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# Adjustments of the adaptive thermal comfort model based on the running mean outdoor temperature for Chinese people: A case study in Changsha China

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A B S T R A C T

A method to develop an adaptive thermal comfort model based on the running mean outdoor temperature for Chinese people was proposed. The determination of two important parameters (neutral temperature and outdoor temperature) in the adaptive thermal comfort model was the focus of this work. A longitudinal survey was conducted from Jan. 2010 to Feb. 2011 in two naturally ventilated office buildings located in Changsha, China. During the survey, the thermal sensation of the subjects was investigated, and the indoor temperature was measured daily. Based on the field data, the neutral temperature and the running mean outdoor temperature were determined. Further, an adaptive thermal comfort model was established by quantifying the relationship between the neutral temperature and the running mean outdoor temperature. The results show that the adaptive thermal comfort model based on the running mean outdoor temperature can well reflect the change of neutral temperature in the two office buildings with the climate of Changsha China. This study provides a reliable method to adjust the adaptive thermal comfort model based on the running mean temperature for Chinese people.



## 1. Introduction

The thermal environment in naturally ventilated buildings always changes with the outdoor climate. Thermal adaptation is an important method to maintain thermal comfort under the effects of dynamic thermal environment [1,2]. For example, occupants are free to adjust clothing, open/close windows and doors, and put on/off curtains when feeling thermally uncomfortable [e.g., 3–5]. These adaptive behaviors lead to a variable requirement on thermal comfort, as reflected by the change of comfort temperatures with outdoor temperatures [6,7]. This is different from the steady comfort temperature settings in air-conditioned buildings [8]. Therefore, a dynamic thermal comfort standard that accounts for wider indoor temperature ranges compared to the conventional comfort standard is necessary for naturally ventilated buildings [9].

The adaptive thermal comfort (ATC) model provides a useful basis to establish the dynamic thermal comfort standard. The ATC model quantifies the relationship between a neutral temperature and the outdoor temperature with a linear regression. Various types of ATC models have been developed for different areas and climate conditions based on field data. The main difference between the existing models can be found in the methods used to determine the neutral temperature and the outdoor temperature. Neutral temperature, which is defined as the indoor temperature corresponding to “neutral” thermal sensation (neither cool nor warm) [8], reflects the thermal-comfort requirement of the occupant. The calculation of the neutral temperature was performed based on the rate of change of the thermal sensation with respect to the indoor temperature. The change rates in the existing studies were obtained via regression analysis on actual data [10–15] or selection of an appropriate Griffiths coefficient [16–23]. The outdoor temperature is used to reflect the outdoor climate condition. The existing studies mainly used the mean monthly outdoor temperature (arithmetic average of the mean daily minimum and the mean daily maximum in one month) [e.g., 10, 24] or the running mean (RM) of the outdoor temperature (exponentially weighted running mean of the daily mean outdoor temperature) [e.g., 16, 25].

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Developing reliable ATC models for Chinese people is beneficial for the conservation of energy in growing numbers of public naturally ventilated buildings in China. To date, no uniform methods have been recommended for developing ATC models in China. Several case studies developed ATC models based on the field data from different cities in China [12–15]. In these ATC models, the neutral temperatures were calculated using the regression method and were related to the monthly mean outdoor temperature [12,13] or the average of outdoor temperature during the survey [14,15]. However, the indices of the outdoor temperature used by the existing ATC models are unsatisfactory for two reasons. First, the indoor and outdoor air temperatures can vary over a wide range within a month or a longer period in China, resulting in changes in the neutral temperature. Second, the effects of the thermal history on the neutral comfort were not considered. Therefore, a more sensitive index of the outdoor temperature is necessary for the ATC models.

The RM outdoor temperature is an improvement of the monthly mean outdoor temperature, which has been successfully applied in the ATC model for the European standard (EN 15251) [16]. Thus, it is expected that the RM outdoor temperature is more suitable for the ATC models for Chinese people. As an official standard of China, the Chinese Standard GB/T50785-2012 determined the comfortable indoor temperature range according to the RM outdoor temperature [26]. However, the standard did not provide the method to develop the ATC model based on the RM outdoor temperature. Because of the distinct climate conditions and human customs of China, it is unsuitable to directly adopt the ATC model recommended by the European standard [27]. The values of some key parameters in the ATC model for the European standard must be validated and adjusted according to the thermal adaption of Chinese people.

This study aimed to propose a method to develop the ATC model based on the RM outdoor temperature for Chinese people. The proposed method was implemented using the field data from a longitudinal investigation conducted in office buildings in Changsha China. The results provide a useful basis to develop universal ATC models for Chinese people in future.

## 2. Method

### 2.1. ATC model based on RM outdoor temperature

The ATC model quantifies the relationship between the neutral temperature and the outdoor temperature using linear regression, as shown in equation (1).

$$T_n = \mathrm{a}T_o + \mathrm{b} \tag{1}$$

where $T_n$ is the neutral temperature, and $T_o$ is the outdoor temperature; $b$ is a constant, and $a$ is the variation rate of the neutral temperature with the outdoor air temperature.

The calculation of the neutral temperature and the outdoor air temperature is the pivotal step of the ATC model.

#### 2.1.1. Calculation of the neutral temperature

The neutral temperature is calculated as

$$T_n = T_{op} - \mathrm{TSV}/\mathrm{G} \tag{2}$$

where *TSV* is the thermal sensation vote, $T_{op}$ is the indoor operative temperature, and *G* is the variation rate of the thermal sensation with indoor temperature.

*TSV* is obtained from a questionnaire on thermal sensation. $T_{op}$ is calculated by the combination of the indoor air temperature, mean radiant temperature and air velocity measured in field investigation [8]. Therefore, *G* is the key to determine the neutral temperature. Two methods can be used to obtain the value of *G*: Griffiths method and regression analysis. The Griffiths method uses a suitable constant proposed by Griffiths to estimate the G value [28]. The regression analysis quantifies the relationship between *TSV* and $T_{op}$ based on field investigation data during one period (e.g., monthly/seasonal/yearly data) as follows:

$$TSV = \mathrm{g}T_{op} + h \tag{3}$$

where *g* is the regression coefficient, and *h* is a constant. According to equation (3), *g* is used as an estimation of the value of G, which reflects the change of the thermal sensation with indoor temperature in real conditions.

#### 2.1.2. Calculation of the RM outdoor temperature

The RM outdoor temperature indicates the cumulative effect of past outdoor air temperatures. The definition of the RM outdoor temperature is given by Equation (4).

$$T_{RMt(\alpha)} = (1-\alpha)\left\{T_{t-1} + \alpha T_{t-2} + \alpha^2 T_{t-3} + \ldots\right\} \tag{4}$$

where $T_{RMt(\alpha)}$ is the RM outdoor temperature on time *t*, and $T_{t-n}$ is the mean outdoor temperature of the n previous time intervals. $\alpha$ can be seen as a time constant ($0 \le \alpha < 1$) that quantitatively reflects the rate at which the effect of any past temperature decays. The higher the value of $\alpha$ the greater is the effect of the past temperature.

The time series gives a RM outdoor temperature that is decreasingly affected by the past outdoor temperatures as time passes (Equation (4)). Therefore, the RM outdoor temperature can reflect the time-dependence of the adaptive thermal comfort on the outdoor air temperature experienced, by establishing the relationship between the neutral temperature and the RM outdoor temperature.

The RM outdoor temperatures can be calculated using an equation with a convenient form as follows:

$$T_{RMt(\alpha)} = \alpha T_{RMt-1} + (1-\alpha)T_{t-1} \tag{5}$$

It is important to find the optimal value of the time constant $\alpha$ in equation (1) when calculating the RM outdoor temperature. The optimal value of $\alpha$ should be related to the adaptive thermal comfort response and can reflect the highest correlation between the RM outdoor temperature and the neutral temperature.

### 2.2. A longitudinal survey in office buildings

A longitudinal survey provided the field data for the analysis of this study. The survey was conducted in two typical offices located in different types of naturally ventilated buildings [4]. Different from most existing studies, the design of this survey used the same subjects during the whole period (>1 year), thus eliminating the influence of individual difference.

#### 2.2.1. Location

The two naturally ventilated office buildings for the field investigation were located in Central South University, Changsha, China, with a climate of hot summer and cold winter. Building A, a four-story building, houses offices for teachers and graduate students on two floors (the second and third floor), and building B, a courtyard house, hosts offices for only graduate students.

In each building, one typical office was selected for the survey. Each office can accommodate 4–8 occupants; this size is very