Thermal comfort and occupants' behavior in Japanese condominium

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1. Abstract

Occupant behavioral setting is one of the parameters that can affect indoor comfort. This research aimed at investigating the thermal adaptation of residential occupants in Japanese condominium. Therefore, a field survey on occupants' behaviors for adaptive thermal comfort together with indoor air temperature measurement was conducted from November 2015 to November 2017, in which 32,988 votes were collected. The data was categorized into free-running (FR), heating (HT), and cooling (CL) mode. The results showed that the indoor air temperature was highly correlated with outdoor air temperature in FR mode. In CL mode, the mean indoor air temperature was 27.2°C, which was close to the recommended air temperature for summer in Japan (28°C). In HT mode it was found that indoor air temperature was maintained at an average of 20.4°C. The occupants' thermal sensation votes were most likely to be neutral. The mean clothing insulation was 0.43 clo in summer and 0.82 clo in winter during FR mode. The occupants were found to take passive adaptive measures along with the use of air conditioning unit for cooling. The findings can be useful in designing more suitable residential spaces which can lead to the reduction of energy consumption.

Keywords - Indoor environment, Thermal comfort, Residential building, Thermal adaptation, Occupant behavior

2. Introduction

The topic of thermal comfort in residential buildings is highly relevant nowadays as it could improve the resident's comfort level while reducing the energy consumption. The conditions of occupants' thermal comfort, thermal sense, and behavioral habits are the key elements which could influence the energy usage. Moreover, it is well-known that occupant's behavior is a factor that affects building energy performance [1]. Several studies [2– 4] have shown that the variety of occupant behaviours can lead to a difference of energy usage in a building. Even a single activity of occupants can have an impact on building energy consumption. For example, Sorgato et al. [5] in their study, evaluated the influence of the occupant behavior regarding the window opening ventilation control and the building thermal mass on the energy consumption related to HVAC systems in residential buildings in Brazil. The window opening behaviour of occupants has been widely studied within various building types in differing climates [1, 5–7]. The possibility of variability in preferences and uses of the residents may result in a gap between predicted and actual building performance [4]. As mentioned by Branco et al. [8], the differences between the real and estimated energy use were due to the real condition of utilisation, the real performance of the technical system and the real weather conditions. They found out that the real energy use was 50% higher than the estimated energy use.

Other than that, occupant behaviour is also connected to comfort, perceived health, and productivity. Fabi et al. [1] highlighted that if an individual is in a state of discomfort in an environment, he or she will take actions such as opening or closing windows, controlling blinds, adjusting the thermostat, changing clothes, or turning lights on and off that would restore a state of well-being based on the adaptive approach. Many previous studies [9–13] have been focused on occupant behaviour regarding thermal comfort. As occupant behaviour assumes more significance, it is necessary for it to be taken into account during the design process. This study aims to determine the relationship between outdoor and indoor air temperature during voting time in different operation modes, to investigate the relationship between comfort temperature and outdoor temperature and to understand the adaptive behaviors (clothing insulation and window opening) of the residents in Japanese condominiums.

3.Methods

3.1 Outdoor air temperature

The outdoor temperature variation in Figure 1 was obtained from data from theTokyo meteorological station. It was located almost 13 km away from the targeted building. As the study site was in Shinagawa, southern part of Tokyo, it lies in the humid subtropical climate zone with hot and humid summer and generally mild winter. The climate is warm and temperate. The hottest month of the year is August with 31.6oC mean daily temperature and January as the coldest month has 3.6oC of mean daily temperature.

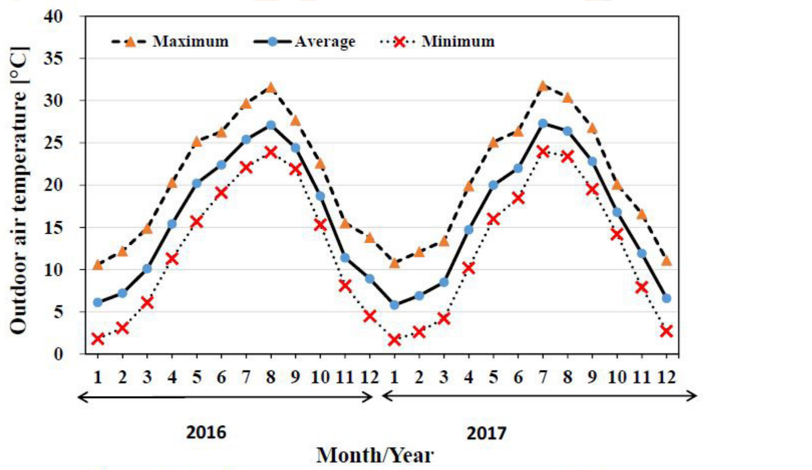

Figure 1: Monthly variation of outdoor temperature in Tokyo

3.2 Building selection and field measurement

The building is an 18-stories condominium in Shinagawa, Tokyo that can accommodate 356 families (Figure 2). For each floor, this Katsushima condominium has 21 flats. The area for each flat ranged from 71 to 90 m2. Katsushima condominium was equipped with Home Energy Management System (HEMS) and a compact fuel-cell based cogeneration system ("Ene-farm" residential fuel cell).

Figure 2: Field measurement location and targeted building. (Source: Google Map).

Indoor air temperature, relative humidity and illuminance were measured in the living room at 2 to 10 min intervals using a data logger as shown in Figure 3. It was placed in the center of the living room. The field measurement and survey were conducted in 64 flats from November 2015 to October 2017. In total, around 32, 988 votes in free-running (FR), cooling (CL) and heating (HT) operation mode. Online questionnaire survey was conducted to understand the thermal comfort level of the residents. The thermal comfort scale as shown in Table 1 was used. The collected data were analyzed by Statistical Package for Social Sciences (SPSS) Statistics version 27.

Figure 3: Sensor used during field measurement.

Table 1: Thermal sensation scale

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

4. Results and discussion

4.1 Outdoor and indoor air temperature in different operation modes

The relationship between indoor and outdoor air temperature during the voting time throughout the whole measurement period is shown in Figure 4. We classified the data into three operation modes (FR, HT, CL). The linear equations (1) – (3) represent the regression equation for each mode. The indoor temperature during FR mode is much more dependent on the outdoor temperature than the one in the other modes. Similarly, the coefficient of the determination between indoor and outdoor temperature for the FR mode is much higher (0.74) than for the HT (0.22) or CL (0.11) mode.

$$\text{FR: } T_{in} = 0.31T_o + 17.0 \quad (1)$$
$$(n = 11559, R^2 = 0.74, S.E. = 0.002, p<0.001)$$
$$\text{HT: } T_{in} = 0.19T_o + 21.9 \quad (2)$$
$$(n = 6818, R^2 = 0.22, S.E. = 0.005, p<0.001)$$
$$\text{CL: } T_{in} = 0.11T_o + 24.24 \quad (3)$$
$$(n = 2453, R^2 = 0.11, S.E. = 0.007, p<0.001)$$

Where T_o indicates the outdoor temperature (°C), Tin is the indoor temperature (°C), n is the number of the sample, R^2 is the coefficient of determination, S.E. is the standard error of the regression coefficient and p is the significant level of regression coefficient.

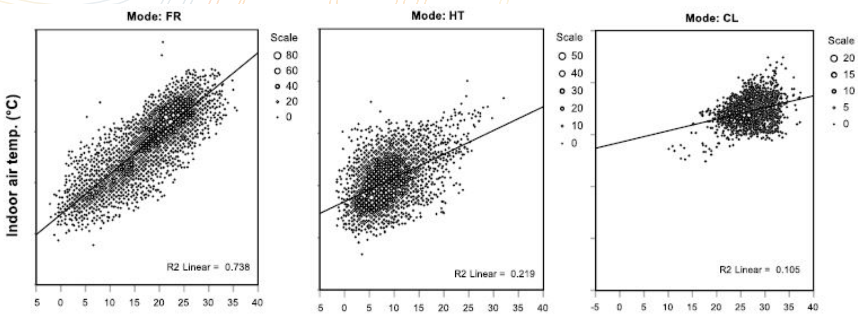

Figure 4: Relation of indoor and outdoor air temperature in different operation modes.

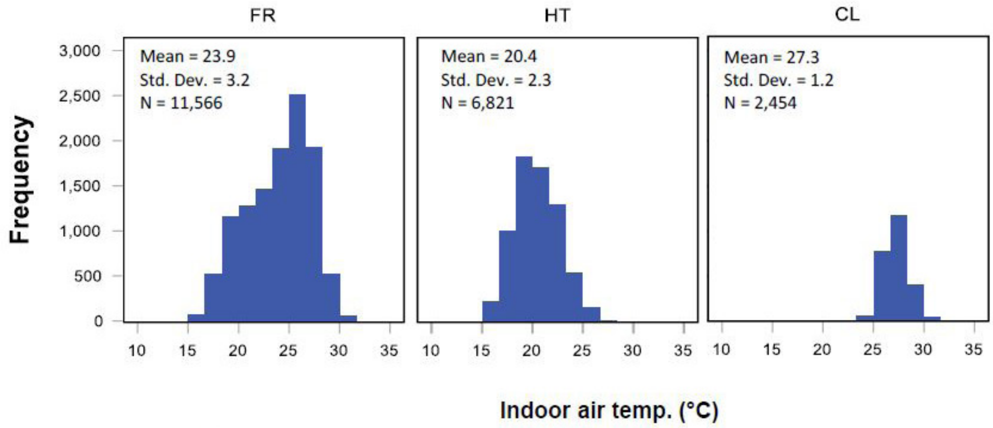

Figure 5: Distribution of the indoor air temperature during different modes.

The distribution of indoor air temperature during FR, HT, and CL modes was shown in Figure 5. The mean was 23.9°C, 20.4°C, and 27.2°C for FR, HT, and CL modes respectively. The Japanese government recommends indoor temperature of 20 °C in winter and 28 °C in summer for energy saving [14]. The results show that the mean indoor temperatures during HT and CL were close to this recommendation.

4.2 Comfort temperature by Griffiths' method

Griffiths' method is a widely used method to determine the comfort temperature ranges in the buildings. Considering the occupants' thermal sensation votes in correspondence with measured indoor air temperature, comfort temperature is predicted using equation below:

$$T_c = T_{in} + (4 - \mathrm{TSV}) / \alpha \qquad (4)$$

Where, Tc is comfort temperature (°C) and α is Griffiths' constant. Griffiths' approach can determine an estimation relationship between comfort vote and temperature when the expected comfort temperature is established for each comfort vote [15]. The comfort temperature may vary due to thermal adaptation, building designs, and seasons [16]. When adopting a seven-point thermal sensation scale (1 to 7), '4' represents the neutral situation, and α is the Griffiths constant, which is the regression coefficient. The value for α [17] was determined to be 0.50. Because the Griffiths constant or the resident's thermal sensitivity level is assumed, the comfort temperature can be set with a single vote. The comfort temperature calculated using a coefficient 0.50 is a representation of 2 °C rise for a unit change in thermal sensation vote.

Figure 6 shows the mean comfort temperature obtained by the Griffiths method which are 23.7°C, 21.0°C, and 26.9°C for FR, HT, and CL, respectively. Even though the Japanese government recommends an indoor temperature of 28°C for cooling and 20°C for heating, it was found that in these buildings the comfort was 1.0°C higher in HT mode and 1.1°C lower in CL mode. In another study, the comfort temperature by the Griffiths' method was 17.6 °C in winter, 21.6 °C in spring, 27.0 °C in summer and 23.9 °C in autumn in FR mode [18].

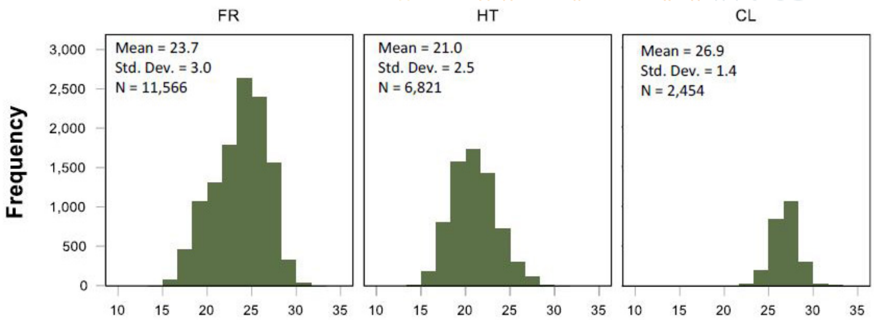

Figure 6: Distribution of comfort temperature.

4.3 Relationship between comfort temperature and outdoor temperature

The equation to calculate the running mean outdoor temperature (Equation 5) is referred to McCartney and Nicol [19]:

$$T_{rm} = \alpha T_{rm-1} + (1 - \alpha)\, T_{od-1} \quad (5)$$

Where T_{rm-1} is the running mean outdoor temperature for the previous day (°C) and Tod-1 is the daily mean outdoor temperature for the previous day (°C). α is a constant between 0 and 1 that defines the speed at which the running mean responds to outdoor air temperature. The value for α is 0.8 used in the derivation of the CEN standard. A linear regression has been analysed between the comfort temperature obtained by the Griffiths' method and the running mean outdoor air temperature as shown in the Figure 7. The equations are as follows:

$$\text{FR mode } T_c = 0.38\ T_{rm} + 16.91;\ (N= 11{,}566,\ R^2 = 0.67,\ S.E. = 0.006,\ p < 0.001) \quad (6)$$

$$\text{HT mode } T_c = 0.35\ T_{rm} + 17.65;\ (N= 6821,\ R^2 = 0.19,\ S.E. = 0.003,\ p < 0.001) \quad (7)$$

$$\text{CL mode } T_c = 0.17\ T_{rm} + 22.39;\ (N= 2454,\ R^2 = 0.07,\ S.E. = 0.001,\ p < 0.001) \quad (8)$$

Where, S.E. is the standard error of the regression coefficient. The regression coefficient and coefficient of determination is higher in FR mode than the HT or CL mode. Also, it is higher than the CEN standard (FR=0.33). However, the CEN standard is based on the field investigation in office buildings, thus it may not be suitable to be compared with residential buildings in this study as the occupants will have more freedom to adapt. In a recent review study that focuses on residential building, the regression coefficient in FR mode is 0.40 and 0.27 in CL mode [20]. It may be also because of the differences of occupant's behaviours and the climatic variations of different regions.

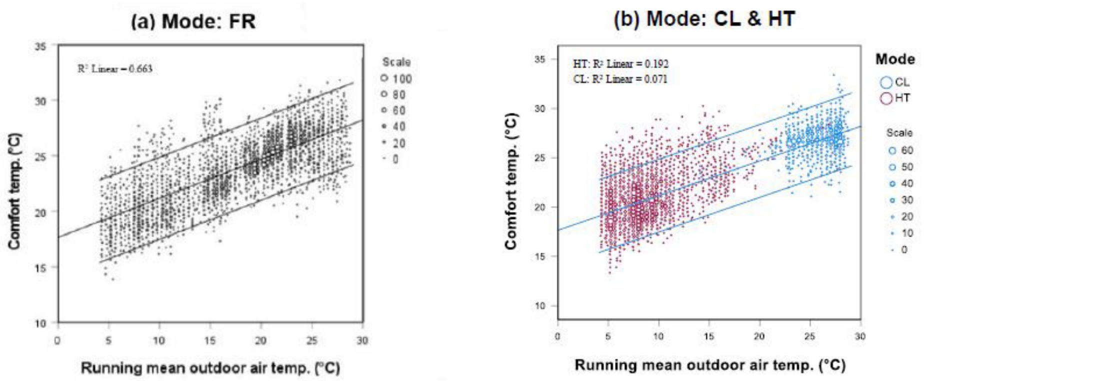

Figure 7: Relationship between comfort temperature and running mean outdoor temperature:(a) FR mode; and (b) CL and HT modes. 95% data band is shown in the figure.

4.4 Clothing adjustment

The comfort temperature varies greatly in residential buildings more than the one that has been found in Japanese offices [21]. The reason might be that the occupants are adapting well in their own homes using various behavioral, physiological and psychological adaptations. One of them is clothing insulation. Figure 8 shows how the clothing insulation of the occupants varies according to the season. The mean clothing insulation can be seen to start decreasing from 0.82 clo in winter to 0.68 clo in spring and 0.43 clo in summer. In autumn, the mean clothing insulation starts to increase to 0.54 clo. Seasonal variation of clothing insulation can also be analysed by regression as shown in Figure 9. Table 2 displays the equations for the relationship between clothing insulation and indoor air temperature. Due to no constraints, the residents could freely adjust their clothing at their own house. Therefore, it is important to investigate how the mean clothing insulation varies with indoor air temperature. The occupants' clothing insulation decreased when the indoor air temperature increased. The slope of the linear regression for autumn and spring seems to be higher than the others. This indicated that the residents had a more sensitive clothing adjustment as indoor air temperature. The similar result can be seen in Ning et al. [22].

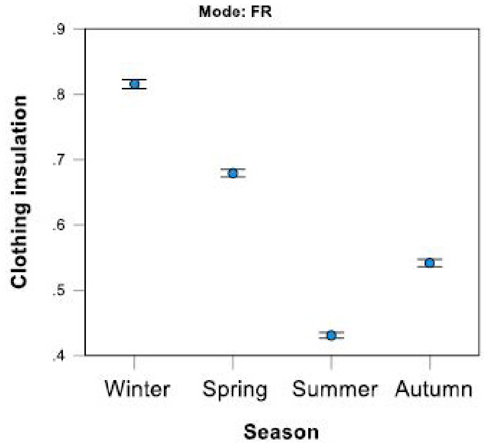

Figure 8: Means of clothing insulation by season with 95% confidence interval (mean ± 2 S.E.).

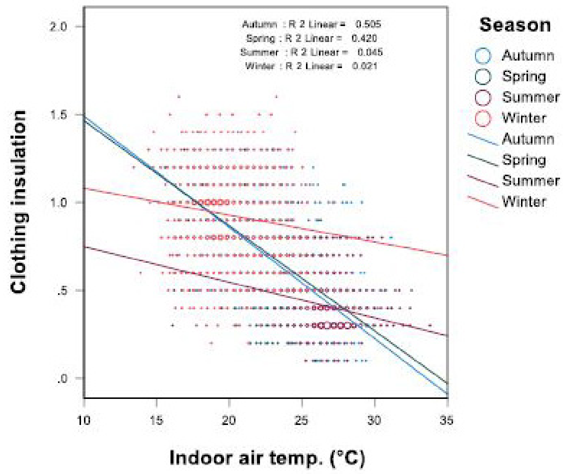

Figure 9: Relationship between clothing insulation and indoor temperature in FR mode.

Table 2: Regression equations in FR mode

Season	Equation	R^2	S.E.	p
Winter	$I_{cl} = -0.02\ T_{in} + 1.23$	0.02	0.03	< 0.001
Spring	$I_{cl} = -0.06\ T_{in} + 12.06$	0.42	0.02	< 0.001
Summer	$I_{cl} = -0.02\ T_{in} + 0.95$	0.05	0.02	< 0.001
Autumn	$I_{cl} = -0.06\ T_{in} + 2.12$	0.51	0.04	< 0.001
All	$I_{cl} = -0.06\ T_{in} + 2.14$	0.57	0.03	< 0.001

I_{cl}: Clothing insulation, T_{in}: Indoor temperature (°C), R^2: coefficient of determination, S.E.: standard error, p: significant value of the regression coefficient.

4.5 Window opening behaviour

Opening a window allows indoor and outdoor air to circulate together, therefore if it is cooler outside than inside, opening a window lowers room temperature. Figure 10 shows the seasonal variation in indoor air temperature for cases when windows are open and closed. The mean indoor air temperature for the window open condition during autumn and spring has the most significant difference. The indoor air temperature for the condition when the window was open is 24.2°C in spring and 26.6°C in autumn, which are 1.2°C and 3.3°C, respectively higher than for the condition of when the window was closed. Rijal et al. [7] found out that the mean indoor air temperature for the window open condition is 27.6°C in the living room and 27.1°C in the bedroom, which is higher by 5.5 K and 6.4 K, respectively, than the condition when the window was closed.

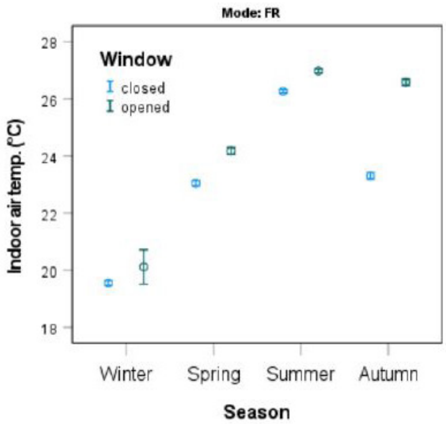

Figure 10: Mean indoor air temperature for windows open and closed in FR mode by season with 95% confidence intervals (mean ±2 S.E.) in FR mode.

5. Conclusions

This paper examined the thermal comfort and occupant behaviours of the residents in a Japanese condominium. The following conclusions are obtained:

1. The correlation between indoor and outdoor temperature for the FR mode is much higher (R=0.86) than for the HT (R=0.47) or CL (R=0.33) mode which indicates that the indoor air temperature is highly related to outdoor air temperature.

2. The regression coefficient of the adaptive model (i.e. the relation between comfort temperature and running mean outdoor temperature (FR = 0.38; CL = 0.17; and HT = 0.35) are higher than CEN standard (FR = 0.33). This might be due to more freedom to adapt in residential buildings.

3. Occupants conducted various behavioural adaptations like clothing adjustments and window opening. The slope of the linear regression for autumn and spring seems to be higher than the others. This indicated that the residents had a more sensitive clothing adjustment as indoor air temperature.

4. By opening the window, the rise in indoor air temperature can be limited in warm weather. In cool weather, closing the window will keep the temperature from decreasing too far. Thus, the window effectively controls the indoor thermal environment.

6. Acknowledgements

We would like to thank the households who participated in the survey. This research was funded by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) on the 'Subsidy for pioneering project about CO2 emission reduction in residential and commercial building II, 2013.'

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