

Analysis of comfort band for adaptive model in Japanese office buildings

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Abstract. Thermal comfort has been discussed subject since 1930. The pattern of the way of global warming and issues regarding the energy has influenced the rise in the interest of this subject lately. This study aims to develop comfort band for adaptive model for Japanese office buildings as the global standard do not include the databases from the Japanese buildings and so might not be applicable in the context of Japan. Field data was conducted in 17 mixed-mode (MM) office buildings located in Tokyo and Kanagawa of Japan. Measurements like air temperature, relative humidity, and other environmental factors was carried out along with the occupant's thermal comfort survey. Probit analysis method was adapted to estimate comfort band. Result suggests that indoor globe temperature ranged from 22.0-27.0 °C during the field survey period. The comfort band obtained by the difference between the indoor globe temperature and comfort temperature (Δt) are $\pm 2.0^\circ\text{C}$ at 90% and $\pm 2.5^\circ\text{C}$ at 80% which were applied in proposed adaptive model for Japanese office buildings.

1 Introduction

ASHRAE formulated the adaptive standard for thermal comfort of the naturally ventilated buildings [1], whereas Comité Européen de Normalisation (CEN) [2] proposed for free-running mode (FR). Also, CIBSE Guide A provides the adaptive thermal comfort approach by providing correlation among comfort temperature with the running mean outdoor temperature for office buildings [3]. These standards indicated the comfort band of adaptive models. ASHRAE suggested 80 % and 90 % comfort band were $\pm 3.5^\circ\text{C}$ and $\pm 2.5^\circ\text{C}$. CEN suggested $\pm 2^\circ\text{C}$, $\pm 3^\circ\text{C}$ and $\pm 4^\circ\text{C}$ for its three classification of buildings (i.e. I, II and III). CIBSE Guide A suggested $\pm 2^\circ\text{C}$, $\pm 3^\circ\text{C}$, $\pm 4^\circ\text{C}$ for FR mode and $\pm 2^\circ\text{C}$ for heated and cooling buildings. However, all of these international models consist the databases from the North American and Northern European subjects which failed to clarify their applicability for the places having different environmental parameters like Japan. There exists a knowledge gap about the potential influence of different climates of the region can have. The indoor temperature ranges for performance hall, department store, shop, office, school, apartment house etc. must be within the range of 17 to 28 °C according to the Japanese Act on Maintenance of Sanitation in Buildings (Law number: Act No. 20) in 1970 [4]. Also,

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Japanese government provided new indoor temperature of 28 °C for cooling and 20 °C for heating while not being reasonable, and also failed in providing the supporting evidences from field studies [5] in the year 2005 for energy saving aspects which are widely known as the “Cool Biz” and “Warm Biz” where “Biz” meaning business. These are two campaigns lunched by Japanese Ministry of Environment which aimed in reducing the CO₂ emissions by encouraging people to use less electricity. Apart from these building protocols, Japan still lies far behind in the context to achieve their own adaptive standards when many countries already have surpassed this level by having their own local standard. Previous studies suggest that these internationally recognised comfort standard may not be necessarily applicable to other parts of the world having different climatic zone [6, 7]. In case of Japanese office buildings, Damiani et al. [8] suffered from the small sample sizes in FR and CL modes. Also, Genjo et al. [9] provided the linear equation for office buildings located in Nagasaki, Japan which failed in providing comfort band required for these types of buildings. With the issues in view, the aims of this study lies for the develop a local comfort band for adaptive model implying towards Japanese office buildings rather than just relying on the previously applied international comfort models. The proposed adaptive models might be useful in calculating indoor comfort temperature using outdoor air temperature. Following sections comprised of detailed explanations in regards to the data collection, and analysis approaches which are followed in this study.

2 Methodology

Two thermal comfort field survey was conducted in 17 mixed-mode (MM) office buildings which are situated in Tokyo, Yokohama and Odawara areas having a climate classified as hot and humid summers and relatively mild winters.

2.1 Investigated office buildings and survey period

17 MM office buildings were chosen for the field survey. Buildings under the investigations belonged to change-over MM types which consists of operable windows and doors, and can be mechanically heated or cooled as per the requirement at certain time of the day or seasons [10].

This study was conducted from 2014 August to 2015 October and 2017 August to 2018 November once obtaining the required permission from these selected office buildings and the participants. In terms of outdoor parameters which gathers the datasets of daily mean, maximum and minimum temperature as well as relative humidity that was collected from the meteorological stations of respective areas around the surveyed office buildings [11]. The data logger instrument setup was placed 1.1 meters above floor level and away from direct solar radiation, was used to record the indoor environmental parameters at every ten-minute interval. The description of the instruments along with the accuracy rate is presented in Khadka et al. [12]. TR-76Ui and TR-74Ui were used to record air temperature, and relative humidity with precision of ± 0.5 °C and $\pm 5\%$ RH, at 25 °C, 50% RH respectively. The globe temperature was recorded using black painted globe of 75mm diameter whose precisions ranged from 60°C to 155°C.

2.2 Indoor environmental parameters and thermal comfort survey

Transverse survey was carried out each month for a day by the researchers visiting these selected office building with the measuring data loggers and the survey questionnaires sheets which are filled by subjects Table 1. To ensure stable measurement, the data were recorded

after 15-20 minutes placing the instrument near to the occupants. During the data collection the data loggers were placed nearby occupants and were asked to fill the questionnaire sheets. The physical data collected from the participants and environmental controls were noted by the researchers while the participants complete their survey. Once, one set of survey was completed, the instruments were shifted towards another group and so on to gather data from every individual available in the room. This procedure was carried out every month for these each and every group of participants.

Table 1. Thermal sensation vote scale

No.	Scale
1	Very cold
2	Cold
3	Slightly cold
4	Neutral
5	Slightly hot
6	Hot
7	Very hot

2.3 Prediction of comfort band

In order to determine the comfort band, probit regression undertaken in regards to different thermal sensation votes with respect to globe temperature for MM. Previously, Rijal et al. [13] explained the methodology for predicting the proportion of the thermal sensation votes for the seven-point ASHRAE scales category in office buildings. Similar to the previous study ordinal regression method using probit using this study was applied to the probit as a link function and indoor globe temperature as the covariate. The equation is shown below.

$$\text{Probability} = \text{CDF.NORMAL}(\text{quant}, \text{mean}, \text{S.D.}) \tag{1}$$

where, CDF.NORMAL: Cumulative distribution function for the normal distribution

quant: Indoor globe temperature (°C)

mean: Constant divided by slope of the equation achieved from the ordinal regression method
S.D.: Inverse of slope.

3 Results and discussion

1111 votes were obtained from field survey under the FR mode. This study applies various analysis process to develop comfort band for the adaptive model of the Japanese office buildings. The initial process is to investigate the environmental conditions during field survey. Probit method is used to obtain the comfort band. The comfort band is calculated and fixed for the adaptive model for the Japanese office building. Once the comfort band is confirmed, the required indoor comfort temperature is estimated by using the Griffiths' method [14]. The Griffiths constant considered for the calculation of comfort temperature was $a=0.50$. Running mean outdoor temperature is also calculated so as to produce the relationship with comfort temperature. To calculate running mean outdoor temperature, value considered for α is 0.80 [15].

3.1 Thermal environmental condition during survey

The environment conditions such as outdoor air temperature, indoor air temperature and indoor globe temperature during the time of voting are analysed as shown in Figure 1. Seasonal differences were narrower for indoor temperature, however outdoor air temperature showed wider range. Globe temperature is almost overlapping to indoor air temperature; hence the results are presented based on globe temperature [16]. The mean globe temperature obtained was 25.1°C for FR mode. Most of the indoor globe temperature ranges between 22-27°C. The mean outdoor temperature is obtained highest for the month August and lowest on February.

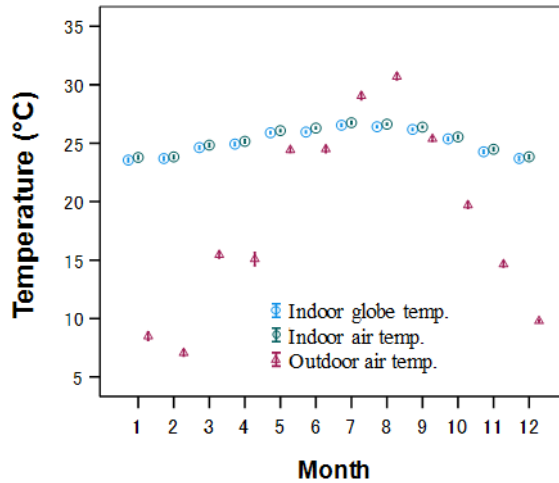


Fig. 1. Outdoor and indoor temperatures during the survey (Mean \pm 2 S.E.)

3.2 Thermal comfort band

Thermal comfort band is calculated by the probit analysis method. Probit analysis equations are for both indoor globe temperature and Δt which is in Table 2. Once the equations and all the required variable are obtained, probits were transformed by using Equation 1 into each TSV scale proportions which gave the areas where each TSV categories existed as shown in Figure 2(a).

Further, three central categories (TSV 3, 4, and 5) are probits transformed to the proportion of votes which is comfortable range resulted in a bell-curve (Figure 2(b)). On considering the globe temperature for 80%, it ranges from 20-28.8°C which resulted in differences of $\pm 4.4^\circ\text{C}$. Similarly, for 90% comfort band was $\pm 3.2^\circ\text{C}$ as shown in Table 3. The obtained band is higher than ASHRAE standard for 80% and 90% which is $\pm 3.5^\circ\text{C}$ and $\pm 2.5^\circ\text{C}$ respectively [1]. This might be because of large seasonal variations in comfort temperature. Nicol and Humphreys [17] stated that wider difference between the room temperature and comfort temperature resulted as causing more discomfort. Therefore, instead of only using indoor globe temperature, the differences of indoor globe temperature and comfort temperature is carried out based on existing previous studies as a dead band ($\Delta t = T_g - T_c$) [18, 19].

Table 2. Equations obtained by probit analysis for T_g and Δt

Indices	Equations*	Mean (°C)	S.D. (°C)	N	R ²	S.E.
T_g	$TSV \leq 1 = 0.355T_g - 5.407$	15.2	2.8	1111	0.27	0.020
	$TSV \leq 2 = 0.355T_g - 6.300$	17.7				
	$TSV \leq 3 = 0.355T_g - 7.741$	21.8				
	$TSV \leq 4 = 0.355T_g - 9.688$	27.3				
	$TSV \leq 5 = 0.355T_g - 11.059$	31.2				
	$TSV \leq 6 = 0.355T_g - 11.973$	33.7				
Δt	$TSV \leq 1 = 1.537\Delta t + 5.998$	-3.9	0.7	1111	0.90	0.048
	$TSV \leq 2 = 1.537\Delta t + 4.725$	-3.1				
	$TSV \leq 3 = 1.537\Delta t + 1.815$	-1.2				
	$TSV \leq 4 = 1.537\Delta t - 1.755$	1.1				
	$TSV \leq 5 = 1.537\Delta t - 4.797$	3.1				
	$TSV \leq 6 = 1.537\Delta t - 6.464$	4.2				

TSV(≤ 1): Probit of proportion of the votes that are 1 and less, TSV(≤ 2): Probit of the proportion that are 2 and less, T_g : Globe temperature (°C), Δt : $T_g - T_c$, T_c : Comfort temperature (°C), S.D.: Standard deviation (°C), N: sample number, R²: Cox and Snell R², S.E.: Standard error, *: Statistical significance in regression coefficient (p<0.001).

Hence, to solve such problems, Δt ($=T_g - T_c$) is used in the dead band of window opening and fan use by Rijal et al. [18, 19], and is also used in this study. On applying Δt to the probit analysis, the relationship resulted as Figure 3. Both 80% and 90% comfort band were obtained smaller than the ASHRAE standard $\pm 3.5^\circ\text{C}$ and $\pm 2.5^\circ\text{C}$ as presented in Table 3 for Δt . Result from probit analysis on considering Δt band obtained was $\pm 2.0^\circ\text{C}$ at 90% and $\pm 2.5^\circ\text{C}$ at 80%. Although the result obtained is lower than the CEN standard [2] and the ISO standard [20] which uses the comfort band of $\pm 2.0^\circ\text{C}$, which suggest that further analysis should be carried out in the future for the different modes as well. However, this study considers the comfort band of $\pm 2.5^\circ\text{C}$ and $\pm 2.0^\circ\text{C}$ for 80% and 90% respectively for the adaptive model of Japanese office buildings in the next section.

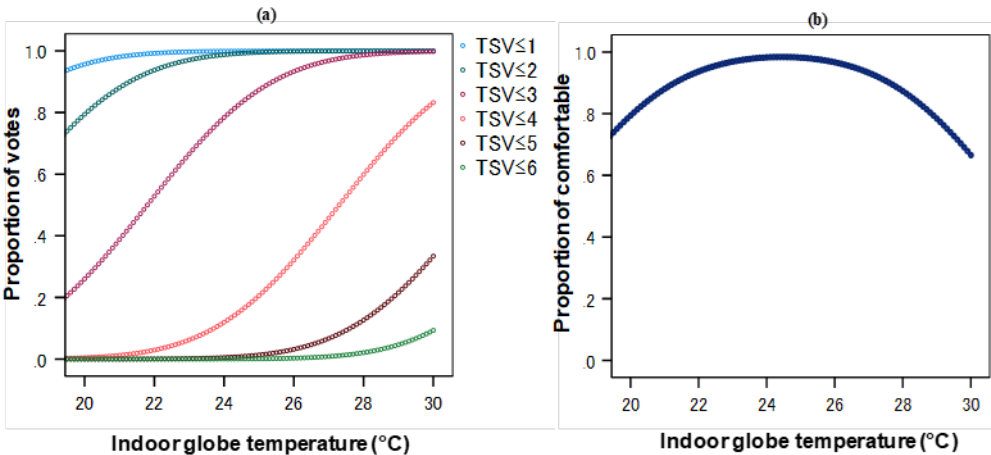


Fig. 2. Proportion of (a) votes and (b) comfortable with indoor globe temperature

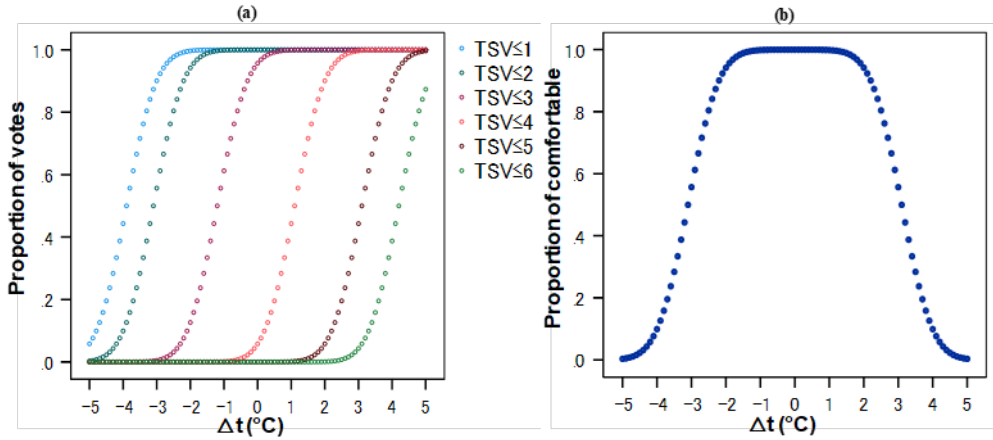


Fig. 3. Proportion of (a) votes and (b) comfortable with Δt

Table 3. Comfort band of adaptive model for T_g and Δt

Index	Limit (%)	Lower (°C)	Upper (°C)	Difference (°C)	Band (°C)
T_g	80	20.0	28.8	8.8	±4.4
	90	21.3	27.6	6.3	±3.2
Δt	80	-2.5	2.5	-	±2.5
	90	-2.0	2.0	-	±2.0

3.3 Adaptive model with comfort band

An adaptive model is the relationship between comfort temperature and outdoor temperature [1, 2]. The standard based on such relationship would imply in energy saving aspects as well [21]. Figure 4 shows the relationship between comfort temperature predicted by Griffiths’ method [13] and running mean outdoor temperature (T_{rm}) along with the comfort band obtained from the previous section using Δt for 80% and 90% whose value were ± 2.5 °C and ± 2.0 °C respectively. The regression equation is given below [16].

$$\text{FR mode } T_c = 0.15T_{rm} + 22.5 \quad (n=1111, R^2=0.20, \text{S.E.}=0.009, p<0.001) \quad (2)$$

where, n: Number of sample, R^2 : Coefficient of determination, S.E.: Standard error of regression coefficient; and p: Significance level of regression coefficient.

The equations for lower limit and upper limit for 80% and 90% for are as below:

$$\text{FR mode (80% limit): } T_c = 0.15T_{rm} + 22.3 \pm 2.5 \quad (3)$$

$$\text{FR mode (90% limit): } T_c = 0.15T_{rm} + 22.3 \pm 2.0 \quad (4)$$

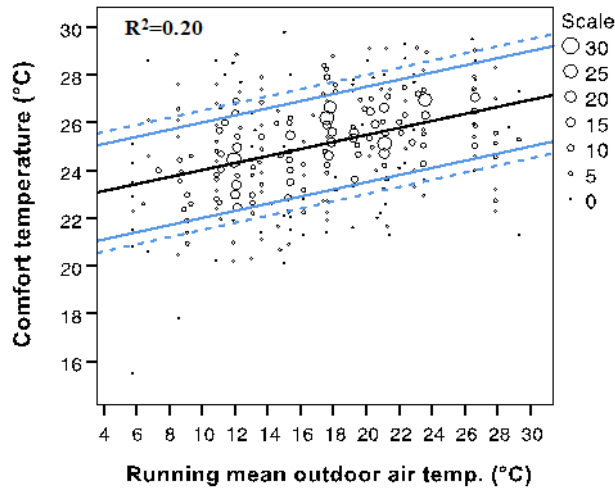


Fig. 4. Adaptive model with proposed comfort band for 80% and 90% acceptability

Figure 4 shows that to change a unit in comfort temperature, it requires 6.7°C ($=1/0.15$) change of running mean outdoor air temperature. The percentage of total datasets inside 80% and 90% comfort band is calculated. In FR mode, 89.6% and 82.5% of datasets are inside the 80% and 90% comfort band respectively which is above 80%. The ASHRAE standard states that thermal comfort can be accomplished when the indoor environmental circumstances can assure 80% of the occupants [1]. This means obtained comfort band is applicable and can be considered as the comfort band for adaptive model of Japanese office buildings.

4 Conclusions

Having analysed the comfort band from probit analysis for adaptive model of Japanese office buildings, following conclusions are obtained.

1. The comfort band obtained by using indoor globe temperature were wider due to the large seasonal differences.
2. The comfort band obtained by Δt is $\pm 2.0^{\circ}\text{C}$ at 90% and $\pm 2.5^{\circ}\text{C}$ at 80%, confirmed by probit analysis which was lower than the ASHRAE standard.
3. The adaptive models proposed might be useful to predict comfort temperature based on outdoor air temperature.

Comfort band has been developed based on the field surveys for FR mode office buildings using Δt . The relationship between the indoor comfort temperature and the outdoor air temperatures enables engineers and building designers to use it in building thermal simulation to validate from the field survey. Japan is climatically diverse country. Therefore, the band obtain for this part of Japan might not be applicable for the other region of Japan. Results obtained from different parts of Japan can be fruitful in developing the comfort band for adaptive standard for Japanese office building.

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