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# Thermal adaptive models in built environment and its energy implications in Eastern China

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**Abstract**

Field investigations and testing on thermal comfort were conducted in Eastern China including 8 representative cities of 4 climate zones of severe cold, cold, hot summer and cold winter, hot summer and warm winter etc. Both subjective questionnaire survey in terms of thermal sensation vote (TSV) and objective on-site measurements were carried out. Clothing levels during summer and winter in 4 climate zones were obtained, and correlations between clothing insulation against operative temperature and outdoor temperature were found, different adaptive models of climate and comfort indoors were developed as well. The energy savings for cooling of indoor design temperature (with and without adaptive model) were calculated in Beijing, Shanghai and Guangzhou, and the total percentage of saving is about 5%, 6.5% and 8%, respectively.


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*Keywords:* Thermal comfort; adaptive model; energy implications; Eastern China

## 1. Introduction

A growing concern on how to use less energy to create a more comfortable and healthy indoor thermal environment has become a focus in architectural research. Numerous thermal comfort field studies show that there is a strong adaptive relation between climate and comfort indoors, and this adaptive approach can be significant in conserving energy in system operation on the demand control side [1]. The

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correlation between indoor comfort temperature against outdoor monthly mean temperature is given in the form of regression equations by Humphreys [2], Auliciems [3] and Nicol [4] as the representatives. Such findings were also confirmed in some individual cities of China [5], but not extending to large zones which are, for instance, 3 steps descending from west to east classified according to topography, or 5 climate zones for thermal design of buildings classified by climate types. The objective of the present work was, therefore, to conduct filed investigation and testing on indoor environment to develop thermal adaptive models in built environment in Eastern China, which is a special region-the lowest step with an altitude less than 1000 m above the sea level among 3 steps and containing 4 climate types named severe cold, cold, hot summer and cold winter, and hot summer and warm winter [6]. Besides, the building energy implications in this zone will be discussed as well, because the building energy consumption of Eastern China is higher for its relatively larger stock of existing buildings.

## 2. General climate of Eastern China

China is a large country with an area of about 9.6 million $km^2$, and more than 25% of the land area on the east edge forms Eastern China which covers 20 provinces, municipalities directly under the central government, autonomous regions and special administrative region. It is from the subtropical zones in the south to the temperate zones (including warm-temperate and cool-temperate) in the north, and the maximum solar altitudes vary a great deal and there is a large diversity in climates, especially the temperature distributions during winters. The monsoon climate tends to be dominant, with a marked change of wind direction between winter and summer as well as seasonal variation of precipitation according to whether the maritime monsoon advances or retreats. Besides, characteristics associated with continental climates can be identified with warmer summer, cooler winter and a larger annual temperature range than other parts of the world with similar latitudes [7]. Based on the average temperatures in the coldest and hottest months of the year, it is divided into four major climate zones in Eastern China mentioned above.

## 3. Methodology and results

### *3.1. Sample selection*

8 representative cities in 4 climate zones were selected considering their geographical position, city scale, climate characteristics, etc. they are Harbin, Changchun and Shenyang of severe cold zone, Beijing and Zhengzhou of cold zone, Nanjing and Shanghai of hot summer and cold winter zone, Guangzhou of hot summer and warm winter zone, and then field thermal comfort investigation were carried out in these cities during summer and winter and 120 occupants were involved in. All subject samples of buildings (including different forms and construction ages) and occupants (different ages and gender) were uniformly distributed.

### *3.2. Investigation method and results*

Field thermal comfort investigation mainly includes indoor thermal environment test and subjective questionnaire. The former contains four parameters: mean indoor air temperature ($t_a$), mean relative humidity (RH), mean air velocity ($v$) and mean radiant temperature ($t_r$), which were tested using temperature and humidity electronic recorder and indoor thermal comfort data recorder. The latter includes the information of occupants (mainly age and gender), human thermal sensation, control and adaptive ways to thermal environment. Statistics of the above two parts were shown in Table 1 and 2.

Besides, all the investigations occurred in four kinds of buildings built in 1970s, 1980s, 1990s and 2000s, and the proportion of each kind was 6%, 16%, 58% and 20%. Among these buildings, there were 6% of bungalow, 82% of multi-storey building and 12% of high-rise building.

Table 1. Statistical information of occupants

| Climate zones | Sample size | Male | Female | Maximum age | Minimum age | Average age |
|---|---|---|---|---|---|---|
| Severe cold | 30 | 19 | 11 | 82 | 14 | 43 |
| Cold | 30 | 17 | 13 | 83 | 14 | 38.8 |
| Hot summer and cold winter | 30 | 13 | 17 | 71 | 15 | 38.4 |
| Hot summer and warm winter | 30 | 16 | 14 | 73 | 15 | 39.8 |

Table 2. Statistical summary of indoor thermal environment parameters

| Climate zones | Parameters | Summer | | | | Winter | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Min. | Max. | Mean | Standard deviations | Min. | Max. | Mean | Standard deviations |
| Severe cold | $t_a$ (°C) | 19.8 | 29.8 | 23.9 | 2.06 | 12.2 | 25.2 | 18.6 | 2.81 |
| | RH (%) | 53.5 | 75.2 | 62.8 | 4.02 | 40.7 | 60.2 | 47.8 | 5.22 |
| | $v$ (m/s) | 0 | 0.45 | 0.15 | 0.12 | 0.01 | 0.06 | 0.04 | 0.01 |
| | $t_r$ (°C) | 20.5 | 30.1 | 24.9 | 2.07 | 13.1 | 26.3 | 19.8 | 2.78 |
| Cold | $t_a$ (°C) | 20.8 | 34.8 | 28.2 | 3.45 | 8.5 | 23.4 | 16 | 2.62 |
| | RH (%) | 52.1 | 80.2 | 63.1 | 5.34 | 48.5 | 69.4 | 57.8 | 4.96 |
| | $v$ (m/s) | 0.05 | 1.5 | 0.42 | 0.32 | 0.01 | 0.06 | 0.04 | 0.01 |
| | $t_r$ (°C) | 21.2 | 35.2 | 29.1 | 3.37 | 9.4 | 24.5 | 17.1 | 2.69 |
| Hot summer and cold winter | $t_a$ (°C) | 24.8 | 35.5 | 29.0 | 2.64 | 13.2 | 20.7 | 16.1 | 1.72 |
| | RH (%) | 55.8 | 80.2 | 68.3 | 4.35 | 52.5 | 75.4 | 63.4 | 6.26 |
| | $v$ (m/s) | 0.10 | 1.20 | 0.40 | 0.33 | 0.01 | 0.08 | 0.03 | 0.02 |
| | $t_r$ (°C) | 25.5 | 36.6 | 29.8 | 2.69 | 12.8 | 19.5 | 15.3 | 1.75 |
| Hot summer and warm winter | $t_a$ (°C) | 24.6 | 33.4 | 29.3 | 2.26 | 12.3 | 23.2 | 16.7 | 2.63 |
| | RH (%) | 60.3 | 80.1 | 66.8 | 4.22 | 65.7 | 89.7 | 82.1 | 4.93 |
| | $v$ (m/s) | 0.10 | 0.80 | 0.40 | 0.26 | 0 | 0.20 | 0.10 | 0.05 |
| | $t_r$ (°C) | 25.9 | 34.6 | 30.2 | 2.21 | 11.4 | 23.9 | 16.5 | 2.86 |

## 4. Analysis

### *4.1. Clothing level and subjective feeling*

Clothing level adjustment is the important adaptation process to maintain the comfort at different temperature. During the comfort survey, it has been found that clothing values are vary from each climate zone and is governed by local climates. The correlation between clothing insulation ($I_{clo}$) against operative temperature ($t_{op}$) and outdoor temperature ($t_o$) is also different. The results are shown in table 3.

Mean Thermal Sensation Vote (MTS) was used to analyze the correlation needed, which is the mean value of Thermal Sensation Vote (TSV) at a temperature range .We chose 0.5°C as the interval of the mean operative temperature ($t_{op}$), then got the linear relationship between $t_{op}$ and MTS which is shown as a formula: MTS=$a+b\cdot t_{op}$. In the same way, a formula of PMV=$a+b\cdot t_{op}$ can be obtained as well, PMV value in which is calculated using a program based on Fanger's PMV equation. Let MTS=0 and PMV=0, respectively, the actual neutral temperature and predicted neutral temperature can be obtained. The results are shown in Table 4. From table 4 we can see that actual thermal neutral temperature was lower than the PMV predicted neutral temperature in winter and higher than it in summer. This suggests that the occupants of different climate zones in China are generally adapted to the local climate. In addition, different zones have different climate characteristics, so human ability to adapt climate was also slightly different. For example, the cold feelings of people in Guangzhou are different from that in Beijing at the same temperature, and hot feelings of people in Harbin and Shanghai are also different.

Table 3. Distribution of $I_{clo}$ and regression equations between $I_{clo}$ against $t_o$ and $t_{op}$

| Climate Zones | Distribution of $I_{clo}$ (clo) | | Regression equations | |
|---|---|---|---|---|
| | Summer | Winter | Between $I_{clo}$ against $t_o$ | Between $I_{clo}$ against $t_{op}$ |
| Severe cold | 0.50~0.65 | 1.20~1.50 | $I_{clo} = -0.018\cdot t_o + 1.035$ ($R^2$=0.816) | $I_{clo} = -0.119\cdot t_{op} + 3.571$ ($R^2$=0.844) |
| Cold | 0.30~0.40 | 1.20~1.50 | $I_{clo} = -0.033\cdot t_o + 1.345$ ($R^2$=0.921) | $I_{clo} = -0.081\cdot t_{op} + 2.704$ ($R^2$=0.886) |
| Hot summer and cold winter | 0.30~0.40 | 1.15~1.35 | $I_{clo} = -0.035\cdot t_o + 1.458$ ($R^2$=0.964) | $I_{clo} = -0.064\cdot t_{op} + 2.239$ ($R^2$=0.925) |
| Hot summer and warm winter | 0.25~0.45 | 1.10~1.30 | $I_{clo} = -0.052\cdot t_o + 1.999$ ($R^2$=0.950) | $I_{clo} = -0.062\cdot t_{op} + 2.226$ ($R^2$=0.927) |

Table 4. Thermal neutral temperature

| Climate Zones | Summer (°C) | | Winter (°C) | |
|---|---|---|---|---|
| | MTS=0 | PMV=0 | MTS=0 | PMV=0 |
| Severe cold | 25.37 | 24.90 | 19.49 | 20.47 |
| Cold | 27.20 | 26.67 | 20.80 | 21.17 |
| Hot summer and cold winter | 27.60 | 27.36 | 18.22 | 20.20 |
| Hot summer and warm winter | 27.47 | 27.70 | 19.74 | 21.11 |

### *4.2. Adaptive models*

An adaptive model that can describe the relationship between the indoor neutral temperature ($T_n$) against outdoor temperature ($t_o$) was put forward in the form of $T_n= a+b\cdot t_o$. Different adaptive models for four climate zones in Eastern China have been obtained, seeing formula (1) to (4). These models are similar but different from previous results [8].

For severe cold zone, the adaptive model is:

$$T_n = 0.121\cdot t_0 + 21.489 \quad (16.3 < T_n < 26.2) \quad \mathrm{R}^2 = 0.6465 \tag{1}$$

For cold zone, it is:

$$T_n = 0.271\cdot t_0 + 20.014 \quad (15.8 < T_n < 29.1) \quad \mathrm{R}^2 = 0.8945 \tag{2}$$

For hot summer and cold winter zone, it is:

$$T_n = 0.326\cdot t_0 + 16.862 \quad (16.5 < T_n < 27.8) \quad \mathrm{R}^2 = 0.8227 \tag{3}$$

And for hot summer and warm winter zone, it is:

$$T_n = 0.554\cdot t_0 + 10.578 \quad (16.2 < T_n < 28.3) \quad \mathrm{R}^2 = 0.9472 \tag{4}$$

### *4.3. Energy implications*

Neutral temperature in PMV model is equal to $t_{op}$ when we make variables (e.g. air temperature, relative humidity, air velocity, clothing thermal insulation and activity levels) into Fanger's PMV formula until the PMV=0 using the iterative calculation, then the relation between the neutral temperature against mean outdoor temperature can be obtained. Taking cold zone for example, Fig. 1 presents the profile as well as the adaptive model, the range of adaptive comfort temperature is so wider that can generate saving energy effect.

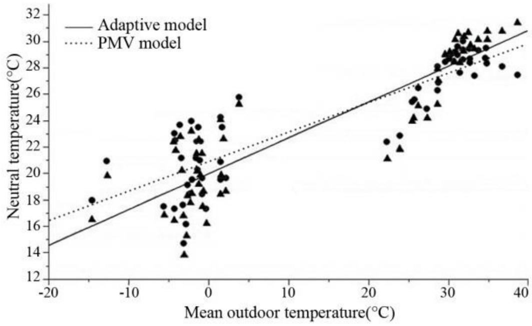


Fig.1 Neutral temperature comparison between PMV model and adaptive model in cold zone

According to the adaptive models found above and the control temperature in summer (26℃) indicated in design code (GB 50736-2012) of China [9], the energy consumptions by the cooling coil in an air handling unit at different combinations of indoor design temperature (with and without adaptive model) were calculated according to equations (5)-(8) [10].

$$Q_{eng}=\rho V[C_{pa}(T_{on}-T_{le})+h_{fg}(g_{on}-g_{le})]S_{sec} \tag{5}$$

Relative humidity to moisture content is calculated by

$$g=0.622\frac{\phi P_{ss}}{P_{at}-\phi P_{ss}} \tag{6}$$

Wet bulb to moisture content is calculated by

$$g=\frac{0.622}{\left[\frac{P_{at}}{P_{ss}'-P_{at}A(t-t')}-1\right]} \tag{7}$$

Saturated vapour pressure is given by

$$P_{SS}=\log^{-1}\left[30.59051-8.2\log(t+273.16)+0.0024804\times(t+273.16)-\frac{3142.31}{(t+273.16)}\right] \tag{8}$$

where $Q_{eng}$ is the energy consumption (kJ); $\rho$ the density of air=1.2 kg·m$^{-3}$; $V$ the total air volume handled (m$^3$/s); $c_{pa}$ the specific heat capacity of air = 1.023 kJ·kg$^{-1}$·K$^{-1}$; $T_{on}$ the on coil temperature (℃); $T_{le}$ the leaving coil temperature (℃); $h_{fg}$ the latent heat of evaporation of water =2454 kJ·kg$^{-1}$; $g_{on}$ the on coil moisture content (kg·kg$^{-1}$); $g_{le}$ the off coil moisture content (kg·kg$^{-1}$); $g$ the moisture content (kg·kg$^{-1}$); $P_{ss}$ the saturated vapour pressure at same temp. (kPa); $P_{at}$ the atmospheric pressure =101.325 kPa; $P_{ss'}$ the saturated vapour pressure at wet bulb temp. (kPa); $A$ the a constant = 6.66×10$^{-4}$ ℃$^{-1}$; $t$ the dry bulb temperature (℃); $\phi$ the relative humidity; $t'$ the wet bulb temperature (℃) and $S_{sec}$ the time (s).

Three cities of Beijing, Shanghai and Guangzhou were taken for examples to calculate the energy savings effect, all the governing parameters for energy consumption can be obtained from the appendix of design code (GB 50736-2012). Finally, for the energy savings with the integration of adaptive model, the total percentage of savings of Beijing, Shanghai and Guangzhou are about 5%, 6.5% and 8%, respectively.

## 5. Conclusions

We have conducted a thermal comfort study of residential buildings in 8 cities of 4 climate zones in Eastern China. On the basis of analyzing the results of the survey, clothing level, correlation between clothing insulation against operative temperature and outdoor temperature and neutral temperature have been found to be different. Subsequently, 4 adaptive models for each climate zone have been developed which are different as well. Finally, the energy implications for cooling of indoor design temperature (with and without adaptive model) were calculated in Beijing, Shanghai and Guangzhou, and the total percentage of saving is about 5%, 6.5% and 8%, respectively.

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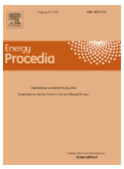


## Biography

Liu Yang, a professor of Xi'an University of Architecture and Technology, China, has been conducting in-depth research on bioclimatic building design as well as climate adjusting techniques. For her distinguished contribution to this filed of China, she was awarded the China Science and Technology Award for Youth in 2013.