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IQBAL, Muhammad
Graduate School of Human-Environment Studies, Kyushu University : Doctoral Program

OZAKI, Akihito
Faculty of Human-Environment Studies, Kyushu University

CHOI, Younhee
Faculty of Human-Environment Studies, Kyushu University

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熱帯地域における自然換気住宅の室内熱的快適性の評価
Assessment of Indoor Thermal Comfort of Naturally Ventilated House in Tropical Region

ムハマド イクバル *，尾崎明仁 **，崔連希 **
Muhammad IQBAL*, Akihito OZAKI**, Younhee CHOI**

Even though the hot and humid conditions throughout the year, most Indonesian stay in a house that uses natural ventilation due to energy poverty and economic conditions. Commonly, they rely on natural ventilation by opening windows to achieve thermal comfort in the indoor environment. Therefore, an on-site survey and questionnaire were performed on more than 240 occupants and 115 naturally ventilated houses to investigate thermal comfort performance between two houses based on thermal sensation vote (TSV) and thermal comfort vote (TCV). In addition, some questions related to airflow scale, air freshness, thermal preference and body response are employed. The results present that type 1 is more comfortable than type 2. The study also reveals that the larger openings ratio is more acceptable than the few ones. Furthermore, this study confirms the adaptive behaviour where most occupants utilize the windows openings in the morning until noon and operate the fans during the night to modify indoor environment conditions to be more comfortable.

Keywords: Naturally ventilated house, Indoor thermal comfort, Assessment, Tropical region
住宅，自然換気，室内の熱的快適性，評価，熱帯地域

1. Introduction

1.1 Background

The indoor environment in naturally ventilated buildings greatly depends on the local climate and the way environmental controls are used. The severity of the effect of outdoor climate can be modified by using controls. Common controls like openable windows, blinds, louvres, lights and fans offer the occupants some opportunity in the thermal environment to pursue comfort[1]. Indonesia is considered as the most extensive tropical country globally and has more than 17.000 islands located in the heart of the equator line, with 6° - 11° North Latitude and 95° - 141° East Longitude. The climate condition depends on the monsoon that creates hot and humid conditions throughout the year. There is no difference in temperature and relative humidity between the rainy and dry seasons. The daily air temperature observed is between 20 and 35 °C, and relative humidity fluctuates from 60% at noon and almost 95% in the morning until late[2].

Especially in recent years, many countries have been facing more extreme weather events due to climate change, and Indonesia has also experienced an increase in outdoor temperature. The increase in external temperatures is driving greater demand for air conditioning, as well as growing the energy poverty to it. Moreover, with the majority of the population in Indonesia living in naturally ventilated houses because of the economic issues, hot and humid Indonesian outdoor conditions can affect significantly the occupants' thermal comfort.

The study of thermal comfort in the tropics started 70 years ago. Webb has observed and analyzed thermal comfort in equatorial climates and examines thermal discomfort in tropical climates by developing a nomogram for the equatorial comfort index[3,4]. Ellis concluded that race, age, or gender difference does not affect thermal comfort[5]. In addition, the following research reveals that the occupant's response to a naturally ventilated room is three

* 空間システム専攻博士後期課程
** 都市・建築学部門

degrees warmer than the perceived ISO thermal comfort standard[6]. Moreover, other studies on thermal comfort focused on testing neutral temperatures based on gender, age, body mass index level and ethnic background[7]. Furthermore, the study on thermal comfort for the naturally ventilated house was conducted to determine the neutral temperature in the naturally ventilated houses in Yogyakarta, Indonesia[8], and an assessment of comfort of houses in Banda Aceh, Indonesia, to determine the comfort range[9]. However, the research on the naturally ventilated house and thermal comfort in tropical climates against window opening ratio is overlooked, especially in Indonesia. Therefore, this research will focus on the impact of window opening ratio on indoor environment conditions and occupant comfort.

As a result most Indonesians rely on natural ventilation by opening the windows to modify indoor environment conditions. Originally, the main purpose of our research is to optimize the window openings of Indonesian dwellings to increase indoor thermal comfort. For this, the overall aim of this paper is 1) to investigate the thermal comfort performance of two types of naturally ventilated houses, 2) to identify airflow scale vote and air freshness scale vote, thermal preference and body response in an indoor environment and 3) to study the adaptive behaviours of occupants in order to modify indoor environment conditions to be more comfortable.

1.2 Overview of approach

Thermal comfort studies adopt three common approaches: model, human-based, and space-based. The scale or virtual model is the first approach that focuses its investigation on simulating the indoor environment's physical conditions and assessing the occupants' thermal comfort level based on certain assumptions and standards. In order to get accurate prediction results, this approach requires proper simulation with the data collected must be measurable and proportional. Secondly, the approach used is human-based for the scope of direct investigation of building occupants. The data and information collected must be controlled through systematic experiments in a particular room or the field. Therefore, a human-based approach is appropriate for a comprehensive evaluation of thermal comfort and developing appropriate standards to obtain excellent and accurate results. Thirdly, an approach based on the use of space on a large scale is used to study whether a particular space is thermally comfortable. This approach can be used through building design studies and building service system studies, such as passive cooling strategies through architectural layout, form, walls and wall insulation. Finally, when comparing the nature of differences between field and laboratory surveys, several factors that do not need to be considered in the laboratory may affect the field survey results. For example, when comparing field survey results from different socioeconomic areas, it is imperative to consider the influence of local conditions and behavioural norms that are not found in the laboratory[10]. Therefore, this study will employ a human-based approach to derive human perception against indoor environment conditions as an initial study for further research in naturally ventilated houses.

1.3 Climatic conditions

Outdoor climatic condition is essential for the naturally ventilated house in the tropical climate because it will affect indoor condition due to window opening in the house. Therefore, the climatic conditions of the study area during the on-site survey were demonstrated[11] in Figures 1, 2, and 3. The average solar radiation recorded is 156.15 W/m² with a maximum value at 01.00 p.m. of 674.99 W/m². The relative humidity demonstrates a high value with a maximum of 98.29%, which tends to occur at night, and the minimum and average relative humidity are 57.04% and 82.65%, respectively. In addition, the average air temperature value is 27.48 °C, where the minimum and maximum values are classified at 23.20 °C and 32.50 °C, respectively. Furthermore, the wind direction flows to the building dominated from the south. Wind speed shows a maximum of 11 m/s and an average of 4.18 m/s, respectively.

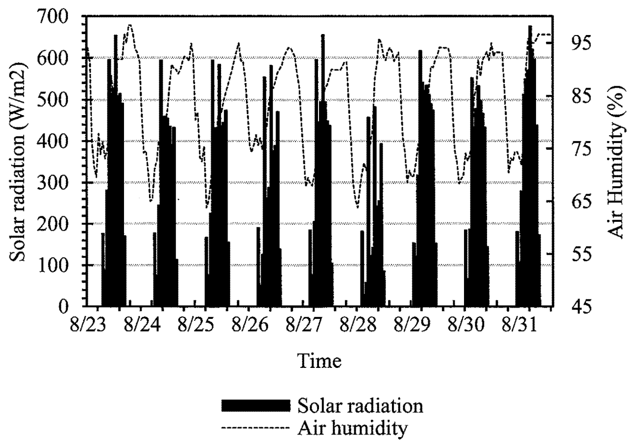

Fig. 1 Solar radiation and air humidity

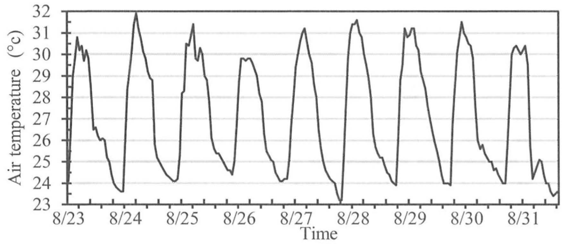

Fig. 2 Air temperature

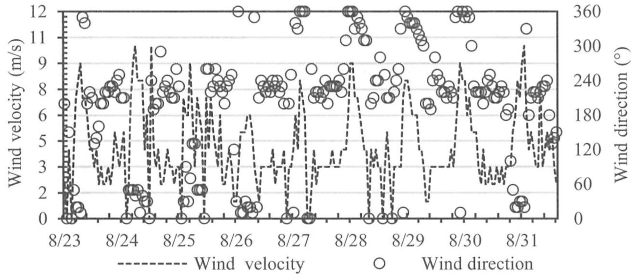

Fig. 3 Wind velocity and wind direction

2. Research object and method

2.1 Research object

Most of the houses in this study are low-cost houses and meet the standards recommended by the Indonesian government. The houses consist of two types, located in Aceh Province, Indonesia. The locations both of types are different. Type 1 is situated on a hill, and type 2 is close to the sea, as shown in Figure 4. However, the two regions' outdoor temperature and absolute humidity were almost similar during the measurements. Therefore, the impact of microclimate on thermal comfort is excluded in this study because it has no significant effect on indoor performance for comparison among the house types.

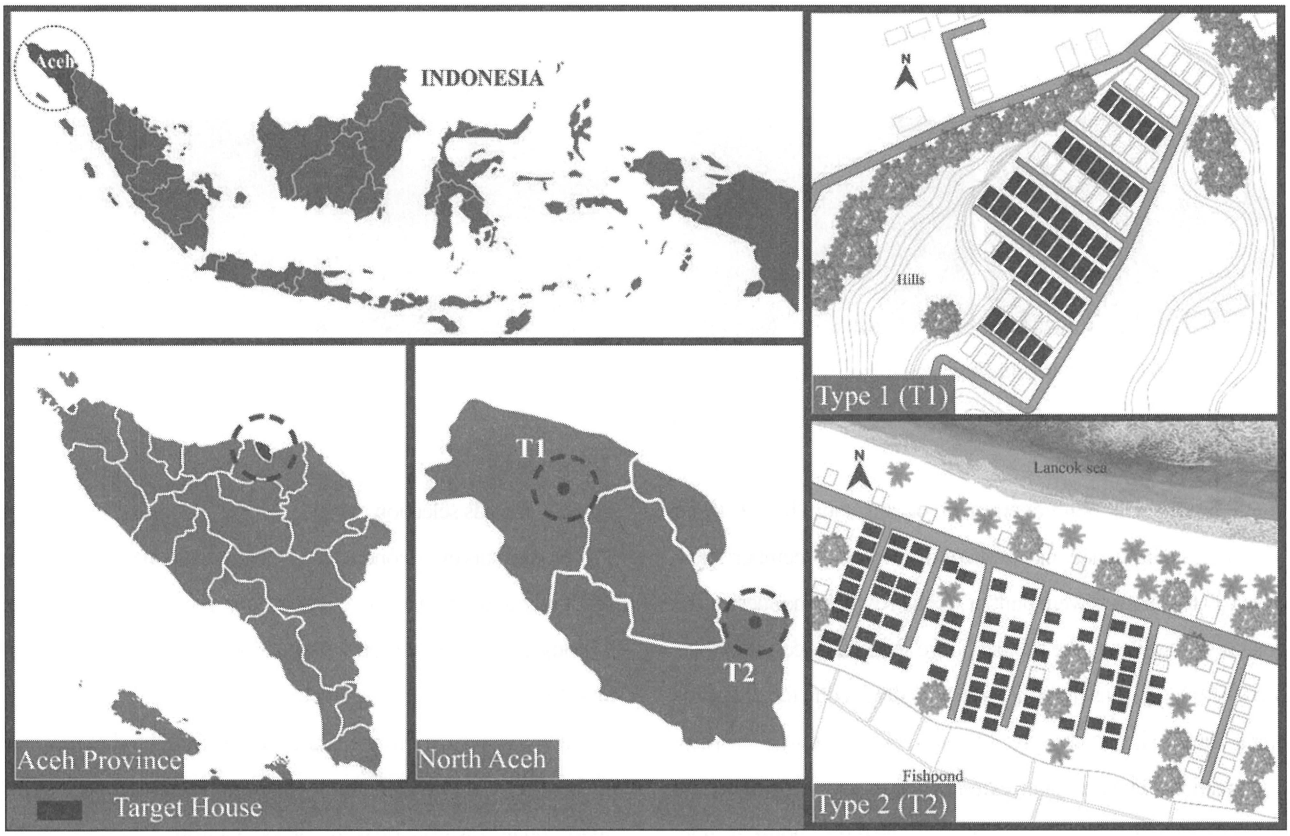

Fig. 4 Site location of the houses

1) Type 1 (Developer House)

The developer house is one of the residential types built by a local private company. It is the most common house found in North Aceh, Indonesia. More than one hundred houses had been built by a local company. The house is a grounded permanent house built in heavyweight construction such as plastered brickwork and concrete structures. Figure 5 and Figure 6 illustrate the floor plan and the exterior and interior appearance of type 1. The house has two bedrooms, a living room and a kitchen, with an area of 33 m^2. Window to wall ratio (WWR) and window to floor area (WFR) are 7.39% and 16.48%, respectively.

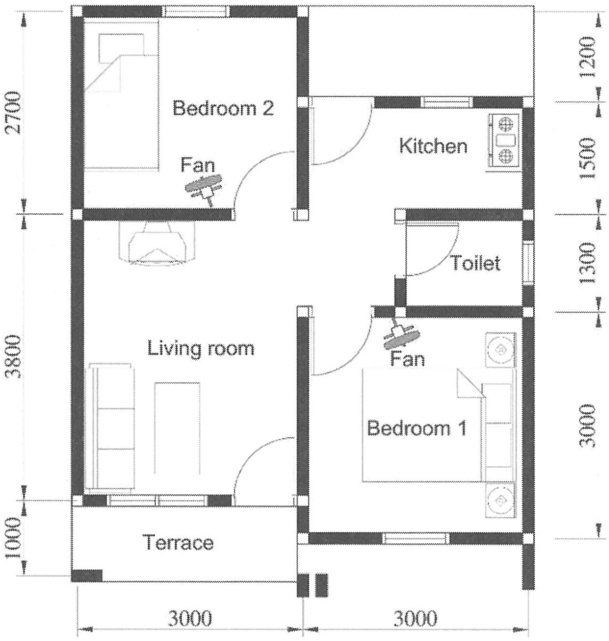

Fig.5 Floor plan of type 1

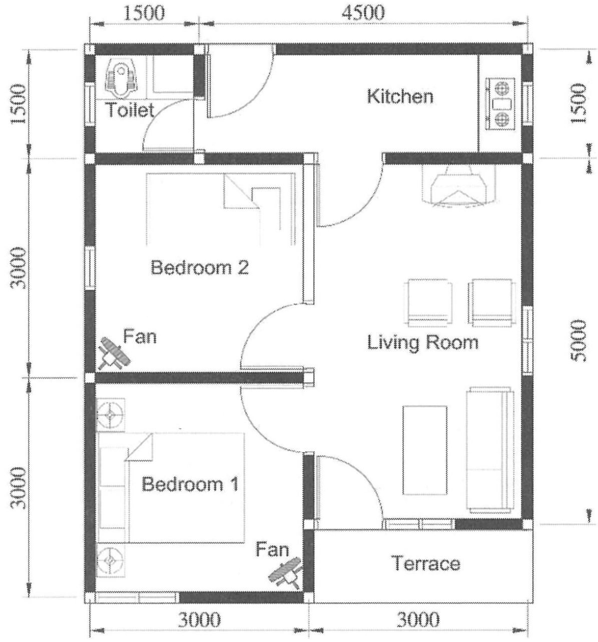

Fig. 7 Floor plan of type 2

Fig. 6 Exterior and interior appearance of type 1

Fig. 8 Exterior and interior appearance of type 2

2) Type 2 (NGO house)

NGO house is a non-government organization house. After Indonesia's earthquake and tsunami disaster in December 2004, over 100,000 houses were built in Aceh Province, Indonesia. The houses are similar to the typical house found in Aceh Province. Most of the type has the same size and shapes due to the houses being built simultaneously by an NGO (non-government organization). The floorplan, exterior, and interior appearance are demonstrated in Figure 7 and Figure 8. The type 2 house is more extensive than type 1 with a uniform room configuration. It has two bedrooms, a living room and a kitchen, with an area of 39.75 m^2. However, the window to wall ratio (WWR) and window to floor ratio (WFR) is 5.58 % and 9.06 %, respectively. Therefore, compared to type 1, type 2 is less than type 1.

2.2 Methods

1) Households selection

The on-site survey is conducted to obtain data on the perception of building users, indoor environment preferences, and user responses due to uncomfortable situations during daily life. More than 200 occupants have been selected that represent a population with a low standard of living. The houses selected and the number of the subject are divided into two types. The on-site survey and questionnaire distribution were carried out from August 23, 2020, to August 31, 2020. However, due to limited access to the case study locations, questionnaires were only conducted in the morning - evening (06:00 - 18:00).

Even though the data is not available on the percentage of air conditioning use in households, it believes that Indonesian commonly performs in non-air-conditioned environments and has a passive regulation in achieving thermal comfort in houses.

For example, the whole subject was initially 90 and 160 respondents for type 1 and typed 2. However, about two respondents on type 1 and six on type 2 were not included because they operate the air conditioner daily. As a result, the subjects surveyed are 88 respondents for type 1 and 154 respondents for type 2. Moreover, in order to measure relevant data from field surveys, some criteria for housing and respondent selection are proposed as follows:

- ✓ The housing relies on passive cooling strategies to create a relaxed indoor environment.
- ✓ Respondents currently occupy the housing in order to catch the real attitude improvement.
- ✓ Residents are willing to fill out the questionnaire simultaneously without any reward.

2) Questionnaire

Recording the response occupants is the most vital aspect of this study. This research used a paper-based questionnaire, and the occupants responded only once in this survey. Therefore, some common questions to investigate thermal sensation and thermal comfort votes have been used. In order to evaluate the whole thermal perception, using both of the seven scales of ASHRAE thermal sensation and the Bedford scale are proposed. It also examines the consistency of response between thermal sensation and perception. Table 1 present the two-scale used for this study.

Table 1 Rating scale used for thermal comfort survey

ASHRAE Scale	Bedford Scale
-3 cold	-3 much too cool
-2 cool	-2 too cool
-1 slightly cool	-1 comfortably cool
0 neutral	0 comfortable
+1 slightly warm	+1 comfortably warm
+2 warm	+2 too warm
+3 hot	+3 much too warm

In addition, the other questions will ask about the occupant's preference, airflow and freshness scale sensation, thermal preference and body response. These questions are required to classify whether the occupant's feelings corresponded well with the perception of the indoor environment. Moreover, it also gathers information about occupants' control and behavioural adaptation in daily life for a whole day. All questionnaires filled by respondents who stayed in naturally ventilated houses have been evaluated except for households with air conditioners.

3. Result and Discussion

3.1 Respondent Information

The respondents' gender and age of dwelling types are evenly distributed. The comparison of distribution between gender and age is commonly similar among the surveyed types. Table 2 presents the respondent information of this study.

Table 2 Respondent

	Type 1	Type 2
Gender		
Male	49 (55.68%)	74 (48.05%)
Female	39 (44.32%)	80 (51.95%)
Age (Years)		
<20	1 (1.14%)	4 (2.6%)
21 - 30	24 (27.27%)	29 (18.83%)
31 - 40	46 (52.27%)	48 (31.17%)
41 - 50	9 (10.23%)	41 (26.62%)
>50	8 (9.09%)	32 (20.78%)

3.2 Thermal comfort between two types of house

The study investigates the window opening area and room area against thermal sensation vote in order to understand the effect of the window openings ratio and room area to thermal sensation vote (TSV) and thermal comfort vote (TCV). In this case, the occupants are requested to sit in the living room and relax before filling out the questionnaire. Moreover, all of the windows in the house are asked to open during this survey. Table 3 presents TSV (ASHRAE scale) and TCV (Bedford scale) between two types of houses. The mean vote for the whole subject of two different house types is 0.58 and 0.48 ASHRAE scale and 1.70 and 1.47 on the Bedford scale. This result also presents the consistency of comfort vote between TSV and TCV, respectively. Moreover, the standard ASHRAE stated that the acceptability of thermal comfort should be defined as the condition where 80% of residents vote for the central three categories (-1,0,1). Therefore, Figure 9 demonstrates the three main categories of the thermal sensation vote (TSV). The occupants of type 1 houses prefer comfort vote for both scales, where the ASHRAE scale and the Bedford scale were 79.55 % and 86.36 %, followed by warm and hot sensations 17.05 % and 10.23 %, respectively. However, most occupants on type 2 felt warm and hot at 53.90 %, followed by a neutral vote of 46.10 %. On the other hand, the Bedford scale shows that the occupants vote dominated by too warm and much too warm at 54.55 %, followed by comfortable warm at 45.45%.

Table 3. Comparison of TSV and TCV on two types of house

Scale	Type 1				Type 2			
	TSV	%	TCV	%	TSV	%	TCV	%
-3	0	0.00	0	0.00	0	0	0	0
-2	3	3.41	3	3.41	0	0	0	0
-1	5	5.68	3	3.41	8	5	2	1
0	36	40.91	42	47.73	30	19	47	31
1	29	32.95	31	35.23	33	21	21	14
2	12	13.64	7	7.95	12	8	44	29
3	3	3.41	2	2.27	71	46	40	26
Total	88	100%	88	100%	154	100%	154	100%
Mean	0.58		0.48		1.70		1.47	

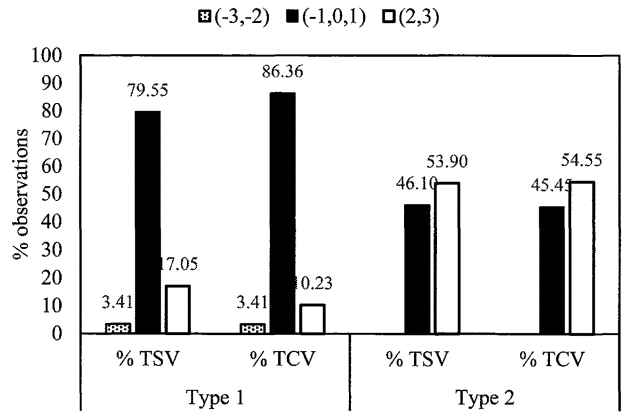

Fig. 9 TSV and TCV on the central three categories

3.3 Airflow and air freshness

The airflow of whole subjects was identified in this study. The occupants were asking, "how do you feel about airflow in this room at this moment?". The chosen answer is much too still, too still, slightly still, just right, slightly breezy, too breezy, and much too breezy. Figure 10 demonstrates the airflow scale vote. Most of the occupants on type 1 voted "just right" with 37.50%, followed by "slightly breezy" and "too breezy" at 23.86% and 11.36%, respectively. In addition, 2.27% voted "much too breezy". However, some occupants also voted "much too stuffy" and "too stuffy". Meanwhile, the vote distribution type 2 was dominated by "too still" 30,52%, followed by "just right" and "much too still" 26.62% and 20.13%. The occupants also vote "slightly breezy" and "too breezy", with 5.84% and 2.6%, respectively. Moreover, the comparison vote for three central categories related to thermal sensation vote (TSV) shows that the occupants of type 1 vote 70.45% as a comfortable sensation, as shown in Figure11. On the other hand, the occupants of type 2 vote 46.10% as a comfortable sensation. Therefore, we can conclude that type 1 performs better airflow in this survey. This study reveals that the larger of opening area, the more significant the air movement in an indoor environment. It has been proved that the value of WFR and WWR affects indoor environment conditions, where the large of WWR and WFR is better than a small one.

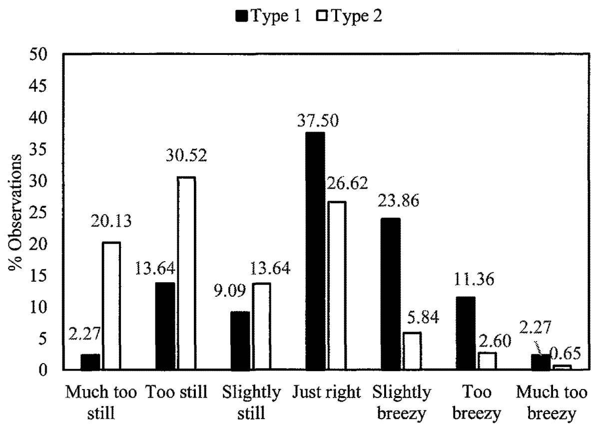

Fig. 10 Airflow scale vote

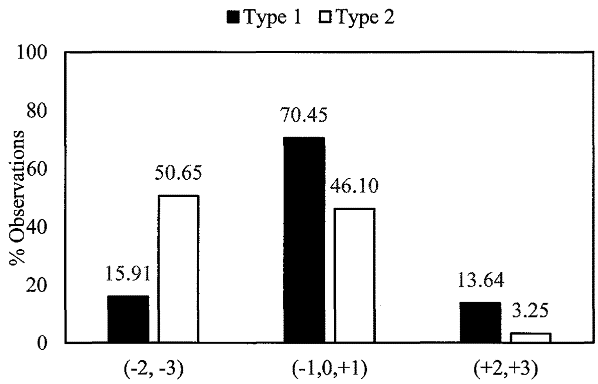

Fig. 11 Airflow scale on the central three categories

Furthermore, using the Bedford scale, the question for the air freshness scale is: "how do you feel about air freshness in this room now?". Generally, the air freshness vote is similar to the airflow vote, as shown in Figure12 and Figure 13. Most occupants on type 1 voted "neutral" at 40.91%, followed by "slightly fresh" at 19.32% and "too fresh" at 11.36%, respectively. In addition, the respondent also votes "much too fresh" at 6.82%. On the other hand, the air freshness vote on house type 2 was dominated by "too stuffy" of 30.52%, followed by "much too stuffy" and "slightly stuffy" of 20.78% and 14.29%, respectively. However, some occupants also vote "neutral", "slightly fresh", and "too fresh", with 22.08%, 11.04% and 1.30%. Moreover, the comparison vote for three central categories related to ASHRAE Scale shows that the occupants on type 1 vote 68.18 as a comfortable sensation. On the other hand, the occupants on type 2 just voted 47.40% as a comfortable sensation. Therefore, we can conclude that type 1 performs better air freshness than type 2 in this study.

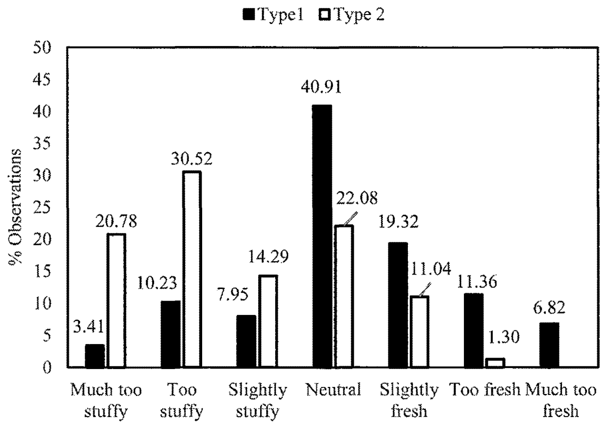

Fig. 12 Air freshness scale vote

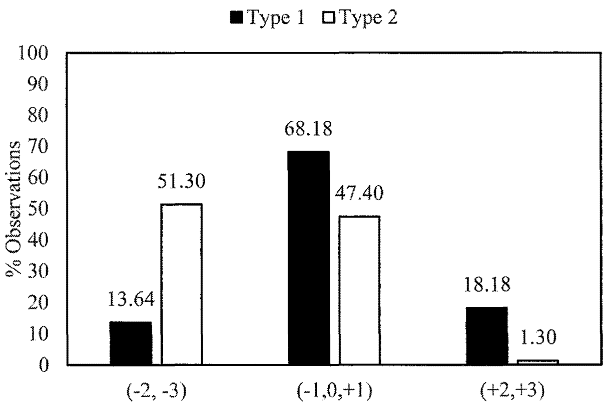

Fig. 13 Air freshness scale on the central three categories

3.4 Thermal preference

The study used the "McIntyre scale" to investigate thermal preference by asking: "How would you prefer the current environment?". There are highly different answers between respondents on type 1 and type 2, where type 1 is better than type 2. Figure 14 shows the thermal preference vote for both types of houses. More than 79% of occupants on type 1 voted "just right". Based on three central categories related to TSV, the survey reported that 2.27% of occupants who vote between warm and hot on the ASHRAE scale also choose "just right" as a thermal preference. The other, 3.41% of the respondents who vote cool and cold want to be warmer in this survey. It is contrary to the occupants on type 2, where most of them want to be cooler 66.23 %, followed by just right 33.77%, and no one votes want to be warmer.

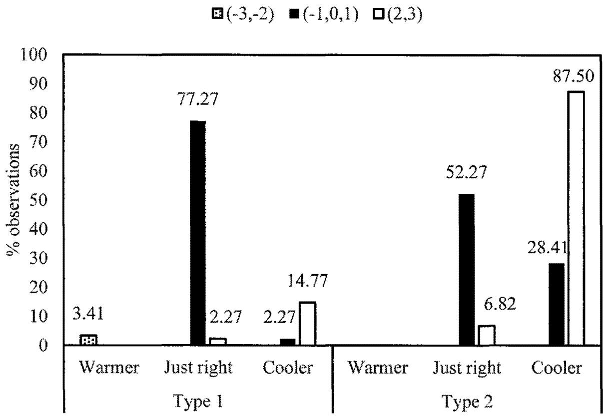

Fig. 14 Thermal preference vote

3.5 Body response

This study also investigated the body response during the survey. This question is essential to understand the current indoor condition's effect on human body response. The body response scale was measured during the on-site survey by asking, "are you sweating now ?". It reports that most occupants of type 1 are not sweating, followed by slightly and moderate. Contrary to another type, they chose "moderate" as a higher response, followed by slightly, no sweating and profusely. The distribution of body response votes is illustrated in Figure 15.

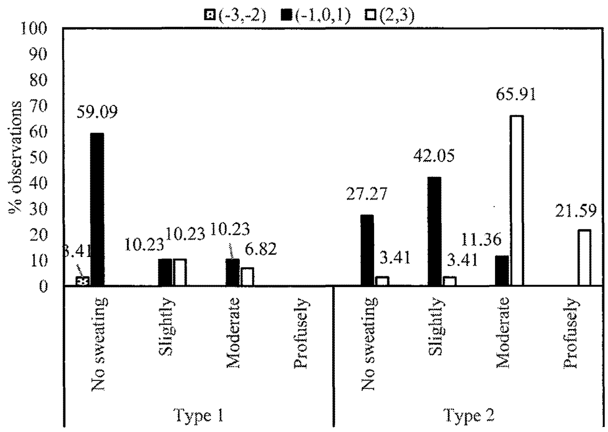

Fig. 15 Body response vote

3.6 Behavioural adaptation

The study identifies the respondent's adaptive actions while staying in the living room. For example, it is commonly changing from just regulating the body by taking a bath more frequently, switching on a fan, opening the window, drinking the water, or changing the clothing. Regarding this concern, the question addressed to the respondent is how likely action is to be taken when the indoor condition is uncomfortable for a whole day. This result indicated that most occupants prefer to open the window, switch on the fan, and take a bath before employing other options to achieve thermal comfort. Furthermore, another analysis that has been carried out is the detailed window openings and switching on the fans in the bedroom. The specification of action time is divided into four different times there are morning (7-12 a.m), afternoon (1-6 a.m), evening (7-12 p.m), and night (1-6 a.m). Generally, the comparison of body action due to uncomfortable conditions between turning on the fan and usage of bedroom windows are 55.74 % and 44.26 %, respectively. The fan usage mainly occurred at noon and night at 23.83 % and 14.47 %. Besides, the evening and morning time is rare, with frequent 7.94 % and 9.50 %. Furthermore, the usage of window bedrooms reported at noon and morning of 20.99 % and 19.72 %, respectively. Therefore, it can be said that most of the occupants prefer to operate the fan together with opening the window at noon. We assume that the indoor environment during noon is slightly warm to warm. Meanwhile, most occupants permanently close the window and switch on the fan during the night to control the indoor environment more relaxed.

3.7 Regression of thermal sensation vote (TSV) and thermal comfort vote (TCV)

The occupant's vote data is used to derive a comfort range by analyzing regression TSV (ASHRAE scale) against TCV (Bedford scale). Figure 16 and Figure 17 present the linear regression between the ASHRAE thermal sensation scale and the Bedford sensation scale for the types surveyed. Based on the correlation value, type 1 performs better in occupant's vote than type 2. The following linear regression equation for type 1 ($r^2 = 0.7804$) and type 2 ($r^2 = 0.6818$) are obtained:

$$TCV = 0.7836\, TSV + 0.0231 \quad (1)$$

$$TCV = 0.9261\, TSV + 0.3363 \quad (2)$$

Moreover, we can calculate the range of neutral in the ASHRAE scale and comfortable in the Bedford scale for the type of house. For example, we calculate the comfort range for type 1. As mentioned earlier, the Bedford scale state that the comfortable range is at TCV = 0. The equation shows that the comfortable range (TCV = 0) on the Bedford scale is at a TSV vote (ASHRAE scale) of -0.0294. Therefore, the value of the TSV result is close to neutral. In addition, another report for TSV that occupants votes for the comfortably cool (TCV = -1) and comfortably warm (TCV = +1) on the Bedford scale are at -1.2466 and 1.3056 on the ASHRAE scale, respectively. Meanwhile, type 2 performs slightly differently between thermal sensation and thermal comfort votes in the comfort range. Therefore, using equation 2, the comfortable range of type 2 is found. While TCV = 0 on the Bedford scale, the TSV is at -0.3631. Therefore, the result shows comfortable range is close to slightly cool. In addition, when the occupants of type 2 vote comfortably cool (-1) and comfortably warm (+1), the TSV is at -1.4429 and 0.7166, respectively.

Furthermore, we can conclude that the comfortable range is at the three central votes in the ASHRAE scale for both types. This result reveals that the respondents feel comfortable in the slightly cool environment (ASHRAE scale) and comfortably warm at slightly warm votes (the Bedford scale).

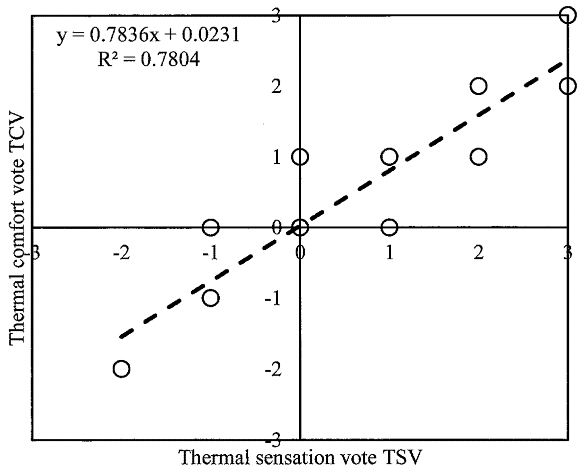

Fig. 16 Regression linear of TSV against TCV for type 1

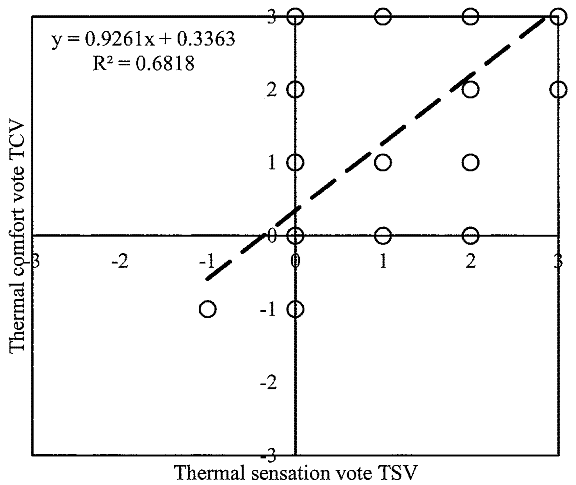

Fig. 17 Regression linear of TSV against TCV for type 2

4. Conclusion

The questionnaire's analysis obtains user responses to thermal comfort assessment and their adaptations in an actual indoor environment. Some of the conclusions are as follows:

- Type 1 performs better thermal comfort than type 2 based on some questions related to airflow, air freshness, thermal preference, and body response.
- The openings ratio affects thermal comfort where the larger openings area is more comfortable than the other.
- This study confirmed the consistency of votes between TSV (ASHRAE) and TCV (Bedford).
- The occupants prefer opening the windows, switching on fans, and taking baths to modify indoor environmental conditions.
- It is necessary to study natural ventilation design factors, especially the effect of opening ratio on ventilation flowrate and thermal comfort for naturally ventilated houses in tropical climates, as further research.

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References

1) Indraganti, M. (2010). Adaptive use of natural ventilation for thermal comfort in Indian apartments. Building and Environment, 45(6), 1490-1507.

2) BMKG, (2020), Weather data of Indonesia, Badan Meteorologi, Klimatologi dan Geofisika, Indonesia. Retrieved from the website: https://www.bmkg.go.id/

3) Webb, C.G. (1959). An Analysis of Some Observations of Thermal Comfort in an Equatorial Climate. British Journal of Industrial Medicine vol.16, (pp. 297-310).

4) Webb, C.G. (1960). Thermal Discomfort in an Equatorial Climate. Journal of the Institution of Heating and Ventilating Engineers,

5) Ellis, F.P. (1953). Thermal Comfort in Warm Humid Atmosphere Observations on Groups and Individuals in Singapore. Journal of Hygiene. Cambridge. 50; 386-404.

6) De Dear, R.J., Leow, K.G., and Foo, S.C. (1991). Thermal Comfort in the Humid Tropics: Field Experiments in Air Conditioned and Naturally Ventilated Buildings in Singapore. International Journal Biometeorology, 34, 259-265.

7) Karyono, T.H. (1998). Report on Thermal Comfort and Building Energy Studies in Jakarta, Indonesia. Building and Environment, 35, 77-90. Pergamon.

8) Feriadi, H; Wong, N.H (2004), Thermal Comfort for Naturally Ventilated Houses in Indonesia, Energy and Buildings 36, pp 614-626.

9) L. Hilma Sari, D.J. Harris, M. Gormley (2013), Indoor Thermal Assessment of Post-Tsunami Housing I n Banda Aceh, Indonesia, Int. Journal for Housing Science, Vol. 37 No. 3 pp.161-173.

10) Cena, K. (1993). Thermal and Non Thermal Aspects of Comfort Surveys in Homes and Offices. In Oseland, N.A., and Humphreys, M.A (Eds). Thermal Comfort: Past, Present, and Future. BRE – Garston.

11) BMKG, (2020), Weather data of North Aceh, Badan Meteorologi, Klimatologi dan Geofisika, Malikussaleh, Indonesia.

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