Development of an adaptive model for thermal comfort in the office buildings of Nagasaki City, Japan

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Abstract. Thermal comfort in office buildings is instrumental in improving the productivity of employees while maintaining their health. The primary objectives of this research were to analyze the comfort temperature in Japanese office buildings and investigate its relationship with outdoor air temperature. Additionally, we examined the differences in comfort temperatures with respect to closed and opened windows to factor in the increase in the opening of windows during the COVID-19 pandemic when air-conditioning systems were operated. We investigated the environmental conditions of office buildings and the thermal comfort of the occupants through monthly visits to each office building over a year. Field data were collected from four office buildings located in Nagasaki City, with 1047 votes obtained from 143 participants. The survey indicated that the occupants were highly satisfied with the thermal environment in their offices. The correlation between indoor comfort temperature and outdoor temperature was high in the FR mode. Based on the analysis, we developed an adaptive model for office buildings in Nagasaki City and compared it with existing adaptive models used for buildings in other regions of Japan. The proposed model is useful for energy-saving designs that bring out human adaptive capacity.

1 Introduction

Several field studies on thermal comfort have been conducted worldwide [1]; however, they cannot be analogously applied to all countries with varying climates, such as East Asian countries, including Japan. Considering the energy consumption of the building sector in Japan, the Ministry of the Environment recommends indoor temperatures at 20 and 28 °C in winter and summer, respectively. However, these values are not based on the results of actual field surveys conducted in Japan. Therefore, it is necessary to confirm how office workers adapt to the thermal environment and whether they feel thermally comfortable in actual office buildings. This warrants the identification of a thermally comfortable work environment and the development of an adaptive model that relates local outdoor temperatures in Japan to indoor temperatures in office buildings.

Several studies have analyzed the comfort temperatures of Japanese office buildings [2–10]. In the Kanto region, the comfort temperatures were determined to be 25.0, 25.4, and 24.3 °C for free-running (FR), cooling (CL), and heating (HT) modes, respectively [8]. Khadka et al. [9] reported that the most suitable comfort temperature ranges were 22–26 °C for the mixed-mode and 23–25 °C for the FR mode in Japanese office buildings. Here, the mixed mode buildings are of the change-over type, in which the building can be in the free running mode, or air-conditioned (AC), depending on the season and time of day. However, most studies were conducted in the Kanto region of Central Japan. Owing to the varying north–south topography, the possibility of regional differences in comfort temperature should be considered.

In this study, we analysed the comfort temperatures in office buildings located in Nagasaki City, Kyusyu region, Japan. Additionally, the relationship between the comfort temperature and outdoor air temperature was investigated to develop an adaptive model [10]. A thermal environment measurement and a thermal comfort survey of workers in four office buildings were conducted. Furthermore, we examined the differences in the comfort temperature with respect to closed and opened windows owing to the increase in the opening of windows during the COVID-19 pandemic when air-conditioning systems were operated. Proposing an appropriate adaptive model according to the local climate is useful for saving energy in buildings while maintaining the thermal comfort and productivity of workers.

2 Survey overview

2.1 Survey method

We investigated the environmental conditions of office buildings and the thermal comfort of the occupants through monthly visits to each office building over a year. The survey was conducted in four office buildings in Nagasaki City. The latitude of Nagasaki City is 32°44' N, and the climate remains relatively warm throughout the year with high temperatures and humidity prevailing during the summer and rainy seasons. Table 1 summarizes a description of the buildings investigated and the number of votes obtained from the survey. Among the office buildings in Nagasaki City, we chose office buildings with windows that can be opened, so the selected buildings were a little older. In Japan, the percentage of office building stock which was completed before 1981 based on the old seismic code is high in local cities, and accounts for 40% in Fukuoka City which is a representative local city in Kyushu region [11]. Since the office buildings in Nagasaki City were considered to be similar to those in Fukuoka City, the surveyed offices are considered to be representative stock office buildings in Nagasaki City without any problems. The survey period was more than one year, from July 2021 to July 2022. Each office building was visited once a month during the survey. The thermal environment measurements of the workspace were obtained in addition to conducting a thermal comfort survey of office workers during each visit. The survey was conducted by administering questionnaires on thermal comfort to the workers in each office. Table 2 lists the scale of the thermal sensation vote used for the survey.

2.2 Analysis method

Thermal comfort votes were categorized into FR, CL, and HT modes for the analysis. During the survey period, certain offices were ventilated by opening windows when air-conditioning systems were operated. Therefore, the thermal comfort votes in the CL and HT modes were further divided into the window opening and closing modes to examine the variations in indoor comfort temperature with respect to modes. We defined the window-opening mode as the case where the window facing outdoors was opened; the opening width of the window was not recorded.

The indoor comfort temperature was also examined based on clothing. The office workers were requested to select the type of clothing closest to the ones they were wearing during the survey. The sum of clo values for each item was calculated as the amount of clothing pieces they wore.

2.3 Calculation of comfort temperature

Both the regression and Griffiths' method can be used to calculate the comfort temperature; in this study, we used Griffiths' method [8, 10, 12] as indicated in Equation (1).

$$T_c = T_g + \frac{(4 - C)}{a}, \quad (1)$$

where T_c denotes the indoor comfort temperature (°C), T_g indicates the indoor globe temperature (°C), C represents the thermal sensation vote (Table 2), and a denotes the Griffiths' constant that corresponds to the rate of change of thermal sensation with indoor air temperature. Previous studies have reported that 0.50 is a suitable value for Griffiths' constant [8, 12]. Therefore, we used the same value for a in this study.

Typically, an adaptive model uses outdoor air temperature to predict the indoor comfort temperature [13]. The running mean outdoor air temperature [10], which represents the average of outdoor air temperatures experienced by building occupants, was used as the index of outdoor air temperature. The outdoor air temperature was obtained from the data provided by the meteorological station in Nagasaki closest to the survey area [14]. The running mean outdoor air temperature was calculated using Equation (2).

$$T_{rm} = \alpha T_{rm-1} + (1 - \alpha) T_{od-1}, \quad (2)$$

Table 1. Descriptions of the buildings analyzed.

Building code	Completion	Building construction	Mode	HVAC control	Window	Natural ventilation opening	Investigated floor/Number of floors	Number of votes
B1	1966	Reinforced concrete	Mixed mode	Local	Openable	None	5F/6F	90
B2	1967	Reinforced concrete	Mixed mode	Local	Openable	None	1F/6F	223
B3	1970	Reinforced concrete	Mixed mode	Local	Openable	None	3F/3F	290
B4	1965	Reinforced concrete	Mixed mode	Local	Openable	None	3F&5F/5F	444

Table 2. Scale of the thermal sensation vote.

Scale	Thermal sensation vote
1	Very cold
2	Cold
3	Slightly cold
4	Neutral (Neither hot nor cold)
5	Slightly hot
6	Hot
7	Very hot

where T_{rm-1} denotes the running mean outdoor temperature of the previous day (°C), and T_{od-1} indicates the daily mean outdoor temperature of the previous day (°C). Here, α is a constant value between 0 and 1, indicating the speed at which the running mean outdoor air temperature responds to the outdoor air temperature; we used α = 0.8 in this study [15]. The running mean outdoor air temperature calculated for one day can be used to calculate that of the subsequent day.

3 Results and discussion

3.1 Indoor comfort temperature, outdoor temperature, and clothing insulation

Field data were collected from four office buildings located in Nagasaki City, with 1047 votes from 143 participants. The mean indoor globe temperatures were 24.2, 26.0, and 22.1 °C in the FR, CL, and HT modes, respectively, with a difference of 3.9 °C among the three modes. Furthermore, the mean outdoor air temperatures were 18.2, 27.3, and 9.9 °C in the FR, CL, and HT modes, respectively.

3.1.1 Distribution of thermal sensation votes

The number of thermal sensation votes was divided into three categories, with 398, 384, and 265 votes for the FR, CL, and HT modes, respectively. Figure 1 depicts the distribution of the thermal sensation votes according to modes. Most of the workers voted for "4. Neutral" regardless of mode, which accounted for 52–65% of the votes. Generally, the thermal sensation votes "3. Slightly cold," "4. Neutral," and "5. Slightly hot" were considered the thermal comfort zone, accounting for 93–97% of the total votes in each mode. The results indicated that most workers were highly satisfied with the thermal environment in their offices.

3.1.2 Comfort temperature

Figure 2 illustrates the distribution of comfort temperatures in each mode. As mentioned in Section 2.3, Griffiths' method was used to calculate the comfort temperature. The mean comfort temperatures were determined to be 24.3, 25.9, and 23.2 °C in the FR, CL, and HT modes, respectively.

Although a difference of 2.7 °C existed in the mean comfort temperature among the three modes, the difference was smaller than that observed in the indoor mean globe temperature. A previous study reported that the mean comfort temperatures in the Kanto region [10] were 24.9, 25.6, and 24.3 °C in the FR, CL, and HT modes, respectively. In comparison with these results [10], the mean comfort temperatures calculated in this study were lower by 0.6 and 1.1 °C in the FR and HT modes, respectively, and that in the CL mode was higher by 0.3 °C. This result was attributed to the window-opening ventilation condition under the CL and HT modes.

Figure 3 shows the comfort temperatures under window-opening ventilation conditions when the air-conditioning systems were operated. The comfort temperatures were divided into window-opening and

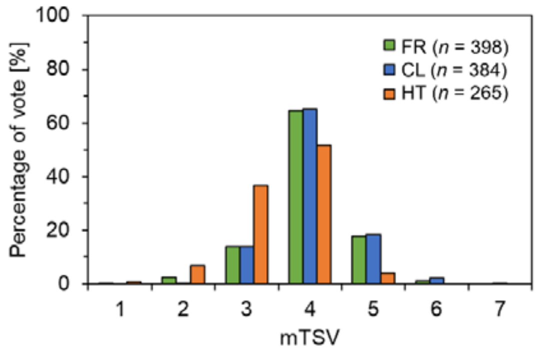

Fig. 1. Distribution of thermal sensation votes according to modes.

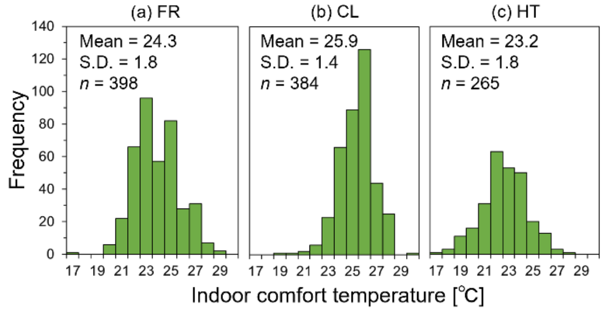

Fig. 2. Distribution of comfort temperatures in each mode.

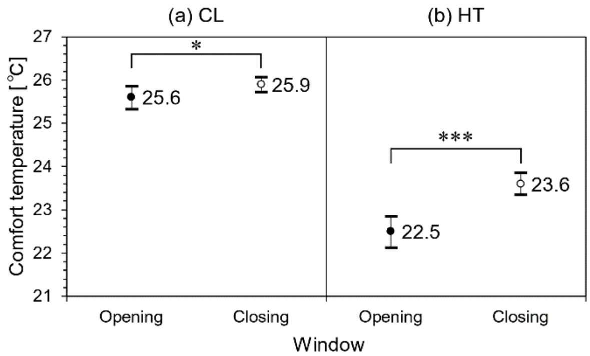

Fig. 3. Comfort temperatures in the window-opening ventilation conditions in CL and HT modes with 95% confidence intervals (*$p < 0.05$, ***$p < 0.001$).

window-closing modes and compared in the CL and HT modes, respectively. The comfort temperature in the window-opening mode was significantly lower than that in the window-closing mode by 0.3 and by 1.1 °C in the CL and HT modes, respectively. The combination of air conditioning and window-opening ventilation may have lowered the comfort temperature. In the CL mode, high-temperature air from the outside entered the room owing to the ventilation through open windows; therefore, the workers preferred lower temperatures. Conversely, low-temperature air from outside entered the room in the HT mode owing to ventilation caused by the open windows. Consequently, the workers attempted to adapt to the environment by adjusting their clothes and other behavioural aspects to feel comfortable.

3.1.3 Relationship between clothing insulation and outdoor temperature

Figure 4 depicts the relationship between clothing insulation and the running mean outdoor temperature. Here, thermal comfort votes were divided into FR and CL&HT modes. The clothing insulation tended to decrease with the increase in the running mean outdoor temperature; this trend was more significant in the CL&HT mode than that in the FR mode. We determined that the workers attempted to adapt in both the FR and CL&HT modes by adjusting their clothes according to the outdoor air temperature fluctuations.

3.2 Relationship between indoor comfort temperature and outdoor temperature

Figure 5 depicts the relationship between the indoor comfort temperature and running mean outdoor temperature. The regression equations are divided into FR and CL&HT modes for appropriate comparison with previously reported results [10]. The regression coefficients were 0.279 and 0.150 for the FR and CL&HT modes, respectively. The regression coefficient of the CL&HT mode in this study was greater than that of the Kanto region (0.10) [10]. This was attributed to the fact that the occupants in certain offices operated air-conditioning systems with the windows open for ventilation owing to the COVID-19 pandemic during the study period; therefore, the indoor comfort temperatures were more affected by the outdoor air temperature than that reported in previous studies.

On the other hand, the regression coefficient of the FR mode in this study was greater than that of the Kanto region (0.15) [10]. This implied that the comfort temperature in the FR mode was more strongly influenced by the outdoor air temperature in the Kyushu region than that in the Kanto region. Our results therefore imply that the effects of opening windows during air-conditioning owing to the COVID-19 pandemic may affect the adaptive model since ventilation system is not necessarily installed in naturally ventilated old office buildings stock in Japan.

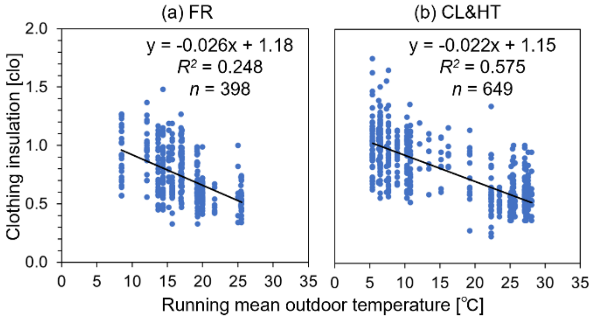

Fig. 4. Relationship between clothing insulation and the running mean outdoor temperature in FR and CL&HT modes.

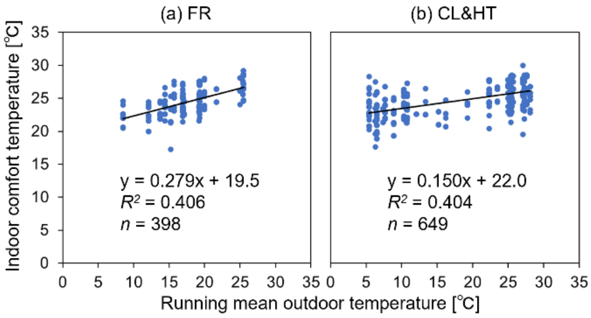

Fig. 5. Relationship between the indoor comfort temperature and running mean outdoor temperature in FR and CL&HT modes.

4 Conclusions

In this study, we conducted a survey of the thermal environment and thermal comfort of the occupants in four office buildings in Nagasaki City, located in the Kyushu region, Japan. The results of the study can be summarized as follows.

1. The mean comfort temperatures during the survey were 24.3, 25.9, and 23.2 °C for the FR, CL, and HT modes, respectively. This indicated a small difference of 2.7 °C among the three modes. Compared to the results in Kanto region, the mean comfort temperatures in this study were lower by 0.6 and 1.1 °C in the FR and HT modes, and that in the CL mode was higher by 0.3 °C.
2. The comfort temperature in the window-opening mode tended to be lower than that in the window-closing mode by 0.3 and by 1.1 °C in the CL and HT modes, respectively. The combination of air conditioning and window-opening ventilation may have lowered the comfort temperature.
3. Compared to the FR mode, CL&HT mode showed a tendency for clothing insulation to decrease as the running mean outdoor temperature increased.
4. The regression coefficients of both the FR mode and the CL&HT mode in this study were greater than that of the Kanto region.

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