On-site measurement and evaluations of indoor thermal environment in low-cost dwellings of urban Kampung district

Murtyas, Solli
Interdisciplinary Graduate School of Engineering Sciences, Kyushu University

Hagishima, Aya
Interdisciplinary Graduate School of Engineering Sciences, Kyushu University

Kusumaningdyah, N. H.
Architecture Department, Faculty of Engineering, Universitas Sebelas Maret

https://hdl.handle.net/2324/4797839

出版情報：Building and Environment. 184, pp.107239-, 2020-10-15. Elsevier
バージョン：

On-site measurement and evaluations of indoor thermal environment in low-cost dwellings of urban Kampung district

Solli Murtyas[a*], Aya Hagishima[a], Kusumaningdyah N.H[b]

[a] Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Japan

[b] Architecture Department, Faculty of Engineering, Universitas Sebelas Maret, Indonesia

Corresponding author

Address: Department of Energy and Environmental Engineering, Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Building F, 6-1 Kasuga Koen, Kasuga, Fukuoka 816-8580, Japan

(E-mail: s.murtyas@kyudai.jp)

Abstract

This paper reported results of a field measurement and questionnaire survey regarding the indoor thermal conditions of 17 low-cost dwellings located in a typical unplanned urban residential district 'Kampung' in Surakarta City, Indonesia. The surveyed dwellings were selected to grasp the indoor thermal features of various conditions, including the building materials, area, occupants' behaviours, and household economic level. The observed time series variations of the indoor air temperature showed significant diversity among the 17 dwellings. The decrement factor *f*, which refers to the ratio of the averaged daily amplitude of the indoor temperature to that of the outdoor temperature, showed a strong linear correlation with the parameter Q, i.e. the heat capacity of a building envelope per unit interior volume, regardless of the occupants' behavioural conditions. In addition, a statistical test using Spearman's rank correlation indicated that both Q and the floor area per interior volume have significant correlations with the percentiles of indoor air temperatures. Furthermore, the time fraction for the thermally neutral range of PMVs lower than 0.5 varied for the sleeping period among the dwellings, from 7% to 55%, owing to the parameter Q, as dwellings with low Q values tend to have a longer time period in the neutral range. These findings imply that the parameter Q and interior geometry of a dwelling can be utilized to establish countermeasures for vulnerable dwellings having a heat risk in Kampung districts.

Keywords: low-cost dwellings, indoor thermal environments, PMV, thermal sensation votes, comfort temperature

1. Introduction

The urban population accounted for 55.3% of the world's population in 2018, and it is projected to exceed more than 60% by 2030 [1]. This implies that the quality of urban environment will significantly affect a large population in regards to various aspects such as health, energy demands, and the economy [2]. Considering the potential future impact of climate change, such as rising global temperatures and more frequent extreme weather events such as heat waves [3], as well as temperature increases specific to urban areas (i.e. the 'urban heat island' phenomenon), there will be a strong need for affordable adaptation strategies to mitigate the heat risks in cities located in hot climate zones.

Indonesia is a developing Asian country that has shown rapid urbanization in recent decades [4]; the percentage of the population considered 'urban' was reported in 2019 as 56% [5]. This percentage is expected to increase to 68% by 2025 [6]. In line with this urbanization, there has been an expansion of densely populated and unplanned settlements. The local government reported in 2019 that 9.86 million people are living in low-quality housing, with limited infrastructure and public services [7].

As is widely known, people spend 87% of their time indoors; thus, the indoor living environment plays a significant role in health, well-being, and work performance [8]. Accordingly, the thermal properties of the building envelopes and building facilities controlling the indoor thermal conditions are key factors in decreasing future heat risks from climate change and urban heat island phenomena [9]. However, providing people with suitable shelters from a hot climate is extremely difficult in developing countries, where many low-income people live in informal urban settlements with poor building quality owing to limited economic capabilities [10].

With this background, understanding the reality of the indoor thermal environment in low-income urban dwellings has become essential, to thereby establish evidence-based strategies for achieving affordable living spaces and reaching sustainable cities and communities. In fact, several studies have been conducted to observe low-income housing worldwide. Sakka et. al (2012) investigated the indoor thermal conditions of 50 non-air-conditioned houses in Athens, Greece over an extremely hot summer in 2007. They found that the indoor temperature reached 30 ºC for more than 85% of the measurement time period[11]. Nix et. al (2015) observed indoor environments in low-income housing in Delhi, India during the winter season. The hourly indoor temperatures of 13 dwellings were monitored for three weeks in December 2013. They found that the indoor thermal conditions of all observed dwellings were below 21 ºC for more than 60% of the hours during the monitoring period. In addition, they reported discomfort and risks to health from exposure to the cold temperatures, based on interviews with the residents [12]. Despite such attempts, research regarding the indoor thermal conditions and building thermal features of low-cost dwellings in developing countries (including Indonesia) remains limited, probably owing to difficulties in access to the local communities of such areas, which are sometimes recognised as urban slums.

Under these circumstances, this study intends to provide a quantitative grasp of the indoor thermal conditions of an urban unplanned residential district called Kampung in Surakarta City, Indonesia, based on a field measurement of 17 low-cost dwellings and a questionnaire survey of the residents. The terminology 'Kampung' for representing an urban district is derived from Indonesian term for 'village'. Kampung in Indonesia is tightly related to informal urban settlements with poor physical and economical qualities [13]. The objectives of this study are as follows:

- to grasp the diversity in indoor thermal environments among dwellings located in the same district having different conditions of building envelopes and occupant thermal behaviours in households;
- to examine the factors indicating the vulnerability of a dwelling in terms of the thermal comfort and heat risks of residents; and
- to investigate the occupant perceptions, preferences, and acceptance in regards to indoor thermal conditions.

2. Outline of field survey

2.1. Site description

Fig. 1 shows the target site: Kampung Sangkrah, Surakarta City, Central Java Province, Indonesia (latitude 7º 34` South and longitude 110º 50` East). It lies along the riverbank of Bengawan, on the eastern edge of Surakarta City. This district has an area of 0.482 km^2 and contains large informal settlements, with a total population of 10,885 in 2016. Of the 2473 existing dwellings, 30% are classified as poor settlements[14]. The livelihood typology consists of informal workers, civil servants, hawkers, scavenger, and casual labourers [15].

This area is categorised as a tropical climate with dry and wet seasons [16]. The dry season period is five months (May-September), and wet season occurs within the seven months from October to April [17]. The annual mean temperature, relative humidity, and annual total precipitation, as recorded from 2015 to 2018, were 26.9 °C, 78.7%, and 804.3 mm, respectively [18].

Fig. 1. A map of Indonesia (taken from Google maps) with target site Kampung Sangkrah in Surakarta City

2.2.Measurement of indoor thermal environment

Fig. 2 shows an aerial photograph of the target site, including the locations of the 17 dwellings selected for the measurement of indoor thermal conditions. These 17 dwellings were selected to collect representative but diverse samples of residential buildings of Kampung in terms of the building construction and materials, floor areas, and number of occupants (ranging from two to nine). All of the selected dwellings were 1-storey houses, and consisted of at least a living room and bedroom. Table 1 shows the wall materials of the 17 dwellings, as classified into six groups. Additional detailed information of the buildings is summarized in **Appendix Table A1**.

In the target 17 dwellings, the air temperature and relative humidity values in living rooms or bedrooms were measured at a height of 1.5 m. A thermo-hygrometer was installed in each room at a position not exposed to direct solar radiation (see Fig. 3). This measurement of indoor thermal conditions was continuously carried out from 26

March to 5 May 2019, at intervals of 10 min. In addition, the outdoor air temperature, relative humidity, wind speed, global solar radiation, and precipitation were measured as climate variables, at a height of 8 m above the playground of a public school in this district, as shown in Fig. 2. The details of the measurement items and instruments are shown in Table 2.

Fig. 2. The location of Kampung Sangkrah, selected dwellings, and weather station site

Fig. 3. Details of the indoor thermal measurement in house A, F, and K

2.3. Questionnaire surveys

In addition to the measurement of the indoor thermal conditions, a questionnaire survey of the residents living in the target dwellings was conducted at their houses between 10 June and 8 August 2019, at times ranging from

9:00 am to 6:00 pm. The total number of respondents was 102 (47 males and 55 females), with ages ranging from 11 to 65 years old. The questionnaire consisted of ten questions related to demographic conditions, perceptions of the indoor thermal comfort in the current state, satisfaction regarding their indoor thermal environments, and daily behaviours for thermal adaptation in their houses. The questions related to the subjective thermal satisfaction, thermal preference votes (TPV), and thermal sensation votes (TSV) were designed based on ASHRAE 55 and ISO 7730. Two human factors in thermal comfort, namely clothing and metabolic rate (as estimated by physical state), were also surveyed. Meanwhile, the air temperature and relative humidity of the rooms where respondents stayed were obtained by the aforementioned thermometers. A detailed description of the questionnaire is provided in **Appendix A**.

Table 1. Wall materials of monitored dwellings

Type	Materials consisting walls ordered from inner to outer position	Dwelling labels
Type 1	Brick + Plywood board	G, K
Type 2	Plywood board	I
Type 3	Cement plaster + Brick +Plywood board	C
Type 4	Brick	E
Type 5	Cement plaster + Brick + Porcelain tile	Q
Type 6	Cement plaster + Brick + Cement plaster	A, B, D, F, H, J, L, M, N, O, P

Table 2. Measurement items and instruments

Measured variables	Instrument specifications	Recording interval	Location
Indoor air temperature (ºC) and relative humidity (%)	TR-72nw T&D Corporation, accuracy ± 0.5 ºC, ± 2.5% RH	10 min	17 houses
Outdoor air temperature (ºC) and relative humidity (%)	S-THB-M002 Onset Computer Corporation, accuracy ± 0.21 ºC, ± 2.5% RH	1 min	Open space of public-school building at 8 m height
Wind speed (m/s)	S-WCG-M003 Onset Computer Corporation, ultrasonic anemometer, accuracy ± 0.8 m/s	1 min	
Solar radiation (W/m^2)	S-LIB-M003 Onset Computer Corporation, accuracy ± 10 W/m^2	1 min	
Precipitation (mm)	S-RGF-M002 Onset Computer Corporation, rain gauge, accuracy ± 4% between 0.2 to 50 mm per hour, ± 5% between 50 to 100 mm per hour	1 min	

3. Results of field measurement

3.1. Weather conditions

The time variations in the hourly means of the outdoor air temperature, relative humidity, solar radiation, wind speed, and daily total precipitation are shown in Fig. 4. The outdoor air temperature fluctuated from 23 ºC to 36 ºC. The relative humidity was high, ranging from 42% to 99%. Such hot and humid weather is typical in the measurement period from the end of the wet season to the beginning of the dry season. The wind speed showed a distinct diurnal time scale and was weak, except for a period in April 28 and 29 with daily peaks of 4 m/s. From

May, the beginning of the dry season, the wind speed showed an increasing trend. The average daily total precipitation was 8.4 mm; in contrast, 15 out of the 41 measurement days had no rain event. In addition, the daily total global solar radiation ranged from 10 MJ/m^2 to 20.7 MJ/m^2, with an average of 15.1 MJ/m^{2}day.

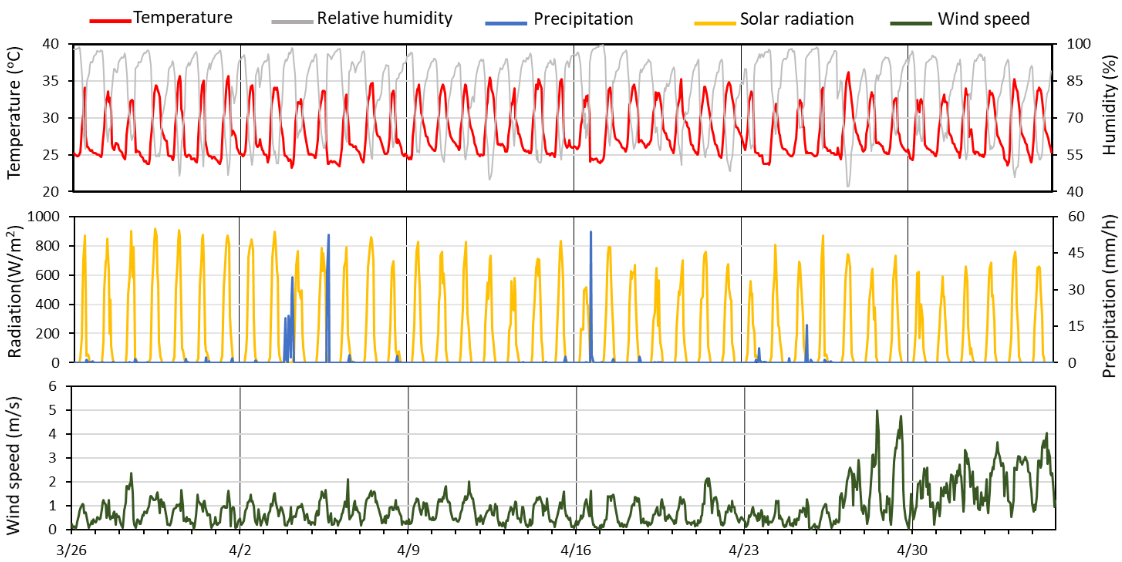


Fig. 4. Weather conditions during the period of 26 March to 5 May 2019

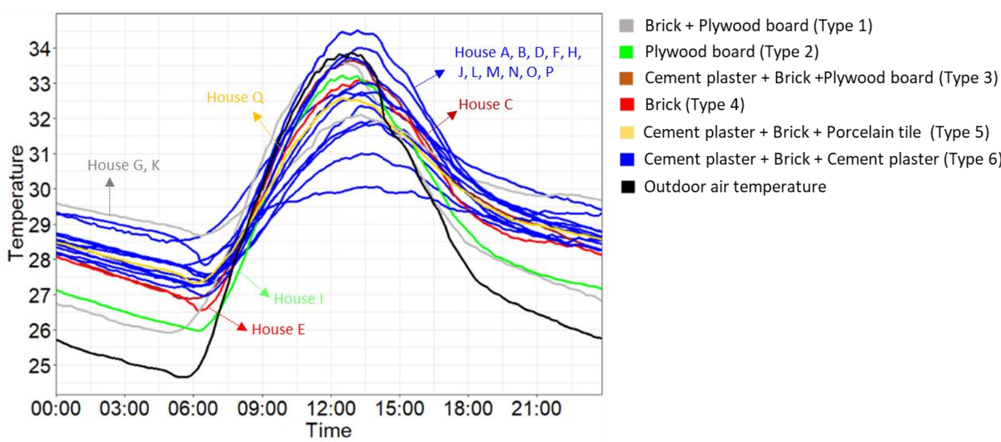


Fig. 5. Averaged diurnal cycle of indoor temperatures and outdoor temperatures (black line) during the measurement period

3.2. Indoor thermal environments

Fig. 5 illustrates the averaged diurnal cycles of the room air temperatures in all of the measured dwellings. The indoor temperatures were higher than the outdoor temperatures at nighttime (18:00 to 06:00). In this period, dwellings having wall Type 6 were relatively warm, probably owing to the higher thermal mass of the building envelopes relative to other dwellings, as a higher amount of heat stored in the daytime is released to the indoor space of the house [19]. Oppositely, most of the dwellings showed a lower indoor temperature than the outdoor temperature in the daytime (09:00 to 14:00). Two houses (H and O) showed a higher daily peak than the outdoor air temperature in daytime. These houses are classified as wall Type 6, but had the smallest floor areas relative to other houses of a similar type.

To characterize the daily variations of the room air temperature in each dwelling, we estimated a decrement factor *f*, expressed in Eq. (1) [20] as follows:

$$f = \frac{T_{i\_max} - T_{i\_min}}{T_{o\_max} - T_{o\_min}} \tag{1}$$

In the above, T_{i_max} and T_{i_min} are the daily maximum and minimum indoor temperature, respectively; and T_{o_max} and T_{o_min} are the daily maximum and minimum outdoor temperature, respectively. *f* indicates the ratio of the amplitude of the daily variation of the indoor temperature to that of the outdoor temperature. In this study, *f* was calculated based on an ensemble average of the daily variations for each dwelling during the entire measurement period shown in Fig. 5.

In addition, the heat capacity of a building envelope per interior volume Q [J $m^{-3}K^{-1}$] was calculated for each dwelling using Eq. (2), based on the observed building materials and size.

$$\mathrm{Q} = \frac{\sum_{i=1}^{n} C_i}{V} \tag{2}$$

Here, V is the indoor air volume of the dwelling [m^3], and indicates the total volume of all interior spaces within all rooms of a dwelling. The heat capacity for each component of a building envelope exposed to the outdoor air C_i is expressed as follows:

$$C_i = A_i \sum_j \rho_j C_{p,j} \Delta x_j \tag{3}$$

In the above, A_i is the area of a component i of the building envelope, such as a wall, roof, or window glass [m^2]; and ρ_j , $C_{p,j}$, and Δx_j are the density [kg m^{-3}], specific heat [J $kg^{-1}K^{-1}$], and thickness [m] of a layer j of the envelope, respectively. The parameter Q indicates the influence of the thermal inertia of the building envelopes on the room air temperatures. Fig. 6 shows the relationship between the decrement factor f and Q. As expected, these two variables show a negative correlation, indicating that a larger thermal inertia causes a more stable daily fluctuation in room air temperature. House G, with the smallest heat capacity of 112.2 kJ $m^{-3}K^{-1}$ and classified into wall Type 1, shows the largest f, in addition to the largest amplitude of daily indoor temperature. In contrast, House B has the highest heat capacity at 144.5 kJ $m^{-3}K^{-1}$ and is classified into wall Type 6, but did not show the most stable indoor temperature. However, it showed the longest delay of the daily peak time, as shown in Fig. 5.

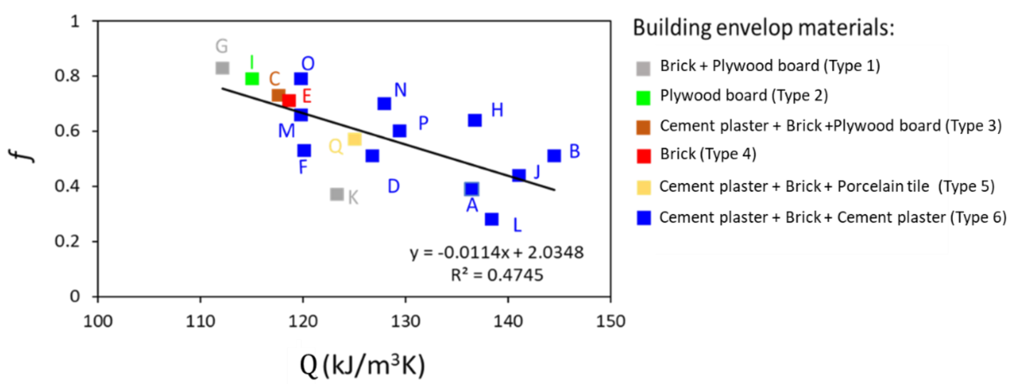


Fig. 6. Scatterplot and regression line demonstrating the relation between decrement factor f and heat capacity of a building envelope per interior volume Q

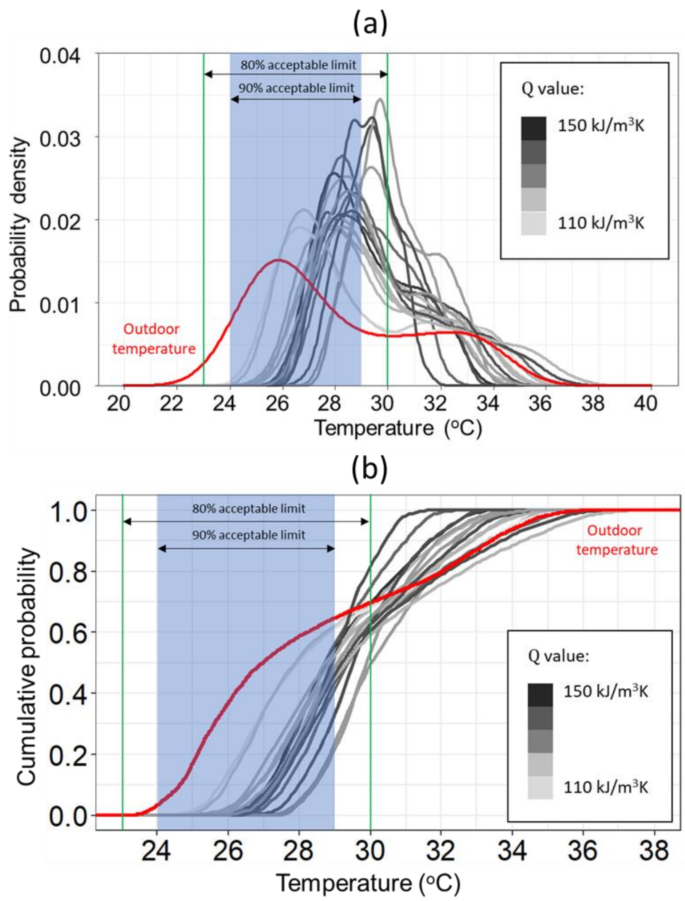


Fig. 7. (a) Probability density distributions (PDDs) and (b) cumulative probability distributions (CPDs) of indoor temperatures of 17 dwellings and outdoor temperatures during the measurement period

Fig. 7 shows the probability density distributions (PDDs) and cumulative probability distributions (CPDs) of the indoor air temperatures for the 17 dwellings. The ranges for 80% and 90% acceptability of the adaptive thermal comfort model in naturally ventilated spaces are also included. These ranges are estimated by using the mean outdoor temperature during the measurement period [21]. Similar to case with the averaged diurnal cycles of the room air temperatures, the PDDs of all dwellings show diverse features. In general, dwellings with higher Q values show a narrower temperature distribution, indicating that the time variations of the indoor air temperature are relatively small. In contrast, dwellings with lower Q values show a relatively wide distribution, indicating large indoor air temperature variations between daytime and nighttime. In addition, the CPDs shown in Fig. 7b reveal that approximately 38% to 80% of the total measurement period is above 29 ºC, and out of the range of 90% thermal acceptability.

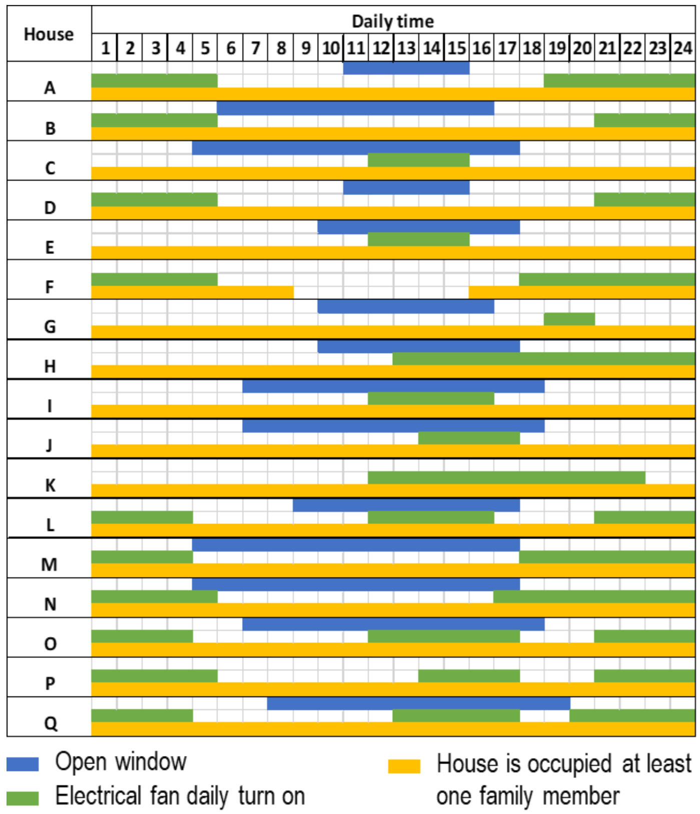


Fig. 8. Daily occupant thermal behaviour schedules in each dwelling

3.3. Occupants' schedules of thermal adaptation behaviours

Fig. 8 shows a schedule related to occupant thermal behaviours, as obtained from the questionnaire survey (**Appendix A**). Most dwellings were occupied by at least one resident during almost all of the 24 h except for house F, where each family member had outdoor activities between 9:00 to 15:00 (working or going to school). In this house, the occupants continuously closed the windows, for safety.

Regarding thermal adaptation behaviours, most residents used an electric fan during the sleeping period. The duration of the use of electric fans varied from 2 to 12 h per day. In most houses, a combination of using fans and opening windows was employed during the daytime. However, some residents of houses A and G only opened windows and did not use fans, despite hot daytime hours. The times when residents started opening the windows were diverse, i.e. from 5:00 to 11:00.

3.4. Statistical analysis of indoor environments and thermophysical factors of dwellings

According to a basic knowledge of building physics, the room air temperature of a naturally ventilated building is mainly affected by convective heat transfer from the inner surfaces of building envelopes, and ventilation from outdoor air. Based on such knowledge, if the architectural designs, including the materials and dimensions of each part, are known, it is easy to predict the indoor temperature and air conditioning load. However, in districts with informal urban settlements such as Kampung, where extremely simple low-cost dwellings with various materials and designs are haphazardly concentrated, the usual legitimate approach to estimating building thermal properties cannot be applied, in both the preconstruction stage and in retrofitting for existing dwellings. To determine simple and easy variables for housing conditions to identify dwellings with a higher heat risk, improved measures need to be implemented; thus, the authors conducted a statistical analysis of the observed room air temperatures.

Table 3 shows the correlation coefficients for the monitored percentiles of room air temperatures in each dwelling ($T_{P2.5}$, T_{P25}, T_{P50}, T_{P75}, and $T_{P97.5}$), with nine variables related to the building design, thermophysical variable Q, and occupants' thermal behaviours. A Spearman’s rank correlation with a confidence interval (CI) of 95% was applied to investigate the strength and direction of the relationship (negative or positive) between these variables. As expected, the house volumetric heat capacity Q shows highest correlation coefficient for $T_{P2.5}$, T_{P25}, and $T_{P97.5}$. Considering the physical meaning of Q, the high correlation is not surprising. Nevertheless, it is instructive that dwellings having lower Q values tend to have a higher heat risk during the daytime, and vice versa for sleeping time. However, the ratio of the floor area per house volume, i.e. the inverse of the ceiling height, shows relatively high correlation coefficients for T_{p75} and $T_{p07.5}$. This result indicates that houses with lower ceiling heights are likely exposed to a higher heat risk during the daytime. The other variables, such as the fraction of each building envelope to the room volume and occupants’ related indices, were not statistically significant.

Table 3. Spearman’s rank correlation test of percentile values (2.5%, 25%, 50%, 75%, and 97.5%) of indoor temperatures against thermophysical variables of dwellings and thermal behavioural variables

Variables	Correlation coefficient (p-value)				
	$T_{P2.5}$	T_{P25}	T_{P50}	T_{P75}	$T_{P97.5}$
Wall area per interior volume	0.03 (0.907)	-0.04 (0.877)	-0.14 (0.578)	-0.27 (0.290)	-0.30 (0.249)
Roof area per interior volume	-0.05 (0.840)	-0.25 (0.334)	-0.21 (0.415)	-0.40 (0.115)	-0.39 (0.119)
Window area per interior volume	-0.05 (0.847)	-0.04 (0.870)	-0.26 (0.312)	-0.39 (0.125)	-0.25 (0.330)
Floor area per interior volume	-0.02 (0.940)	-0.12 (0.651)	-0.26 (0.311)	**-0.53 (0.027)**	-0.42 (0.090)
Occupants per floor area	-0.06 (0.825)	-0.08 (0.771)	-0.09 (0.739)	0.11 (0.682)	0.27 (0.288)
Ceiling height from the ground	0.19 (0.460)	0.15 (0.558)	0.09 (0.719)	-0.24 (0.377)	-0.37 (0.139)
Heat capacity of building envelope per volume (Q)	**0.64 (0.006)**	**0.59 (0.012)**	-0.37 (0.142)	-0.38 (0.134)	**-0.56 (0.018)**
Duration of windows open in a day	-0.19 (0.457)	-0.12 (0.658)	-0.00 (0.992)	-0.20 (0.438)	0.35 (0.166)
Duration of electric wind fan usage in a day	0.33 (0.197)	0.40 (0.115)	0.32 (0.213)	-0.02 (0.930)	-0.02 (0.951)

*bold numbers indicated statistically significant correlation ($p < 0.05$)

3.5. Thermal comfort indices derived from observed data

In recent years, various studies have suggested that the estimated thermal comfort based on the PMV often shows a discrepancy from the actual thermal sensation votes of occupants in naturally ventilated buildings [21–23]. Accordingly, an approach denoted the adaptive thermal comfort model; has become popular as an adequate tool for estimating the comfortable temperature range in such buildings [24]. Considering these findings, the adaptive thermal comfort approach (rather than PMV) would be suitable for the evaluation of thermal comfort in the dwellings surveyed in this study. Nevertheless, we considered a PMV derived from personal (clothing insulation and metabolic rate) and environmental variables (air temperature, relative humidity, mean radiant temperature, and air velocity) as a comprehensive thermal comfort index, for a relative comparison of indoor thermal conditions among the surveyed dwellings [25]. Fig. 9 shows the averaged daily variations of the PMV for each dwelling, as derived from the observed room air temperature and relative humidity. The mean radiation temperature was assumed as equivalent to the measured room air temperature. In contrast, the wind speed was determined based on the results of the questionnaire survey related to the occupants' behaviour schedules (shown in Fig. 8). During the period when occupants used electric fans, the wind speed was assumed as 0.3 m/s; in contrast, when windows were opened, 0.2 m/s was adopted. In the remaining periods with no fans and no openings of windows, the wind speed was assumed as 0.1 m/s [26]. The metabolic rate was determined as 1 met, which is equivalent to the occupant's activity level when we conducted the questionnaire survey. In addition, the clothing value was calculated based on the combination of clothes that the occupant wore, and ranged from 0.5 to 0.7.

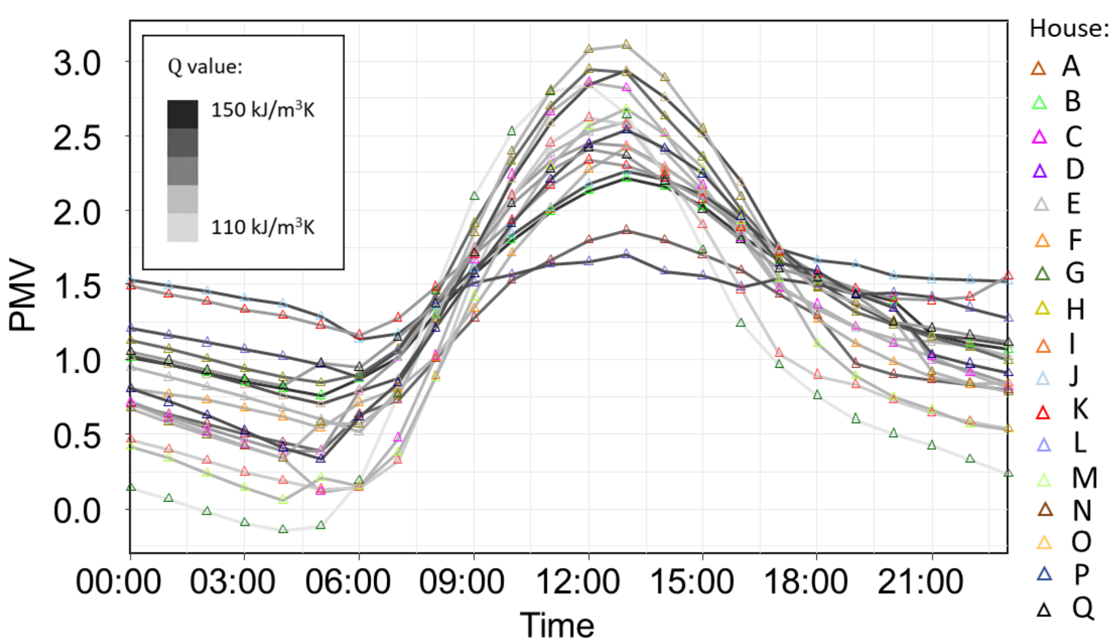


Fig. 9. Averaged diurnal cycles of predicted mean vote (PMV) for 17 dwellings

In general, the diurnal cycles of the PMV show similar features based on the diverse daily amplitudes of room air temperatures, as shown in Fig. 5. The daily peaks of the PMV arise from 12:20 to 14:20, with a range of 1.8 to 3.2; these values fail the standard of thermal comfort suggested by ASHRAE 55, except for two houses (G and I).

These dwellings exhibited an acceptable thermal comfort range at night for approximately 7 and 4 h, respectively. In other words, dwellings with light building materials (wall Types 1 and 2) and thus relatively low Q values were beneficial to achieving an acceptable thermal environment during most of the sleeping period.

Houses A and L showed the best indoor thermal environments in terms of the mitigation of hot sensations in the activity period, with the PMV values lower than 2, whereas the other dwellings showed PMV values ranging from 2.2 to 3.2. However, house L experienced a higher PMV than most of other dwellings in the sleeping period with a PMV value greater than 1.3, whereas the other dwellings could achieve cooler conditions, with PMV values range between 0.1 to 1.2. This trend suggests that higher values of Q in dwellings will help achieve cooler conditions as compared to lower Q values in activity times, as expected; nonetheless, they will lead to a hotter indoor environment during the sleeping time.

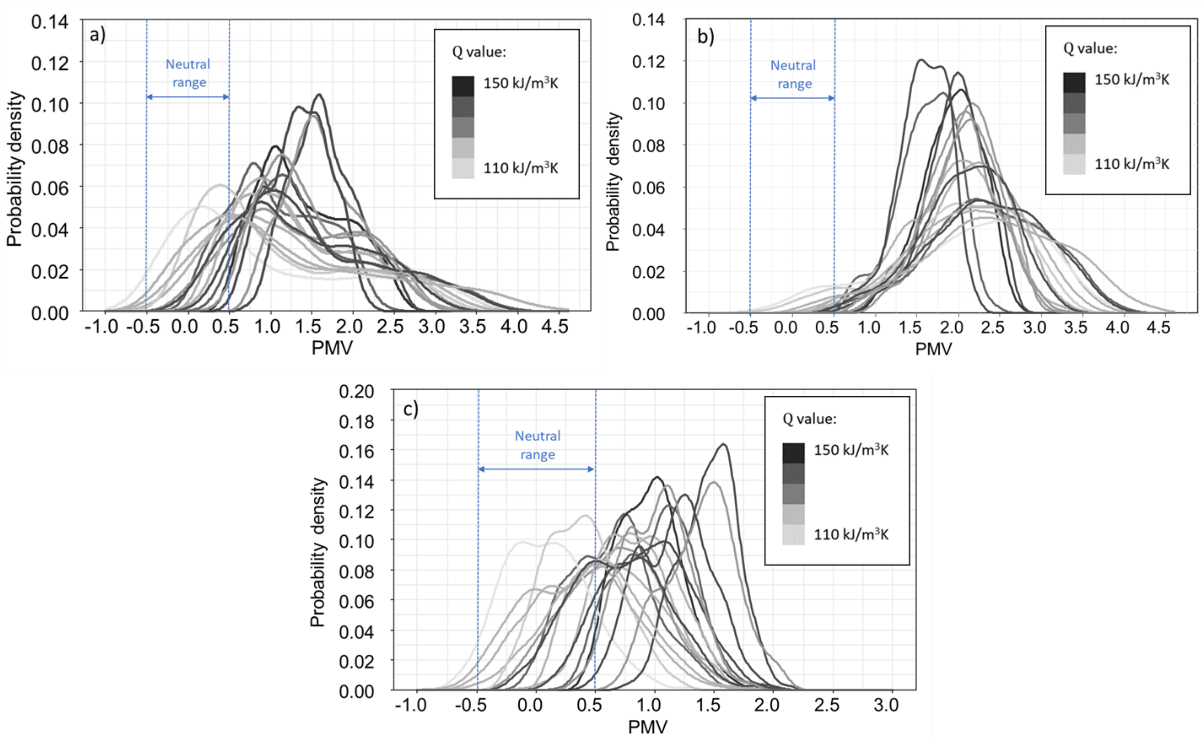


Fig. 10. Probability density distributions of PMV based daily occupant behaviour model during the period of measurement: (a) all period, (b) activity period and (c) sleeping period

The PDDs and CPDs of the PMVs in all of the dwellings are shown in Figs. 10 and 11. The data were classified into three time periods: the entire observed period, activity period, and sleeping period. The latter two periods were determined based on the questionnaire results from each dwelling, as shown in Fig. 8. As can be seen from the graphs, the PDDs of all dwellings show diverse patterns, ranging between -1 and +4.6 during the entire measurement period (see Fig. 10a). The CPDs of all dwellings shown in Fig. 11a illustrate that 20% of monitoring period had a PMV value higher than 1.8. Despite the differences in building construction materials, all dwellings showed PMV values between 1.5 to 2.5 during most of their activity period, and 50% of the observed period showed PMV values of more than 1.7, as shown in Figs. 10b and 11b, respectively. During the sleeping period, the time fraction of the thermally neutral range of the PMV (lower than 0.5) varies among the dwellings, from 7% to 55%. This variety is generally consistent with the Q values, namely, dwellings with low Q values tend to have longer time period for the neutral range. Oppositely, in the activity period, dwellings with low Q values were found to have longer time periods for warm and hot conditions.

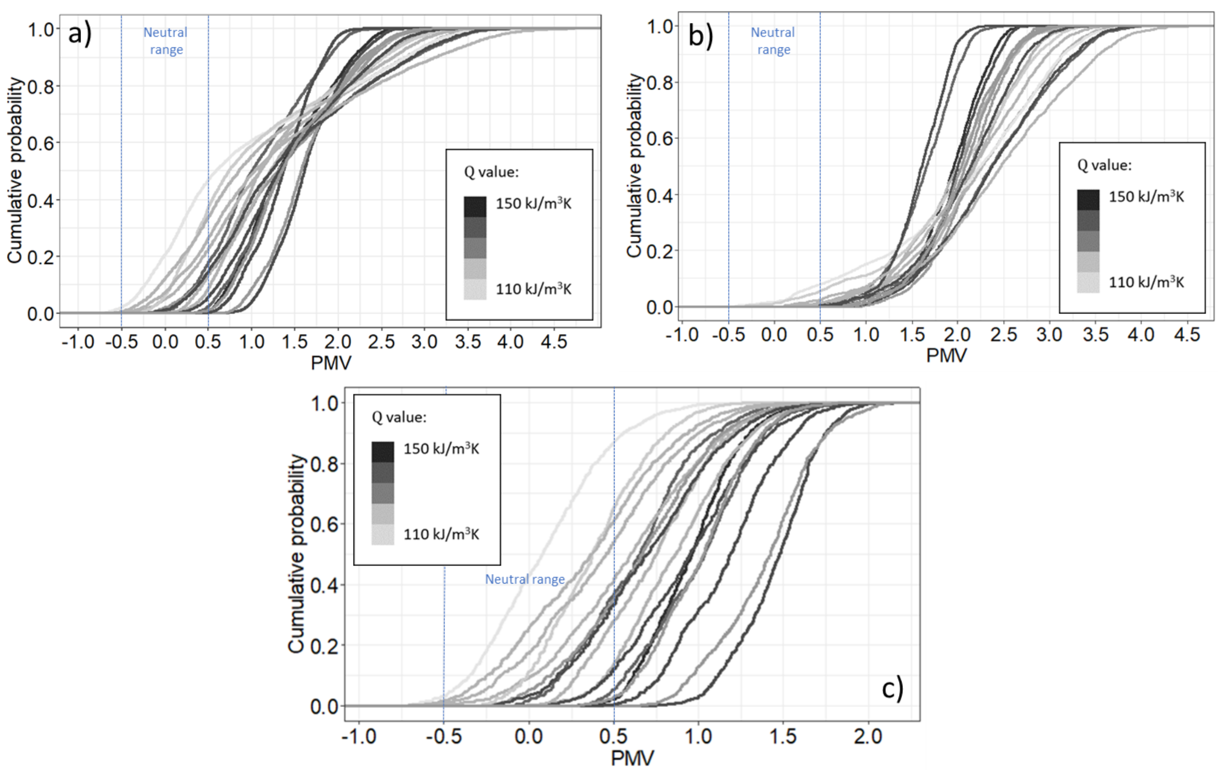


Fig. 11. Cumulative probability of PMV based daily occupant behaviour model during the period of measurement: (a) all period, (b) activity period and (c) sleeping period

To identify affordable cooling measures in this district, it would be interesting to estimate the potential influence of the wind speed, which can be increased by natural ventilation or by less expensive electric fans. Accordingly, the authors estimated the PMVs of all dwellings under two conditions of wind speed, 0.1 m/s and 0.8 m/s. The air speed of 0.1 m/s represented the calm air conditions, whereas 0.8 m/s represented a condition of simultaneously using fans and opening windows. Fig. 12 shows the relations of the percentiles of the PMV between these two assumptions. The plots are almost in a linear line regardless of the percentile, and the reduction of the PMV owing to increased wind speed is more significant for low-PMV conditions. According to the estimation of the PMV shown in Figs. 10 and 11, the activity period is the time that requires mitigation to achieve thermal comfort, as compared to the sleeping period. However, Fig. 12 implies that the thermal mitigation effect of increasing the air speed during the activity period is generally weak, which is consistent with ASHRAE 55 2010 section 5.2.3.1 [21] and ISO 7730:2005 Annex G [26]. In contrast, increasing the air speed is more effective at lower air temperatures, such as during the sleeping period of the surveyed dwellings. This fact is in line with the observed occupants' behaviour, i.e. people tended to turn on an electrical fan during sleeping time (rather than during activity time, with higher indoor air temperature). Meanwhile, during the activity period, people might be more tolerant to a relatively hot indoor thermal environment, and accept the given conditions owing to the less-effective impact of using a wind fan and electricity to achieve thermal comfort. Thus, they might prefer to wear light clothing as a feasible alternative to mitigating the hot sensation.

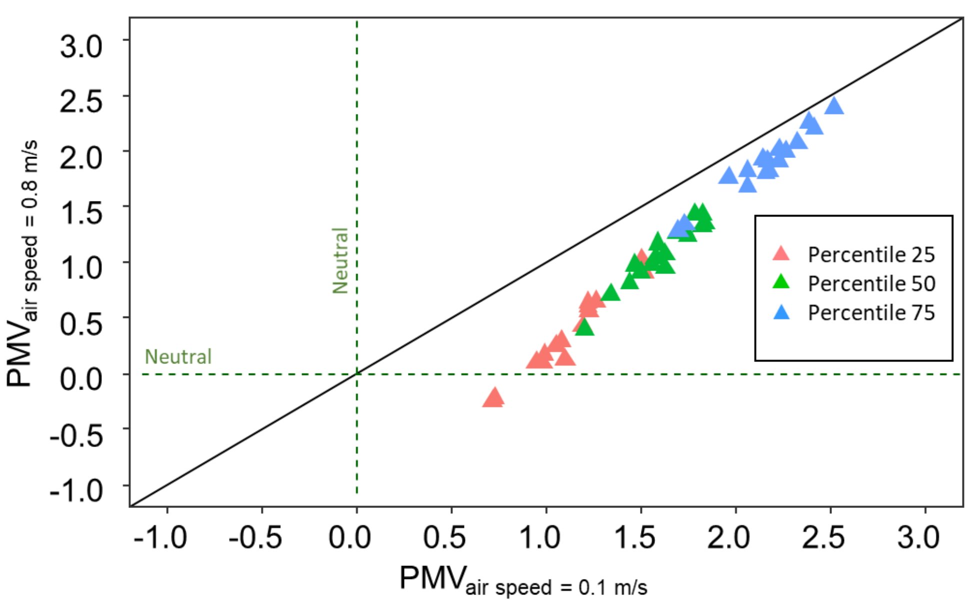


Fig. 12. Relation of percentiles of PMV as estimated with the assumption of calm air conditions of 0.1 m/s, and those with the assumption of air speed at 0.8 m/s [21]

4. Results of subjective thermal responses

4.1. Relation between thermal sensation vote (TSV) and indoor air temperature

Fig. 13 illustrates the TSVs and TPVs as collected by the questionnaire survey against the indoor air temperatures. Data from previous studies of naturally ventilated dwellings in tropical climate regions, i.e. Yogyakarta City, Indonesia [27], Jaipur City, India [22], and Kinabalu City, Malaysia [28], are also included. Although the sample size of the present survey is not large, a linear regression for TSV and TPV finds the below equations.

$$TSV = 0.3536T_a - 9.1574\ (N = 102, R^2 = 0.19, p < 0.05) \tag{4}$$

$$TPV = -0.171T_a + 4.1569\ (N = 102, R^2 = 0.12, p < 0.05) \tag{5}$$

Here, T_a is the indoor air temperature; R^2 is the coefficient of determination; N represents number of votes; and p indicates the significance level of the regression coefficient.

The regression line of the current data shows a slight overestimation of neutral conditions as compared to the past three studies conducted in Jaipur City, India [22], Yogyakarta City, Indonesia [27], and Kinabalu City, Malaysia [28]. By assuming TSV = 0 in Eq. (4), we estimated the indoor air temperature using a thermally neutral sensation temperature of 25.9 ºC. This value is lower than the estimated values for other past studies, by 2 to 3 ºC.

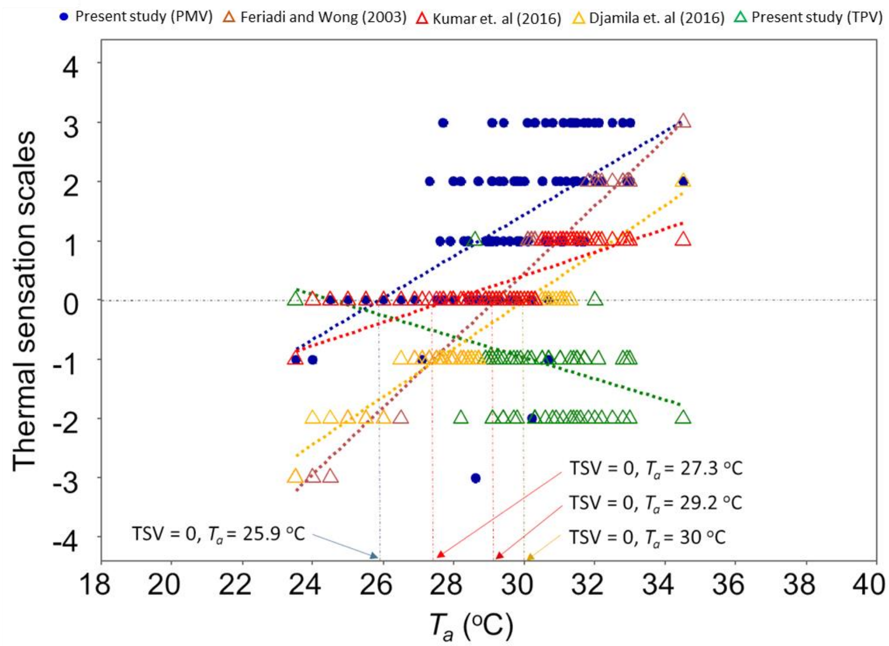


Fig. 13. Scatter plot of thermal sensation votes (TSVs) and thermal preference votes (TPVs) versus indoor air temperature of the current study compared to previous studies with similar climatic condition conducted by Feriadi and Wong (2003) in Indonesia[27], Kumar et. al (2016) in India[22] and Djamila et. al (2016) in Malaysia[28]

Fig. 14 shows a histogram of the comfort temperature T_c as derived from the Griffith method expressed by Eq. (6), with the assumption of a Griffith constant G of 0.50 $^{\circ}C^{-1}$ [22, 27, 31].

$$T_c = T_a - (0 - TSV)/G \tag{6}$$

The histogram illustrates that the highest proportion of subjective comfortable temperatures from all respondents ranged between 28 °C and 30 °C, whereas the mean and median comfortable temperatures were 28.3 °C and 28.6 °C, respectively. This Griffith method finding is in closer agreement with the comfortable temperatures from the previous studies.

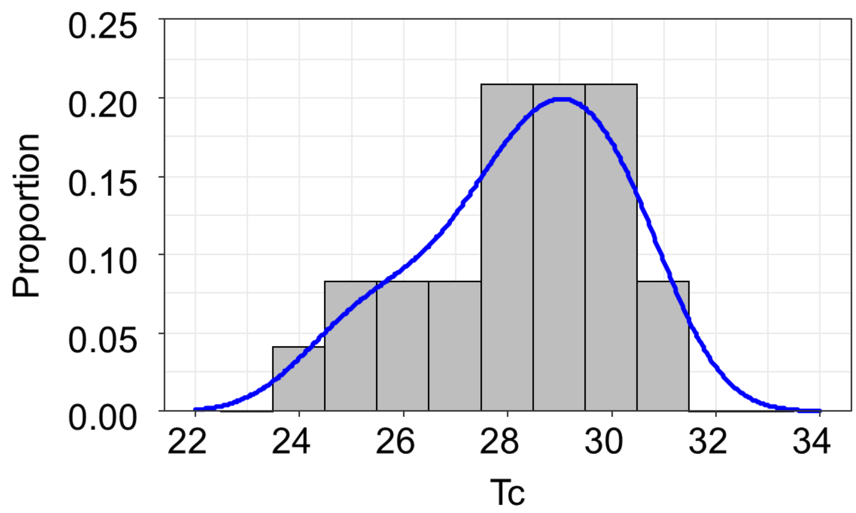


Fig. 14. Histogram of comfort temperature (T_c) from all respondents based on Griffith method

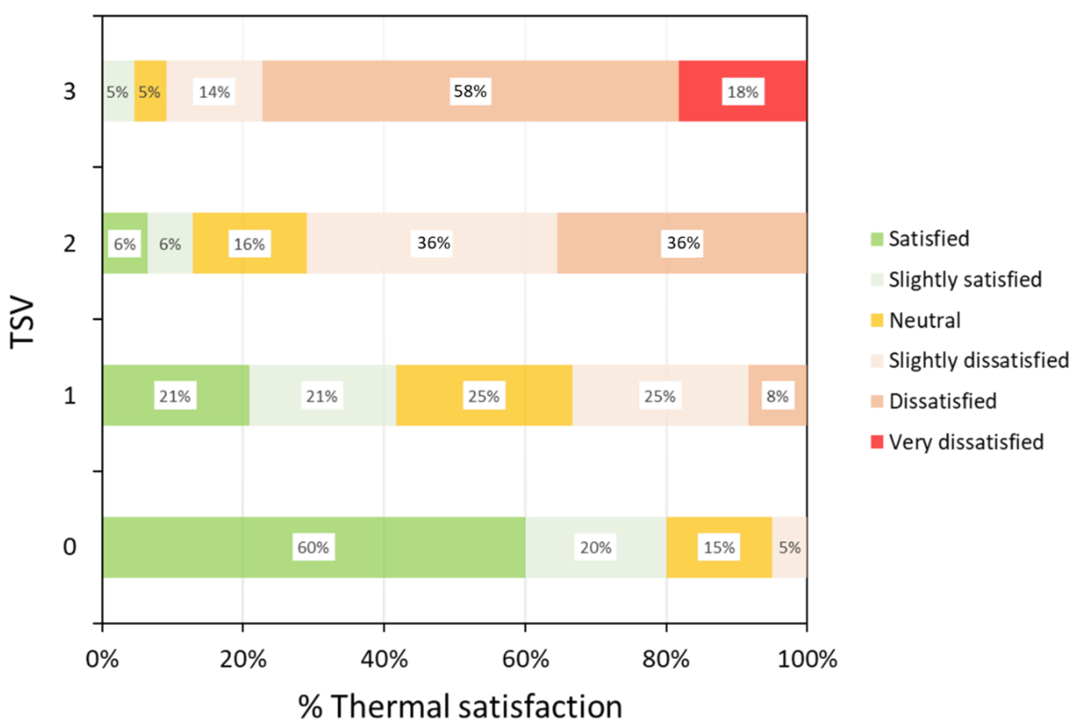


Fig. 15. Thermal satisfaction percentage for each TSV

4.2. Thermal satisfaction and thermal sensation

In addition to the TSV and TPV, the authors asked respondents regarding their satisfaction with the indoor thermal conditions. Fig. 15 illustrates the percentages of the thermal satisfaction levels of respondents, as classified by their TSVs. The ratio of positive answers including ‘Neutral’, ‘Slightly satisfied’, and ‘Satisfied’ were 95% (TSV = 0 or ‘Neutral’), 67% (TSV = 1 or ‘Slightly warm’), 28% (TSV = 2 or ‘Warm’), and 10% (TSV = 3 ‘Hot’). In contrast, the total observed percentages of negative answers, including the options of ‘Slightly dissatisfied’, ‘Dissatisfied’, and ‘Very dissatisfied’ were 5 % (TSV = 0), 33% (TSV = 1), 72% (TSV = 2), and 90% (TSV = 3). Notably, the predicted percentage of dissatisfied (PPD) values, as determined by PMV values at PMV = 1, 2, and 3, are 26%, 77%, and 99%, respectively. As pointed out by Cheung et al (2019), the PPD model is less accurate in tropical climate areas with larger discrepancies in warm sensations in naturally ventilated buildings [31], and the current analysis is consistent with the previous study.

5. Conclusion

This paper reported the results of a field measurement and questionnaire survey regarding the indoor thermal conditions of 17 low-cost dwellings located in a typical unplanned urban residential district in Surakarta City, Indonesia. The surveyed dwellings were selected to grasp the indoor thermal features of various conditions, including the building materials, area, occupants’ behaviours, and household economic level.

The observed time series variations and PDDs of the indoor air temperature showed significant diversity among the 17 surveyed dwellings. Based on the observed indoor air temperatures, the decrement factor *f*, which refers to the ratio of the averaged daily amplitude of the indoor temperature to that of the outdoor temperature, was derived for each dwelling. It showed a strong linear correlation with the parameter Q, i.e. the heat capacity of a building envelope per unit interior volume, regardless of the occupants’ behavioural conditions. In addition, a statistical test using Spearman’s rank correlation indicated that both Q and the floor area per interior volume have significant correlations with the percentiles of indoor air temperatures. This implies that the parameter Q and interior geometry of a dwelling can be utilized to detect vulnerable dwellings having a heat risk in Kampung districts.

The PDDs and CPDs of the estimated thermal comfort index PMVs suggested that most of the activity times in all of the surveyed dwellings were classified as out of thermally neutral conditions, i.e. they were slightly warm, warm, or hot. In contrast, the time fraction for the thermally neutral range of PMVs lower than 0.5 varied for the sleeping period among the dwellings, from 7% to 55%. This variation among dwellings is mainly attributed to the parameter Q, as dwellings with low Q values tend to have a longer time period in the neutral range. This fact suggests that rugged buildings made by heavy materials, which are usually considered as secure and favourable buildings in regions with cold winter, cannot necessarily provide a better indoor thermal environment in tropical regions if mechanical air-conditioning devices are not installed. A comparison of the estimated PMV values under two different assumption of air speed indicated that any thermal mitigation owing to increased wind speed is not very evident during the daytime, with higher indoor temperatures than the sleeping period. This result might be a reason why people in the tropics living in naturally ventilated buildings tend to use an electric wind fan more frequently during nighttime rather than daytime.

Acknowledgement

This project was partially funded by Robert T. Huang Entrepreneurship Center of Kyushu University and Obayashi Foundation. The authors are grateful for a support and assistance from all member of Urban-Rural Design and Conservation Laboratory, Department of Architecture, Sebelas Maret University, Indonesia. Thanks to Dr. Yosafat Winarto and Ms. Anita Dianingrum who strived to provide a conducive research activity especially to the students who accompanied the authors conducting field measurement.

References

[1] UN, The World’s Cities in 2018, 2018.

[2] Y. Takane, Urban warming and future air-conditioning use in an Asian megacity : importance of positive feedback, Npj Clim. Atmos. Sci. 39 (2019) 1–11. https://doi.org/10.1038/s41612-019-0096-2.

[3] D. Lauwaet, H. Hooyberghs, B. Maiheu, W. Lefebvre, G. Driesen, S. Van Looy, K. De Ridder, Detailed urban heat island projections for cities worldwide: Dynamical downscaling CMIP5 global climate models, Climate 3 (2015) 391–415. https://doi.org/10.3390/cli3020391.

[4] E. Birch, S. Wachter, Sustainable Urbanization: Place Matters, Philadelphia, 2014.

[5] BPS, 2019 Statistical Yearbook of Indonesia, 2019.

[6] World Bank, Indonesia’s Urban Story, 2016.

[7] H. Marhaeni, Indonesia poverty profile in 2019, 2019.

[8] N.E. Klepeis, W.C. Nelson, W.R. Ott, J.P. Robinson, A.M. Tsang, P. Switzer, J. V. Behar, S.C. Hern, W.H. Engelmann, The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants, J. Expo. Anal. Environ. Epidemiol. 11 (2001) 231–252.

https://doi.org/10.1038/sj.jea.7500165.

[9] N. Nazarian, N. Dumas, J. Kleissl, L. Norford, Effectiveness of cool walls on cooling load and urban temperature in a tropical climate, Energy Build. 187 (2019) 144–162. https://doi.org/10.1016/j.enbuild.2019.01.022.

[10] I. Tsoulou, C.J. Andrews, R. He, G. Mainelis, J. Senick, Summertime thermal conditions and senior resident behaviors in public housing: A case study in Elizabeth, NJ, USA, Build. Environ. 168 (2020) 106411. https://doi.org/10.1016/j.buildenv.2019.106411.

[11] A. Sakka, M. Santamouris, I. Livada, F. Nicol, M. Wilson, On the thermal performance of low income housing during heat waves, Energy Build. (2012). https://doi.org/10.1016/j.enbuild.2012.01.023.

[12] E. Nix, C. Shrubsole, P. Das, M. Davies, Indoor environmental quality of low-income housing in Delhi, India: Findings from a field study, in: Energy Procedia, 2015. https://doi.org/10.1016/j.egypro.2015.11.714.

[13] I.A.W. Hutama, Exploring the Sense of Place of an Urban, University of Twente, 2016.

[14] R. Fillaili, Addressing Urban Poverty: Increasing Learning on Urban Poverty Reduction in Kota Surakarta and Kota Makassar , Indonesia Increasing Learning on Urban Poverty Reduction, Jakarta, 2011. https://www.smeru.or.id/sites/default/files/publication/urbanpoverty_eng.pdf.

[15] Dinas Kependudukan, Civil Development Report of Surakarta 2016, 2016.

[16] T.H. Karyono, Predicting comfort temperature in Indonesia, an initial step to reduce cooling energy consumption, Buildings 5 (2015) 802–813. https://doi.org/10.3390/buildings5030802.

[17] Isharyanto, Responding to climate change: Surakarta city tourism on legal and policy perspectives, IOP Conf. Ser. Earth Environ. Sci. 200 (2018) 1–4. https://doi.org/10.1088/1755-1315/200/1/012047.

[18] BPS, Surakarta in figure 2012–2018, 2019.

[19] B. Givoni, Climate Consideration in Buildings and Urban Design, John Wiley & Sons, New York, 1998.

[20] L. Bellahcene, A. Cheknane, S. Bekkouche, D. Sahel, The effect of the thermal inertia on the thermal transfer in building wall, E3S Web Conf. 22 (2017) 00013. https://doi.org/10.1051/e3sconf/20172200013.

[21] S.C. Turner, G. Paliaga, B.M. Lynch, E.A. Arens, R.M. Aynsley, G.S. Brager, J.J. Deringer, J.M. Ferguson, J.M. Filler, J.J. Hogeling, D. Int-hout, A.G. Kwok, H.F. Levy, E.M. Sterling, J.L. Stoops, S.T. Taylor, R.W. Tinsley, K.W. Cooper, K.W. Dean, F. Myers, J.C. Peterson, ASHRAE Standard 55-2010 Thermal environmental conditions for human occupancy, 2010 (2010) 30.

[22] S. Kumar, M.K. Singh, V. Loftness, J. Mathur, S. Mathur, Thermal comfort assessment and characteristics of occupant's behaviour in naturally ventilated buildings in composite climate of India, Energy Sustain. Dev. 33 (2016) 108–121. https://doi.org/10.1016/j.esd.2016.06.002.

[23] S.I.U.H. Gilani, M.H. Khan, W. Pao, Thermal Comfort Analysis of PMV Model Prediction in Air Conditioned and Naturally Ventilated Buildings, Energy Procedia. 75 (2015) 1373–1379. https://doi.org/10.1016/j.egypro.2015.07.218.

[24] R.J. De Dear, G.S. Brager, Thermal comfort in naturally ventilated buildings: Revisions to ASHRAE Standard 55, Energy Build. 34 (2002) 549–561. https://doi.org/10.1016/S0378-7788(02)00005-1.

[25] A. Omidvar, J. Kim, Modification of sweat evaporative heat loss in the PMV/PPD model to improve thermal comfort prediction in warm climates, Build. Environ. 176 (2020) 106868. https://doi.org/10.1016/j.buildenv.2020.106868.

[26] ISO E 7730, Ergonomics of the Thermal Environment. Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria,

International Standardisation Organisation, 2005.

[27] H. Feriadi, N.H. Wong, Thermal comfort for naturally ventilated houses in Indonesia, Energy Build. 36 (2004) 614–626. https://doi.org/10.1016/j.enbuild.2004.01.011.

[28] H. Djamila, C.M. Chu, S. Kumaresan, Field study of thermal comfort in residential buildings in the equatorial hot-humid climate of Malaysia, Build. Environ. 62 (2013) 133–142. https://doi.org/10.1016/j.buildenv.2013.01.017.

[29] F. Nurhanis Hassan Sadzli, S. Ahmad Zaki, H. Bahadur Rijal, A. Hagishima, F. Yakub, Field Survey of Thermal Comfort and Sleep Quality in the Bedrooms with Different Cooling Strategies in Malaysia, KnE Soc. Sci. 2019 (2019) 270–283. https://doi.org/10.18502/kss.v3i21.4974.

[30] M. Khoshbakht, Z. Gou, F. Zhang, A pilot study of thermal comfort in subtropical mixed-mode higher education office buildings with different change-over control strategies, Energy Build. 196 (2019) 194–205. https://doi.org/10.1016/j.enbuild.2019.05.030.

[31] T. Cheung, S. Schiavon, T. Parkinson, P. Li, G. Brager, Analysis of the accuracy on PMV – PPD model using the ASHRAE Global Thermal Comfort Database II, Build. Environ. 153 (2019) 205–217. https://doi.org/10.1016/j.buildenv.2019.01.055.

Appendix

Thermal Sensations and Occupant Behaviors Questionnaire

Date and time: ___/____/_____ at:

1. How are you feeling for the air temperature now? *(check only one)*
   ◯hot ◯ warm ◯ slightly warm ◯Neutral ◯slightly cool ◯ cool ◯ cold
2. How satisfied are you with the temperature now in your home? *(check only one)*
   ◯very satisfied ◯ satisfied ◯ slightly satisfied ◯Neutral ◯Slightly dissatisfied ◯ dissatisfied ◯ very dissatisfied
3. What would you prefer for the air temperature? *(check only one)*
   ◯much warmer ◯Bit warmer ◯No change ◯bit cooler ◯much cooler
4. What is your activity level right now? *(check the one that is most appropriate)*
   ◯reclining ◯seated ◯standing relaxed ◯light activity standing ◯medium activity
5. Using the list below, please check each item of clothing that you are wearing right now (*check all that apply*)

Checklists	**Items**	**Material**	**Clo**	**Additional notes**
		Underwear		
	Bra	Foam/tricot	0.01	
	Panties	Knit cotton	0.03	
	Men’s brief	Silk cotton	0.04	
	Full slip	Nylon-polyester	0.16	
	Men’s tank top/sleeveless	Cotton	0.12	
		Shirts and Dress		
	Short sleeve knit sport shirt	Cotton	0.17	
	Short-sleeve dress shirt	Silk cotton	0.19	
	T-shirt	Cotton	0.08	
	Long-sleeve dress shirt	Silk cotton	0.25	
	Long-sleeve sweatshirt	Cotton	0.34	
	Sleeveless, scoop neck thin	Cotton	0.23	
	Short-sleeve shirtdress thin	Cotton-foam	0.29	
	Long-sleeve shirtdress (thick)/Gamis	Cotton	0.47	
	Light hijab	cotton	0.06	
	Medium Hijab	Knittwd nylon-lycra cotton	0.08	
	Heavy/long hijab	Synthetic nylon	0.25	
		Skirts and trousers		
	Skirt thin	Cotton-polyester	0.14	
	Long Skirt thick	Jeans Denim	0.23	

	Walking short	Jeans Denim	0.11	
	Walking short	Polyester	0.08	
	Sweat pant	Cotton	0.28	
	Straight trousers thin	Silk-cotton	0.15	
	Straight trousers thick	Jeans Denim	0.24	
		Footwear		
	Socks	Knit	0.03	
	Slipper/sandals	Rubber	0.02	
	Shoes	Synthetic	0.02	

6. What do you usually do in the daytime? *(check all that apply)*
   ◯ washing the clothes ◯ cooking ◯family gathering ◯watching TV ◯home base production ◯Using Internet ◯other_________
7. When do you usually start your activities in the morning? ___ am
8. When do you usually stay at home? From _____ to ______
9. When do you usually sleep in the night? ___pm
10. When do you open or turn on following appliances in the house in daily? *(check all that apply)*
    - **Window**:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

- **Fan**:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Table A1. Selected dwellings characteristics

House	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**
Orientation	S	S	S	S	E	W	S	W	S	S	W	N	W	S	S	N	W
Wall area (m^2)	80.4	110.4	78.6	119.7	63.3	119.8	121.7	76.8	147.6	93.9	87	87	129.3	91.8	60.6	86.1	65.4
Wall material	Ip-B-Op	Ip-B-Op	Ip-B-Pb	Ip-B-Op	B	Ip-B-Op	B-Pb	Ip-B-Op	Pb	Ip-B-Op	B-Pb	Ip-B-Op	Ip-B-Op	Ip-B-Op	Ip-B-Op	Ip-B-Op	Ip-B-P
Roof area (m^2)	50.9	77.2	38.2	82.8	31.5	91.5	79.1	48.5	128.8	64.3	53.7	62.2	119.5	61.1	31.1	65	32.8
Roof Material	40%Ct-60%Ga	Ct	Ct	Ga	Ct	Ct	Ct	Ga	50%Ct-50%As	As	Ct	As	Ct	Ct	Ct	Ct	Ct
Floor area (m^2)	41.7	63.3	31.3	67.9	25.8	75	64.9	39.8	105.6	52.7	44	51	98	50.1	25.5	53.3	26.9
Floor material	P	P	P-Cp	P	P	P	Cp	P	P	P	Cp	P	P	P	P	P	P
Window area (m^2)	3	4.4	1.2	1.1	2.1	2.4	1.7	2.6	2.8	1.5	1.6	2.2	1.8	2.6	0.8	2.3	1.8
Window material	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG
Occupants	8	3	4	2	4	8	6	8	9	4	4	5	7	5	4	2	4
Ceiling	Yes	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	No	No	No	No
Sensor location	Living room	Living room	Bedroom	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room
Q (kJ/m^3K)	136.4	144.5	117.6	126.7	118.6	120.1	112.2	136.7	115	141	123.3	138.4	119.8	127.9	119.8	129.4	125

*S = South; E = East; W = West; N = North; Ip = Inner cement plaster; B = Brick; Op = Outer cement plaster; Pb = Plywood board; P = Porcelain tile; Ct = Clay tile; Ga = Galvalume; As = Asbestos; Cp = Cement plaster; SG = Single glassed

On-site measurement and evaluations of indoor thermal environment in low-cost dwellings of urban Kampung district

Solli Murtyas[a*], Aya Hagishima[a], Kusumaningdyah N.H[b]

[a] Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Japan

[b] Architecture Department, Faculty of Engineering, Universitas Sebelas Maret, Indonesia

Corresponding author

Address: Department of Energy and Environmental Engineering, Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Building F, 6-1 Kasuga Koen, Kasuga, Fukuoka 816-8580, Japan

E-mail address: s.murtyas@kyudai.jp (S.Murtyas)

Abstract

This paper reported results of a field measurement and questionnaire survey regarding the indoor thermal conditions of 17 low-cost dwellings located in a typical unplanned urban residential district ‘Kampung’ in Surakarta City, Indonesia. The surveyed dwellings were selected to grasp the indoor thermal features of various conditions, including the building materials, area, occupants’ behaviours, and household economic level. The observed time series variations of the indoor air temperature showed significant diversity among the 17 dwellings. The decrement factor *f*, which refers to the ratio of the averaged daily amplitude of the indoor temperature to that of the outdoor temperature, showed a strong linear correlation with the parameter Q, i.e. the heat capacity of a building envelope per unit interior volume, regardless of the occupants’ behavioural conditions. In addition, a statistical test using Spearman’s rank correlation indicated that both Q and the floor area per interior volume have significant correlations with the percentiles of indoor air temperatures. Furthermore, estimated thermal comfort index PMVs suggested that most of the activity times in all of the surveyed dwellings were classified as out of thermally neutral conditions, i.e. they were slightly warm, warm, or hot. In contrast, the time fraction for the thermally neutral range of PMVs lower than 0.5 varied for the sleeping period among the dwellings, from 7% to 55%, owing to the parameter Q, as dwellings with low Q values tend to have a longer time period in the neutral

range. These findings imply that the parameter Q and interior geometry of a dwelling can be utilized to establish countermeasures for vulnerable dwellings having a heat risk in Kampung districts.

Keywords: low-cost dwellings, indoor thermal environments, PMV, thermal sensation votes, comfort temperature

1. Introduction

The urban population accounted for 55.3% of the world's population in 2018, and it is projected to exceed more than 60% by 2030 [1]. This implies that the quality of urban environment will significantly affect a large population in regards to various aspects such as health, energy demands, and the economy [2]. Considering the potential future impact of climate change, such as rising global temperatures and more frequent extreme weather events such as heat waves [3], as well as temperature increases specific to urban areas (i.e. the 'urban heat island' phenomenon), there will be a strong need for affordable adaptation strategies to mitigate the heat risks in cities located in hot climate zones.

Indonesia is a developing Asian country that has shown rapid urbanization in recent decades [4]; the percentage of the population considered 'urban' was reported in 2019 as 56% [5]. This percentage is expected to increase to 68% by 2025 [6]. In line with this urbanization, there has been an expansion of densely populated and unplanned settlements. The local government reported in 2019 that 9.86 million people are living in low-quality housing, with limited infrastructure and public services [7].

The national human activity pattern survey which involved 9386 respondents in the United States of America reported that 87% of respondents spent their time indoors. This high percentage indicates that the indoor living environment plays a significant role in health, well-being, and work performance [8]. Accordingly, the thermal properties of the building envelopes and building facilities controlling the indoor thermal conditions are key factors in decreasing future heat risks from climate change and urban heat island phenomena [9]. However, providing people with suitable shelters from a hot climate is extremely difficult in developing countries, where many low-income people live in informal urban settlements with poor building quality owing to limited economic capabilities [10].

With this background, understanding the reality of the indoor thermal environment in low-income urban dwellings has become essential, to thereby establish evidence-based strategies for achieving affordable living spaces and reaching sustainable cities and communities. In fact, several studies have been conducted to observe low-income housing worldwide. Sakka et al. (2012) investigated the indoor thermal conditions of 50 non-air-conditioned houses in Athens, Greece over an extremely hot summer in 2007. They found that the indoor temperature reached 30 ºC for more than 85% of the measurement time period[11]. Nix et al. (2015) observed indoor environments in low-income housing in Delhi, India during the winter season. The hourly indoor temperatures of 13 dwellings were monitored for three weeks in December 2013. They found that the indoor thermal conditions of all observed dwellings were below 21 ºC for more than 60% of the hours during the monitoring period. In addition, they reported discomfort and risks to health from exposure to the cold temperatures, based on interviews with the residents [12]. Hashemi (2017) conducted a building energy simulation by using EnergyPlus targeting low-income tropical dwellings in Uganda. He adopted 96 scenarios for his case study to evaluate indoor thermal comfort under various conditions of insulation and construction methods. As result, he reported that the roof insulation is the most effective to improve thermal comfort and reduce the heat risk [13]. Nutkiewicz et al. (2018) investigated the effect of redevelopment of urban informal settlements in Mumbai, India on the thermal comfort based on a series of numerical simulation. In their work, various parameters related to building design as well as building morphology were systematically varied among numerous case study simulation. They reported that the window-to-wall ratio was the most sensitive design parameter for thermal comfort [14]. Despite such attempts, research regarding the indoor thermal conditions and building thermal features of low-cost dwellings in developing countries (including Indonesia) remains limited, probably owing to difficulties in access to the local communities of such areas, which are sometimes recognised as urban slums.

Under these circumstances, this study intends to provide a quantitative grasp of the indoor thermal conditions of an urban unplanned residential district called Kampung in Surakarta City, Indonesia, based on a field measurement of 17 low-cost dwellings and a questionnaire survey of the residents. The terminology 'Kampung' for representing an urban district is derived from Indonesian term for 'village'. Kampung in Indonesia is tightly related to informal urban settlements with poor physical and economical qualities [15]. The objectives of this study are as follows:

- to grasp the diversity in indoor thermal environments among dwellings located in the same district having different conditions of building envelopes and occupant thermal behaviours in households;
- to examine the factors indicating the vulnerability of a dwelling in terms of the thermal comfort and heat risks of residents; and
- to investigate the occupant perceptions, preferences, and acceptance in regards to indoor thermal conditions.

2. Outline of field survey

2.1. Site description

Fig. 1 shows the target site: Kampung Sangkrah, Surakarta City, Central Java Province, Indonesia (latitude 7° 34` South and longitude 110° 50` East). It lies along the riverbank of Bengawan, on the eastern edge of Surakarta City. This district has an area of 0.482 km^2 and contains large informal settlements, with a total population of 10,885 in 2016. Of the 2473 existing dwellings, 30% are classified as poor settlements[16]. The livelihood typology consists of informal workers, civil servants, hawkers, scavenger, and casual labourers [17]. An aerial photograph of the target site is shown in fig. 2.

This area is categorised as a tropical climate with dry and wet seasons [18]. The dry season period is five months (May-September), and wet season occurs within the seven months from October to April [19]. The annual mean temperature, relative humidity, and annual total precipitation, as recorded from 2015 to 2018, were 26.9 °C, 78.7%, and 804.3 mm, respectively [20]. The standard deviation of the monthly temperature from 2015 to 2018 was 0.9 °C, and the difference between the wet and dry seasons is generally small [20].

Fig. 1. A map of Indonesia (taken from Google maps) with target site Kampung Sangkrah in Surakarta City

2.2.Measurement of indoor thermal environment

Fig. 2 shows an aerial photograph of the target site, including the locations of the 17 dwellings selected for the measurement of indoor thermal conditions. These 17 dwellings were selected to collect representative but diverse samples of residential buildings of Kampung in terms of the building construction and materials, floor areas, and number of occupants (ranging from two to nine). All of the selected dwellings were 1-storey houses, and consisted of at least a living room and bedroom. Table 1 shows the wall materials of the 17 dwellings, as classified into six groups. Additional detailed information of the buildings is summarized in **Appendix Table A1**.

In the target 17 dwellings, the air temperature and relative humidity values in living rooms or bedrooms were measured at a height of 1.5 m. A thermo-hygrometer was installed in each room at a position not exposed to direct solar radiation (see Fig. 3). This measurement of indoor thermal conditions was continuously carried out from 26 March to 5 May 2019, at intervals of 10 min. In addition, the outdoor air temperature, relative humidity, wind speed, global solar radiation, and precipitation were measured as climate variables, at a height of 8 m above the playground of a public school in this district, as shown in Fig. 2. The details of the measurement items and instruments are shown in Table 2.

Fig. 2. The location of Kampung Sangkrah, selected dwellings, and weather station site

Fig. 3. Details of the indoor thermal measurement in house A, F, and K

Fig. 4. Residents filling the questioner survey in house D, M, and P

2.3. Questionnaire surveys

In addition to the measurement of the indoor thermal conditions, a questionnaire survey of the residents living in the target dwellings was conducted at their houses between 10 June and 8 August 2019, at times ranging from 9:00 am to 6:00 pm. The total number of respondents was 102 (47 males and 55 females), with ages ranging from 11 to 65 years old (see fig. 4). The questionnaire consisted of ten questions related to demographic conditions, perceptions of the indoor thermal comfort in the current state, satisfaction regarding their indoor thermal environments, and daily behaviours for thermal adaptation in their houses. The questions related to the subjective thermal satisfaction, thermal preference votes (TPV), and thermal sensation votes (TSV) were designed based on ASHRAE 55 and ISO 7730. Two human factors in thermal comfort, namely clothing and metabolic rate (as estimated by physical state), were also surveyed. Meanwhile, the air temperature and relative humidity of the rooms where respondents stayed were obtained by the aforementioned thermometers. A detailed description of the questionnaire is provided in **Appendix A**.

Table 1. Wall materials of monitored dwellings

Type	Materials consisting walls ordered from inner to outer position	Dwelling labels
Type 1	Brick + Plywood board	G, K
Type 2	Plywood board	I
Type 3	Cement plaster + Brick +Plywood board	C
Type 4	Brick	E
Type 5	Cement plaster + Brick + Porcelain tile	Q
Type 6	Cement plaster + Brick + Cement plaster	A, B, D, F, H, J, L, M, N, O, P

Table 2. Measurement items and instruments

Measured variables	Instrument specifications	Recording interval	Location

Indoor air temperature (°C) and relative humidity (%)	TR-72nw T&D Corporation, accuracy ± 0.5 °C, ± 2.5% RH	10 min	17 houses
Outdoor air temperature (°C) and relative humidity (%)	S-THB-M002 Onset Computer Corporation, accuracy ± 0.21 °C, ± 2.5% RH	1 min	Open space of public-school building at 8 m height
Wind speed (m/s)	S-WCG-M003 Onset Computer Corporation, ultrasonic anemometer, accuracy ± 0.8 m/s	1 min	
Solar radiation (W/m^2)	S-LIB-M003 Onset Computer Corporation, accuracy ± 10 W/m^2	1 min	
Precipitation (mm)	S-RGF-M002 Onset Computer Corporation, rain gauge, accuracy ± 4% between 0.2 to 50 mm per hour, ± 5% between 50 to 100 mm per hour	1 min	

3. Results of field survey on indoor thermal environment

3.1.Weather conditions

The time variations in the hourly means of the outdoor air temperature, relative humidity, solar radiation, wind speed, and daily total precipitation are shown in Fig. 5. The outdoor air temperature fluctuated from 23 °C to 36 °C. The relative humidity was high, ranging from 42% to 99%. Such hot and humid weather is typical in the measurement period from the end of the wet season to the beginning of the dry season. The wind speed showed a distinct diurnal time scale and was weak, except for a period in April 28 and 29 with daily peaks of 4 m/s. From May, the beginning of the dry season, the wind speed showed an increasing trend. The average daily total precipitation was 8.4 mm; in contrast, 15 out of the 41 measurement days had no rain event. In addition, the daily total global solar radiation ranged from 10 MJ/m^2 to 20.7 MJ/m^2, with an average of 15.1 MJ/m^2day.

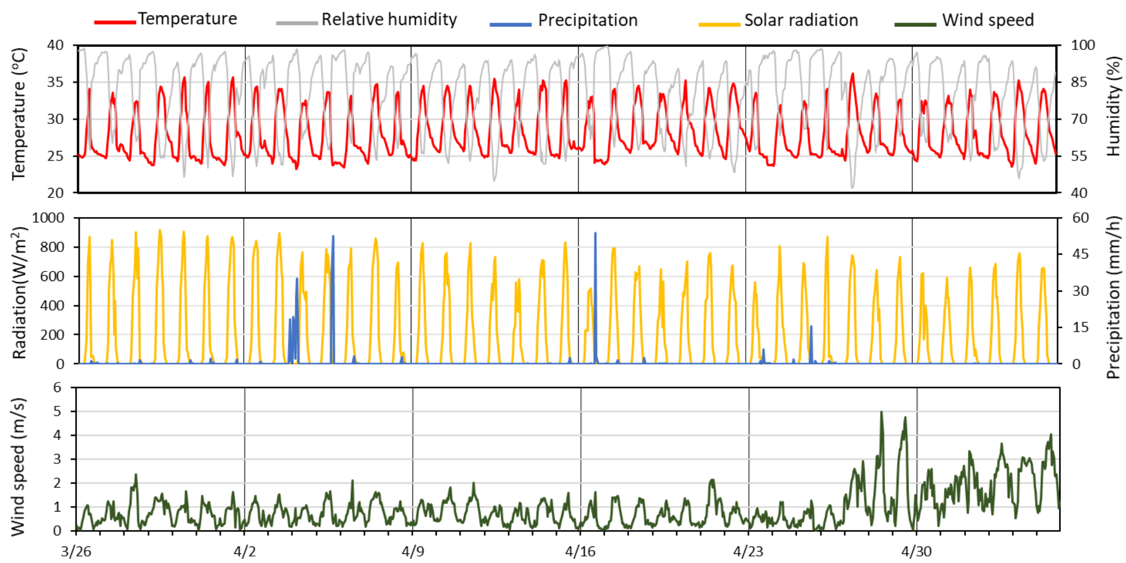


Fig. 5. Weather conditions during the period of 26 March to 5 May 2019

3.2. Occupants' behaviour schedules

Typical occupants' behaviour schedules related to room air temperature and occupants' thermal sensation were obtained from by the questionnaire survey (**Appendix A**) as shown in Fig. 6. Most dwellings were occupied by at least one resident during almost all of the 24 h except for house F, where each family member had outdoor activities between 9:00 to 15:00 (working or going to school).

Regarding thermal adaptation behaviours, most residents used an electric fan during the sleeping period. The duration of the use of electric fans varied from 2 to 12 h per day. In most houses, a combination of using fans and opening windows was employed during the daytime. However, some residents of houses A and G only opened windows and did not use fans, despite hot daytime hours. The times when residents start opening the windows were diverse, i.e. from 5:00 to 11:00 except for dwelling F, K and P where the occupants continuously closed the windows. According to additional interview, residents of two dwellings explained this behaviour is for security from thievery. In contrast, residents of another dwelling explained that opening windows does not have a significant cooling effect, oppositely, closing windows can reduce the odor from the sewerage close to their dwelling.

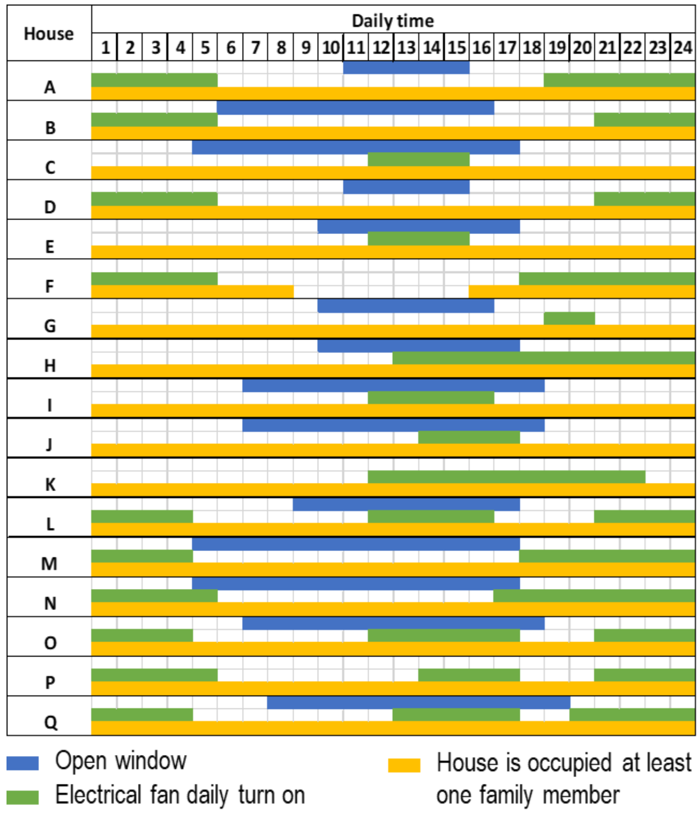


Fig. 6. Daily occupant thermal behaviour schedules in each dwelling

3.3 Diversity of room air temperature in the surveyed dwellings

Fig. 6 illustrates the averaged diurnal cycles of the room air temperatures in all of the measured dwellings. The indoor temperatures were higher than the outdoor temperatures at nighttime (18:00 to 06:00). In this period, dwellings having wall Type 6 were relatively warm, probably owing to the higher thermal mass of the building envelopes relative to other dwellings, as a higher amount of heat stored in the daytime is released to the indoor space of the house [21]. On the other hand, it is shown that wall Type 6 having diverse diurnal variations. For instance, two houses (H and O) showed a higher daily peak than the outdoor air temperature, but house L having the most stable indoor daily temperature compared to the other houses in daytime. Accordingly, it indicates the wall construction types that we classified is not effective to specify the features of room air temperature.

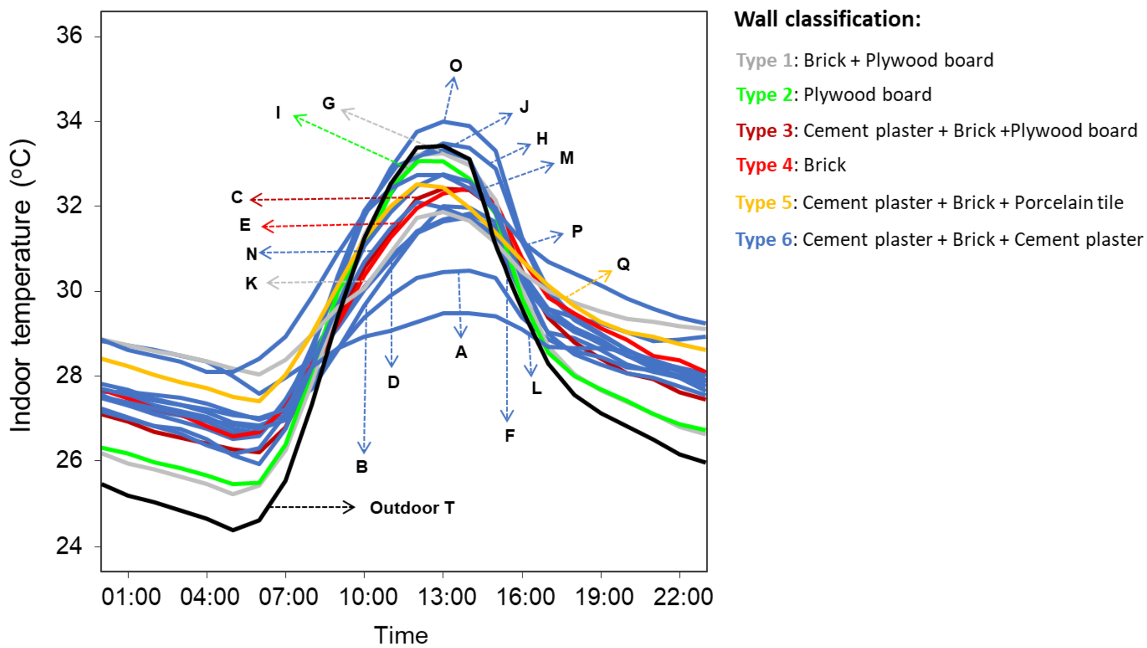


Fig. 7. Averaged diurnal cycle of indoor temperatures and outdoor temperatures (black line) during the measurement period

To characterize the daily variations of the room air temperature in each dwelling, we introduce *f* value for each dwelling as a representative information of diurnal variation of the room air temperature, and show the relation between *f* and Q (heat capacity of a building envelope per interior volume). We estimated a decrement factor *f*, expressed in Eq. (1) [22] as follows:

$$f = \frac{T_{i\_max} - T_{i\_min}}{T_{o\_max} - T_{o\_min}} \quad (1)$$

In the above, T_{i_max} and T_{i_min} are the daily maximum and minimum indoor temperature, respectively; and T_{o_max} and T_{o_min} are the daily maximum and minimum outdoor temperature, respectively. *f* indicates the ratio of the amplitude of the daily variation of the indoor temperature to that of the outdoor temperature. In this study, single *f* value was calculated based on an ensemble average of the daily variations for each dwelling during the entire measurement period.

In addition, the heat capacity of a building envelope per interior volume Q [J $m^{-3}K^{-1}$] was calculated for each dwelling using Eq. (2), based on the observed building materials and size.

$$Q = \frac{\sum_{i=1}^{n} C_i}{V} \tag{2}$$

Here, V is the indoor air volume of the dwelling [m^3], and indicates the total volume of all interior spaces within all rooms of a dwelling. The heat capacity for each component of a building envelope exposed to the outdoor air C_i is expressed as follows:

$$C_i = A_i \sum_j \rho_j C_{p,j} \Delta x_j \tag{3}$$

In the above, A_i is the area of a component i of the building envelope, such as a wall, roof, or window glass [m^2]; and ρ_j , $C_{p,j}$, and Δx_j are the density [kg m^{-3}], specific heat [J $kg^{-1}K^{-1}$], and thickness [m] of a layer j of the envelope, respectively. The standard thickness and thermal properties of construction materials provided by the National Standardization Body of Indonesia (ID number 03-6389-2011) were used for the estimation of Ci (see Appendix Table A2) [23]. The parameter Q indicates the influence of the thermal inertia of the building envelopes on the room air temperatures. Fig. 8 shows the relationship between the decrement factor f and Q. As expected, these two variables show a negative correlation, indicating that a larger thermal inertia causes a more stable daily fluctuation in room air temperature. House G, with the smallest heat capacity of 112.2 kJ $m^{-3}K^{-1}$ and classified into wall Type 1, shows the largest f, in addition to the largest amplitude of daily indoor temperature. In contrast, House B has the highest heat capacity at 144.5 kJ $m^{-3}K^{-1}$ and is classified into wall Type 6, but did not show the most stable indoor temperature.

As for the scatter of plots, one can theoretically point out potential factors. In case of three dwellings (L, B, and J) having top three large Q values and slightly different f values, presence of ceiling, wall type, U-value of roof, and schedule of window opening are similar. In contrast, the heat gain of the solar radiation on wall surfaces was probably different among the three dwellings due to the difference of the orientation and number of external walls enclosing measured room (See Table A1). The surveyed room of dwelling L was enclosed by three partition walls and only one external wall facing to north. As a result, the room air temperature of dwelling L might be not significantly affected by solar heating during the daytime, as shown in the lowest temperature at around noon of Fig.7, resulting the lowest f value.

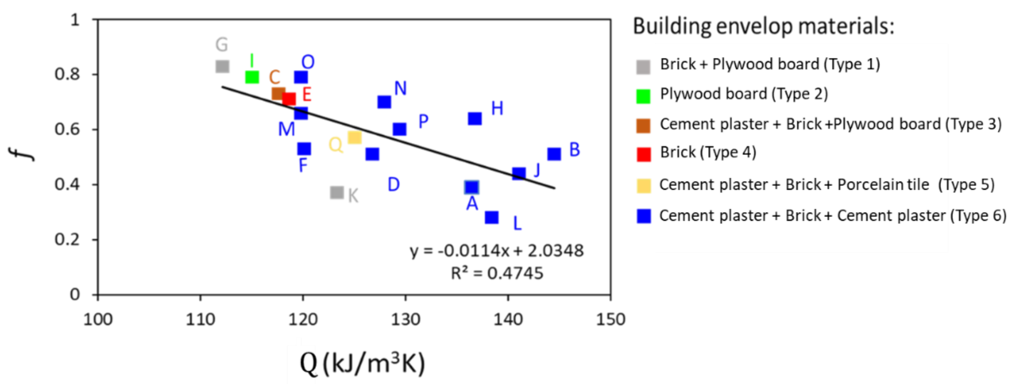


Fig. 8. Scatterplot and regression line demonstrating the relation between decrement factor *f* and heat capacity of a building envelope per interior volume Q

Fig. 9 shows the probability density distributions (PDDs) and cumulative probability distributions (CPDs) of the indoor air temperatures for the 17 dwellings. The ranges for 80% and 90% acceptability of the adaptive thermal comfort model in naturally ventilated spaces are also included. These ranges are estimated by using the mean outdoor temperature during the measurement period [24]. Similar to case with the averaged diurnal cycles of the room air temperatures, the PDDs of all dwellings show diverse features. In general, dwellings with higher Q values show a narrower temperature distribution, indicating that the time variations of the indoor air temperature are relatively small. In contrast, dwellings with lower Q values show a relatively wide distribution, indicating large indoor air temperature variations between daytime and nighttime. In addition, the CPDs shown in Fig. 9b reveals that approximately 38% to 80% of the total measurement period is above 29 ºC, and out of the range of 90% thermal acceptability.

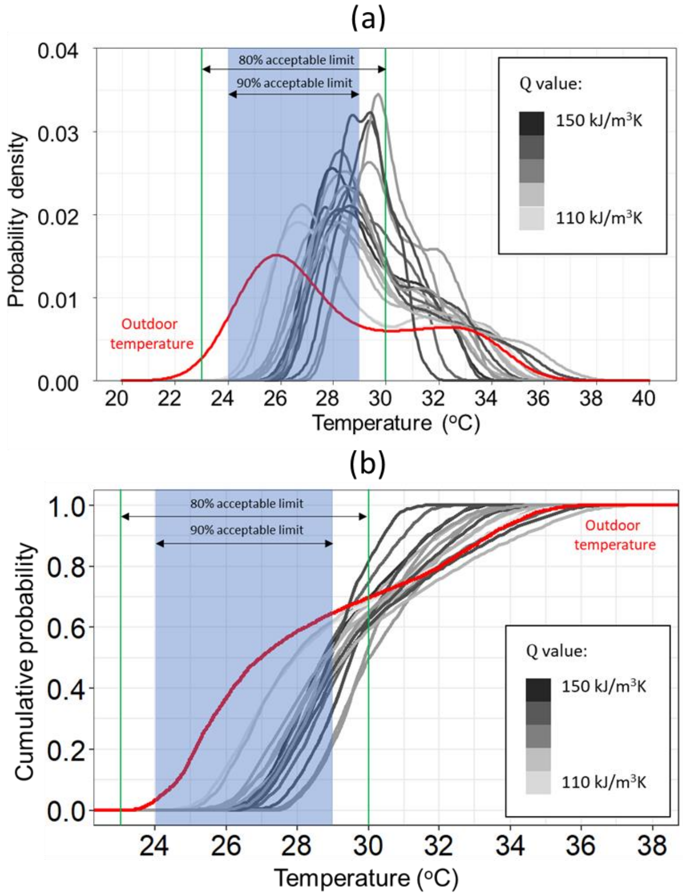


Fig. 9. (a) Probability density distributions (PDDs) and (b) cumulative probability distributions (CPDs) of indoor temperatures of 17 dwellings and outdoor temperatures during the measurement period

3.4 Statistical analysis of room air temperature and thermophysical factors of dwellings

According to a basic knowledge of building physics, the room air temperature of a naturally ventilated building is mainly affected by convective heat transfer from the inner surfaces of building envelopes, and ventilation from outdoor air. Based on such knowledge, if the architectural designs, including the materials and dimensions of each part, are known, it is easy to predict the indoor temperature and air conditioning load. However, in districts with informal urban settlements such as Kampung, where extremely simple low-cost dwellings with various materials and designs are haphazardly concentrated, the usual legitimate approach to estimating building thermal properties cannot be applied, in both the preconstruction stage and in retrofitting for existing dwellings. To clarify simple and easy housing variables, which enable to identify dwellings with a higher heat risk, the authors conducted a statistical analysis of the observed room air temperatures.

Table 3 shows the correlation coefficients for the monitored percentiles of room air temperatures in each dwelling ($T_{P2.5}$, T_{P25}, T_{P50}, T_{P75}, and $T_{P97.5}$), with nine variables related to the building design, thermophysical variable Q, and occupants' thermal behaviours. A Spearman's rank correlation with a confidence interval (CI) of 95% was applied to investigate the strength and direction of the relationship (negative or positive) between these variables. As expected, the house volumetric heat capacity Q shows highest correlation coefficient for $T_{P2.5}$, T_{P25}, and $T_{P97.5}$. Considering the physical meaning of Q, the high correlation is not surprising. Nevertheless, it is instructive that dwellings having lower Q values tend to have a higher heat risk during the daytime, and vice versa for sleeping time. However, the ratio of the floor area per house volume, i.e. the inverse of the ceiling height, shows relatively high correlation coefficients for T_{p75} and $T_{p07.5}$. This result indicates that houses with lower ceiling heights are likely exposed to a higher heat risk during the daytime. The other variables, such as the fraction of each building envelope to the room volume and occupants' related indices, were not statistically significant.

Table 3. Spearman's rank correlation test of percentile values (2.5%, 25%, 50%, 75%, and 97.5%) of indoor temperatures against thermophysical variables of dwellings and thermal behavioural variables

Variables	Correlation coefficient between percentile and variables				
	2.5^{th} : $T_{P2.5}$	25^{th}: T_{P25}	50^{th}: T_{P50}	75^{th} : T_{P75}	97.5^{th} :$T_{P97.5}$
Wall area per interior volume	0.03 (0.907)	-0.04 (0.877)	-0.14 (0.578)	-0.27 (0.290)	-0.30 (0.249)
Roof area per interior volume	-0.05 (0.840)	-0.25 (0.334)	-0.21 (0.415)	-0.40 (0.115)	-0.39 (0.119)
Window area per interior volume	-0.05 (0.847)	-0.04 (0.870)	-0.26 (0.312)	-0.39 (0.125)	-0.25 (0.330)
Floor area per interior volume	-0.02 (0.940)	-0.12 (0.651)	-0.26 (0.311)	**-0.53 (0.027)**	-0.42 (0.090)
Occupants per floor area	-0.06 (0.825)	-0.08 (0.771)	-0.09 (0.739)	0.11 (0.682)	0.27 (0.288)
Ceiling height from the ground	0.19 (0.460)	0.15 (0.558)	0.09 (0.719)	-0.24 (0.377)	-0.37 (0.139)
Heat capacity of building envelope per volume (Q)	**0.64 (0.006)**	**0.59 (0.012)**	-0.37 (0.142)	-0.38 (0.134)	**-0.56 (0.018)**

Duration of windows open in a day	-0.19 (0.457)	-0.12 (0.658)	-0.00 (0.992)	-0.20 (0.438)	0.35 (0.166)
Duration of electric wind fan usage in a day	0.33 (0.197)	0.40 (0.115)	0.32 (0.213)	-0.02 (0.930)	-0.02 (0.951)

*bold numbers indicated statistically significant correlation ($p < 0.05$) and numeral in parentheses is p-value.

3.5 Thermal comfort indices derived from observed data

In recent years, various studies have suggested that the estimated thermal comfort based on the PMV often shows a discrepancy from the actual thermal sensation votes of occupants in naturally ventilated buildings [21–23]. Accordingly, an approach denoting adaptive thermal comfort, which basically rely on questionnaire surveys at a target site to collect thermal sensation votes (TSVs) of occupants, has become popular as an adequate tool for estimating the comfortable temperature range in such buildings [27]. Considering these findings, the adaptive thermal comfort approach (rather than PMV) might be suitable for the evaluation of thermal comfort in the dwellings surveyed in this study. Nevertheless, we considered a PMV derived from personal (clothing insulation and metabolic rate) and environmental variables (air temperature, relative humidity, mean radiant temperature, and air velocity) as a comprehensive thermal comfort index, for a relative comparison of indoor thermal conditions among the surveyed dwellings [28]. In addition, PMV, which can be calculated by time-series observed data for 24 hours throughout the measurement period, is supposed to be advantageous to acquire large sample numbers to evaluate the overall heat risk of occupants.

Fig. 10 shows the averaged daily variations of the PMV for each dwelling, as derived from the observed room air temperature and relative humidity. The mean radiation temperature was assumed as equivalent to the measured room air temperature. In contrast, the wind speed was determined based on the results of the questionnaire survey related to the occupants' behaviour schedules (shown in Fig. 6). During the period when occupants used electric fans, the wind speed was assumed as 0.3 m/s; in contrast, when windows were opened, 0.2 m/s was adopted. In the remaining periods with no fans and no openings of windows, the wind speed was assumed as 0.1 m/s [29]. The metabolic rate was determined as 1 met, which is equivalent to the occupant' activity level when we conducted the questionnaire survey. In addition, the clothing value was calculated based on the combination of clothes that the occupant wore, and ranged from 0.5 to 0.7.

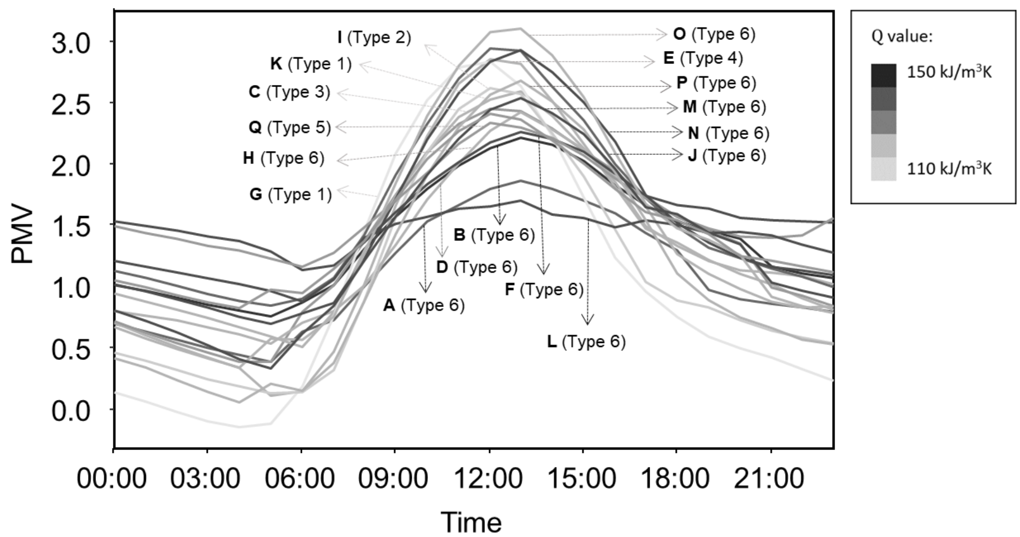


Fig. 10. Averaged diurnal cycles of predicted mean vote (PMV) for 17 dwellings

In general, the diurnal cycles of the PMV show similar features based on the diverse daily amplitudes of room air temperatures, as shown in Fig. 7. The daily peaks of the PMV arise from 12:20 to 14:20, with a range of 1.8 to 3.2; these values fail the standard of thermal comfort suggested by ASHRAE 55, except for two houses (G and I). These dwellings exhibited an acceptable thermal comfort range at night for approximately 7 and 4 h, respectively. In other words, dwellings with light building materials (wall Types 1 and 2) and thus relatively low Q values were beneficial to achieving an acceptable thermal environment during most of the sleeping period.

Houses A and L showed the best indoor thermal environments in terms of the mitigation of hot sensations in the activity period, with the PMV values lower than 2, whereas the other dwellings showed PMV values ranging from 2.2 to 3.2. However, house L experienced a higher PMV than most of other dwellings in the sleeping period with a PMV value greater than 1.3, whereas the other dwellings could achieve cooler conditions, with PMV values range between 0.1 to 1.2. This trend suggests that higher values of Q in dwellings will help achieve cooler conditions as compared to lower Q values in activity times, as expected; nonetheless, they will lead to a hotter indoor environment during the sleeping time.

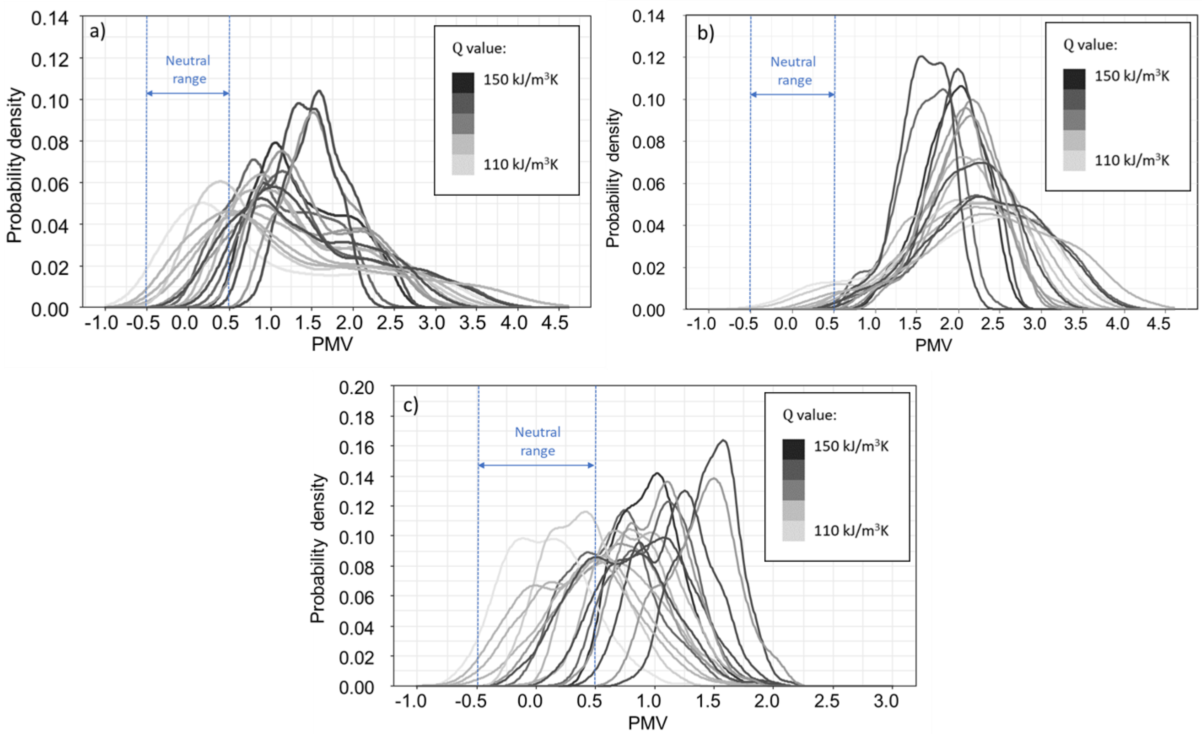


Fig. 11. Probability density distributions of PMV based daily occupant behaviour model during the period of measurement: (a) all period, (b) activity period and (c) sleeping period

The PDDs and CPDs of the PMVs in all of the dwellings are shown in Figs. 11 and 12. The data were classified into three time periods: the entire observed period, activity period, and sleeping period. The latter two periods were determined based on the questionnaire results from each dwelling, as shown in Fig. 9. As can be seen from the graphs, the PDDs of all dwellings show diverse patterns, ranging between -1 and +4.6 during the entire measurement period (see Fig. 11a). The CPDs of all dwellings shown in Fig. 12a illustrate that 20% of monitoring period had a PMV value higher than 1.8. Despite the differences in building construction materials, all dwellings showed PMV values between 1.5 to 2.5 during most of their activity period, and 50% of the observed period showed PMV values of more than 1.7, as shown in Figs. 11b and 12b, respectively. During the sleeping period, the time fraction of the thermally neutral range of the PMV (lower than 0.5) varies among the dwellings, from 7% to 55%. This variety is generally consistent with the Q values, namely, dwellings with low Q values tend to have longer time period for the neutral range. Oppositely, in the activity period, dwellings with low Q values were found to have longer time periods for warm and hot conditions.

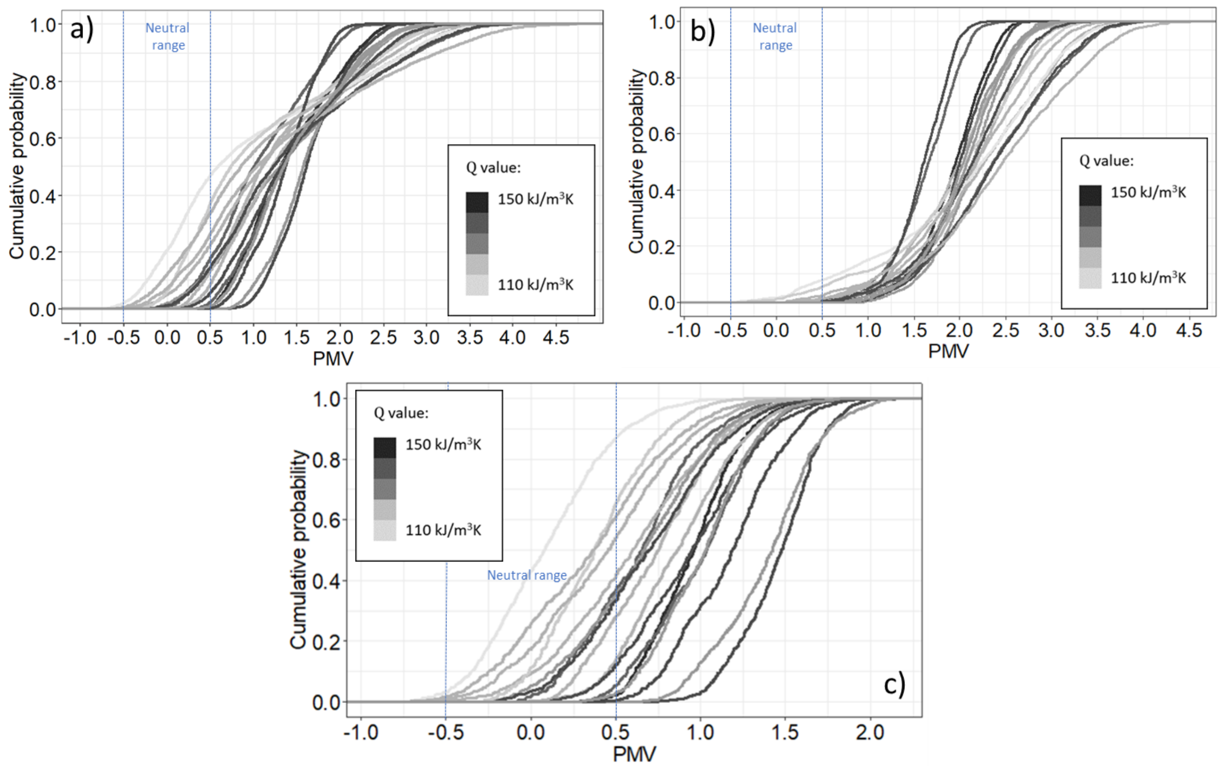


Fig. 12. Cumulative probability distributions of PMV based daily occupant behaviour model during the period of measurement: (a) all period, (b) activity period and (c) sleeping period

To identify affordable cooling measures in this district, it would be interesting to estimate the potential influence of the wind speed, which can be increased by natural ventilation or by less expensive electric fans. Accordingly, the authors estimated the PMVs of all dwellings under two conditions of wind speed, 0.1 m/s and 0.8 m/s. The air speed of 0.1 m/s represented the calm air conditions, whereas 0.8 m/s represented a condition of simultaneously using fans and opening windows. Fig. 13 shows the relations of the percentiles of the PMV between these two assumptions. The plots are almost in a linear line regardless of the percentile, and the reduction of the PMV owing to increased wind speed is more significant for low-PMV conditions. According to the estimation of the PMV shown in Figs. 11 and 12, the activity period is the time that requires mitigation to achieve thermal comfort, as compared to the sleeping period. However, Fig. 13 implies that the thermal mitigation effect of increasing the air speed during the activity period is generally weak, which is consistent with ASHRAE 55 2010 section 5.2.3.1 [24] and ISO 7730:2005 Annex G [29]. In contrast, increasing the air speed is more effective at lower air temperatures, such as during the sleeping period of the surveyed dwellings. This fact is in line with the observed occupants' behaviour, i.e. people tended to turn on an electrical fan during sleeping time (rather than during activity time, with higher indoor air temperature). Meanwhile, during the activity period, people might be more tolerant to a relatively hot indoor thermal environment, and accept the given conditions owing to the less-effective impact of using a wind fan and electricity to achieve thermal comfort. Thus, they might prefer to wear light clothing as a feasible alternative to mitigating the hot sensation.

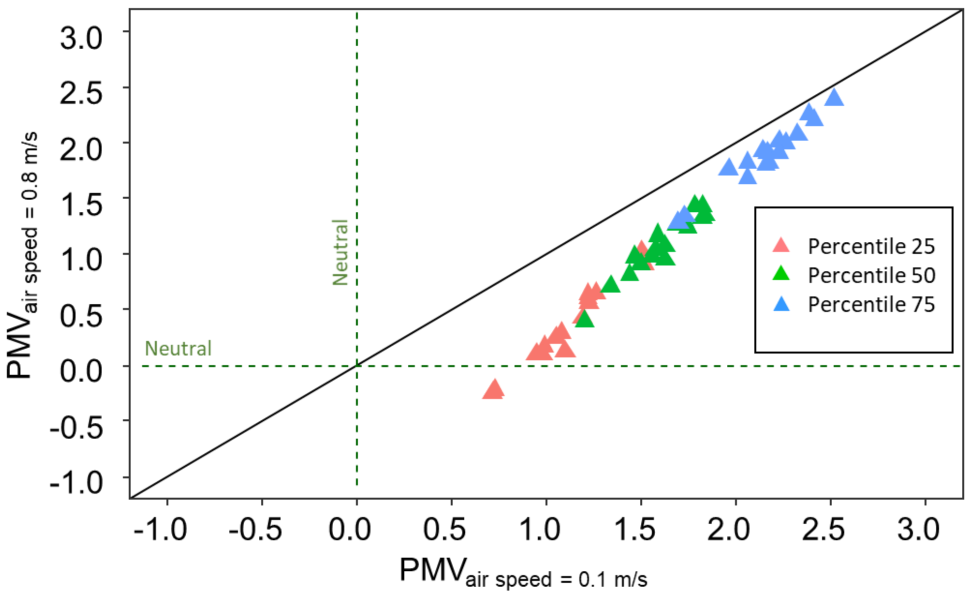


Fig. 13. Relation of percentiles of PMV as estimated with the assumption of calm air conditions of 0.1 m/s, and those with the assumption of air speed at 0.8 m/s [24]

4. Results of subjective thermal responses

4.1 Relation between thermal sensation vote (TSV), thermal preference vote (TPV), and indoor air temperature

Fig. 14 illustrate the TSV and TPV obtained by the questionnaire survey under the different condition of the indoor air temperatures. It indicates that all the occupants exposed to the room air temperature between 24.5 °C to 27 °C recognized as thermally neutral and no need to change. In contrast, for the condition of temperature from 30.5 to 31 °C, only 20% of respondents answered that they felt thermally neutral while more than 50% answered warm or hot sensation. On the other hand, the temperature, at which respondents felt warm and preferred to have cooler conditions, ranged from 27-27.5 °C. All of the respondents were found to prefer cooler condition at the temperature above 32.5 °C.

In order to quantify the relationship between TSV and indoor temperature, we conducted the receiver operating characteristic (ROC) analysis with logistic regression model as shown in Fig. 15. It allows the diagnostic test evaluation between true positive rate (sensitivity) against the false positive (1-specificity) for each TSV scale [30]. The area under curve (AUC) with the value ranged between 0-1 indicates the probability of occupant sensitivity to detect temperature threshold of TSVs [31]. The higher area under the curve is, the better probability model to classify occupants' thermal sensations across all indoor temperature thresholds[32]. As a result, AUC values of TSV= 0 (neutral), TSV=1 (slightly warm), TSV=2 (warm), and TSV=3 (hot) were 0.804, 0.546, 0.428, and 0.774 respectively (see Fig. 15a). Considering the standard interpretation of AUC in which more than 0.7 is acceptable discrimination [33], the current result implies that a threshold value of indoor temperature to diagnose TSV is applicable for only TSV = 0 (neutral) and TSV =3 (hot). Meanwhile, Fig. 15b illustrates the CPDs of indoor temperatures for each TSV scale. It emphasizes the indoor temperature threshold of people to vote for thermal neutrality, slightly warm, warm, and hot sensations were 24.5-31 °C, 27.5-32 °C, 27-34.5 °C and 27.5-34.5 °C respectively.

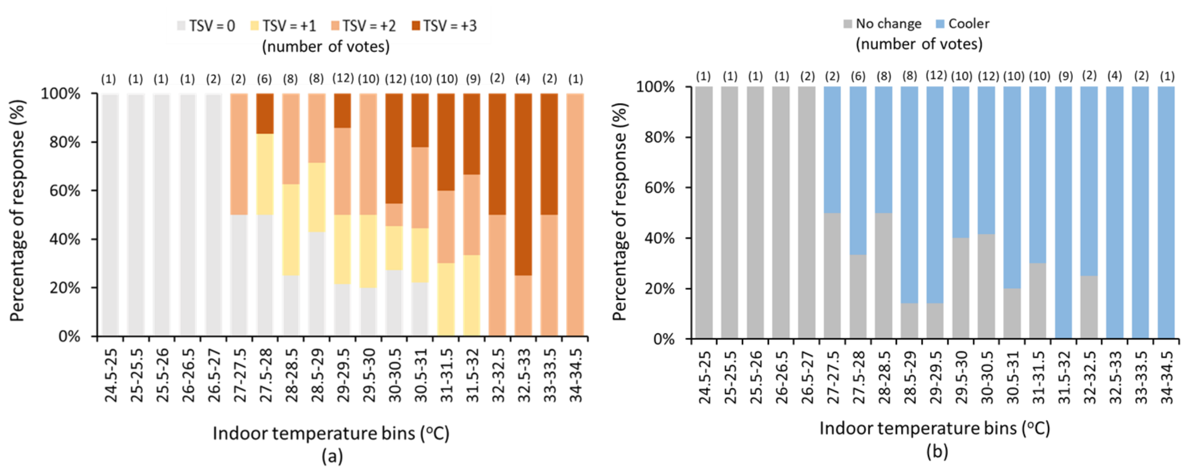


Fig. 14. Percentage of (a) TSVs and (b) TPVs against the increment of indoor temperature with 0.5 °C interval

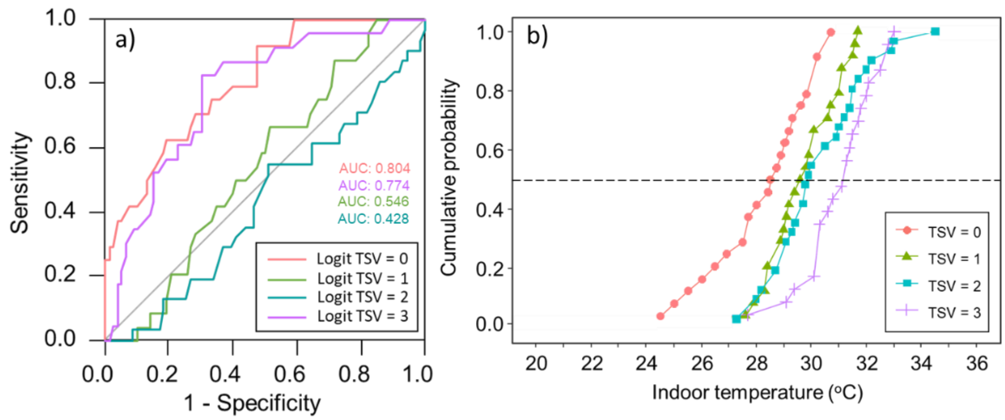


Fig. 15. (a) ROC curves of logistic regression and (b) cumulative probability distributions of indoor temperatures for each TSV scale

Fig. 16 shows a histogram of the comfort temperature T_c as derived from the Griffith method expressed by Eq. (4), with the assumption of a Griffith constant G of 0.33 °C $^{-1}$ according to previous field studies conducted in residential buildings[34–36].

$$T_c = T_a + (0 - TSV)/G \quad (4)$$

The histogram illustrates that the highest proportion of subjective comfortable temperatures from all respondents ranged between 28 °C and 30 °C, whereas the mean and median comfortable temperatures were 28.3 °C and 28.6 °C, respectively. This result is similar to the past three studies conducted in similar climate such as Jaipur City, India [25], Yogyakarta City, Indonesia [37], and Kinabalu City, Malaysia [38].

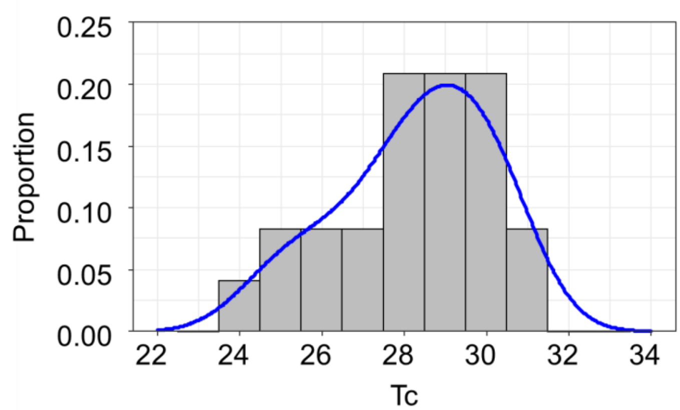


Fig. 16. Histogram of comfort temperature (T_c) from all respondents based on Griffith method

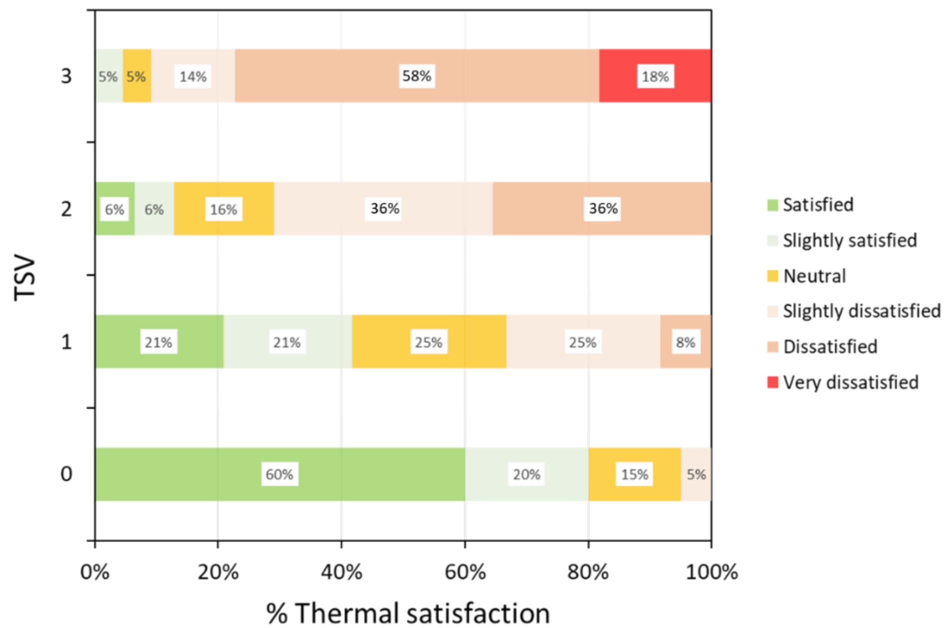


Fig. 17. Thermal satisfaction percentage for each TSV

1.1.Thermal satisfaction and thermal sensation

In addition to the TSV and TPV, the authors asked respondents regarding their satisfaction with the indoor thermal conditions. Fig. 17 illustrates the percentages of the thermal satisfaction levels of respondents, as classified by their TSVs. The ratio of positive answers including ‘Neutral’, ‘Slightly satisfied’, and ‘Satisfied’ were 95% (TSV = 0 or ‘Neutral’), 67% (TSV = 1 or ‘Slightly warm’), 28% (TSV = 2 or ‘Warm’), and 10% (TSV = 3 ‘Hot’). In contrast, the total observed percentages of negative answers, including the options of ‘Slightly dissatisfied’, ‘Dissatisfied’, and ‘Very dissatisfied’ were 5 % (TSV = 0), 33% (TSV = 1), 72% (TSV = 2), and 90% (TSV = 3). Notably, the predicted percentage of dissatisfied (PPD) values, as determined by PMV values at PMV = 1, 2, and 3, are 26%, 77%, and 99%, respectively. As pointed out by Cheung et al (2019), the PPD model is less accurate in tropical climate areas with larger discrepancies in warm sensations in naturally ventilated buildings [39], and the current analysis is consistent with the previous study.

2. Conclusion

This paper reported the results of a field measurement and questionnaire survey regarding the indoor thermal conditions of 17 low-cost dwellings located in a typical unplanned urban residential district in Surakarta City, Indonesia. The surveyed dwellings were selected to grasp the indoor thermal features of various conditions, including the building materials, area, occupants' behaviours, and household economic level.

The observed time series variations and PDDs of the indoor air temperature showed significant diversity among the 17 surveyed dwellings. Based on the observed indoor air temperatures, the decrement factor *f*, which refers to the ratio of the averaged daily amplitude of the indoor temperature to that of the outdoor temperature, was derived for each dwelling. It showed a strong linear correlation with the parameter Q, i.e. the heat capacity of a building envelope per unit interior volume, regardless of the occupants' behavioural conditions. In addition, a statistical test using Spearman's rank correlation indicated that both Q and the floor area per interior volume have significant correlations with the percentiles of indoor air temperatures. This suggests that the parameter Q and interior geometry of a dwelling can be utilized to detect vulnerable dwellings having a heat risk in Kampung districts.

The PDDs and CPDs of the estimated thermal comfort index PMVs suggested that most of the activity times in all of the surveyed dwellings were classified as out of thermally neutral conditions, i.e. they were slightly warm, warm, or hot. In contrast, the time fraction for the thermally neutral range of PMVs lower than 0.5 varied for the sleeping period among the dwellings, from 7% to 55%. This variation among dwellings is mainly attributed to the parameter Q, as dwellings with low Q values tend to have a longer time period in the neutral range. This fact suggests that rugged buildings made by heavy materials, which are usually considered as secure and favourable buildings in regions with cold winter, cannot necessarily provide a better indoor thermal environment in tropical regions if mechanical air-conditioning devices are not installed. A comparison of the estimated PMV values under two different assumptions of air speed indicated that any thermal mitigation owing to increased wind speed is not very evident during the daytime, with higher indoor temperatures than the sleeping period. This result might be a reason why people in the tropics living in naturally ventilated buildings tend to use an electric wind fan more frequently during nighttime rather than daytime.

This study demonstrated the necessity of the improvement of the current hot indoor environment and heat risk in low cost dwellings in Indonesia. Even though the number of surveyed dwellings was only 17 compared to numerous low-cost dwellings spreading in the country, the findings of this study can be interpreted as follows: A simple time-series measurement of indoor thermal variables in multiple dwellings with diverse building and behavioural conditions is possible to statistically clarify the influential factors of the indoor thermal quality. In addition, the determined factors can be utilized for detecting dwellings which need prior implementation of countermeasures. Although this paper is recognized as a case study in a district of Indonesia, the approach used in this study would be applicable for researchers, engineers and government officials that seek for health and comfort living environment toward sustainable development goals (SDGs) in various regions.

Acknowledgement

This project was partially funded by Robert T. Huang Entrepreneurship Center of Kyushu University and Obayashi Foundation. The authors are grateful for a support and assistance from all member of Urban-Rural Design and Conservation Laboratory, Department of Architecture, Sebelas Maret University, Indonesia. Thanks to Dr. Yosafat Winarto and Ms. Anita Dianingrum who strived to provide a conducive research activity especially to the students who accompanied the authors conducting field measurement.

Appendix A

Thermal Sensations and Occupant Behaviors Questionnaire

Date and time: ___/____/_____ at:

1. How are you feeling for the air temperature now? *(check only one)*
   ◯hot ◯ warm ◯ slightly warm ◯Neutral ◯slightly cool ◯ cool ◯ cold
2. How satisfied are you with the temperature now in your home? *(check only one)*
   ◯very satisfied ◯ satisfied ◯ slightly satisfied ◯Neutral ◯Slightly dissatisfied ◯ dissatisfied ◯ very dissatisfied
3. What would you prefer for the air temperature? *(check only one)*
   ◯much warmer ◯Bit warmer ◯No change ◯bit cooler ◯much cooler
4. What is your activity level right now? *(check the one that is most appropriate)*
   ◯reclining ◯seated ◯standing relaxed ◯light activity standing ◯medium activity
5. Using the list below, please check each item of clothing that you are wearing right now (*check all that apply*)

Checklists	Items	Material	Clo	Additional notes
		Underwear		
	Bra	Foam/tricot	0.01	
	Panties	Knit cotton	0.03	
	Men's brief	Silk cotton	0.04	
	Full slip	Nylon-polyester	0.16	
	Men's tank top/sleeveless	Cotton	0.12	
		Shirts and Dress		
	Short sleeve knit sport shirt	Cotton	0.17	
	Short-sleeve dress shirt	Silk cotton	0.19	
	T-shirt	Cotton	0.08	
	Long-sleeve dress shirt	Silk cotton	0.25	
	Long-sleeve sweatshirt	Cotton	0.34	
	Sleeveless, scoop neck thin	Cotton	0.23	
	Short-sleeve shirtdress thin	Cotton-foam	0.29	
	Long-sleeve shirtdress (thick)/Gamis	Cotton	0.47	
	Light hijab	cotton	0.06	
	Medium Hijab	Knittwd nylon-lycra cotton	0.08	
	Heavy/long hijab	Synthetic nylon	0.25	
		Skirts and trousers		
	Skirt thin	Cotton-polyester	0.14	
	Long Skirt thick	Jeans Denim	0.23	

	Walking short	Jeans Denim	0.11	
	Walking short	Polyester	0.08	
	Sweat pant	Cotton	0.28	
	Straight trousers thin	Silk-cotton	0.15	
	Straight trousers thick	Jeans Denim	0.24	
Footwear				
	Socks	Knit	0.03	
	Slipper/sandals	Rubber	0.02	
	Shoes	Synthetic	0.02	

6. What do you usually do in the daytime? *(check all that apply)*
   ◯ washing the clothes ◯ cooking ◯family gathering ◯watching TV ◯home base production ◯Using Internet ◯other__________
7. When do you usually start your activities in the morning? ___ am
8. When do you usually stay at home? From _____ to ______
9. When do you usually sleep in the night? ___pm
10. When do you open or turn on following appliances in the house in daily? *(check all that apply)*
    - **Window**:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

- **Fan**:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Table A1. Selected dwellings characteristics

House	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**
Orientation *	N, S	S, W, E	N, S, W	N, S	N, E	S, W	S, E	N, W	S, W	S, W	W	N	N, W	S, W	S, W	N, E	M, W
Wall area (m^2)	80.4	110.4	78.6	119.7	63.3	119.8	121.7	76.8	147.6	93.9	87	87	129.3	91.8	60.6	86.1	65.4
Wall material	Ip-B-Op	Ip-B-Op	Ip-B-Pb	Ip-B-Op	B	Ip-B-Op	B-Pb	Ip-B-Op	Pb	Ip-B-Op	B-Pb	Ip-B-Op	Ip-B-Op	Ip-B-Op	Ip-B-Op	Ip-B-Op	Ip-B-P
Roof area (m^2)	50.9	77.2	38.2	82.8	31.5	91.5	79.1	48.5	128.8	64.3	53.7	62.2	119.5	61.1	31.1	65	32.8
Roof Material	40%Ct-60%Ga	Ct	Ct	Ga	Ct	Ct	Ct	Ga	50%Ct-50%As	As	Ct	As	Ct	Ct	Ct	Ct	Ct
Floor area (m^2)	41.7	63.3	31.3	67.9	25.8	75	64.9	39.8	105.6	52.7	44	51	98	50.1	25.5	53.3	26.9
Floor material	P	P	P-Cp	P	P	P	Cp	P	P	P	Cp	P	P	P	P	P	P
Window area (m^2)	3	4.4	1.2	1.1	2.1	2.4	1.7	2.6	2.8	1.5	1.6	2.2	1.8	2.6	0.8	2.3	1.8
Window material	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG
Occupants	8	3	4	2	4	8	6	8	9	4	4	5	7	5	4	2	4
Ceiling	Yes	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	No	No	No	No
Sensor location	Living room	Living room	Bedroom	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room
Q (kJ/m^3K)	136.4	144.5	117.6	126.7	118.6	120.1	112.2	136.7	115	141	123.3	138.4	119.8	127.9	119.8	129.4	125

*The orientation of walls which are exposed to outdoor air of the measured room; S = South; E = East; W = West; N = North; Ip = Inner cement plaster; B = Brick; Op = Outer cement plaster; Pb = Plywood board; P = Porcelain tile; Ct = Clay tile; Ga = Galvalume; As = Asbestos; Cp = Cement plaster; SG = Single glassed

Table A2. Thermal properties of building envelopes utilized for estimation of Q

Envelopes	Materials	Thickness (m)	Thermal Conductivity (W/m.K) [23,40]	Specific heat capacity (kJ/kg.K) [23]	Density (kg/m^3) [23]	U-Value (W/m^{2}K)	Dwelling labels
Wall Type 1	Brick	0.1 [41]	0.81	0.80	1920	1.32	G, K
	Plywood board	0.009 [42]	0.098	1.30	750		
Wall Type 2	Plywood board	0.009 [42]	0.098	1.30	750	1.57	I
Wall Type 3	Inner cement plaster	0.015 [43]	0.721	0.84	1762	1.28	C
	Brick	0.1 [41]	0.81	0.80	1920		
	Plywood board	0.009 [42]	0.098	1.30	750		
Wall Type 4	Brick	0.1 [41]	0.81	0.80	1920	1.50	E
Wall Type 5	Inner cement plaster	0.015 [43]	0.721	0.84	1762	1.44	Q
	Brick	0.1 [41]	0.81	0.80	1920		
	Porcelain tile	0.007 [44]	1.298	0.80	23000		
Wall Type 6	Inner cement plaster	0.015 [43]	0.721	0.84	1762	1.41	A, B, D, F, H, J, L, M, N, O, P
	Brick	0.1 [41]	0.81	0.80	1920		
	Outer cement plaster	0.015 [43]	0.721	0.84	1762		
Window	Single glassed	0.008 [45]	1.053	0.72	2512	1.81	All
Roof	Clay tile	0.01 [44]	0.71	0.62	1800	1.79	A, B, C, E, F, G, I, K, M, N, O, P, Q
	Asbestos	0.005 [44]	0.154	0.84	2000	1.73	L, I
	Galvalume steel	0.001 [44]	62	0.47	7850	1.84	D, A, H,

References

[1] UN, The World 's Cities in 2018, 2018.

[2] Y. Takane, Urban warming and future air-conditioning use in an Asian megacity : importance of positive feedback, Npj Clim. Atmos. Sci. 39 (2019) 1–11. https://doi.org/10.1038/s41612-019-0096-2.

[3] D. Lauwaet, H. Hooyberghs, B. Maiheu, W. Lefebvre, G. Driesen, S. Van Looy, K. De Ridder, Detailed urban heat island projections for cities worldwide: Dynamical downscaling CMIP5 global climate models, Climate. 3 (2015) 391–415. https://doi.org/10.3390/cli3020391.

[4] E. Birch, S. Wachter, Sustainable Urbanization: Place Matters, Philadelphia, 2014.

[5] BPS, 2019 Statistical Yearbook of Indonesia, 2019.

[6] World Bank, Indonesia's Urban Story, 2016.

[7] H. Marhaeni, Indonesia poverty profile in 2019, 2019.

[8] N.E. mortalit. Klepeis, W.C. Nelson, W.R. Ott, J.P. Robinson, A.M. Tsang, P. Switzer, J. V. Behar, S.C. Hern, W.H. Engelmann, The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants, J. Expo. Anal. Environ. Epidemiol. 11 (2001) 231–252. https://doi.org/10.1038/sj.jea.7500165.

[9] N. Nazarian, N. Dumas, J. Kleissl, L. Norford, Effectiveness of cool walls on cooling load and urban temperature in a tropical climate, Energy Build. 187 (2019) 144–162. https://doi.org/10.1016/j.enbuild.2019.01.022.

[10] I. Tsoulou, C.J. Andrews, R. He, G. Mainelis, J. Senick, Summertime thermal conditions and senior resident behaviors in public housing: A case study in Elizabeth, NJ, USA, Build. Environ. 168 (2020) 106411. https://doi.org/10.1016/j.buildenv.2019.106411.

[11] A. Sakka, M. Santamouris, I. Livada, F. Nicol, M. Wilson, On the thermal performance of low income housing during heat waves, Energy Build. (2012). https://doi.org/10.1016/j.enbuild.2012.01.023.

[12] E. Nix, C. Shrubsole, P. Das, M. Davies, Indoor environmental quality of low-income housing in Delhi, India: Findings from a field study, in: Energy Procedia, 2015. https://doi.org/10.1016/j.egypro.2015.11.714.

[13] A. Hashemi, Effects of thermal insulation on thermal comfort in low-income tropical housing, Energy Procedia. 134 (2017) 815–824. https://doi.org/10.1016/j.egypro.2017.09.535.

[14] A. Nutkiewicz, R.K. Jain, R. Bardhan, Energy modeling of urban informal settlement redevelopment: Exploring design parameters for optimal thermal comfort in Dharavi, Mumbai, India, Appl. Energy. 231 (2018) 433–445. https://doi.org/10.1016/j.apenergy.2018.09.002.

[15] I.A.W. Hutama, Exploring the Sense of Place of an Urban, University of Twente, 2016.

[16] R. Fillaili, Addressing Urban Poverty: Increasing Learning on Urban Poverty Reduction in Kota Surakarta and Kota Makassar , Indonesia Increasing Learning on Urban Poverty Reduction, Jakarta, 2011. https://www.smeru.or.id/sites/default/files/publication/urbanpoverty_eng.pdf.

[17] Dinas Kependudukan, Civil Development Report of Surakarta 2016, 2016.

[18] T.H. Karyono, Predicting comfort temperature in Indonesia, an initial step to reduce cooling energy consumption, Buildings. 5 (2015) 802–813. https://doi.org/10.3390/buildings5030802.

[19] Isharyanto, Responding to climate change: Surakarta city tourism on legal and policy perspectives, IOP Conf. Ser. Earth Environ. Sci. 200 (2018) 1–4. https://doi.org/10.1088/1755-1315/200/1/012047.

[20] BPS, Surakarta in figure 2012-2018, 2019.

[21] B. Givoni, Climate Consideration in Buildings and Urban Design, John Wiley & Sons, New York, 1998.

[22] L. Bellahcene, A. Cheknane, S. Bekkouche, D. Sahel, The effect of the thermal inertia on the thermal transfer in building wall, E3S Web Conf. 22 (2017) 00013. https://doi.org/10.1051/e3sconf/20172200013.

[23] SNI 03-6389-2011, Building Envelopes Standard for Energy Conservation (Indonesia Language), National Standardization Body of Indonesia, 2011.

[24] S.C. Turner, G. Paliaga, B.M. Lynch, E.A. Arens, R.M. Aynsley, G.S. Brager, J.J. Deringer, J.M. Ferguson, J.M. Filler, J.J. Hogeling, D. Int-hout, A.G. Kwok, H.F. Levy, E.M. Sterling, J.L. Stoops, S.T. Taylor, R.W. Tinsley, K.W. Cooper, K.W. Dean, F. Myers, J.C. Peterson, ASHRAE Standard 55-2010 Thermal environmental conditions for human occupancy, 2010 (2010) 30.

[25] S. Kumar, M.K. Singh, V. Loftness, J. Mathur, S. Mathur, Thermal comfort assessment and characteristics of occupant's behaviour in naturally ventilated buildings in composite climate of India, Energy Sustain. Dev. 33 (2016) 108–121. https://doi.org/10.1016/j.esd.2016.06.002.

[26] S.I.U.H. Gilani, M.H. Khan, W. Pao, Thermal Comfort Analysis of PMV Model Prediction in Air Conditioned and Naturally Ventilated Buildings, Energy Procedia. 75 (2015) 1373–1379. https://doi.org/10.1016/j.egypro.2015.07.218.

[27] R.J. De Dear, G.S. Brager, Thermal comfort in naturally ventilated buildings: Revisions to ASHRAE Standard 55, Energy Build. 34 (2002) 549–561. https://doi.org/10.1016/S0378-7788(02)00005-1.

[28] A. Omidvar, J. Kim, Modification of sweat evaporative heat loss in the PMV/PPD model to improve thermal comfort prediction in warm climates, Build. Environ. 176 (2020) 106868. https://doi.org/10.1016/j.buildenv.2020.106868.

[29] ISO E 7730, Ergonomics of the Thermal Environment. Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, International Standardisation Organisation, 2005.

[30] Y. Xie, J. Liu, T. Huang, J. Li, J. Niu, C.M. Mak, T. cheung Lee, Outdoor thermal sensation and logistic regression analysis of comfort range of meteorological parameters in Hong Kong, Build. Environ. 155 (2019) 175–186. https://doi.org/10.1016/j.buildenv.2019.03.035.

[31] Y. Ji, Z. Wang, Thermal adaptations and logistic regression analysis of thermal comfort in severe cold area based on two case studies, Energy Build. 205 (2019) 109560. https://doi.org/10.1016/j.enbuild.2019.109560.

[32] J. Kim, Y. Zhou, S. Schiavon, P. Raftery, G. Brager, Personal comfort models: Predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning, Build. Environ. 129 (2018) 96–106. https://doi.org/10.1016/j.buildenv.2017.12.011.

[33] S. Yang, G. Berdine, The receiver operating characteristic (ROC) curve, Southwest Respir. Crit. Care Chronicles. 5 (2017) 34. https://doi.org/10.12746/swrccc.v5i19.391.

[34] J. Ryu, J. Kim, W. Hong, R. de Dear, Defining the thermal sensitivity (Griffiths constant) of building occupants in the Korean residential context, Energy Build. 208 (2020) 109648. https://doi.org/10.1016/j.enbuild.2019.109648.

[35] R.F. Rupp, J. Kim, E. Ghisi, R. de Dear, Thermal sensitivity of occupants in different building typologies: The Griffiths Constant is a Variable, Energy Build. 200 (2019) 11–20. https://doi.org/10.1016/j.enbuild.2019.07.048.

[36] Z. Wu, N. Li, P. Wargocki, J. Peng, J. Li, H. Cui, Adaptive thermal comfort in naturally ventilated dormitory buildings in Changsha, China, Energy Build. 186 (2019) 56–70. https://doi.org/10.1016/j.enbuild.2019.01.029.

[37] H. Feriadi, N.H. Wong, Thermal comfort for naturally ventilated houses in Indonesia, Energy Build. 36 (2004) 614–626. https://doi.org/10.1016/j.enbuild.2004.01.011.

[38] H. Djamila, C.M. Chu, S. Kumaresan, Field study of thermal comfort in residential buildings in the equatorial hot-humid climate of Malaysia, Build. Environ. 62 (2013) 133–142. https://doi.org/10.1016/j.buildenv.2013.01.017.

[39] T. Cheung, S. Schiavon, T. Parkinson, P. Li, G. Brager, Analysis of the accuracy on PMV – PPD model using the ASHRAE Global Thermal Comfort Database II, Build. Environ. 153 (2019) 205–217. https://doi.org/10.1016/j.buildenv.2019.01.055.

[40] Morrison Hershfield, Thermal Performance of Sheet Steel Wall, 2014.

[41] S. Handayani, Quality of Brick with Additional Sawdust (Indonesian Languange), Tek. Sipil Perenc. 12 (2010) 41–50. https://doi.org/10.15294/jtsp.v12i1.1339.

[42] A. Ramadhan, Kurniawan, Physical Properties of Plywoods (Indonesian Language), 2017.

[43] SNI-2837-2008, The Procedure for Building and Housing Construction, National Standardization Body of Indonesia, 2008.

[44] PUPR, Guideline for Housing Construction, Jakarta, 2016.

[45] SNI-14-0047-2005, Glass Layer Standard, National Standardization Body of Indonesia, 2005.

On-site measurement and evaluations of indoor thermal environment in low-cost dwellings of urban Kampung district

Solli Murtyas[a*], Aya Hagishima[a], Kusumaningdyah N.H[b]

[a] Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Japan

[b] Architecture Department, Faculty of Engineering, Universitas Sebelas Maret, Indonesia

*Corresponding author

Address: Department of Energy and Environmental Engineering, Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Building F, 6-1 Kasuga Koen, Kasuga, Fukuoka 816-8580, Japan

E-mail address: s.murtyas@kyudai.jp (S.Murtyas)

Abstract

This paper reported results of a field measurement and questionnaire survey regarding the indoor thermal conditions of 17 low-cost dwellings located in a typical unplanned urban residential district 'Kampung' in Surakarta City, Indonesia. The surveyed dwellings were selected to grasp the indoor thermal features of various conditions, including the building materials, area, occupants' behaviours, and household economic level. The observed time series variations of the indoor air temperature showed significant diversity among the 17 dwellings. The decrement factor *f*, which refers to the ratio of the averaged daily amplitude of the indoor temperature to that of the outdoor temperature, showed a strong linear correlation with the parameter Q, i.e. the heat capacity of a building envelope per unit interior volume, regardless of the occupants' behavioural conditions. In addition, a statistical test using Spearman's rank correlation indicated that both Q and the floor area per interior volume have significant correlations with the percentiles of indoor air temperatures. Furthermore, estimated thermal comfort index PMVs suggested that most of the activity times in all of the surveyed dwellings were classified as out of thermally neutral conditions, i.e. they were slightly warm, warm, or hot. In contrast, the time fraction for the thermally neutral range of PMVs lower than 0.5 varied for the sleeping period among the dwellings, from 7% to 55%, owing to the parameter Q, as dwellings with low Q values tend to have a longer time period in the neutral range. These findings imply that the parameter Q and interior geometry of a dwelling can be utilized to establish countermeasures for vulnerable dwellings having a heat risk in Kampung districts.

Keywords: low-cost dwellings, indoor thermal environments, PMV, thermal sensation votes, comfort temperature

1. Introduction

The urban population accounted for 55.3% of the world's population in 2018, and it is projected to exceed more than 60% by 2030 [1]. This implies that the quality of urban environment will significantly affect a large population in regards to various aspects such as health, energy demands, and the economy [2]. Considering the potential future impact of climate change, such as rising global temperatures and more frequent extreme weather events such as heat waves [3], as well as temperature increases specific to urban areas (i.e. the 'urban heat island' phenomenon), there will be a strong need for affordable adaptation strategies to mitigate the heat risks in cities located in hot climate zones.

Indonesia is a developing Asian country that has shown rapid urbanization in recent decades [4]; the percentage of the population considered 'urban' was reported in 2019 as 56% [5]. This percentage is expected to increase to 68% by 2025 [6]. In line with this urbanization, there has been an expansion of densely populated and unplanned settlements. The local government reported in 2019 that 9.86 million people are living in low-quality housing, with limited infrastructure and public services [7].

The national human activity pattern survey which involved 9386 respondents in the United States of America reported that 87% of respondents spent their time indoors. This high percentage indicates that the indoor living environment plays a significant role in health, well-being, and work performance [8]. Accordingly, the thermal properties of the building envelopes and building facilities controlling the indoor thermal conditions are key factors in decreasing future heat risks from climate change and urban heat island phenomena [9]. However, providing people with suitable shelters from a hot climate is extremely difficult in developing countries, where many low-income people live in informal urban settlements with poor building quality owing to limited economic capabilities [10].

With this background, understanding the reality of the indoor thermal environment in low-income urban dwellings has become essential, to thereby establish evidence-based strategies for achieving affordable living spaces and reaching sustainable cities and communities. In fact, several studies have been conducted to observe low-income housing worldwide. Sakka et al. (2012) investigated the indoor thermal conditions of 50 non-air-conditioned houses in Athens, Greece over an extremely hot summer in 2007. They found that the indoor temperature reached 30 ºC for more than 85% of the measurement time period[11]. Nix et al. (2015) observed indoor environments in low-income housing in Delhi, India during the winter season. The hourly indoor temperatures of 13 dwellings were monitored for three weeks in December 2013. They found that the indoor thermal conditions of all observed dwellings were below 21 ºC for more than 60% of the hours during the monitoring period. In addition, they reported discomfort and risks to health from exposure to the cold temperatures, based on interviews with the residents [12]. Hashemi (2017) conducted a building energy simulation by using EnergyPlus targeting low-income tropical dwellings in Uganda. He adopted 96 scenarios for his case study to evaluate indoor thermal comfort under various conditions of insulation and construction methods. As result, he reported that the roof insulation is the most effective to improve thermal comfort and reduce the heat risk [13]. Nutkiewicz et al. (2018) investigated the effect of redevelopment of urban informal settlements in Mumbai, India on the thermal comfort based on a series of numerical simulation. In their work, various parameters related to building design as well as building morphology were systematically varied among numerous case study simulation. They reported that the window-to-wall ratio was the most sensitive design parameter for thermal comfort [14]. Despite such attempts, research regarding the indoor thermal conditions and building thermal features of low-cost dwellings in developing countries (including Indonesia) remains limited, probably owing to difficulties in access to the local communities of such areas, which are sometimes recognised as urban slums.

Under these circumstances, this study intends to provide a quantitative grasp of the indoor thermal conditions of an urban unplanned residential district called Kampung in Surakarta City, Indonesia, based on a field measurement of 17 low-cost dwellings and a questionnaire survey of the residents. The terminology 'Kampung' for representing an urban district is derived from Indonesian term for 'village'. Kampung in Indonesia is tightly related to informal urban settlements with poor physical and economical qualities [15]. The objectives of this study are as follows:

- to grasp the diversity in indoor thermal environments among dwellings located in the same district having different conditions of building envelopes and occupant thermal behaviours in households;
- to examine the factors indicating the vulnerability of a dwelling in terms of the thermal comfort and heat risks of residents; and
- to investigate the occupant perceptions, preferences, and acceptance in regards to indoor thermal conditions.

2. Outline of field survey

2.1. Site description

Fig. 1 shows the target site: Kampung Sangkrah, Surakarta City, Central Java Province, Indonesia (latitude 7^{o} 34\` South and longitude 110$^{o}$ 50\` East). It lies along the riverbank of Bengawan, on the eastern edge of Surakarta City. This district has an area of 0.482 km^2 and contains large informal settlements, with a total population of 10,885 in 2016. Of the 2473 existing dwellings, 30% are classified as poor settlements[16]. The livelihood typology consists of informal workers, civil servants, hawkers, scavenger, and casual labourers [17]. An aerial photograph of the target site is shown in Fig. 2.

This area is categorised as a tropical climate with dry and wet seasons [18]. The dry season period is five months (May-September), and wet season occurs within the seven months from October to April [19]. The annual mean temperature, relative humidity, and annual total precipitation, as recorded from 2015 to 2018, were 26.9 ^{o}C, 78.7%, and 804.3 mm, respectively [20]. The standard deviation of the monthly temperature from 2015 to 2018 was 0.9 ^{o}C, and the difference between the wet and dry seasons is generally small [20].

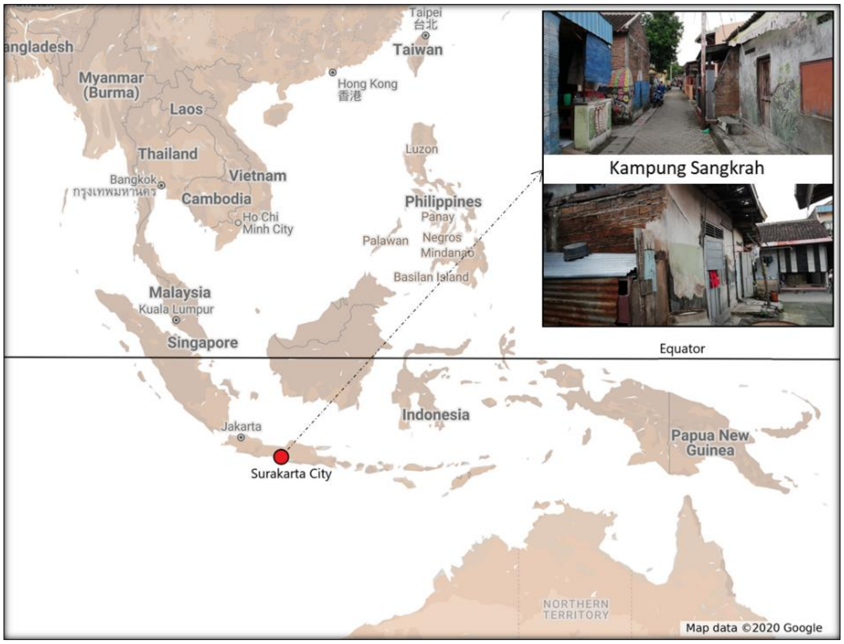


Fig. 1. A map of Indonesia (taken from Google maps) with target site Kampung Sangkrah in Surakarta City

2.2.Measurement of indoor thermal environment

Fig. 2 shows an aerial photograph of the target site, including the locations of the 17 dwellings selected for the measurement of indoor thermal conditions. These 17 dwellings were selected to collect representative but diverse samples of residential buildings of Kampung in terms of the building construction and materials, floor areas, and number of occupants (ranging from two to nine). All of the selected dwellings were 1-storey houses, and consisted of at least a living room and bedroom. Table 1 shows the wall materials of the 17 dwellings, as classified into six groups. Additional detailed information of the buildings is summarized in **Appendix Table A1**.

In the target 17 dwellings, the air temperature and relative humidity values in living rooms or bedrooms were measured at a height of 1.5 m. A thermo-hygrometer was installed in each room at a position not exposed to direct solar radiation (see Fig. 3). This measurement of indoor thermal conditions was continuously carried out from 26 March to 5 May 2019, at intervals of 10 min. In addition, the outdoor air temperature, relative humidity, wind speed, global solar radiation, and precipitation were measured as climate variables, at a height of 8 m above the playground of a public school in this district, as shown in Fig. 2. The details of the measurement items and instruments are shown in Table 2.

Fig. 2. The location of Kampung Sangkrah, selected dwellings, and weather station site

Fig. 3. Details of the indoor thermal measurement in house A, F, and K

Fig. 4. Residents filling the questioner survey in house D, M, and P

2.3. *Questionnaire surveys*

In addition to the measurement of the indoor thermal conditions, a questionnaire survey of the residents living in the target dwellings was conducted at their houses between 10 June and 8 August 2019, at times ranging from 9:00 am to 6:00 pm. The total number of respondents was 102 (47 males and 55 females), with ages ranging from 11 to 65 years old (see Fig. 4). The questionnaire consisted of ten questions related to demographic conditions, perceptions of the indoor thermal comfort in the current state, satisfaction regarding their indoor thermal environments, and daily behaviours for thermal adaptation in their houses. The questions related to the subjective thermal satisfaction, thermal preference votes (TPV), and thermal sensation votes (TSV) were designed based on ASHRAE 55 and ISO 7730. Two human factors in thermal comfort, namely clothing and metabolic rate (as estimated by physical state), were also surveyed. Meanwhile, the air temperature and relative humidity of the rooms where respondents stayed were obtained by the aforementioned thermometers. A detailed description of the questionnaire is provided in **Appendix A**.

Table 1. Wall materials of monitored dwellings

Type	Materials consisting walls ordered from inner to outer position	Dwelling labels
Type 1	Brick + Plywood board	G, K
Type 2	Plywood board	I
Type 3	Cement plaster + Brick +Plywood board	C
Type 4	Brick	E
Type 5	Cement plaster + Brick + Porcelain tile	Q
Type 6	Cement plaster + Brick + Cement plaster	A, B, D, F, H, J, L, M, N, O, P

Table 2. Measurement items and instruments

Measured variables	Instrument specifications	Recording interval	Location

Indoor air temperature (°C) and relative humidity (%)	TR-72nw T&D Corporation, accuracy ± 0.5 °C, ± 2.5% RH	10 min	17 houses
Outdoor air temperature (°C) and relative humidity (%)	S-THB-M002 Onset Computer Corporation, accuracy ± 0.21 °C, ± 2.5% RH	1 min	Open space of public-school building at 8 m height
Wind speed (m/s)	S-WCG-M003 Onset Computer Corporation, ultrasonic anemometer, accuracy ± 0.8 m/s	1 min	
Solar radiation (W/m^2)	S-LIB-M003 Onset Computer Corporation, accuracy ± 10 W/m^2	1 min	
Precipitation (mm)	S-RGF-M002 Onset Computer Corporation, rain gauge, accuracy ± 4% between 0.2 to 50 mm per hour, ± 5% between 50 to 100 mm per hour	1 min	

3. Results of field survey on indoor thermal environment

3.1. Weather conditions

The time variations in the hourly means of the outdoor air temperature, relative humidity, solar radiation, wind speed, and daily total precipitation are shown in Fig. 5. The outdoor air temperature fluctuated from 23 °C to 36 °C. The relative humidity was high, ranging from 42% to 99%. Such hot and humid weather is typical in the measurement period from the end of the wet season to the beginning of the dry season. The wind speed showed a distinct diurnal time scale and was weak, except for a period in April 28 and 29 with daily peaks of 4 m/s. From May, the beginning of the dry season, the wind speed showed an increasing trend. The average daily total precipitation was 8.4 mm; in contrast, 15 out of the 41 measurement days had no rain event. In addition, the daily total global solar radiation ranged from 10 MJ/m^2 to 20.7 MJ/m^2, with an average of 15.1 MJ/m^2day.

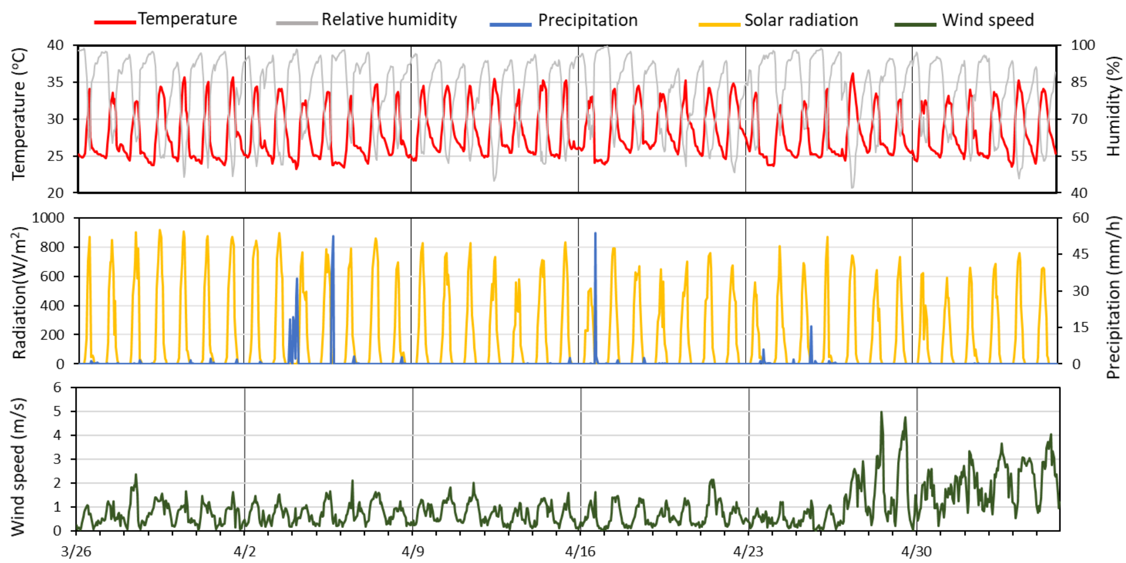


Fig. 5. Weather conditions during the period of 26 March to 5 May 2019

3.2. Occupants' behaviour schedules

Typical occupants' behaviour schedules related to room air temperature and occupants' thermal sensation were obtained from by the questionnaire survey (**Appendix A**) as shown in Fig. 6. Most dwellings were occupied by at least one resident during almost all of the 24 h except for house F, where each family member had outdoor activities between 9:00 to 15:00 (working or going to school).

Regarding thermal adaptation behaviours, most residents used an electric fan during the sleeping period. The duration of the use of electric fans varied from 2 to 12 h per day. In most houses, a combination of using fans and opening windows was employed during the daytime. However, some residents of houses A and G only opened windows and did not use fans, despite hot daytime hours. The times when residents start opening the windows were diverse, i.e. from 5:00 to 11:00 except for dwelling F, K and P where the occupants continuously closed the windows. According to additional interview, residents of two dwellings explained this behaviour is for security from thievery. In contrast, residents of another dwelling explained that opening windows does not have a significant cooling effect, oppositely, closing windows can reduce the odor from the sewerage close to their dwelling.

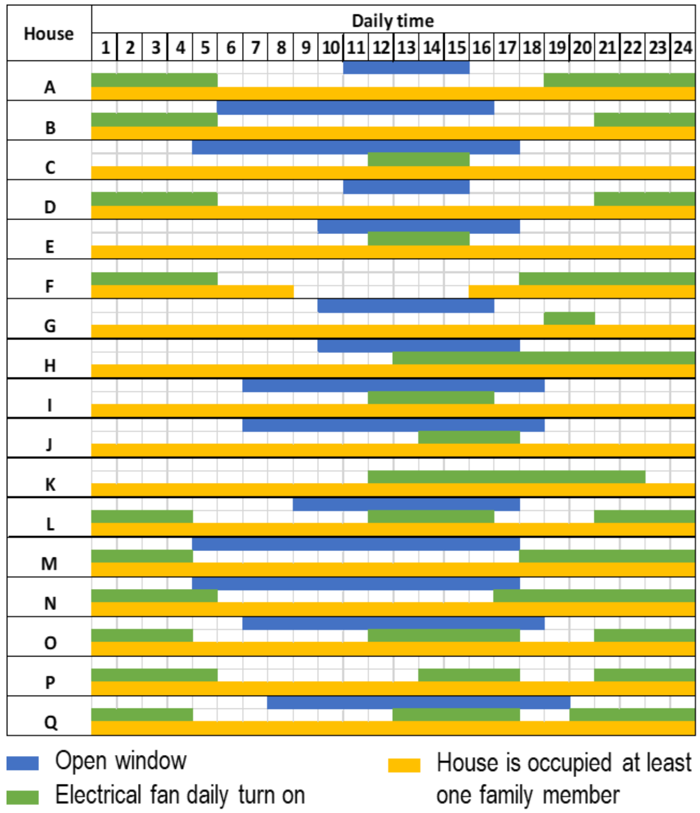


Fig. 6. Daily occupant thermal behaviour schedules in each dwelling

3.3 Diversity of room air temperature in the surveyed dwellings

Fig. 6 illustrates the averaged diurnal cycles of the room air temperatures in all of the measured dwellings. The indoor temperatures were higher than the outdoor temperatures at nighttime (18:00 to 06:00). In this period, dwellings having wall Type 6 were relatively warm, probably owing to the higher thermal mass of the building envelopes relative to other dwellings, as a higher amount of heat stored in the daytime is released to the indoor space of the house [21]. On the other hand, it is shown that wall Type 6 having diverse diurnal variations. For instance, two houses (H and O) showed a higher daily peak than the outdoor air temperature, but house L having the most stable indoor daily temperature compared to the other houses in daytime. Accordingly, it indicates the wall construction types that we classified is not effective to specify the features of room air temperature.

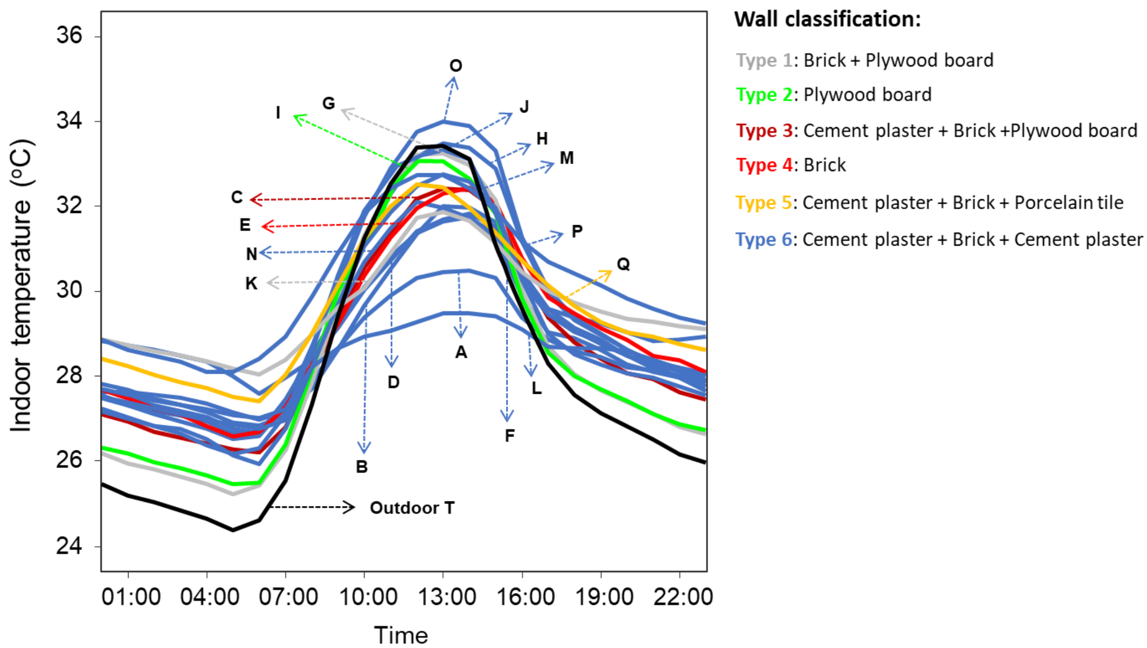


Fig. 7. Averaged diurnal cycle of indoor temperatures and outdoor temperatures (black line) during the measurement period

To characterize the daily variations of the room air temperature in each dwelling, we introduce *f* value for each dwelling as a representative information of diurnal variation of the room air temperature, and show the relation between *f* and Q (heat capacity of a building envelope per interior volume). We estimated a decrement factor *f*, expressed in Eq. (1) [22] as follows:

$$f = \frac{T_{i\_max} - T_{i\_min}}{T_{o\_max} - T_{o\_min}} \tag{1}$$

In the above, T_{i_max} and T_{i_min} are the daily maximum and minimum indoor temperature, respectively; and T_{o_max} and T_{o_min} are the daily maximum and minimum outdoor temperature, respectively. *f* indicates the ratio of the amplitude of the daily variation of the indoor temperature to that of the outdoor temperature. In this study, single *f* value was calculated based on an ensemble average of the daily variations for each dwelling during the entire measurement period.

In addition, the heat capacity of a building envelope per interior volume Q [J m^{-3}K^{-1}] was calculated for each dwelling using Eq. (2), based on the observed building materials and size.

$$Q = \frac{\sum_{i=1}^{n} C_i}{V} \quad (2)$$

Here, V is the indoor air volume of the dwelling [m^3], and indicates the total volume of all interior spaces within all rooms of a dwelling. The heat capacity for each component of a building envelope exposed to the outdoor air C_i is expressed as follows:

$$C_i = A_i \sum_j \rho_j C_{p,j} \Delta x_j \quad (3)$$

In the above, A_i is the area of a component i of the building envelope, such as a wall, roof, or window glass [m^2]; and ρ_j , $C_{p,j}$, and Δx_j are the density [kg m^{-3}], specific heat [J $kg^{-1}K^{-1}$], and thickness [m] of a layer j of the envelope, respectively. The standard thickness and thermal properties of construction materials provided by the National Standardization Body of Indonesia (ID number 03-6389-2011) were used for the estimation of Ci (see Appendix Table A2) [23]. The parameter Q indicates the influence of the thermal inertia of the building envelopes on the room air temperatures. Fig. 8 shows the relationship between the decrement factor f and Q. As expected, these two variables show a negative correlation, indicating that a larger thermal inertia causes a more stable daily fluctuation in room air temperature. House G, with the smallest heat capacity of 112.2 kJ $m^{-3}K^{-1}$ and classified into wall Type 1, shows the largest f, in addition to the largest amplitude of daily indoor temperature. In contrast, House B has the highest heat capacity at 144.5 kJ $m^{-3}K^{-1}$ and is classified into wall Type 6, but did not show the most stable indoor temperature.

As for the scatter of plots, one can theoretically point out potential factors. In case of three dwellings (L, B, and J) having top three large Q values and slightly different f values, presence of ceiling, wall type, U-value of roof, and schedule of window opening are similar. In contrast, the heat gain of the solar radiation on wall surfaces was probably different among the three dwellings due to the difference of the orientation and number of external walls enclosing measured room (See Table A1). The surveyed room of dwelling L was enclosed by three partition walls and only one external wall facing to north. As a result, the room air temperature of dwelling L might be not significantly affected by solar heating during the daytime, as shown in the lowest temperature at around noon of Fig.7, resulting the lowest f value.

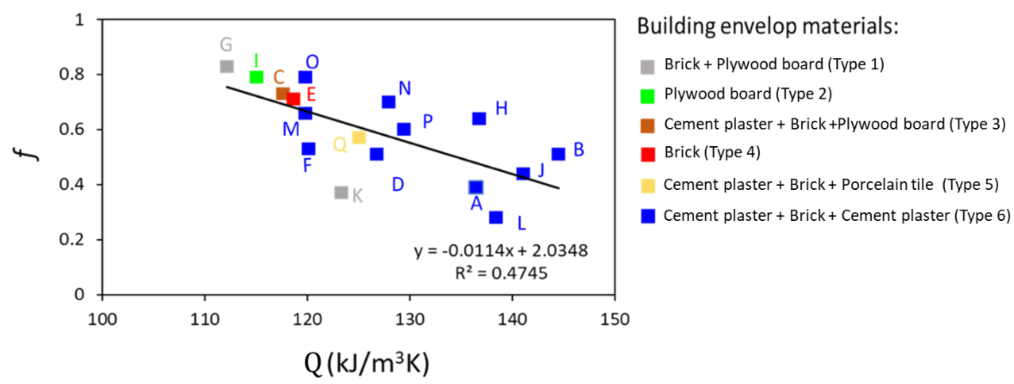


Fig. 8. Scatterplot and regression line demonstrating the relation between decrement factor *f* and heat capacity of a building envelope per interior volume Q

Fig. 9 shows the probability density distributions (PDDs) and cumulative probability distributions (CPDs) of the indoor air temperatures for the 17 dwellings. The ranges for 80% and 90% acceptability of the adaptive thermal comfort model in naturally ventilated spaces are also included. These ranges are estimated by using the mean outdoor temperature during the measurement period [24]. Similar to case with the averaged diurnal cycles of the room air temperatures, the PDDs of all dwellings show diverse features. In general, dwellings with higher Q values show a narrower temperature distribution, indicating that the time variations of the indoor air temperature are relatively small. In contrast, dwellings with lower Q values show a relatively wide distribution, indicating large indoor air temperature variations between daytime and nighttime. In addition, the CPDs shown in Fig. 9b reveals that approximately 38% to 80% of the total measurement period is above 29 ºC, and out of the range of 90% thermal acceptability.

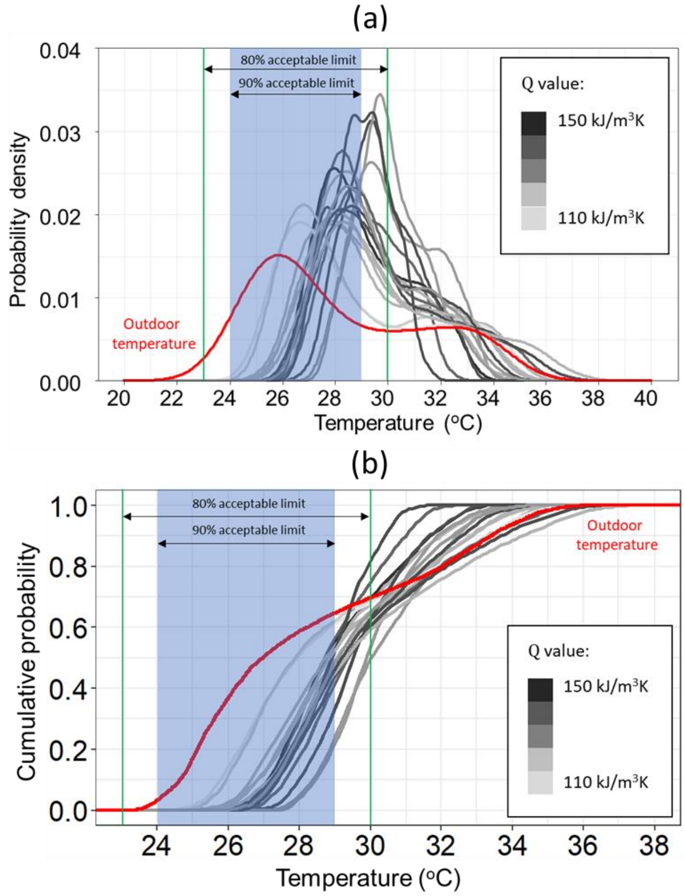


Fig. 9. (a) Probability density distributions (PDDs) and (b) cumulative probability distributions (CPDs) of indoor temperatures of 17 dwellings and outdoor temperatures during the measurement period

3.4 Statistical analysis of room air temperature and thermophysical factors of dwellings

According to a basic knowledge of building physics, the room air temperature of a naturally ventilated building is mainly affected by convective heat transfer from the inner surfaces of building envelopes, and ventilation from outdoor air. Based on such knowledge, if the architectural designs, including the materials and dimensions of each part, are known, it is easy to predict the indoor temperature and air conditioning load. However, in districts with informal urban settlements such as Kampung, where extremely simple low-cost dwellings with various materials and designs are haphazardly concentrated, the usual legitimate approach to estimating building thermal properties cannot be applied, in both the preconstruction stage and in retrofitting for existing dwellings. To clarify simple and easy housing variables, which enable to identify dwellings with a higher heat risk, the authors conducted a statistical analysis of the observed room air temperatures.

Table 3 shows the correlation coefficients for the monitored percentiles of room air temperatures in each dwelling ($T_{P2.5}$, T_{P25}, T_{P50}, T_{P75}, and $T_{P97.5}$), with nine variables related to the building design, thermophysical variable Q, and occupants' thermal behaviours. A Spearman's rank correlation with a confidence interval (CI) of 95% was applied to investigate the strength and direction of the relationship (negative or positive) between these variables. As expected, the house volumetric heat capacity Q shows highest correlation coefficient for $T_{P2.5}$, T_{P25}, and $T_{P97.5}$. Considering the physical meaning of Q, the high correlation is not surprising. Nevertheless, it is instructive that dwellings having lower Q values tend to have a higher heat risk during the daytime, and vice versa for sleeping time. However, the ratio of the floor area per house volume, i.e. the inverse of the ceiling height, shows relatively high correlation coefficients for T_{p75} and $T_{p07.5}$. This result indicates that houses with lower ceiling heights are likely exposed to a higher heat risk during the daytime. The other variables, such as the fraction of each building envelope to the room volume and occupants' related indices, were not statistically significant.

Table 3. Spearman's rank correlation test of percentile values (2.5%, 25%, 50%, 75%, and 97.5%) of indoor temperatures against thermophysical variables of dwellings and thermal behavioural variables

Variables	Correlation coefficient between percentile and variables				
	2.5^{th} : $T_{P2.5}$	25^{th}: T_{P25}	50^{th}: T_{P50}	75^{th} : T_{P75}	97.5^{th} :$T_{P97.5}$
Wall area per interior volume	0.03 (0.907)	-0.04 (0.877)	-0.14 (0.578)	-0.27 (0.290)	-0.30 (0.249)
Roof area per interior volume	-0.05 (0.840)	-0.25 (0.334)	-0.21 (0.415)	-0.40 (0.115)	-0.39 (0.119)
Window area per interior volume	-0.05 (0.847)	-0.04 (0.870)	-0.26 (0.312)	-0.39 (0.125)	-0.25 (0.330)
Floor area per interior volume	-0.02 (0.940)	-0.12 (0.651)	-0.26 (0.311)	**-0.53** **(0.027)**	-0.42 (0.090)
Occupants per floor area	-0.06 (0.825)	-0.08 (0.771)	-0.09 (0.739)	0.11 (0.682)	0.27 (0.288)
Ceiling height from the ground	0.19 (0.460)	0.15 (0.558)	0.09 (0.719)	-0.24 (0.377)	-0.37 (0.139)
Heat capacity of building envelope per volume (Q)	**0.64** **(0.006)**	**0.59** **(0.012)**	-0.37 (0.142)	-0.38 (0.134)	**-0.56** **(0.018)**

Duration of windows open in a day	-0.19 (0.457)	-0.12 (0.658)	-0.00 (0.992)	-0.20 (0.438)	0.35 (0.166)
Duration of electric wind fan usage in a day	0.33 (0.197)	0.40 (0.115)	0.32 (0.213)	-0.02 (0.930)	-0.02 (0.951)

*bold numbers indicated statistically significant correlation ($p < 0.05$) and numeral in parentheses is p-value.

3.5 Thermal comfort indices derived from observed data

In recent years, various studies have suggested that the estimated thermal comfort based on the PMV often shows a discrepancy from the actual thermal sensation votes of occupants in naturally ventilated buildings [21–23]. Accordingly, an approach denoting adaptive thermal comfort, which basically rely on questionnaire surveys at a target site to collect thermal sensation votes (TSVs) of occupants, has become popular as an adequate tool for estimating the comfortable temperature range in such buildings [27]. Considering these findings, the adaptive thermal comfort approach (rather than PMV) might be suitable for the evaluation of thermal comfort in the dwellings surveyed in this study. Nevertheless, we considered a PMV derived from personal (clothing insulation and metabolic rate) and environmental variables (air temperature, relative humidity, mean radiant temperature, and air velocity) as a comprehensive thermal comfort index, for a relative comparison of indoor thermal conditions among the surveyed dwellings [28]. In addition, PMV, which can be calculated by time-series observed data for 24 hours throughout the measurement period, is supposed to be advantageous to acquire large sample numbers to evaluate the overall heat risk of occupants.

Fig. 10 shows the averaged daily variations of the PMV for each dwelling, as derived from the observed room air temperature and relative humidity. The mean radiation temperature was assumed as equivalent to the measured room air temperature. In contrast, the wind speed was determined based on the results of the questionnaire survey related to the occupants' behaviour schedules (shown in Fig. 6). During the period when occupants used electric fans, the wind speed was assumed as 0.3 m/s; in contrast, when windows were opened, 0.2 m/s was adopted. In the remaining periods with no fans and no openings of windows, the wind speed was assumed as 0.1 m/s [29]. The metabolic rate was determined as 1 met, which is equivalent to the occupant' activity level when we conducted the questionnaire survey. In addition, the clothing value was calculated based on the combination of clothes that the occupant wore, and ranged from 0.5 to 0.7.

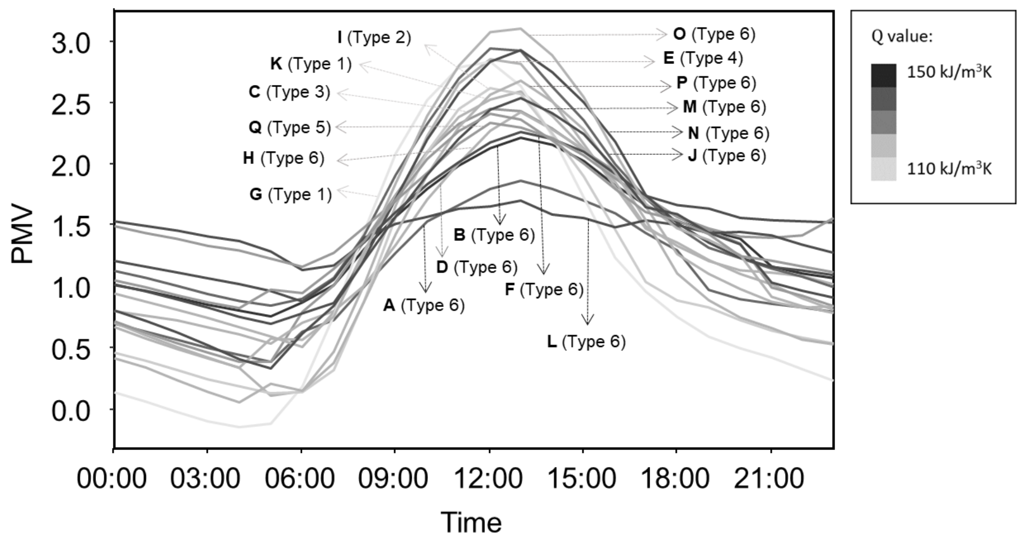


Fig. 10. Averaged diurnal cycles of predicted mean vote (PMV) for 17 dwellings

In general, the diurnal cycles of the PMV show similar features based on the diverse daily amplitudes of room air temperatures, as shown in Fig. 7. The daily peaks of the PMV arise from 12:20 to 14:20, with a range of 1.8 to 3.2; these values fail the standard of thermal comfort suggested by ASHRAE 55, except for two houses (G and I). These dwellings exhibited an acceptable thermal comfort range at night for approximately 7 and 4 h, respectively. In other words, dwellings with light building materials (wall Types 1 and 2) and thus relatively low Q values were beneficial to achieving an acceptable thermal environment during most of the sleeping period.

Houses A and L showed the best indoor thermal environments in terms of the mitigation of hot sensations in the activity period, with the PMV values lower than 2, whereas the other dwellings showed PMV values ranging from 2.2 to 3.2. However, house L experienced a higher PMV than most of other dwellings in the sleeping period with a PMV value greater than 1.3, whereas the other dwellings could achieve cooler conditions, with PMV values range between 0.1 to 1.2. This trend suggests that higher values of Q in dwellings will help achieve cooler conditions as compared to lower Q values in activity times, as expected; nonetheless, they will lead to a hotter indoor environment during the sleeping time.

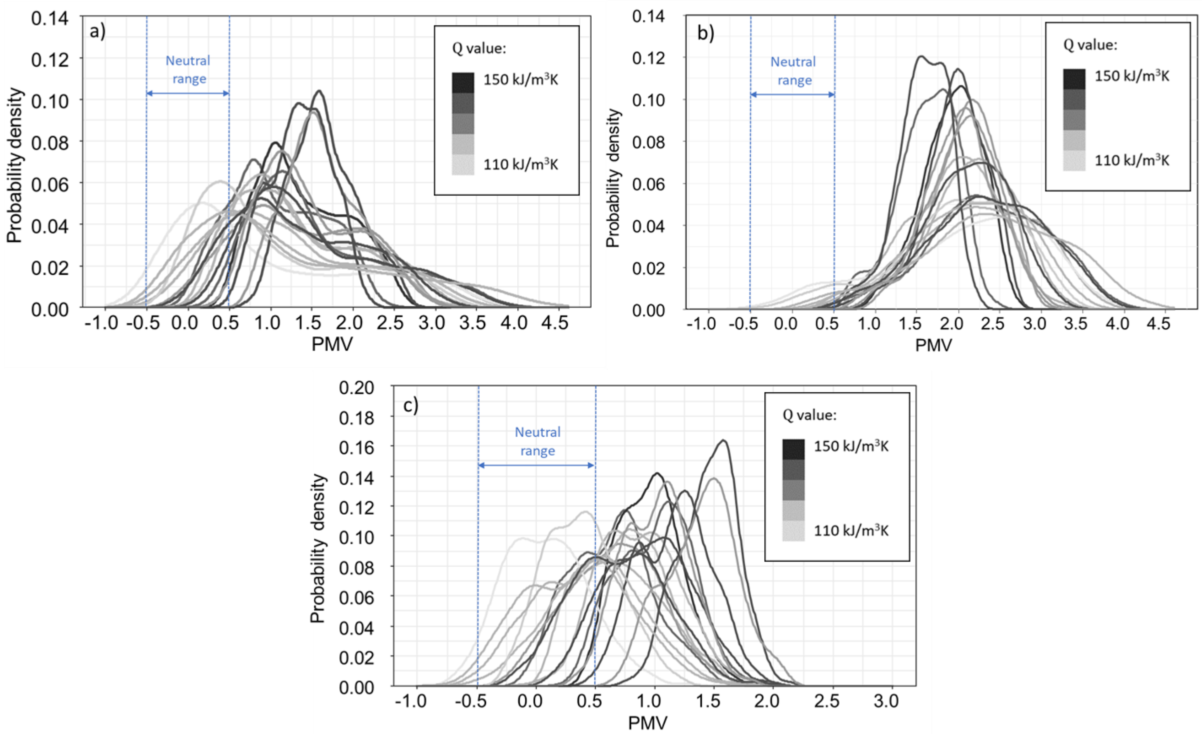


Fig. 11. Probability density distributions of PMV based daily occupant behaviour model during the period of measurement: (a) all period, (b) activity period and (c) sleeping period

The PDDs and CPDs of the PMVs in all of the dwellings are shown in Figs. 11 and 12. The data were classified into three time periods: the entire observed period, activity period, and sleeping period. The latter two periods were determined based on the questionnaire results from each dwelling, as shown in Fig. 9. As can be seen from the graphs, the PDDs of all dwellings show diverse patterns, ranging between -1 and +4.6 during the entire measurement period (see Fig. 11a). The CPDs of all dwellings shown in Fig. 12a illustrate that 20% of monitoring period had a PMV value higher than 1.8. Despite the differences in building construction materials, all dwellings showed PMV values between 1.5 to 2.5 during most of their activity period, and 50% of the observed period showed PMV values of more than 1.7, as shown in Figs. 11b and 12b, respectively. During the sleeping period, the time fraction of the thermally neutral range of the PMV (lower than 0.5) varies among the dwellings, from 7% to 55%. This variety is generally consistent with the Q values, namely, dwellings with low Q values tend to have longer time period for the neutral range. Oppositely, in the activity period, dwellings with low Q values were found to have longer time periods for warm and hot conditions.

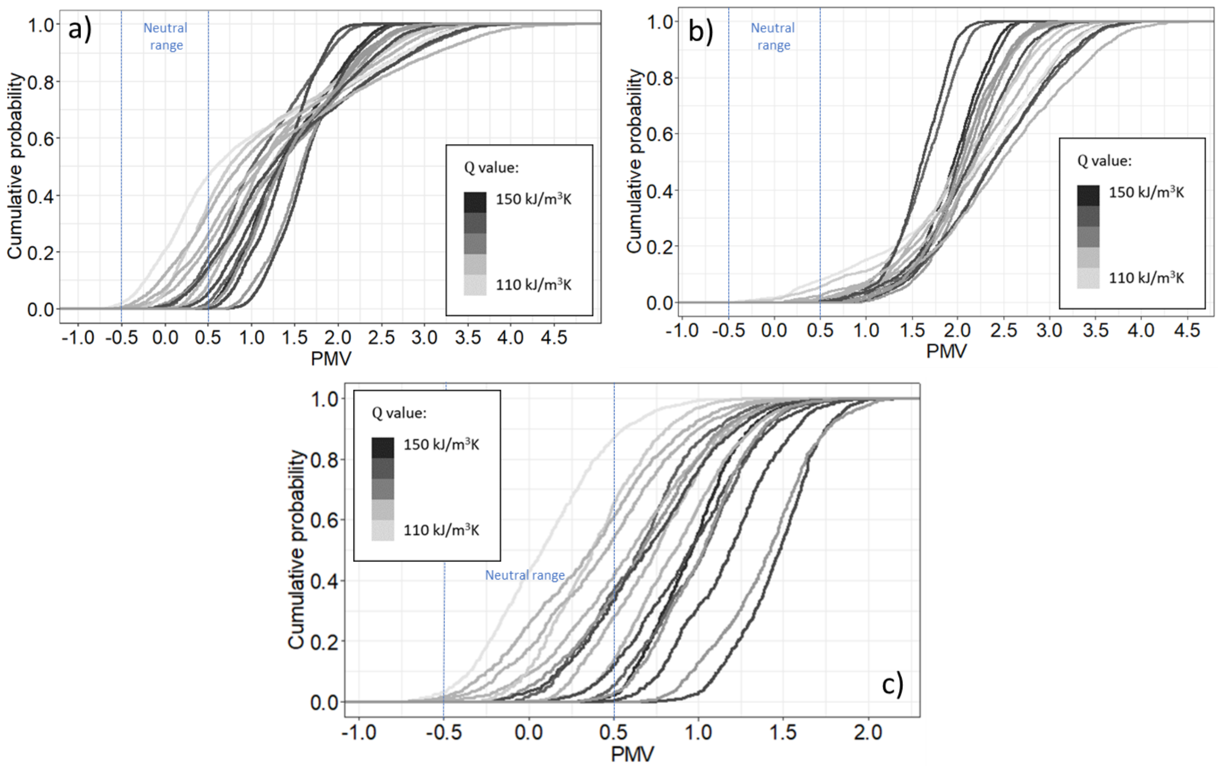


Fig. 12. Cumulative probability distributions of PMV based daily occupant behaviour model during the period of measurement: (a) all period, (b) activity period and (c) sleeping period

To identify affordable cooling measures in this district, it would be interesting to estimate the potential influence of the wind speed, which can be increased by natural ventilation or by less expensive electric fans. Accordingly, the authors estimated the PMVs of all dwellings under two conditions of wind speed, 0.1 m/s and 0.8 m/s. The air speed of 0.1 m/s represented the calm air conditions, whereas 0.8 m/s represented a condition of simultaneously using fans and opening windows. Fig. 13 shows the relations of the percentiles of the PMV between these two assumptions. The plots are almost in a linear line regardless of the percentile, and the reduction of the PMV owing to increased wind speed is more significant for low-PMV conditions. According to the estimation of the PMV shown in Figs. 11 and 12, the activity period is the time that requires mitigation to achieve thermal comfort, as compared to the sleeping period. However, Fig. 13 implies that the thermal mitigation effect of increasing the air speed during the activity period is generally weak, which is consistent with ASHRAE 55 2010 section 5.2.3.1 [24] and ISO 7730:2005 Annex G [29]. In contrast, increasing the air speed is more effective at lower air temperatures, such as during the sleeping period of the surveyed dwellings. This fact is in line with the observed occupants' behaviour, i.e. people tended to turn on an electrical fan during sleeping time (rather than during activity time, with higher indoor air temperature). Meanwhile, during the activity period, people might be more tolerant to a relatively hot indoor thermal environment, and accept the given conditions owing to the less-effective impact of using a wind fan and electricity to achieve thermal comfort. Thus, they might prefer to wear light clothing as a feasible alternative to mitigating the hot sensation.

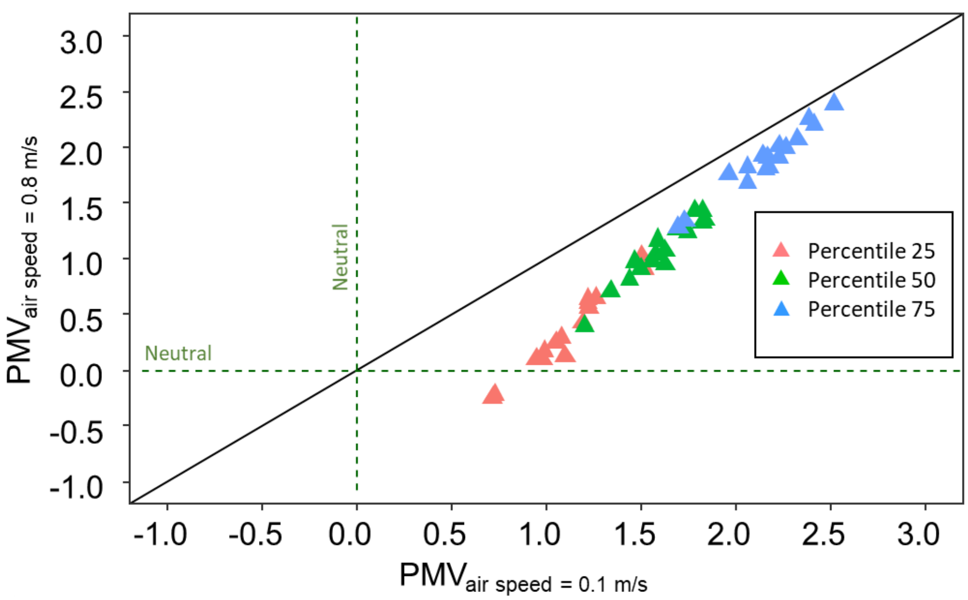


Fig. 13. Relation of percentiles of PMV as estimated with the assumption of calm air conditions of 0.1 m/s, and those with the assumption of air speed at 0.8 m/s [24]

4. Results of subjective thermal responses

4.1 Relation between thermal sensation vote (TSV), thermal preference vote (TPV), and indoor air temperature

Fig. 14 illustrate the TSV and TPV obtained by the questionnaire survey under the different condition of the indoor air temperatures. It indicates that all the occupants exposed to the room air temperature between 24.5 ºC to 27 ºC recognized as thermally neutral and no need to change. In contrast, for the condition of temperature from 30.5 to 31 ºC, only 20% of respondents answered that they felt thermally neutral while more than 50% answered warm or hot sensation. On the other hand, the temperature, at which respondents felt warm and preferred to have cooler conditions, ranged from 27-27.5 °C. All of the respondents were found to prefer cooler condition at the temperature above 32.5 °C.

In order to quantify the relationship between TSV and indoor temperature, we conducted the receiver operating characteristic (ROC) analysis with logistic regression model as shown in Fig. 15. It allows the diagnostic test evaluation between true positive rate (sensitivity) against the false positive (1-specificity) for each TSV scale [30]. The area under curve (AUC) with the value ranged between 0-1 indicates the probability of occupant sensitivity to detect temperature threshold of TSVs [31]. The higher area under the curve is, the better probability model to classify occupants' thermal sensations across all indoor temperature thresholds[32]. As a result, AUC values of TSV= 0 (neutral), TSV=1 (slightly warm), TSV=2 (warm), and TSV=3 (hot) were 0.804, 0.546, 0.428, and 0.774 respectively (see Fig. 15a). Considering the standard interpretation of AUC in which more than 0.7 is acceptable discrimination [33], the current result implies that a threshold value of indoor temperature to diagnose TSV is applicable for only TSV = 0 (neutral) and TSV =3 (hot). Meanwhile, Fig. 15b illustrates the CPDs of indoor temperatures for each TSV scale. It emphasizes the indoor temperature threshold of people to vote for thermal neutrality, slightly warm, warm, and hot sensations were 24.5-31 °C, 27.5-32 °C, 27-34.5 °C and 27.5-34.5 °C respectively.

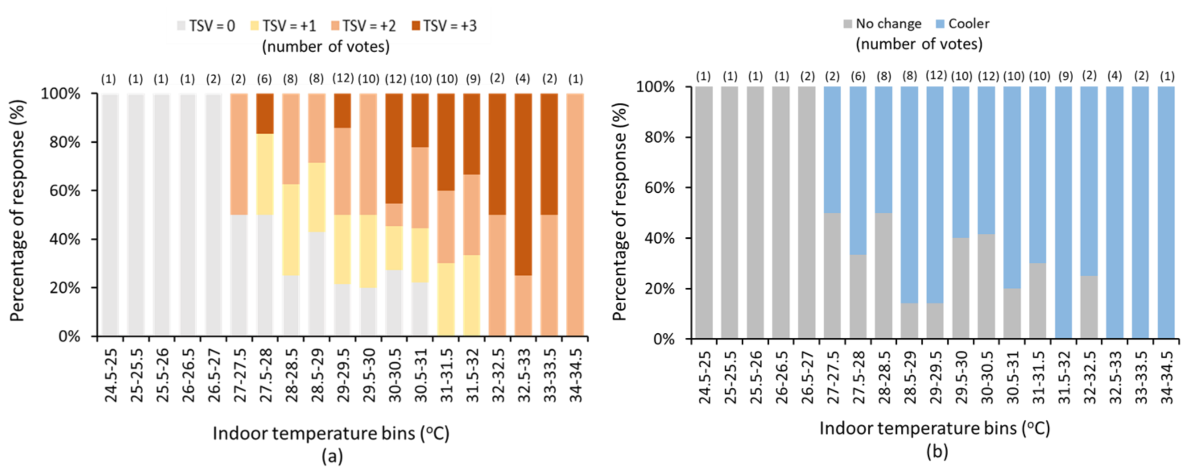


Fig. 14. Percentage of (a) TSVs and (b) TPVs against the increment of indoor temperature with 0.5 °C interval

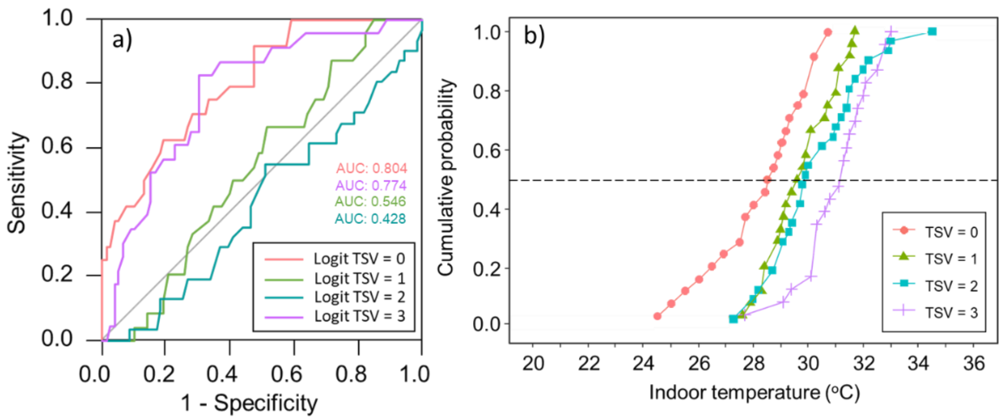


Fig. 15. (a) ROC curves of logistic regression and (b) cumulative probability distributions of indoor temperatures for each TSV scale

Fig. 16 shows a histogram of the comfort temperature T_c as derived from the Griffith method expressed by Eq. (4), with the assumption of a Griffith constant G of 0.33 °C $^{-1}$ according to previous field studies conducted in residential buildings[34–36].

$$T_c = T_a + (0 - TSV)/G \tag{4}$$

The histogram illustrates that the highest proportion of subjective comfortable temperatures from all respondents ranged between 28 °C and 30 °C, whereas the mean and median comfortable temperatures were 28.3 °C and 28.6 °C, respectively. This result is similar to the past three studies conducted in similar climate such as Jaipur City, India [25], Yogyakarta City, Indonesia [37], and Kinabalu City, Malaysia [38].

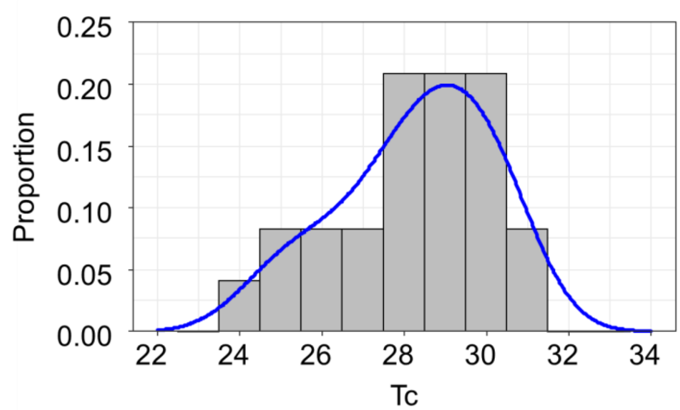


Fig. 16. Histogram of comfort temperature (T_c) from all respondents based on Griffith method

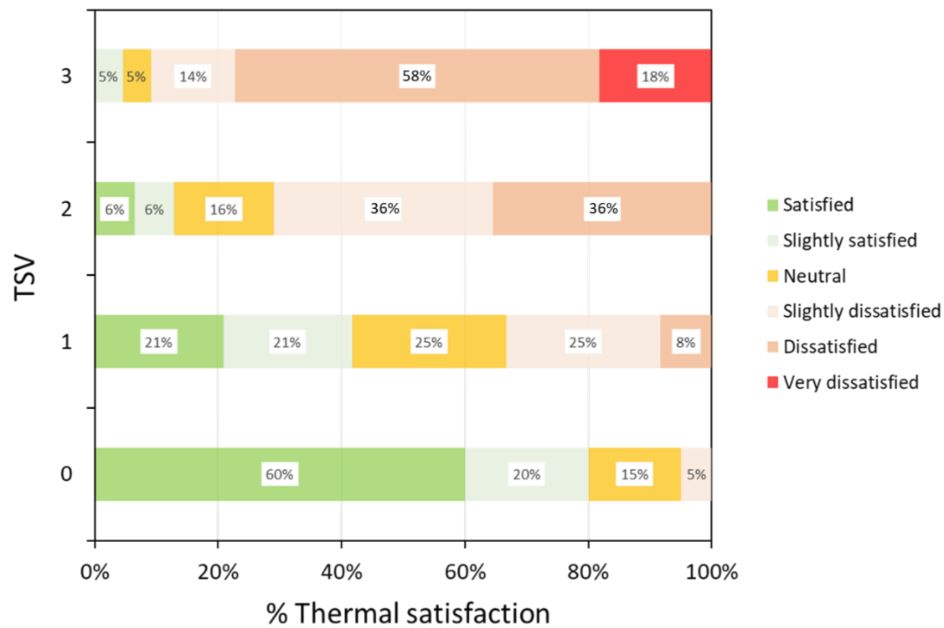


Fig. 17. Thermal satisfaction percentage for each TSV

1.1.Thermal satisfaction and thermal sensation

In addition to the TSV and TPV, the authors asked respondents regarding their satisfaction with the indoor thermal conditions. Fig. 17 illustrates the percentages of the thermal satisfaction levels of respondents, as classified by their TSVs. The ratio of positive answers including ‘Neutral’, ‘Slightly satisfied’, and ‘Satisfied’ were 95% (TSV = 0 or ‘Neutral’), 67% (TSV = 1 or ‘Slightly warm’), 28% (TSV = 2 or ‘Warm’), and 10% (TSV = 3 ‘Hot’). In contrast, the total observed percentages of negative answers, including the options of ‘Slightly dissatisfied’, ‘Dissatisfied’, and ‘Very dissatisfied’ were 5 % (TSV = 0), 33% (TSV = 1), 72% (TSV = 2), and 90% (TSV = 3). Notably, the predicted percentage of dissatisfied (PPD) values, as determined by PMV values at PMV = 1, 2, and 3, are 26%, 77%, and 99%, respectively. As pointed out by Cheung et al (2019), the PPD model is less accurate in tropical climate areas with larger discrepancies in warm sensations in naturally ventilated buildings [39], and the current analysis is consistent with the previous study.

2. Conclusion

This paper reported the results of a field measurement and questionnaire survey regarding the indoor thermal conditions of 17 low-cost dwellings located in a typical unplanned urban residential district in Surakarta City, Indonesia. The surveyed dwellings were selected to grasp the indoor thermal features of various conditions, including the building materials, area, occupants' behaviours, and household economic level.

The observed time series variations and PDDs of the indoor air temperature showed significant diversity among the 17 surveyed dwellings. Based on the observed indoor air temperatures, the decrement factor f, which refers to the ratio of the averaged daily amplitude of the indoor temperature to that of the outdoor temperature, was derived for each dwelling. It showed a strong linear correlation with the parameter Q, i.e. the heat capacity of a building envelope per unit interior volume, regardless of the occupants' behavioural conditions. In addition, a statistical test using Spearman's rank correlation indicated that both Q and the floor area per interior volume have significant correlations with the percentiles of indoor air temperatures. This suggests that the parameter Q and interior geometry of a dwelling can be utilized to detect vulnerable dwellings having a heat risk in Kampung districts.

The PDDs and CPDs of the estimated thermal comfort index PMVs suggested that most of the activity times in all of the surveyed dwellings were classified as out of thermally neutral conditions, i.e. they were slightly warm, warm, or hot. In contrast, the time fraction for the thermally neutral range of PMVs lower than 0.5 varied for the sleeping period among the dwellings, from 7% to 55%. This variation among dwellings is mainly attributed to the parameter Q, as dwellings with low Q values tend to have a longer time period in the neutral range. This fact suggests that rugged buildings made by heavy materials, which are usually considered as secure and favourable buildings in regions with cold winter, cannot necessarily provide a better indoor thermal environment in tropical regions if mechanical air-conditioning devices are not installed. A comparison of the estimated PMV values under two different assumptions of air speed indicated that any thermal mitigation owing to increased wind speed is not very evident during the daytime, with higher indoor temperatures than the sleeping period. This result might be a reason why people in the tropics living in naturally ventilated buildings tend to use an electric wind fan more frequently during nighttime rather than daytime.

This study demonstrated the necessity of the improvement of the current hot indoor environment and heat risk in low cost dwellings in Indonesia. Even though the number of surveyed dwellings was only 17 compared to numerous low-cost dwellings spreading in the country, the findings of this study can be interpreted as follows: A simple time-series measurement of indoor thermal variables in multiple dwellings with diverse building and behavioural conditions is possible to statistically clarify the influential factors of the indoor thermal quality. In addition, the determined factors can be utilized for detecting dwellings which need prior implementation of countermeasures. Although this paper is recognized as a case study in a district of Indonesia, the approach used in this study would be applicable for researchers, engineers and government officials that seek for health and comfort living environment toward sustainable development goals (SDGs) in various regions.

Acknowledgement

This project was partially funded by Robert T. Huang Entrepreneurship Center of Kyushu University and Obayashi Foundation. The authors are grateful for a support and assistance from all member of Urban-Rural Design and Conservation Laboratory, Department of Architecture, Sebelas Maret University, Indonesia. Thanks to Dr. Yosafat Winarto and Ms. Anita Dianingrum who strived to provide a conducive research activity especially to the students who accompanied the authors conducting field measurement.

Appendix A

Thermal Sensations and Occupant Behaviors Questionnaire

Date and time: ___/____/_____ at:

1. How are you feeling for the air temperature now? *(check only one)*
   ◯hot ◯ warm ◯ slightly warm ◯Neutral ◯slightly cool ◯ cool ◯ cold
2. How satisfied are you with the temperature now in your home? *(check only one)*
   ◯very satisfied ◯ satisfied ◯ slightly satisfied ◯Neutral ◯Slightly dissatisfied ◯ dissatisfied ◯ very dissatisfied
3. What would you prefer for the air temperature? *(check only one)*
   ◯much warmer ◯Bit warmer ◯No change ◯bit cooler ◯much cooler
4. What is your activity level right now? *(check the one that is most appropriate)*
   ◯reclining ◯seated ◯standing relaxed ◯light activity standing ◯medium activity
5. Using the list below, please check each item of clothing that you are wearing right now (*check all that apply*)

Checklists	Items	Material	Clo	Additional notes
		Underwear		
	Bra	Foam/tricot	0.01	
	Panties	Knit cotton	0.03	
	Men's brief	Silk cotton	0.04	
	Full slip	Nylon-polyester	0.16	
	Men's tank top/sleeveless	Cotton	0.12	
		Shirts and Dress		
	Short sleeve knit sport shirt	Cotton	0.17	
	Short-sleeve dress shirt	Silk cotton	0.19	
	T-shirt	Cotton	0.08	
	Long-sleeve dress shirt	Silk cotton	0.25	
	Long-sleeve sweatshirt	Cotton	0.34	
	Sleeveless, scoop neck thin	Cotton	0.23	
	Short-sleeve shirtdress thin	Cotton-foam	0.29	
	Long-sleeve shirtdress (thick)/Gamis	Cotton	0.47	
	Light hijab	cotton	0.06	
	Medium Hijab	Knittwd nylon-lycra cotton	0.08	
	Heavy/long hijab	Synthetic nylon	0.25	
		Skirts and trousers		
	Skirt thin	Cotton-polyester	0.14	
	Long Skirt thick	Jeans Denim	0.23	

	Walking short	Jeans Denim	0.11	
	Walking short	Polyester	0.08	
	Sweat pant	Cotton	0.28	
	Straight trousers thin	Silk-cotton	0.15	
	Straight trousers thick	Jeans Denim	0.24	
Footwear				
	Socks	Knit	0.03	
	Slipper/sandals	Rubber	0.02	
	Shoes	Synthetic	0.02	

6. What do you usually do in the daytime? *(check all that apply)*
   ◯ washing the clothes ◯ cooking ◯family gathering ◯watching TV ◯home base production ◯Using Internet ◯other__________
7. When do you usually start your activities in the morning? ___ am
8. When do you usually stay at home? From _____ to ______
9. When do you usually sleep in the night? ___pm
10. When do you open or turn on following appliances in the house in daily? *(check all that apply)*

- **Window**:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

- **Fan**:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Table A1. Selected dwellings characteristics

House	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**
Orientation *	N, S	S, W, E	N, S, W	N, S	N, E	S, W	S, E	N, W	S, W	S, W	W	N	N, W	S, W	S, W	N, E	M, W
Wall area (m^2)	80.4	110.4	78.6	119.7	63.3	119.8	121.7	76.8	147.6	93.9	87	87	129.3	91.8	60.6	86.1	65.4
Wall material	Ip-B-Op	Ip-B-Op	Ip-B-Pb	Ip-B-Op	B	Ip-B-Op	B-Pb	Ip-B-Op	Pb	Ip-B-Op	B-Pb	Ip-B-Op	Ip-B-Op	Ip-B-Op	Ip-B-Op	Ip-B-Op	Ip-B-P
Roof area (m^2)	50.9	77.2	38.2	82.8	31.5	91.5	79.1	48.5	128.8	64.3	53.7	62.2	119.5	61.1	31.1	65	32.8
Roof Material	40%Ct-60%Ga	Ct	Ct	Ga	Ct	Ct	Ct	Ga	50%Ct-50%As	As	Ct	As	Ct	Ct	Ct	Ct	Ct
Floor area (m^2)	41.7	63.3	31.3	67.9	25.8	75	64.9	39.8	105.6	52.7	44	51	98	50.1	25.5	53.3	26.9
Floor material	P	P	P-Cp	P	P	P	Cp	P	P	P	Cp	P	P	P	P	P	P
Window area (m^2)	3	4.4	1.2	1.1	2.1	2.4	1.7	2.6	2.8	1.5	1.6	2.2	1.8	2.6	0.8	2.3	1.8
Window material	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG	SG
Occupants	8	3	4	2	4	8	6	8	9	4	4	5	7	5	4	2	4
Ceiling	Yes	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	No	No	No	No
Sensor location	Living room	Living room	Bedroom	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room	Living room
Q (kJ/m^3K)	136.4	144.5	117.6	126.7	118.6	120.1	112.2	136.7	115	141	123.3	138.4	119.8	127.9	119.8	129.4	125

*The orientation of walls which are exposed to outdoor air of the measured room; S = South; E = East; W = West; N = North; Ip = Inner cement plaster; B = Brick; Op = Outer cement plaster; Pb = Plywood board; P = Porcelain tile; Ct = Clay tile; Ga = Galvalume; As = Asbestos; Cp = Cement plaster; SG = Single glassed

Table A2. Thermal properties of building envelopes utilized for estimation of Q

Envelopes	Materials	Thickness (m)	Thermal Conductivity (W/m.K) [23,40]	Specific heat capacity (kJ/kg.K) [23]	Density (kg/m^3) [23]	U-Value (W/m^{2}K)	Dwelling labels
Wall Type 1	Brick	0.1 [41]	0.81	0.80	1920	1.32	G, K
	Plywood board	0.009 [42]	0.098	1.30	750		
Wall Type 2	Plywood board	0.009 [42]	0.098	1.30	750	1.57	I
Wall Type 3	Inner cement plaster	0.015 [43]	0.721	0.84	1762	1.28	C
	Brick	0.1 [41]	0.81	0.80	1920		
	Plywood board	0.009 [42]	0.098	1.30	750		
Wall Type 4	Brick	0.1 [41]	0.81	0.80	1920	1.50	E
Wall Type 5	Inner cement plaster	0.015 [43]	0.721	0.84	1762	1.44	Q
	Brick	0.1 [41]	0.81	0.80	1920		
	Porcelain tile	0.007 [44]	1.298	0.80	23000		
Wall Type 6	Inner cement plaster	0.015 [43]	0.721	0.84	1762	1.41	A, B, D, F, H, J, L, M, N, O, P
	Brick	0.1 [41]	0.81	0.80	1920		
	Outer cement plaster	0.015 [43]	0.721	0.84	1762		
Window	Single glassed	0.008 [45]	1.053	0.72	2512	1.81	All
Roof	Clay tile	0.01 [44]	0.71	0.62	1800	1.79	A, B, C, E, F, G, I, K, M, N, O, P, Q
	Asbestos	0.005 [44]	0.154	0.84	2000	1.73	L, I
	Galvalume steel	0.001 [44]	62	0.47	7850	1.84	D, A, H,

References

[1] UN, The World 's Cities in 2018, 2018.

[2] Y. Takane, Urban warming and future air-conditioning use in an Asian megacity : importance of positive feedback, Npj Clim. Atmos. Sci. 39 (2019) 1–11. https://doi.org/10.1038/s41612-019-0096-2.

[3] D. Lauwaet, H. Hooyberghs, B. Maiheu, W. Lefebvre, G. Driesen, S. Van Looy, K. De Ridder, Detailed urban heat island projections for cities worldwide: Dynamical downscaling CMIP5 global climate models, Climate. 3 (2015) 391–415. https://doi.org/10.3390/cli3020391.

[4] E. Birch, S. Wachter, Sustainable Urbanization: Place Matters, Philadelphia, 2014.

[5] BPS, 2019 Statistical Yearbook of Indonesia, 2019.

[6] World Bank, Indonesia's Urban Story, 2016.

[7] H. Marhaeni, Indonesia poverty profile in 2019, 2019.

[8] N.E. mortalit. Klepeis, W.C. Nelson, W.R. Ott, J.P. Robinson, A.M. Tsang, P. Switzer, J. V. Behar, S.C. Hern, W.H. Engelmann, The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants, J. Expo. Anal. Environ. Epidemiol. 11 (2001) 231–252. https://doi.org/10.1038/sj.jea.7500165.

[9] N. Nazarian, N. Dumas, J. Kleissl, L. Norford, Effectiveness of cool walls on cooling load and urban temperature in a tropical climate, Energy Build. 187 (2019) 144–162. https://doi.org/10.1016/j.enbuild.2019.01.022.

[10] I. Tsoulou, C.J. Andrews, R. He, G. Mainelis, J. Senick, Summertime thermal conditions and senior resident behaviors in public housing: A case study in Elizabeth, NJ, USA, Build. Environ. 168 (2020) 106411. https://doi.org/10.1016/j.buildenv.2019.106411.

[11] A. Sakka, M. Santamouris, I. Livada, F. Nicol, M. Wilson, On the thermal performance of low income housing during heat waves, Energy Build. (2012). https://doi.org/10.1016/j.enbuild.2012.01.023.

[12] E. Nix, C. Shrubsole, P. Das, M. Davies, Indoor environmental quality of low-income housing in Delhi, India: Findings from a field study, in: Energy Procedia, 2015. https://doi.org/10.1016/j.egypro.2015.11.714.

[13] A. Hashemi, Effects of thermal insulation on thermal comfort in low-income tropical housing, Energy Procedia. 134 (2017) 815–824. https://doi.org/10.1016/j.egypro.2017.09.535.

[14] A. Nutkiewicz, R.K. Jain, R. Bardhan, Energy modeling of urban informal settlement redevelopment: Exploring design parameters for optimal thermal comfort in Dharavi, Mumbai, India, Appl. Energy. 231 (2018) 433–445. https://doi.org/10.1016/j.apenergy.2018.09.002.

[15] I.A.W. Hutama, Exploring the Sense of Place of an Urban, University of Twente, 2016.

[16] R. Fillaili, Addressing Urban Poverty: Increasing Learning on Urban Poverty Reduction in Kota Surakarta and Kota Makassar , Indonesia Increasing Learning on Urban Poverty Reduction, Jakarta, 2011. https://www.smeru.or.id/sites/default/files/publication/urbanpoverty_eng.pdf.

[17] Dinas Kependudukan, Civil Development Report of Surakarta 2016, 2016.

[18] T.H. Karyono, Predicting comfort temperature in Indonesia, an initial step to reduce cooling energy consumption, Buildings. 5 (2015) 802–813. https://doi.org/10.3390/buildings5030802.

[19] Isharyanto, Responding to climate change: Surakarta city tourism on legal and policy perspectives, IOP Conf. Ser. Earth Environ. Sci. 200 (2018) 1–4. https://doi.org/10.1088/1755-1315/200/1/012047.

[20] BPS, Surakarta in figure 2012-2018, 2019.

[21] B. Givoni, Climate Consideration in Buildings and Urban Design, John Wiley & Sons, New York, 1998.

[22] L. Bellahcene, A. Cheknane, S. Bekkouche, D. Sahel, The effect of the thermal inertia on the thermal transfer in building wall, E3S Web Conf. 22 (2017) 00013. https://doi.org/10.1051/e3sconf/20172200013.

[23] SNI 03-6389-2011, Building Envelopes Standard for Energy Conservation (Indonesia Language), National Standardization Body of Indonesia, 2011.

[24] S.C. Turner, G. Paliaga, B.M. Lynch, E.A. Arens, R.M. Aynsley, G.S. Brager, J.J. Deringer, J.M. Ferguson, J.M. Filler, J.J. Hogeling, D. Int-hout, A.G. Kwok, H.F. Levy, E.M. Sterling, J.L. Stoops, S.T. Taylor, R.W. Tinsley, K.W. Cooper, K.W. Dean, F. Myers, J.C. Peterson, ASHRAE Standard 55-2010 Thermal environmental conditions for human occupancy, 2010 (2010) 30.

[25] S. Kumar, M.K. Singh, V. Loftness, J. Mathur, S. Mathur, Thermal comfort assessment and characteristics of occupant's behaviour in naturally ventilated buildings in composite climate of India, Energy Sustain. Dev. 33 (2016) 108–121. https://doi.org/10.1016/j.esd.2016.06.002.

[26] S.I.U.H. Gilani, M.H. Khan, W. Pao, Thermal Comfort Analysis of PMV Model Prediction in Air Conditioned and Naturally Ventilated Buildings, Energy Procedia. 75 (2015) 1373–1379. https://doi.org/10.1016/j.egypro.2015.07.218.

[27] R.J. De Dear, G.S. Brager, Thermal comfort in naturally ventilated buildings: Revisions to ASHRAE Standard 55, Energy Build. 34 (2002) 549–561. https://doi.org/10.1016/S0378-7788(02)00005-1.

[28] A. Omidvar, J. Kim, Modification of sweat evaporative heat loss in the PMV/PPD model to improve thermal comfort prediction in warm climates, Build. Environ. 176 (2020) 106868. https://doi.org/10.1016/j.buildenv.2020.106868.

[29] ISO E 7730, Ergonomics of the Thermal Environment. Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, International Standardisation Organisation, 2005.

[30] Y. Xie, J. Liu, T. Huang, J. Li, J. Niu, C.M. Mak, T. cheung Lee, Outdoor thermal sensation and logistic regression analysis of comfort range of meteorological parameters in Hong Kong, Build. Environ. 155 (2019) 175–186. https://doi.org/10.1016/j.buildenv.2019.03.035.

[31] Y. Ji, Z. Wang, Thermal adaptations and logistic regression analysis of thermal comfort in severe cold area based on two case studies, Energy Build. 205 (2019) 109560. https://doi.org/10.1016/j.enbuild.2019.109560.

[32] J. Kim, Y. Zhou, S. Schiavon, P. Raftery, G. Brager, Personal comfort models: Predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning, Build. Environ. 129 (2018) 96–106. https://doi.org/10.1016/j.buildenv.2017.12.011.

[33] S. Yang, G. Berdine, The receiver operating characteristic (ROC) curve, Southwest Respir. Crit. Care Chronicles. 5 (2017) 34. https://doi.org/10.12746/swrccc.v5i19.391.

[34] J. Ryu, J. Kim, W. Hong, R. de Dear, Defining the thermal sensitivity (Griffiths constant) of building occupants in the Korean residential context, Energy Build. 208 (2020) 109648. https://doi.org/10.1016/j.enbuild.2019.109648.

[35] R.F. Rupp, J. Kim, E. Ghisi, R. de Dear, Thermal sensitivity of occupants in different building typologies: The Griffiths Constant is a Variable, Energy Build. 200 (2019) 11–20. https://doi.org/10.1016/j.enbuild.2019.07.048.

[36] Z. Wu, N. Li, P. Wargocki, J. Peng, J. Li, H. Cui, Adaptive thermal comfort in naturally ventilated dormitory buildings in Changsha, China, Energy Build. 186 (2019) 56–70. https://doi.org/10.1016/j.enbuild.2019.01.029.

[37] H. Feriadi, N.H. Wong, Thermal comfort for naturally ventilated houses in Indonesia, Energy Build. 36 (2004) 614–626. https://doi.org/10.1016/j.enbuild.2004.01.011.

[38] H. Djamila, C.M. Chu, S. Kumaresan, Field study of thermal comfort in residential buildings in the

equatorial hot-humid climate of Malaysia, Build. Environ. 62 (2013) 133–142. https://doi.org/10.1016/j.buildenv.2013.01.017.

[39] T. Cheung, S. Schiavon, T. Parkinson, P. Li, G. Brager, Analysis of the accuracy on PMV – PPD model using the ASHRAE Global Thermal Comfort Database II, Build. Environ. 153 (2019) 205–217. https://doi.org/10.1016/j.buildenv.2019.01.055.

[40] Morrison Hershfield, Thermal Performance of Sheet Steel Wall, 2014.

[41] S. Handayani, Quality of Brick with Additional Sawdust (Indonesian Languange), Tek. Sipil Perenc. 12 (2010) 41–50. https://doi.org/10.15294/jtsp.v12i1.1339.

[42] A. Ramadhan, Kurniawan, Physical Properties of Plywoods (Indonesian Language), 2017.

[43] SNI-2837-2008, The Procedure for Building and Housing Construction, National Standardization Body of Indonesia, 2008.

[44] PUPR, Guideline for Housing Construction, Jakarta, 2016.

[45] SNI-14-0047-2005, Glass Layer Standard, National Standardization Body of Indonesia, 2005.

Figure

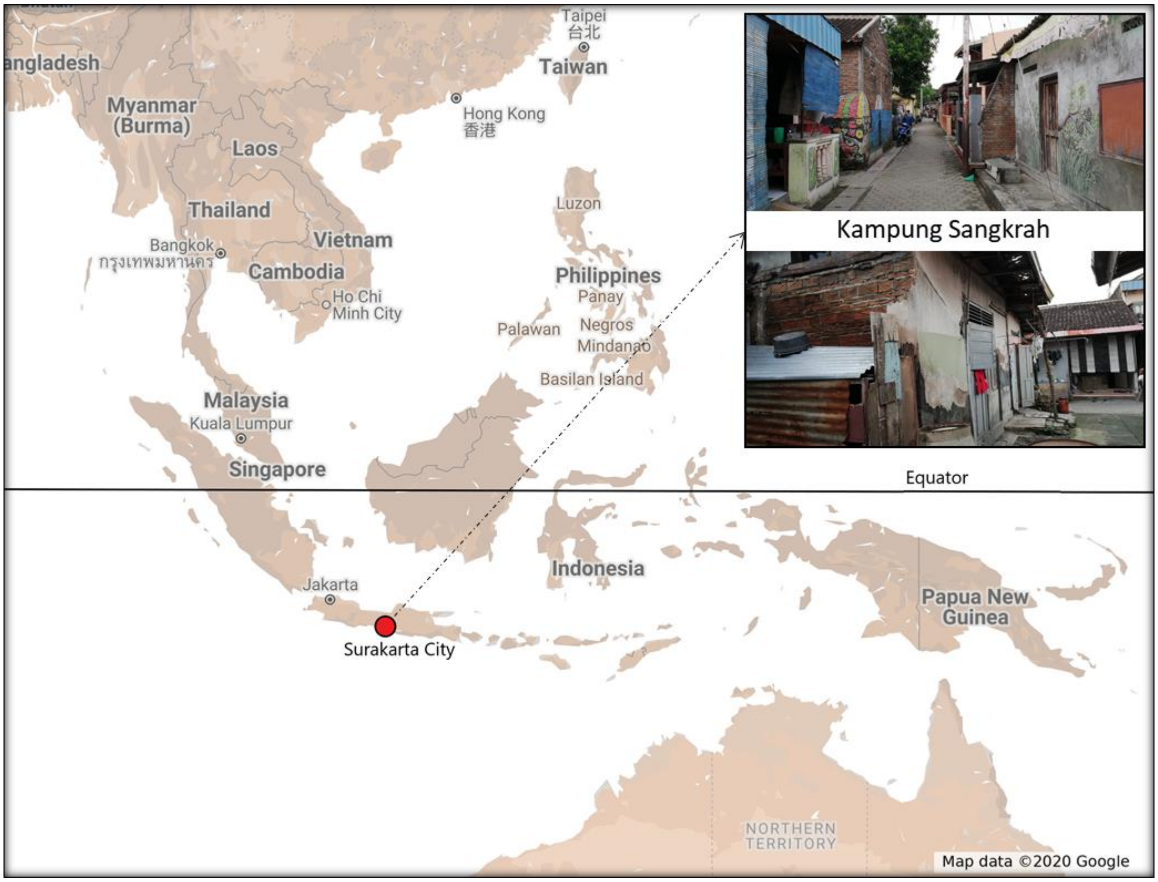


Fig. 1. A map of Indonesia (taken from Google maps) with target site Kampung Sangkrah in Surakarta City

Fig. 2. The location of Kampung Sangkrah, selected dwellings, and weather station site

Fig. 3. Details of the indoor thermal measurement in house A, F, and K

Fig. 4. Residents filling the questioner survey in house D, M, and P

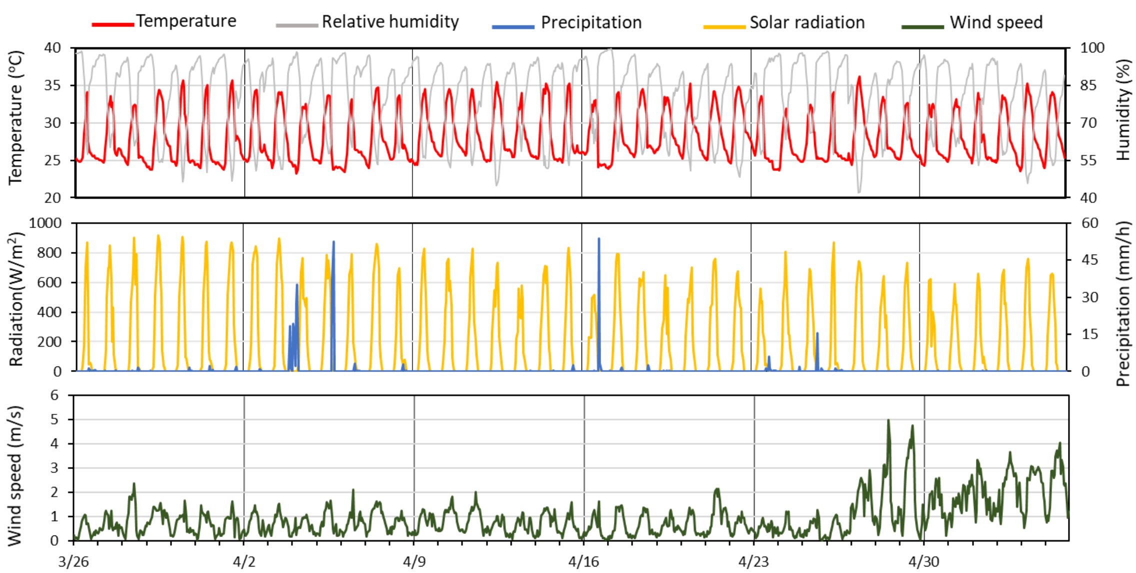


Fig. 5. Weather conditions during the period of 26 March to 5 May 2019

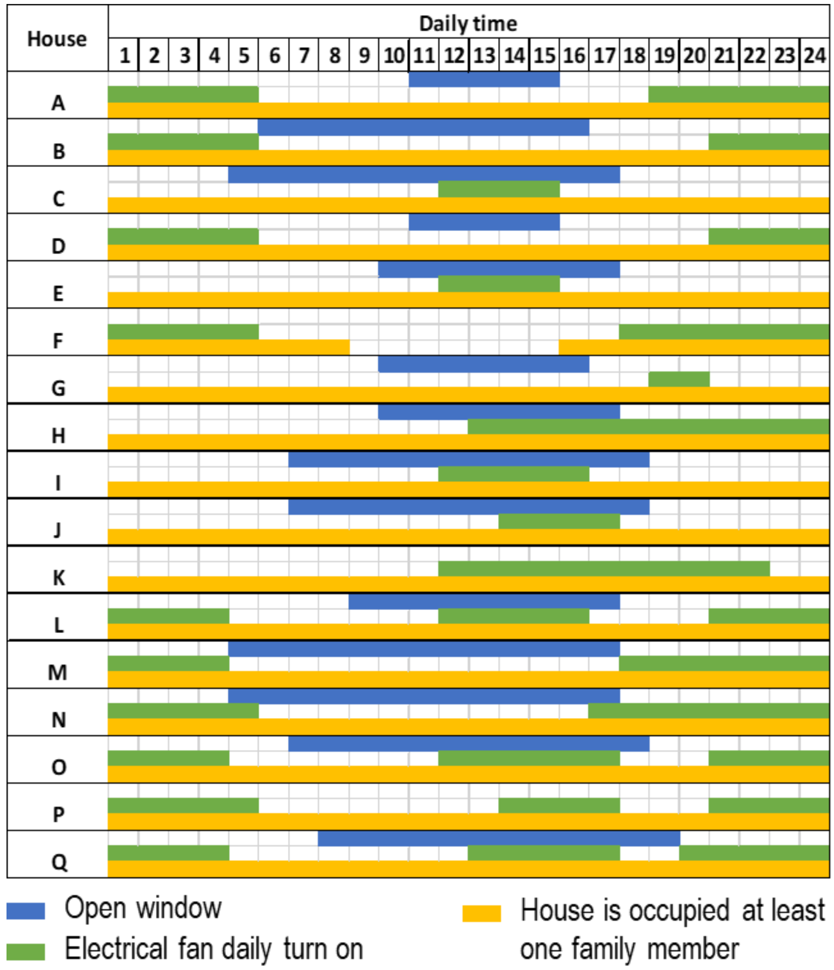


Fig. 6. Daily occupant' thermal behavior schedule in each dwelling

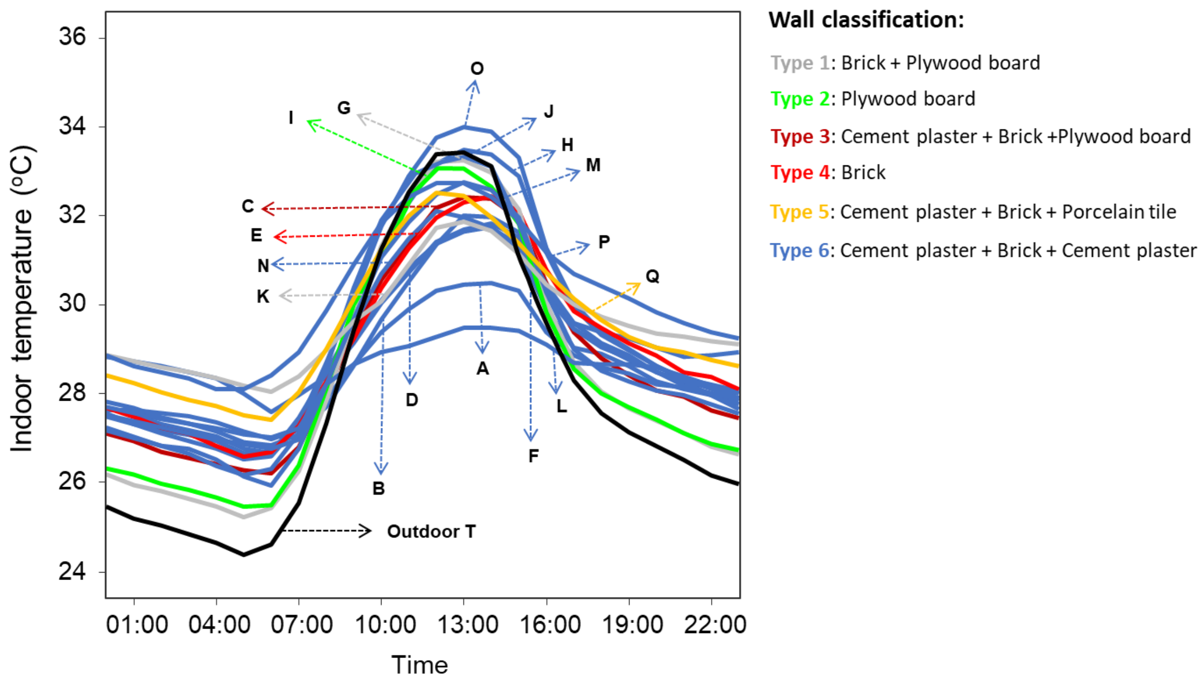


Fig. 7. Averaged diurnal cycle of indoor temperatures and outdoor temperatures (black line) during the measurement period

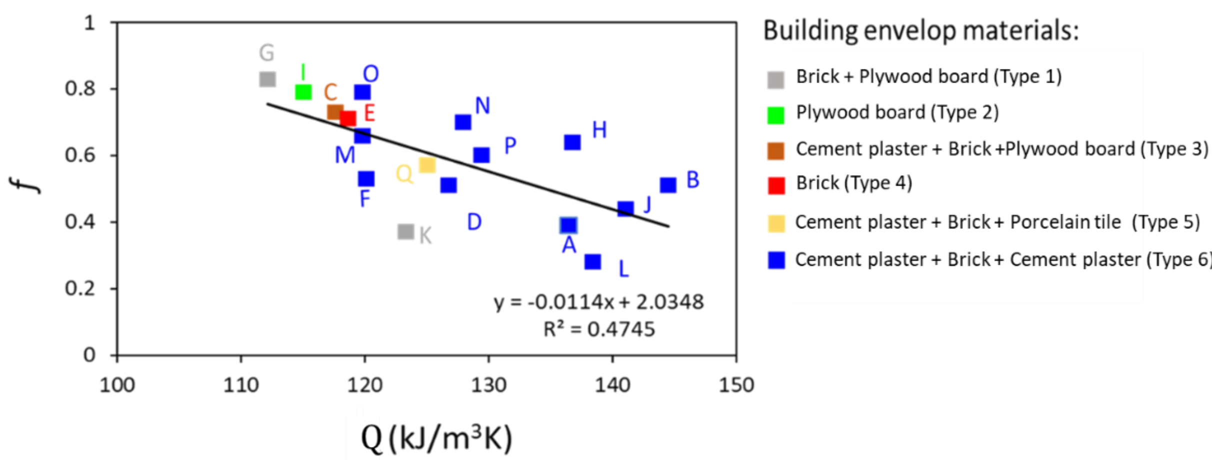
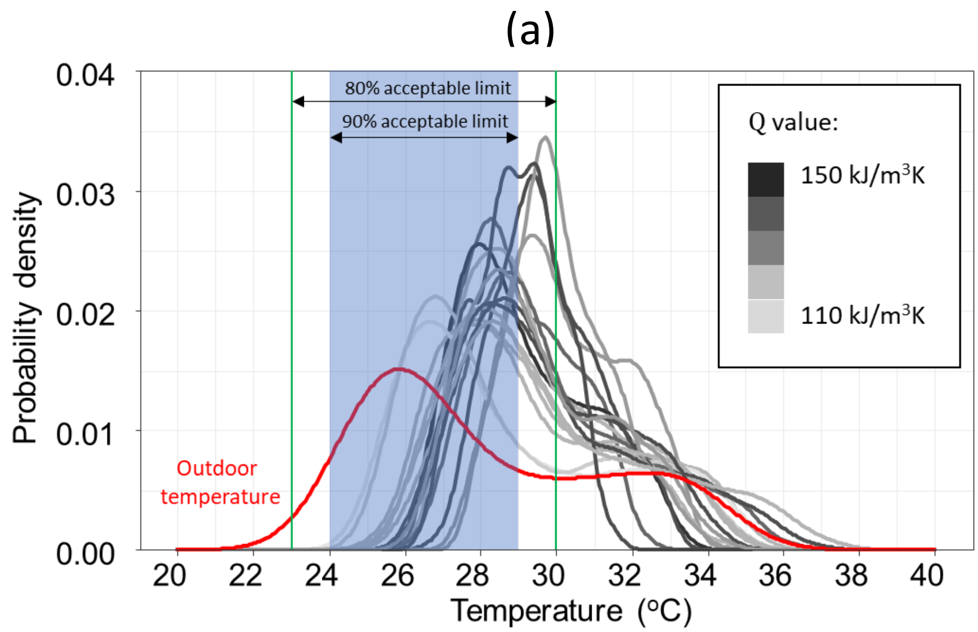


Fig. 8. Scatterplot and regression line demonstrating the relation between decrement factor *f* and heat capacity per house volume Q



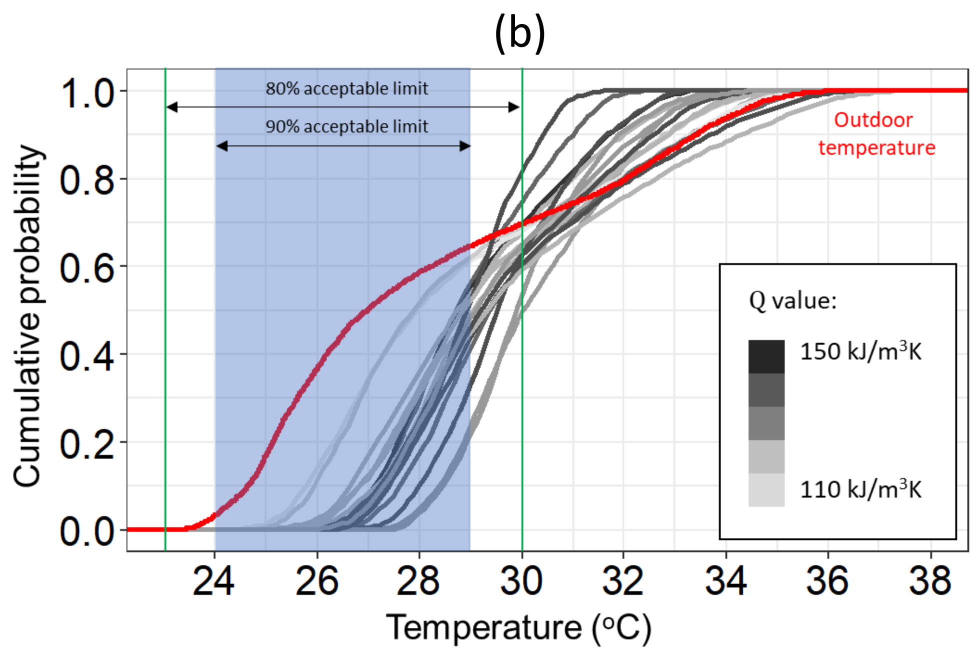


Fig. 9. (a) Probability density distributions (PDDs) and (b) cumulative probability distributions (CPDs) of indoor temperatures of 17 dwellings and outdoor temperatures during the measurement period

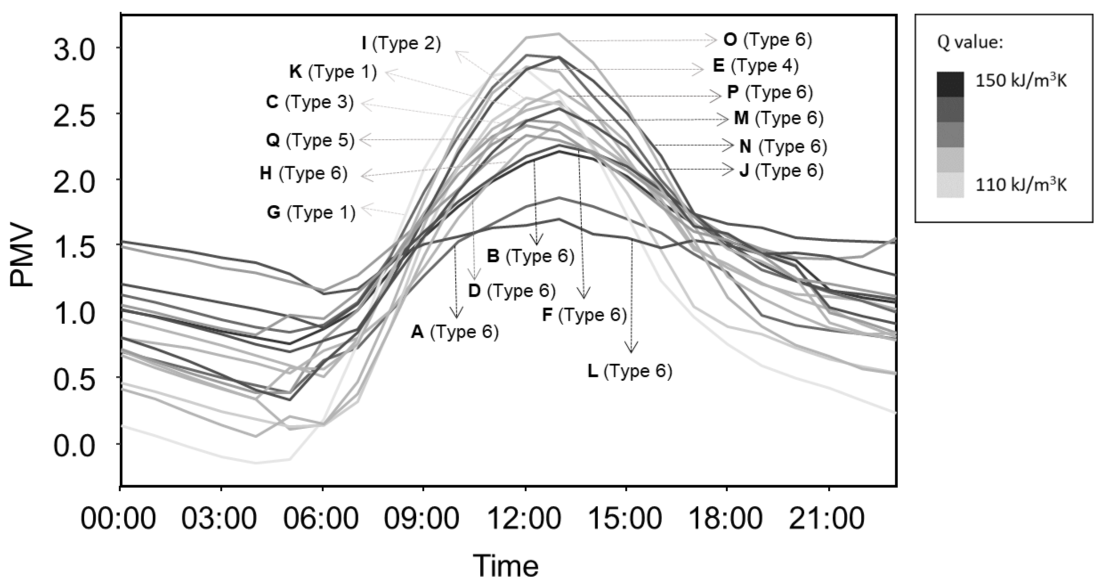


Fig. 10. Averaged diurnal cycles of predicted mean vote (PMV) for 17 dwellings

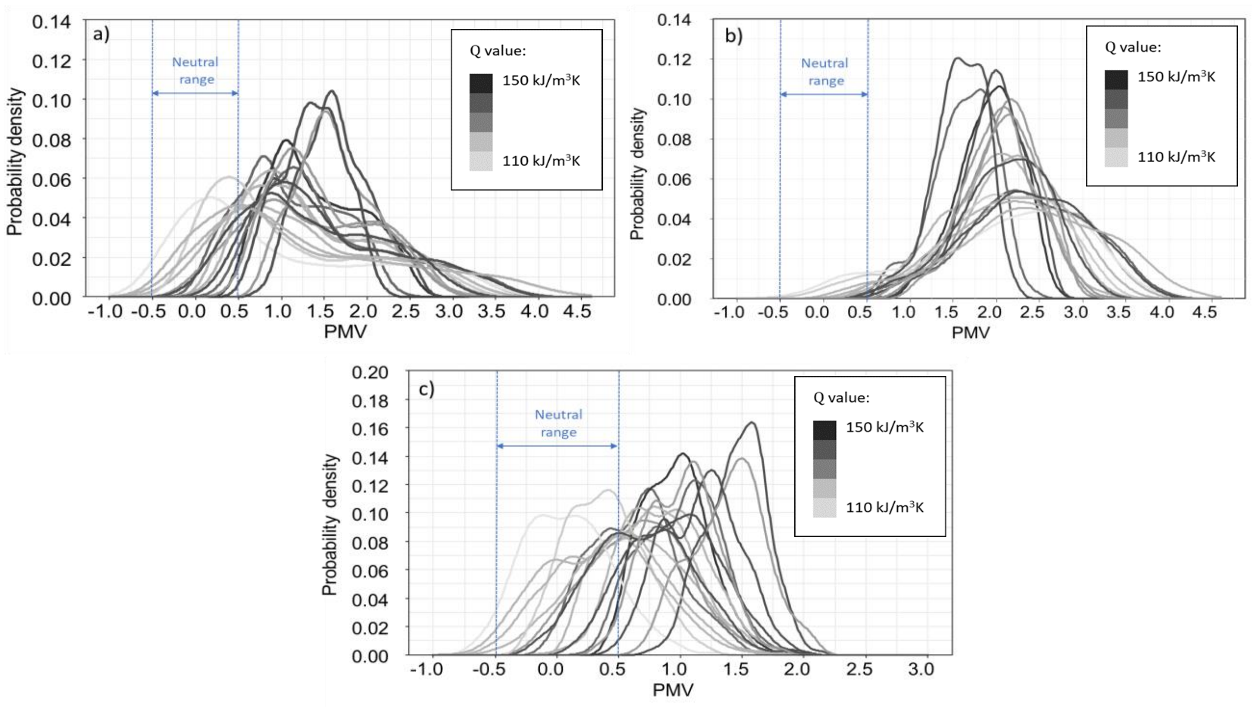


Fig. 11. Probability density of PMV based daily occupant behavior model during the period of measurement: (a) all period, (b) activity period and (c) sleeping period

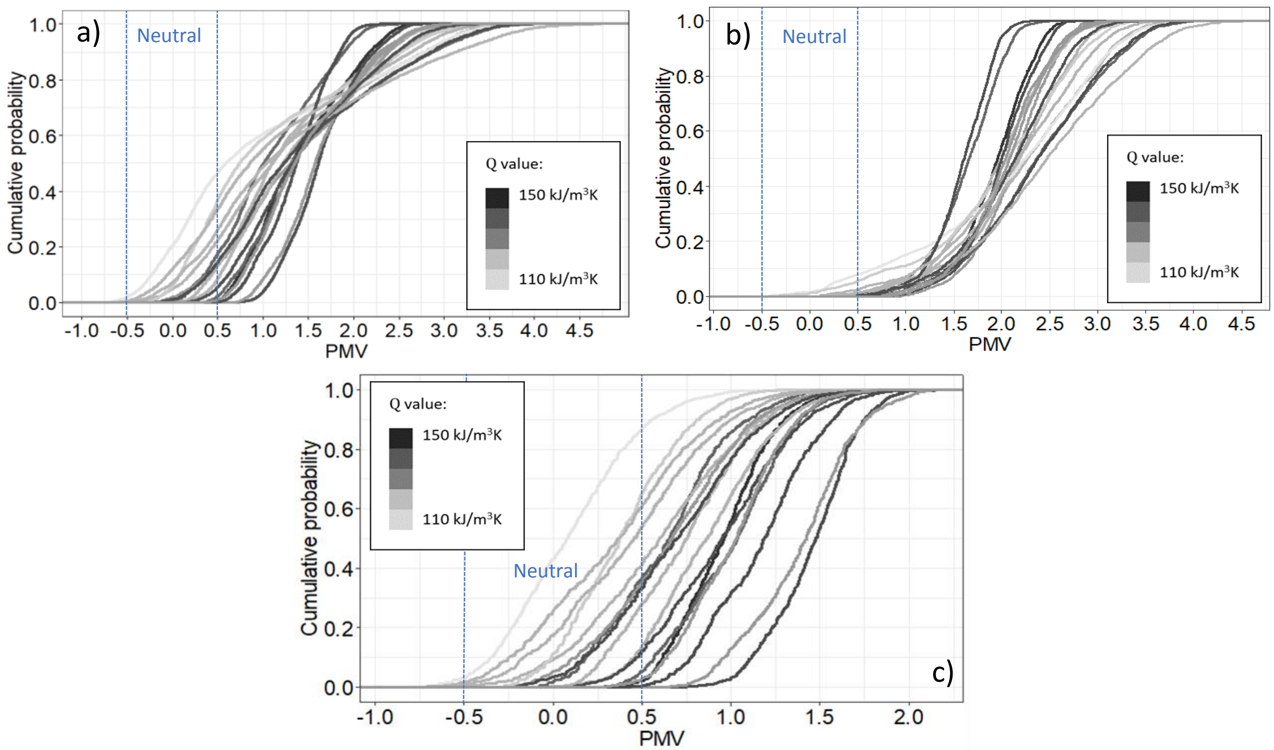


Fig. 12. Cumulative probability of PMV based daily occupant' behavior model during the period of measurement: (a) all period, (b) activity period and (c) sleeping period

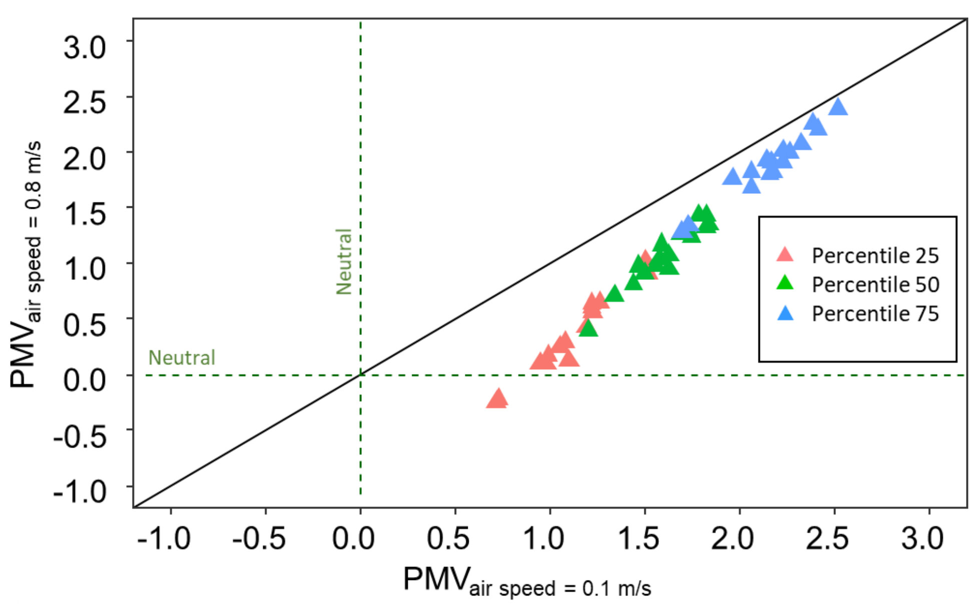


Fig. 13. Decreasing of estimated PMV considering the increase of air speed 0.8 m/s as the upper limit of average air speed without occupant control

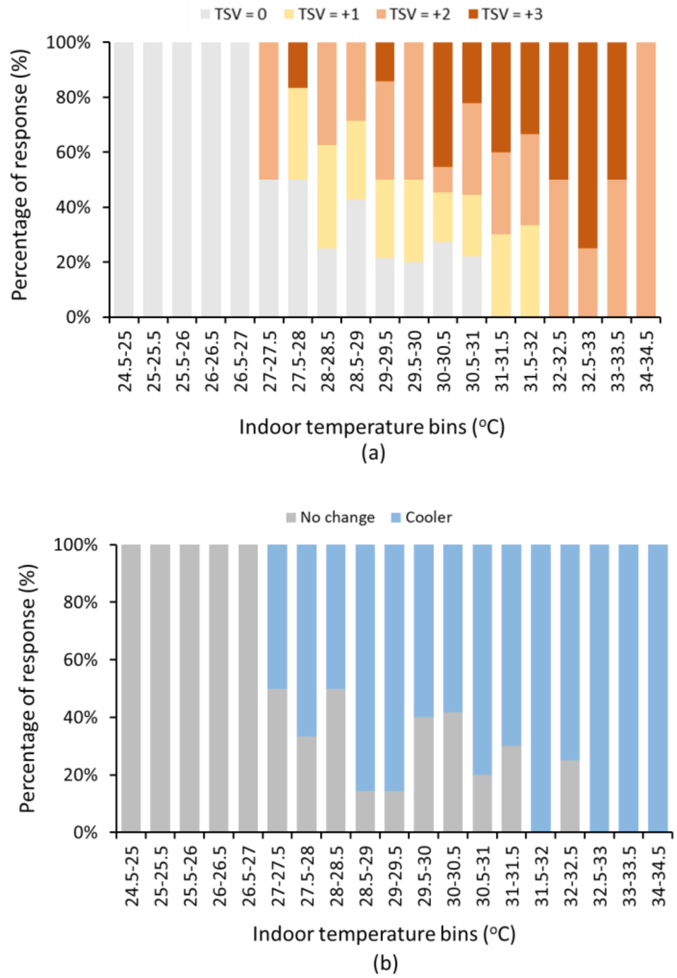


Fig. 14. Percentage of responses on (a) TSVs and (b) TPVs against the increment of indoor temperature with 0.5 ^{o}C interval

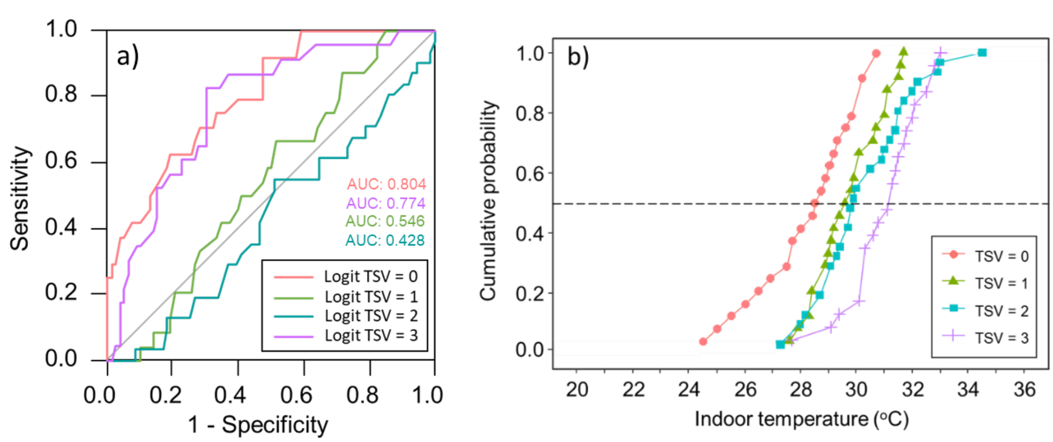


Fig. 15. ROC curves of logistic regression result for (a) TSVs and (b) TPVs

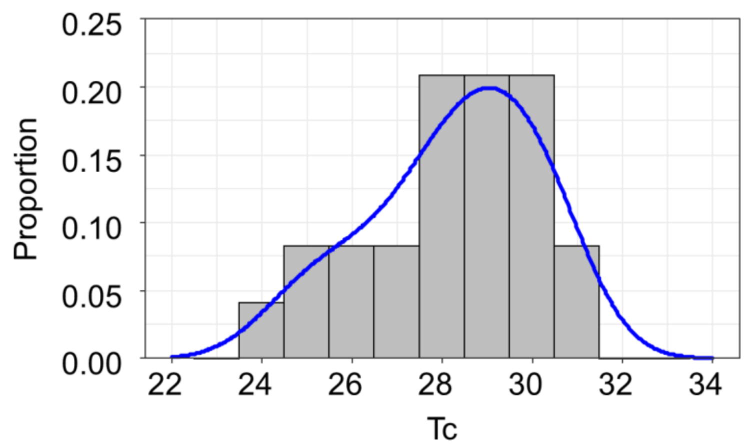


Fig. 16. Histogram of comfort temperature (T_c) from all respondents based on Griffith method

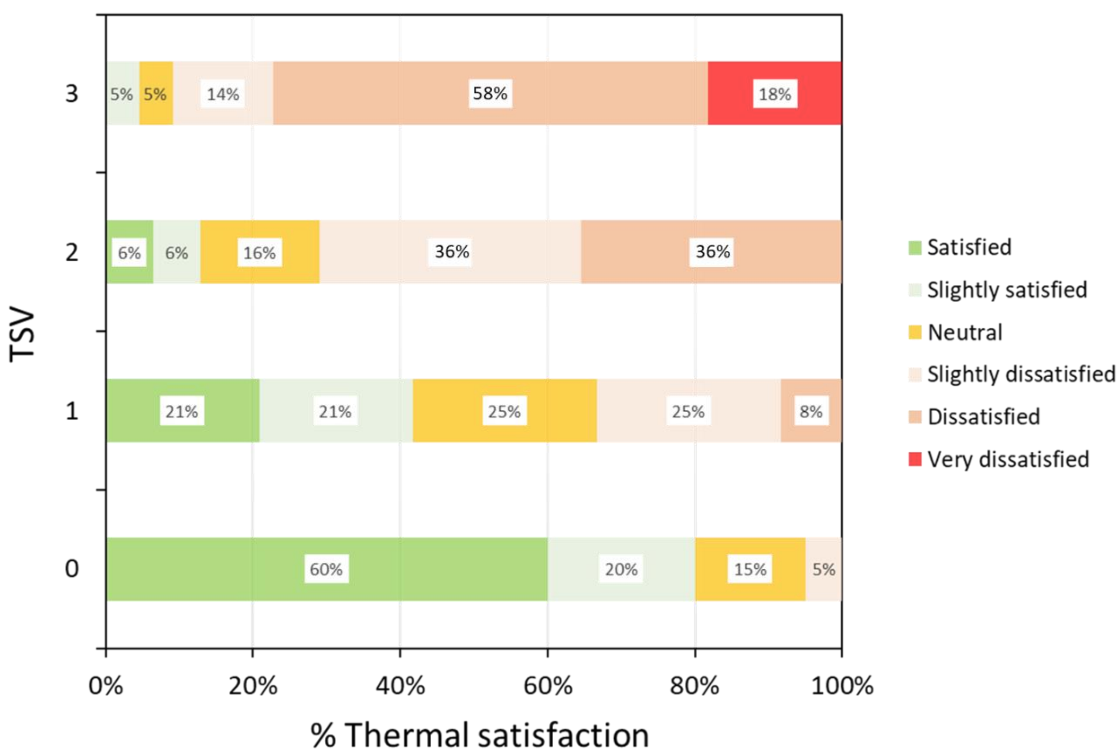


Fig. 17. Thermal satisfaction percentage for each thermal sensation vote