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Occupant time period of thermal adaption to change of outdoor air temperature in naturally ventilated buildings

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Abstract

The present work proposed a method to determine time period of thermal adaption of occupants in naturally ventilated building, based on the relationship between their neutral temperatures and running mean outdoor air temperature. Based on the data of the field investigation, the subjects' time period of thermal adaption was obtained with the proposed method. The result revealed that the subjects needed to take 4.25 days to fully adapt to a step-change in outdoor air temperature. The time period of thermal adaption for the occupants in five European countries was also calculated and compared with the value of the subjects in this study. The comparison shows that the occupants in China might have a shorter time period of thermal adaption than European occupants, which means that Chinese occupants can adapt to a new outdoor climate condition faster.

Keywords: Thermal adaption; Time period; Neutral temperature; Running mean temperature

1. Introduction

Indoor thermal environment in a naturally ventilated building always changes with outdoor climate, leading to variable thermal comfort requirement of occupants (ASHRAE, 2004; EN15251, 2007). Thermal adaption has been widely accepted as the theoretical principle of thermal comfort in naturally ventilated buildings (Brager and de Dear, 1998). Time period of thermal adaption, the period of the thermal adaption process, is a key factor to occupant adaptive thermal comfort (Nicol, 2000; Nicol and Humphreys, 2002). Occupants need sufficient time to fully adapt to the change in outdoor climate conditions in order to restore thermal comfort. However, almost no existing studies were carried out to obtain the value of the time period of thermal adaption. This study proposed a method to determine the value of time period of thermal adaption for occupants in naturally ventilated building. The method was realized based on the data of a long-term field investigation.

2. Method

2.1 Time period of thermal adaption

Time period of thermal adaption is defined as the time that occupants spent in adapting to outdoor climate change with the thermal adaption modes. Numerically, time period of thermal adaption should be determined based on human thermal comfort response after a step-change in outdoor climate condition as shown in Fig. 1. However, the actual outdoor climate condition always continuously changes within day and from day to day. The step-change in outdoor climate condition almost does not occur. Therefore it is hard to directly obtain the value of time period of thermal adaption according to the actual conditions. However, the quantitative relation between the thermal comfort response and outdoor climate condition can be established based on field investigation data under actual conditions, which provides a basis to the determination of time period of thermal adaption.

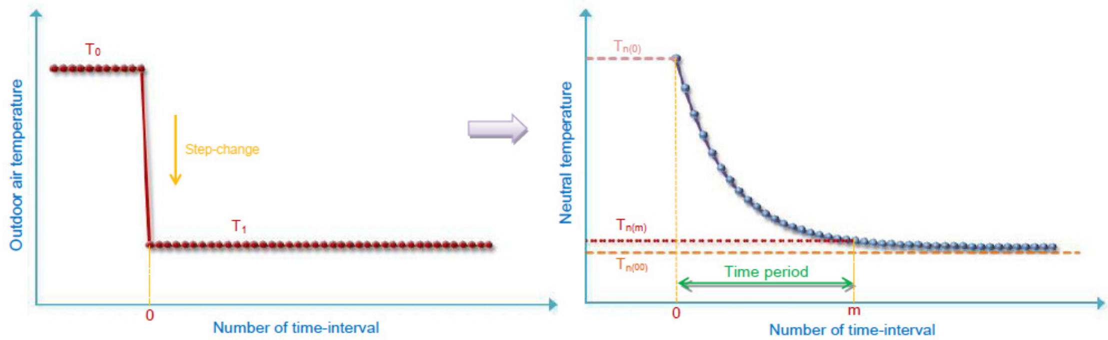

Fig. 1 Definition of time period of thermal adaption. The outdoor air temperature suddenly changed from T_0 to T_1. $T_{n(0)}$ is the neutral temperature at the initial time "0". $T_{n(\infty)}$ is the theoretical boundary of the neutral temperature during the thermal adaption process. $T_{n(0)}$ is the neutral temperature at the *m*th time-interval.

Neutral temperature is defined as the operative temperature at which an average person will be thermally neutral (ASHRAE, 2001). Neutral temperature is always used as occupants' comfort temperature to establish adaptive comfort models and thermal comfort standards for naturally ventilated buildings (ASHRAE, 2004; EN15251, 2007). Therefore, this study selected neutral temperature as a key index to reflect human thermal comfort response in naturally ventilated buildings.

In order to get full use of survey samples, here Griffiths method was applied to calculate the value of the neutral temperature based on thermal comfort vote. The equation is given as (Griffiths, 1990),

$$T_{n-TSV} = T_{op} - TSV / G \quad (1)$$

where $T_{n\text{-}TSV}$ is the neutral temperature according to thermal sensation votes from field investigation, T_{op} is the operative temperature calculated based on the measured air temperature and mean radiant temperature, *TSV* is the thermal sensation vote of occupants and *G* Griffiths coefficient.

The existing studies indicated that occupant neutral temperature is associated with his thermal history with more recent experiences being more influential (Nicol and Humphreys, 2010). Therefore, the exponentially – weighted running mean outdoor temperature was adopted to reflect the significant role of the past and current thermal experiences with outdoor climate condition, which had been applied as the basis of the adaptive thermal comfort model for free-running buildings in European standards EN15251 (Nicol and Humphreys, 2010).

The equation for the running mean outdoor temperature is (Nicol and Humphreys, 2010)

$$T_{rm} = (1-\alpha)\{T_{t-1} + \alpha T_{t-2} + \alpha^2 T_{t-3} \ldots\} \tag{2}$$

where T_{rm} is the running mean outdoor temperature at time *t*, T_{t-n} the instantaneous outdoor air temperature (the mean for equal time interval - hours, days, etc.) at *n* time-intervals previously. α 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 bigger the value of α the greater is the effect of past temperature.

According to equation (2), the time series gives a running mean outdoor temperature that is decreasingly affected by past outdoor temperatures as time passes. Therefore, the running mean 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 running mean outdoor temperature.

The quantitative relationship between running mean outdoor temperature and occupant neutral temperature was developed as,

$$T_n = aT_{rm} + b \tag{3}$$

where T_n is neutral temperature, *a* the variation rate of neutral temperature with running mean outdoor temperature and *b* a constant.

As illustrated in Fig. 1, the value of time period of thermal adaption was calculated as the time span that the neutral temperature reaches a new steady value after a step-change in outdoor climate condition. Using equation (3), the trend of the neutral temperature after a step-change in outdoor air temperature can be obtained.

Based on equations (2) and (3), the time period of thermal adaption can be obtained as the following equation (see Appendix),

$$TP = round[\frac{ln(1-r)}{ln(\alpha)}] \times \Delta d \tag{4}$$

where the function *round*[data] means the data in the square brackets is rounded up. *TP* is the time period (day) of thermal adaption and *r* is a ratio reflecting the degree that the neutral temperature at the final time-interval is close to its limit value during the adaption process. α is the time constant and Δd is the time-interval in equation (2).

In all, the method to estimate the time period of thermal adaption can be simply described by Fig. 2.

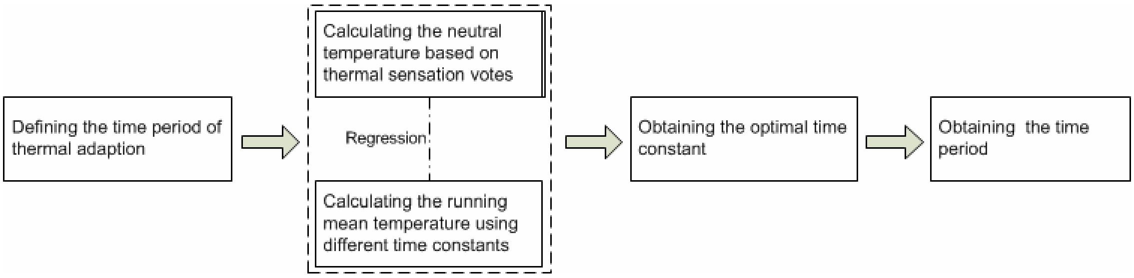

Fig. 2 The method to estimate the time period of thermal adaption

2.2 A longitudinal survey

A longitudinal survey provided field data for the present study, which was carried out in two typical offices located in different types of naturally ventilated buildings.

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. As shown in Fig.3(a), building A, a four-story building, houses offices for teachers and graduated students on two floors (the second and third floor), and building B, a courtyard house, hosts offices just for graduated students.

In each building, one office was selected for the survey (see Fig. 3(b)). Each office can accommodate 4~8 occupants, which was very common in universities of China. Office A, a west-facing room on the third floor of building A, has an area of 40 m2 (7.7x5.2 m) and a height of 3 m. Office B is a south-facing room in building B with an area of 43.2 m2 (7.2x6 m) and a height of 4.5 m. It can be seen in Fig. 3(b) that there are operable windows and doors in both offices. A floor-standing air conditioner (cooling and heating) is equipped in each office, which were only used in hot (summer) and cold (winter) weather. Different from office A, there are four wall fans and two ceiling fans in office B, which also provided a cooling strategy in hot weather.

(a) Buildings A (left) and B (right)

(b) Offices A (left) and B (right)

Fig. 3 The naturally ventilated offices for the long-term survey

2.2.2 Subjects

All subjects in both offices are healthy graduated students, including 9 males and 6 females (mean ± SEM of age: 23.9 ± 0.6 years, height: 168.6 ± 2.1 cm, weight: 59.9 ± 2.6 kg). They mainly carried out office related work, such as reading, writing and typing in a computer. Every student has lived in the university for more than one year and acclimatizes themselves to the climate in Changsha. All of them participated as subjects in the long-term survey. All protocols were approved by the university's ethics committee and conformed to the guidelines contained within the Declaration of Helsinki. Verbal and written informed consent was obtained from each subject prior to the participation in the survey.

During the period of survey, there were 4~6 students in Office A and 6~8 students in office B. Among these students, three graduated from the university in May 2010 and one left the office in Sep. 2010, while two joined in Oct. 2010.

2.2.3 Instrumentation

Four important indoor thermal environment parameters were monitored. Air velocity, temperature and relative humidity were collected using a multifunctional heat line anemoscope (TSI 9545-A VELOCICALC, TSI Incorporated, USA). Globe temperature was measured with a standard black-bulb (D 150mm, KIMO, FR). The precision of each instrument is listed in Table 1.

Table 1 Instruments for the measurement of indoor thermal environment parameters

Parameter	Instrument	Range	Accuracy	Resolution
Globe temperature	Digital thermometer TR102	-100 ~ 400 °C	±0.3 °C	0.1 °C
Air temperature	Velocicalc TSI-9545	-10 ~ 60 °C	±0.3 °C	0.1 °C
Air velocity	Velocicalc TSI-9545	0 ~ 30 m/s	±3%	0.01 m/s
Relative humidity	Velocicalc TSI-9545	0 ~ 95%	±3%	0.10%

The indoor environmental parameter measurement site was located near each subject at 1.1 m height, as displayed in Fig. 2(b). The location of each subject was more than 2.0 m away from the doors, windows and fans.

2.2.4 Protocol

The survey was conducted daily from Jan. 2010 to Feb. 2011, except for some holidays such as some days during summer and winter vacations (Jul.-Aug. and Jan.-Feb.). Every day, the researchers carried out the survey three times (morning/afternoon/night) at most. The periods for the survey in morning, afternoon and night were respectively 10:30-11:30, 16:00-17:00 and 20:00-21:00. The survey was done on the subjects being in the offices for at least 20 minutes.

During a single survey, each subject in both offices was asked to fill out the electronic questionnaire reflecting their subjective responses, clothing, and activity level in the preceding 20 minutes. At the same time, the thermal environment close to each subject was continuously monitored for 5 minutes. Subjects' controls on window, door, curtain, fan and air-conditioner were carefully recorded by the same researcher. The time of each investigation spent in each office was about 30 minutes.

2.2.5 Questionnaire

A questionnaire was designed to provide the following main information:

(1) Subjective thermal responses, including thermal sensation, thermal acceptability and thermal preference. In this study, only the response of thermal sensation was analyzed, which was evaluated using the ASHARE 7-points continuous scale from -3 (cold) to +3 (hot).

(2) Current clothing level. The subjects were asked to record the combination of their clothing in order from underwear to outerwear. A fairly detailed clothing garment list was provided for reference. According to the records of subjects' clothing in the survey, ensemble clothing insulation (CLO) was estimated based on procedures in ASHRAE Standard 55 (ASHRAE, 2004).

(3) Activity level in the preceding 20 minutes. This item asked the subjects to describe the primary activity during the last 20 minutes in the offices.

The questionnaire was written in Chinese. The subjects completed the questionnaire on their computers in 5 minutes.

2.3 Meteorological data

Meteorological data for the period of the longitudinal survey were obtained from a local station near the university. The data contains outdoor air temperature, humidity and wind speed. They were recorded on an hourly basis. The data of the hourly outdoor air temperature was used to calculate the running mean outdoor temperature in this study.

2.4 Statistical analysis

Linear regression method was applied to establish the relation between running mean outdoor temperature and occupant neutral temperature based on the filed survey data. To evaluate a linear regression equation, determination coefficient R^2 was used to indicate the goodness of fit and the level of significance was set at $p < 0.05$.

3. Results

3.1 The variation in the observed neutral temperature over different periods

As shown in equation (2), the running mean outdoor temperature is calculated based on the mean outdoor air temperature over each time-interval. For each time-interval, occupant neutral temperature was assumed as a steady value. In order to determine an appropriate time interval for the calculation of running mean outdoor temperature, it is necessary to investigate the variation in occupant neutral temperature over different periods (day/ week/ month/ season) during the field survey.

Two indexes, standard deviation (S.D.) and range (the difference between maximum and minimum), were used to reflect the variation in the values of the neutral temperature during each period. As shown in Fig. 4, the mean S.D. and range of the observed neutral temperature (corresponding to the thermal sensation vote of "neutral" in the survey) raised with the increase in period (from day to season). For the period of a day, both the mean S.D. and range of the observed neutral temperature had the smallest values (about 1 °C). According to the trend, the variation in occupant neutral temperature should be smaller than 1 °C in a period less than a day.

Therefore, 6 hours (1/4 day) was selected as the time-interval to calculate the running mean outdoor temperature in this study, considering the time to conduct a single survey (see section 2.2.4). The 1/4 day time-intervals were separately: 7:00 ~ 12:00, 13:00 ~ 18:00, 19:00 ~ 24:00 and 1:00 ~ 6:00 in each day.

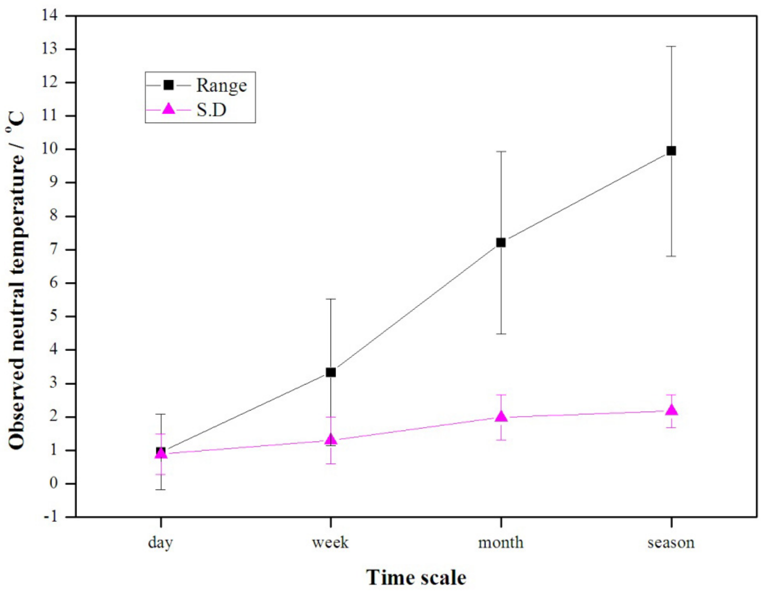

Fig. 4 The variation in the observed neutral temperature of occupants over different periods

3.2 The optimal time constant α for the running mean outdoor temperature

As depicted in section 2.1, it is important to find the optimal value of the time constant α in equation (2) when calculating the running mean outdoor temperature. The optimal value of α should be related to the adaptive thermal comfort response and can reflect the highest correlation of occupant neutral temperature with the running mean outdoor temperature.

Here, the running mean outdoor temperature was calculated from the mean outdoor air temperature over the time-interval of 1/4 day using a range of values of α. The running mean outdoor temperature was then correlated with the neutral temperature $T_{n\text{-}TSV}$. The values of the correlation coefficient c were obtained with different values of α, which provided a basis for the determination of the optimal value of α.

For the neutral temperature $T_{n\text{-}TSV}$, the value of c rose to a maximum (0.939) at a value of α of 0.841. Therefore, 0.841 can be used as the optimal value of α to calculate the running mean outdoor temperature.

3.3 Time period of thermal adaption due to different thermal adaption modes

Based on the data of the longitudinal survey, the quantitative relationship between the neutral temperature and running mean outdoor temperature was developed as,

$$T_{n-TSV} = 0.598 \times T_{rm} + 11.7 \quad (\alpha = 0.841,\, R^2 = 0.882,\, p < 0.001) \qquad (5)$$

According to equation (4), the time period of thermal adaption was calculated using the values of α and time-interval. The value of r in equation (4) was set as 0.95. As referred before, the time-interval was 6 hours (1/4 day). The calculation was shown as follows.

$$TP = round[\frac{ln(1-0.95)}{ln(0.841)}]\times\frac{1}{4} = 17\times\frac{1}{4} = 4.25\,day$$

The result means that occupants need to take about four days to fully adapt to a step-change in outdoor air temperature.

4. Discussion

It is interesting to compare the time period of thermal adaption of Chinese with those of occupants in other countries. Based on the best values of the time constant α for the occupants in five European countries (McCartney and Nicol, 2002), the time period of thermal adaption was calculated with equation (4) (the value of r was set as 0.95) and compared with the result given by this study. The comparison was listed in Table 2.

Table 2 Comparison of the time period of thermal adaption between the occupants in European countries and those in China

Country	The best time constant	Time-interval	Calculation of neutral temperature	Time period of thermal adaption	Type of survey data
France	0.70	1 day	Griffiths method	8 days	Longitudinal
Greece	0.94	1 day	Griffiths method	48 days	Longitudinal
Portugal	0.80	1 day	Griffiths method	13 days	Longitudinal
Sweden	0.33	1 day	Griffiths method	3 days	Longitudinal
UK	0.45	1 day	Griffiths method	4 days	Longitudinal
All	0.80	1 day	Griffiths method	13 days	Longitudinal
China	0.944	1/4 day	Griffiths method	4.25 days	Longitudinal

Among the five European countries, the time period of thermal adaption of the occupants in Greece was much longer than those in the other countries, while the occupants in Sweden took the least days to fully adapt to the change of the outdoor climate condition. The value of the time period of thermal adaption for the occupants in China was slightly bigger (1/4 day) than that in UK. However, obvious difference can be found in the time period of thermal adaption between China and the other four European countries. If the data from five European countries was combined (see “All” in Table 2), the occupants in China had a shorter time period of thermal adaption than European occupants, which indicated that the Chinese occupants can adapt to a new outdoor climate condition faster. The main reason to the difference might be the distinct behavioral adjustment (the physical adaption) (Liu et al, 2012) and expectation of the occupants (the psychological adaption) (Liu et al, 2013) caused by the totally different climate conditions in European countries and China. However, considering that the field data were obtained from several countries in Europe and one city in China, the result of this comparison needs to be validated by adequate field investigation conducted in more cities and countries.

The result of this study was obtained based on the long-term investigation conducted in the buildings where the air-conditioner could be used (Liu et al, 2012). For the naturally ventilated buildings without air-conditioners, the time period may be different. However, the proposed method can be applied for any naturally ventilated building based on the data of field investigation.

5. Conclusion

Main conclusions were obtained as follows.

(1) The time period of thermal adaption can be determined based on the relationship between the neutral temperature and running mean outdoor temperature.

(2) The occupants need to take 4.25 days to fully adapt to a step-change in outdoor air temperature.

(3) The occupants in China might have a shorter time period of thermal adaption than the occupants in the European countries.

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Appendix. Determination of time period of thermal adaption

Suppose that the outdoor air temperature kept at a start value of T_0 before a step-change and suddenly changed to a value of T_1 at an initial time "0" (see Fig. 1), as described by the following equation,

$$T_0 = T_1 + \Delta T \quad (6)$$

where ΔT is the variation in the outdoor air temperature.

According to equation (3), the neutral temperature at the ith time-interval after the step-change of the outdoor air temperature was given as,

$$T_{n(i)} = aT_{rm(i)} + b \quad (7)$$

where $T_{n(i)}$ and $T_{rm(i)}$ are the neutral temperature and running mean outdoor temperature at the time-interval i, respectively.

The running mean outdoor temperature at the ith time-interval can be calculated using the value of the running mean and of the mean outdoor temperature for the previous time-interval (Nicol and Humphreys, 2010).

$$T_{rm(i)} = (1-\alpha)T_{i-1} + \alpha T_{rm(i-1)} \tag{8}$$

where T_{i-1} and $T_{rm(i-1)}$ are the mean and running mean outdoor temperature at the time-interval (*i-1)*, respectively.

At the initial time (0), the running mean outdoor temperature ($T_{rm(0)}$) was equal to the start temperature T_0. Accordingly, the neutral temperature ($T_{n(0)}$) was calculated with equation (7).

$$T_{n(0)} = aT_0 + b \tag{9}$$

The neutral temperature at the *i*th time-interval ($i > 0$) can be obtained by substituting equation (8) into equation (7).

$$T_{n(i)} = a[(1-\alpha)T_{i-1} + \alpha T_{rm(i-1)}] + b \tag{10}$$

Equation (10) can be extended as,

$$\begin{aligned} T_{n(i)} &= a[(1-\alpha)(T_1 + \alpha T_1 + \alpha^2 T_1 + \cdots + \alpha^{i-1}T_1) + \alpha^i T_{rm(0)}] + b \\ &= a[(1-\alpha)T_1(1+\alpha+\alpha^2+\cdots+\alpha^{i-1}) + \alpha^i T_0] + b \\ &= a[(1-\alpha)T_1 \frac{1-\alpha^i}{1-\alpha} + \alpha^i T_0] + b \\ &= a[T_1 + \alpha^i \Delta T] + b \end{aligned} \tag{11}$$

Further, the theoretical boundary of the neutral temperature ($T_{n(\infty)}$) can be gotten with equation (11),

$$\begin{aligned} T_{n(\infty)} &= \lim_{i\to\infty}(a[T_1 + \alpha^i \Delta T] + b) \\ &= aT_1 + b \end{aligned} \tag{12}$$

After the step change of the outdoor air temperature, the neutral temperature gradually tends to the theoretical boundary. Here, a ratio *r* was defined as follows.

$$\begin{aligned} r &= \frac{T_{n(i)} - T_{n(0)}}{T_{n(\infty)} - T_{n(0)}} \\ &= \frac{a(\alpha^i - 1)\Delta T}{-a\Delta T} \\ &= 1-\alpha^i \end{aligned} \tag{13}$$

The value of *r* ($0 < r < 1$) can reflect the degree that the neutral temperature ($T_{n(i)}$) is close to the limit value ($T_{n(\infty)}$) during the process of change. Giving *r* a value close to 1, the corresponding value of the neutral temperature ($T_{n(m)}$) was regarded as the new steady value after the step-change of the outdoor air temperature. The corresponding number (*m*) of time-intervals was calculated according to equation (13).

$$m = round\left[\frac{ln(1-r)}{ln\alpha}\right] \tag{14}$$

where *round* [data] means that the data in the square brackets is rounded up.

The time period of thermal adaption (*TP*) was obtained on the basis of equation (14), according to its definition as mentioned in section 2.1.

$$TP = m \times \Delta d = round\left[\frac{ln(1-r)}{ln\alpha}\right] \times \Delta d \quad (15)$$

where Δd is the value of the time-interval.

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