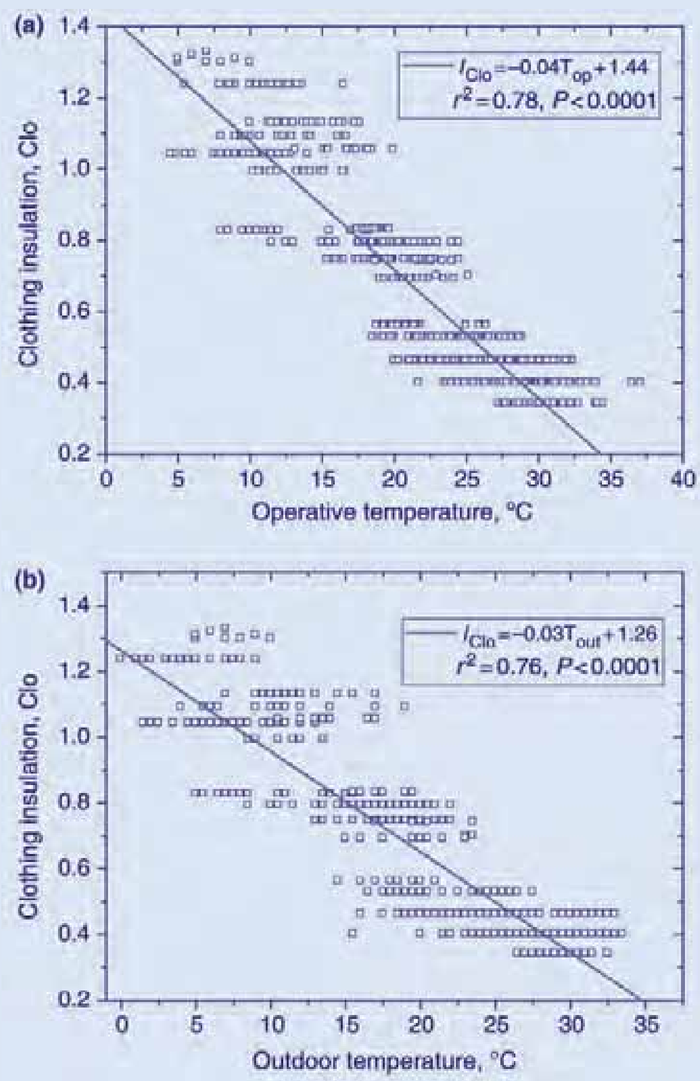
Information about the buildings.

- *Tabel 2* -



Outdoor temperature of Shanghai in 2003 and 2004 (obtained from National Meteorological Information Centre of China).

- FIGURE 1 -



(a) Change of clothing insulation with indoor operative temperature in Shanghai.
(b) Change of clothing insulation with outdoor temperature in Shanghai.

- FIGURE 2 -

months from April 2003 to November 2004. A total of 1.768 returned questionnaires were collected in the study. The subjects were between 18 and 42 years of age, with an average age of 28,7 years and standard deviation of 6,4 years. The shortest subject was 158 cm and the tallest subject was 184 cm, with a mean height of 171,6 cm and standard deviation of 5,3 cm. They were in good health. Subjects in the study could freely adjust their clothing according to the change in climate. Metabolic rates and clothing insulation were estimated in accordance with ASHRAE Standard 55-1992 (ASHRAE, 1992). Metabolic rates of the subjects were 1,2 met (70 W/m^2), which represents the value for sedentary activities.

RESULTS AND DISCUSSIONS

Outdoor climatic data

The outdoor weather data for the period of survey was obtained from National Meteorological Information Centre of China. The monthly mean outdoor temperature in 2003 and 2004 is shown in figure 1.
The maximum mean temperature in 2003 is 33,7 °C T_a and that in 2004 is 34,2 °C T_a.

Clothing insulation

Clothing is an important behavioral adaptation to achieve thermal comfort at different temperatures [5]. The clothing pattern of subjects has a strong correlation with indoor and outdoor temperatures. A large scatter of the indoor Clo value has been observed (0,35–1,35 Clo) in naturally ventilated buildings. Figure 2a,b shows how the Clo value varies with the indoor operative temperature (T_{op}) and the outdoor temperature (T_{out}). The linear regressed equations are described by equations 1 and 2. Equation 1 shows that mean clothing insulation (I_{Clo}) decreases by an average of 0,1 Clo for every 2,5 °C increase in mean indoor temperature:

$$I_{Clo} = -0{,}04\,T_{op} + 1{,}44 \qquad (1)$$

$$I_{Clo} = -0{,}03\,T_{out} + 1{,}26 \qquad (2)$$

Other similar regressions for clothing and globe indoor temperature (T_g) or operative temperature are given in equation 3 [5], equation 4 [13], and equation 5 [27]:

$$I_{Clo} = -0{,}035\,T_g + 1{,}39 \quad (3)$$

$$I_{Clo} = -0{,}04\,T_{op} + 1{,}73 \quad (4)$$

$$I_{Clo} = -0{,}04\,T_{op} + 1{,}76 \quad (5)$$

The correlation between clothing insulation and outdoor temperature in this study (Equation 2) is very close to the result in Tunisia (No AC building), which is given in equation 6 [5]:

$$I_{Clo} = -0{,}038\,T_{out} + 1{,}33 \quad (6)$$

Although there are some differences between those regressed equations and all the above regression equations in that they do not have a uniform slope and intercept, they are very similar. This suggests that the dependence of occupants' clothing levels on temperature is broadly similar between this Shanghai study and the [5] study.

Indoor air velocity

Air velocity has an effect on thermal comfort. In naturally ventilated buildings, people often open doors or windows when they feel the air temperature is high. The rate of air change is very small when air temperature is low in Shanghai. The change in indoor air velocity was small in this investigation, and the proportion of indoor air velocity less than 0,5 m/s is more than 95 % (95,2 %), as described in ASHRAE standard 55 (ASHRAE, 1992). The regressed equation of indoor air velocity against operative temperature is shown in table 3. Compared with other studies, there is only a little difference between the regression equations.

Thermal sensation

In a thermal comfort study, the relationship between thermal sensation and operative temperature forms the basis of research into thermal neutral temperature. One recognized method to predict the subjective comfort which results from a given temperature is regression analysis. Figure 3 demonstrates the influence of indoor mean operative temperature on thermal sensation vote (TSV). The range of accepted temperature in Shanghai is between 14,7 and 29,8 °C T_{op}. The result is similar to other researches.

Researcher	Location	Regressive curve	Correlation coefficient (r^2)
de Dear and Brager (1998)	Several countries	$v = 0{,}03T_{op} - 0{,}56$	0,34
Mui and Chan (2003)	Hong Kong	$v = 0{,}02T_{op} - 0{,}35$	0,34
This study (2003-2004)	Shanghai	$v = 0{,}02T_{op} - 0{,}25$	0,39

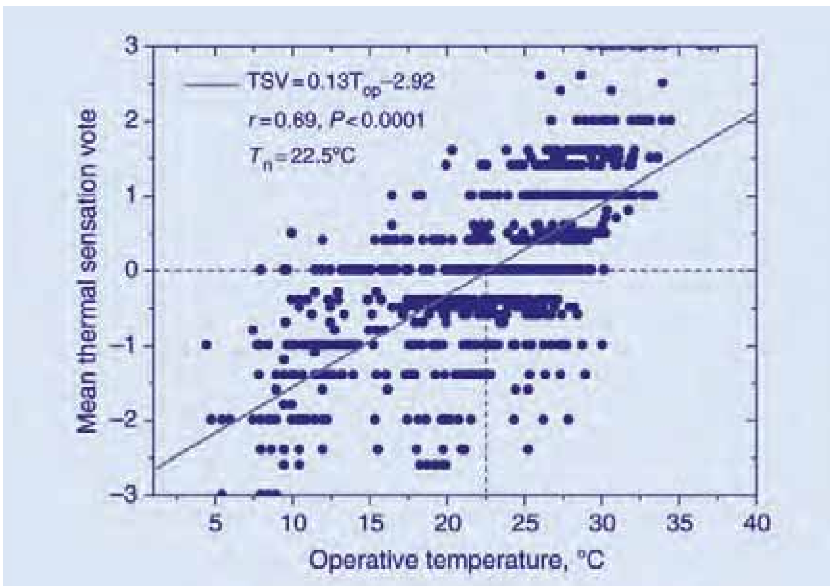
The regress relationship between mean air velocity and operative temperature in different studies

- TABLE 3 -

Researcher	Location	Regressive curve	Correlation coefficient (r^2)
Mallick (1996)	Dhaka	$TSV = 0{,}18\,T_{op} - 5{,}11$	0,25
de Dear and Brager (1998)	NV buildings	$TSV = 0{,}27\,T_{op} - 6{,}65$	-
Karyono (2000)	Jakarta	$TSV = 0{,}31\,T_{op} - 8{,}33$	0,40
Fato et al. (2004)	Bari	$TSV = 0{,}28\,T_{op} - 5{,}82$	0,87
Brager et al. (2004)	San Francisco	$TSV = 0{,}19\,T_{op} - 4{,}20$	0,69
This study (2003-2004)	Shanghai	$TSV = 0{,}13\,T_{op} - 2{,}92$	0,48

The regress relationship between mean thermal sensation vote and operative temperature in different study (for naturally ventilated buildings).

- TABLE 4 -



Indoor thermal sensation vote and operative temperature in Shanghai.

- FIGURE 3 -

With the same technique in Beijing, the upper limitation of acceptable operative temperature reached 30 °C in naturally ventilated buildings [33]. However, the upper limitation of acceptable temperature is less than 27 °C when subjects stay in air-conditioned buildings. For naturally ventilated buildings, the correlation between TSV against T_{op} in Shanghai is given in equation 7:

$$TSV = 0{,}13\,T_{op} - 2{,}92 \quad (7)$$

The standard deviation is 0,93, the correlation coefficient r is 0,69 and the correlation is statistically significant ($P < 0,0001$). The annual neutral temperature for naturally ventilated buildings in Shanghai was 22,5 °C T_{op} in 2003 and 2004. The regression relationship between mean TSV and operative temperature in other studies is shown in table 4. The gradient of the regression model is related to the sensitivity of mean thermal sensation to the operative temperature [13]. A weighted linear regression model of the relationship between mean thermal sensation and mean indoor operative temperature was used to judge how quickly people felt too warm or too cool as temperatures deviated from the optimum [7]. The slope of the regression line of Shanghai is small. Equation 7 also suggests that occupants in Shanghai are more tolerant of a wider range of temperatures than occupants in other studies.

During the survey, the subjects stayed in residential buildings or university apartments. In contrast to occupants in office buildings, residential building occupants are free to move around. They can adjust their clothing and activities substantially in response to any thermal stress in their environment freely. We think that the reason for the small gradient in the Shanghai regression model is because the subjects adjusted their clothing more in Shanghai.

Monthly thermal neutral temperature

Many field studies have also suggested that neutral temperatures differ by climate or season [10]. The relationship between monthly mean neutral temperature (T_n) and indoor air temperature (T_a) is shown in figure 4. The correlation between T_n against T_a in Shanghai is given in Equation 8:

$$T_n = 0,41\ T_a + 13,93 \qquad (8)$$

The correlation coefficient r is 0,84 and the correlation is statistically significant ($P < 0,0001$).

The results of monthly neutral temperature for the long-term studies in Shanghai and in other countries are shown in table 5. Table 5 shows that there are differences in thermal neutral temperature in differentmonths. This could be due to climate, lifestyle, etc. Therefore, thermal neutral temperature cannot to be 'one-size-fits-all'. For energy conservation and more comfort, the thermal neutral temperature should be different for each month and it should be fitted for season. Moreover, the thermal neutral temperature varies in each country (Table 5). The mean difference between Shanghai and Australia [4] is 4,2 °C, it is 2,3 °C between Shanghai and Pakistan [29] and it is 1,7 °C between Shanghai and Iran [17]. The air-conditioning set-point temperature in each country should be in according to its own monthly neutral temperature.

Adaptive model

The PMV model does not include the influence of outdoor climate [2]. However, some studies suggest that outdoor climate could have an influence on thermal sensation [12; 13]. It is because people have a natural tendency to adapt in changing conditions in their environment. This natural tendency is expressed in the adaptive approach to thermal comfort [12].

In practice, the temperature inside a building normally bears some relation to the temperature outside, and so indoor comfort temperatures are found to be linked to weather conditions outside. In naturally ventilated buildings, outdoor temperature (T_{out}) has been shown to be linearly related to neutral temperature, to account for a large percentage of the variance in neutral temperatures, and to often be a better predictor of thermal sensation than the PMV model [12]. Therefore, the relationship between T_n and T_{out} is particularly interesting because it is evidence of adaptive action taken by building occupants. A scatter plot of mean thermal neutral temperature in Shanghai and the mean outdoor temperature is shown in figure 5. Figure 5 shows that the neutral temperature is closely correlated with the mean outdoor temperature. The correlation between T_n against T_{out} in Shanghai is given in equation 9:

$$T_n = 0,42\,T_{out} + 15,12 \qquad (9)$$

The standard deviation is 2,02, the correlation coefficient r for the relationship is 0,86 and the correlation is statistically significant ($P < 0,0001$).

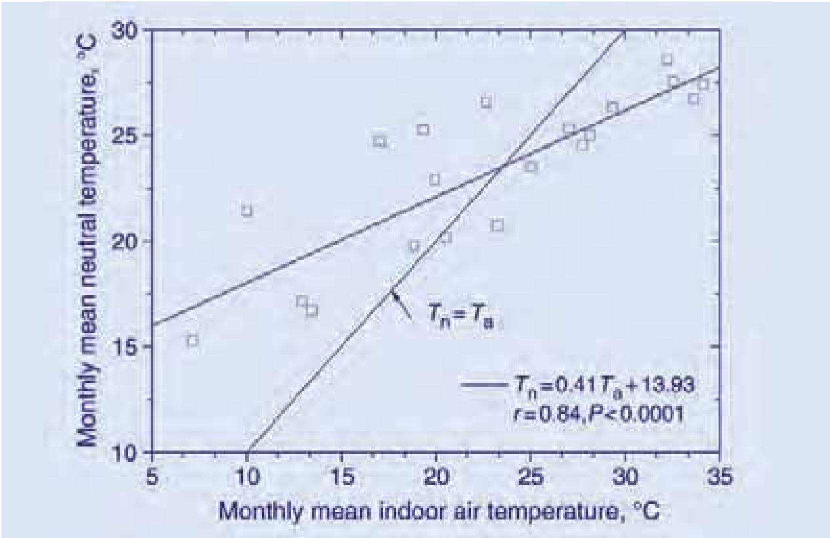
At temperatures in excess of about 25,9 °C (at which point $T_n = T_{out}$), the preferred comfortable temperature is below the outdoor temperature.

The regression equation of neutral temperature and outdoor air temperature in other countries are listed in table 6. A large number of field studies show that outdoor climate has a stronger influence on the thermal neutral temperature in naturally ventilated buildings [14]. Some studies show that such a variable set-point does not

Researcher	Location	Montly mean thermal neutral temperatures (°C)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Humphreys (1978)		20,9	22,0	23,5	26,0	29,2	30,1	31,0	30,9	29,8	27,7	25,5	20,8
Auliciems and de Dear (1986)	Australia	22,7	23,2	24,2	25,7	27,5	28,0	28,5	28,5	27,8	26,6	25,4	22,7
Heidari and Shaplples (2002)	Iran	20,9	21,3	21,8	22,1	22,3	25,9	27,6	26,8	25,7	24,6	23,1	21,4
Nicol (2004)	Pakistan	17,1	17,9	20,4	23,5	26,4	28,2	27,6	27,4	26,0	23,8	20,6	17,9
This Study (2003-2004)	Shanghai	15,2	17,1	16,7	19,9	22,1	24,8	27,0	28,1	25,8	25,9	23,8	21,4

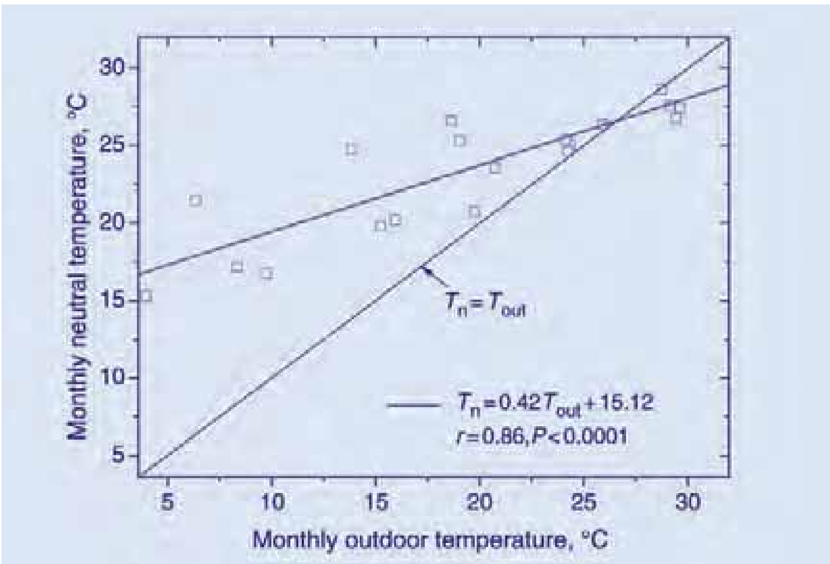
Montly mean thermal neutral temperature in different study.

- TABLE 5 -



The relationship between thermal neutral temperature and outdoor temperature in Shanghai.

- *Figure 4* -



Thermal neutral temperature and monthly mean indoor temperature in Shanghai.

- *Figure 5* -

Researcher	Regressive curve	$T_n = T_{out}$
This study (2003–2004)	$T_n = 0{,}42T_{out} + 15{,}1$	25,9
Humphreys (1978)	$T_n = 0{,}53T_{out} + 11{,}9$	25,5
Nicol (2004)	$T_n = 0{,}38T_{out} + 17{,}0$	27,4
Auliciems and de Dear (1986)	$T_n = 0{,}31T_{out} + 17{,}6$	25,7
Auliciems (1983)	$T_n = 0{,}52T_{out} + 12{,}3$	25,6

The regressive relationship between thermal neutral temperature and outdoor temperature in different studies.

- *Table 5* -

increase discomfort and allows significant reductions in energy use in buildings [19]. With the use of the adaptive model, it is possible to reduce temperature shock and the thermal comfort dissatisfaction rate of occupants [27]. These trends are also supported by analyses conducted on the ASHRAE RP-884 database. The research project (RP-884) used the adaptive approach to reanalyze available global data from various field studies and to develop adaptive model of four continents and a broad spectrum of climatic zones [13].

CONCLUSIONS

China is a country with very limited energy resources and its electrical load is huge, especially in summer. Last year, 24 provinces had to limit usage of power in the cooling season. Therefore, saving energy is the main problem in China. Numerous adaptive model studies have been carried out in many countries. With the goal of saving energy, it has been suggested that thermal comfort standards can apply the comfort charts of non-air-conditioned buildings to airconditioned buildings {24}. However [13] pointed that the range of average neutral temperature in HVAC buildings is different from that in NV buildings. Therefore, the comfortable temperature in NV buildings could not be used in HVAC buildings directly. It could lead to unacceptably high levels of complaint in HVAC buildings. However, the study in NV buildings suggests how to set indoor temperature values in HVAC buildings. It could help designers to judge whether heating and cooling techniques are appropriate for the climate under consideration. And it could save energy if comfortable temperature could be variable according to local climate or outdoor temperature. With the long-term survey in Shanghai, physical measurement and subjective response were collected in different seasons of a full year. The result reports the adaptive comfort model in Shanghai. Outdoor temperature can be a useful predictor of thermal sensation with an adaptive model. The annual neutral temperature for naturally ventilated buildings in Shanghai was 22,5° C T_{op} in 2003 and 2004. The range of accepted temperature in Shanghai is between 14,7 and 29,8 °C T_{op}. Thermal comfort temperature varies in different months. For energy conservation and more comfort, the thermal neutral temperature should be different for each month and it should be fitted for season.

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