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Indoor Thermal Comfort Improvement of the Naturally Ventilated House in Tropical Climate, Indonesia

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ABSTRACT
Two models of houses in North Aceh, Indonesia, are investigated in this study. 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 thermal preference and body response are employed. This study also examines thermal comfort with a numerical simulations program called THERB for HAM, a coupled analysis software for heat, moisture, and air. The results show that the room comfort level was not optimal, where most occupants' feelings were warm and hot. However, type 1 is more comfortable than type 2, and simulation results confirm indoor environmental conditions. Furthermore, this study presents 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: *Natural ventilation, Thermal comfort, Improvement, Tropical climate.*

1. INTRODUCTION

1.1 Background

People in many activities always hope to find a comfortable living environment in their residences, workplace, or recreation areas. The thermal comfort living environment is expected to improve quality of life, productivity, and health. Creating a thermally comfortable environment is a challenging stage where people must adapt to various climates, naturally challenging environmental conditions, and diversification of human character in psychology and physiology. There is no surprise that if we look at people living in different climates, they have adapted to the natural environment condition and have built their character and architectural form based on traditional and modern situations. This unique climate perhaps caused a more significant effect on thermal comfort perception in people as occupants of the building. People intentionally changed their natural environment by building and creating optimal living conditions. Thus, the building is made for filtering, absorbing, and rejecting environmental elements that cannot contribute positively to achieving people's thermal comfort in whole aspects. The indoor environment in naturally ventilated buildings dramatically 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. Standard 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 the most extensive tropical country globally and has more than 18.000 islands located in the heart of the equator line, with 6° - 11° North Latitude and 95° - 141º East Longitude. Climate conditions depend on the monsoon that creates hot and humid conditions throughout the year. There is no temperature and relative humidity difference between the rainy and dry seasons. The daily air temperature observed is between 20 and 35 ℃, 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 increased outdoor temperatures. The increase in external temperatures is driving greater demand for air conditioning and increasing energy poverty. In addition, with most of the population in Indonesia living in naturally ventilated houses because of economic issues, hot and humid Indonesian outdoor conditions can significantly affect 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 degrees warmer than the perceived ISO thermal comfort standard [6]. 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 the 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 windows to modify indoor environment conditions. Initially, the primary purpose of our research was 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 thermal preference and body response in an indoor environment, 3) to estimate indoor environmental conditions by numerical simulation and 4) 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 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 must be controlled through systematic experiments in a particular room or field. Therefore, a human-based approach is appropriate for comprehensively evaluating 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 and 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 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. In addition, numerical simulation THERB for HAM was employed to confirm indoor environment conditions during the survey periods.

1.3 Climatic Conditions

Outdoor climatic condition is essential for a naturally ventilated house in the tropical climate because it will affect indoor condition due to window opening. Therefore, the climatic conditions [11] of the study area during the on-site survey were demonstrated in Figures 1-3. The average solar radiation recorded is 156.15 W/m² with a maximum value at 01.00 pm 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 ℃, where the minimum and maximum values are classified at 23.20 ℃ and 32.50 ℃, 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.

1.4 THERB for HAM

This study uses numerical simulation THERB for HAM to simulate indoor environment conditions. This software has been developed to estimate the hygrothermal environment in buildings, providing complete HAM features, including the transferring moisture principle within the wall, and validated through standard testing in Japan BESTEST. THERB is one of the official software that the Japanese government approves. In General, the software for predicting a building's temperature, humidity, heating, and cooling load does not calculate the humidity transfer within the installed wall. The humidity calculation used in software only affects the ventilation and only focuses on the building space. THERB was developed to simulate humidity conditions in building spaces and installed walls in detail. Thermal theories of conduction, convection, radiation, and ventilation are based on complex phenomena. The P-model uses water potential, defined as thermodynamic energy, an advanced feature of THERB. This feature combines moisture transfer, including water absorption and wall desorption. THERB can predict the hygrothermal environment of the buildings by considering the complex relationship between heat and humidity transfer and airflow [12].

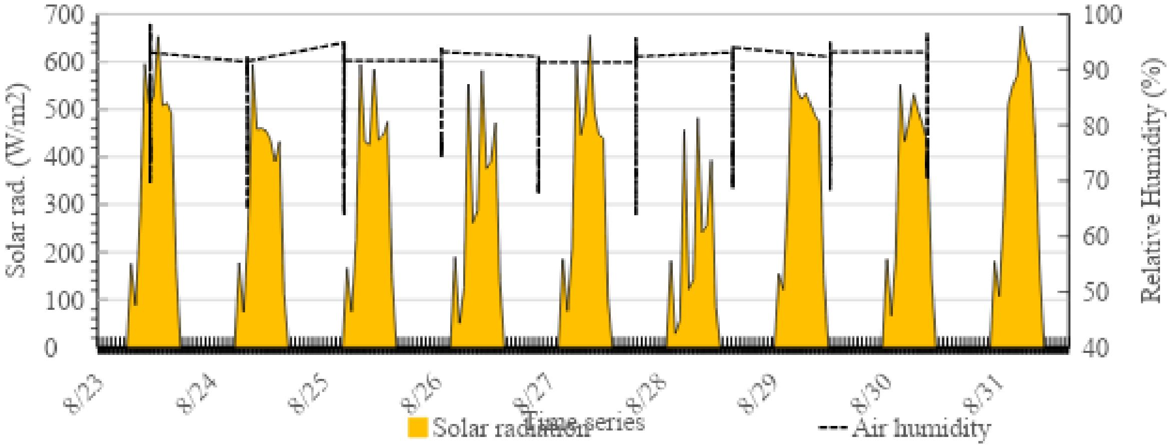


Figure 1 Solar radiation and air humidity

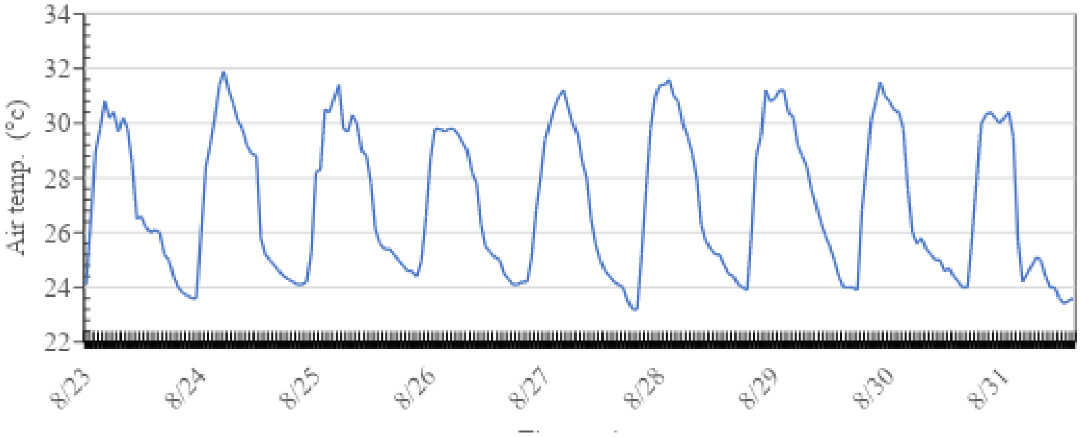


Figure 2 Air temperature

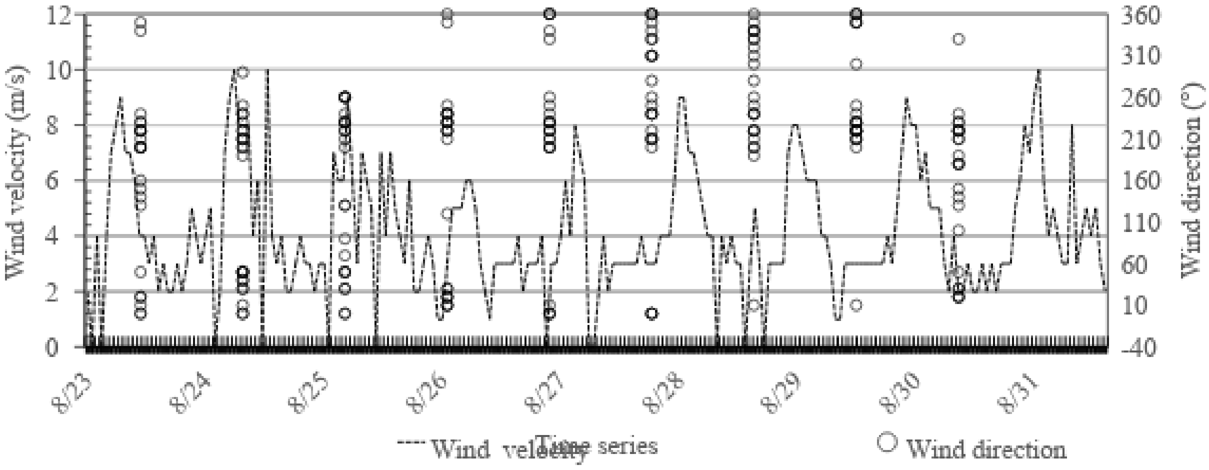


Figure 3 Wind velocity and wind direction

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 of both 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.

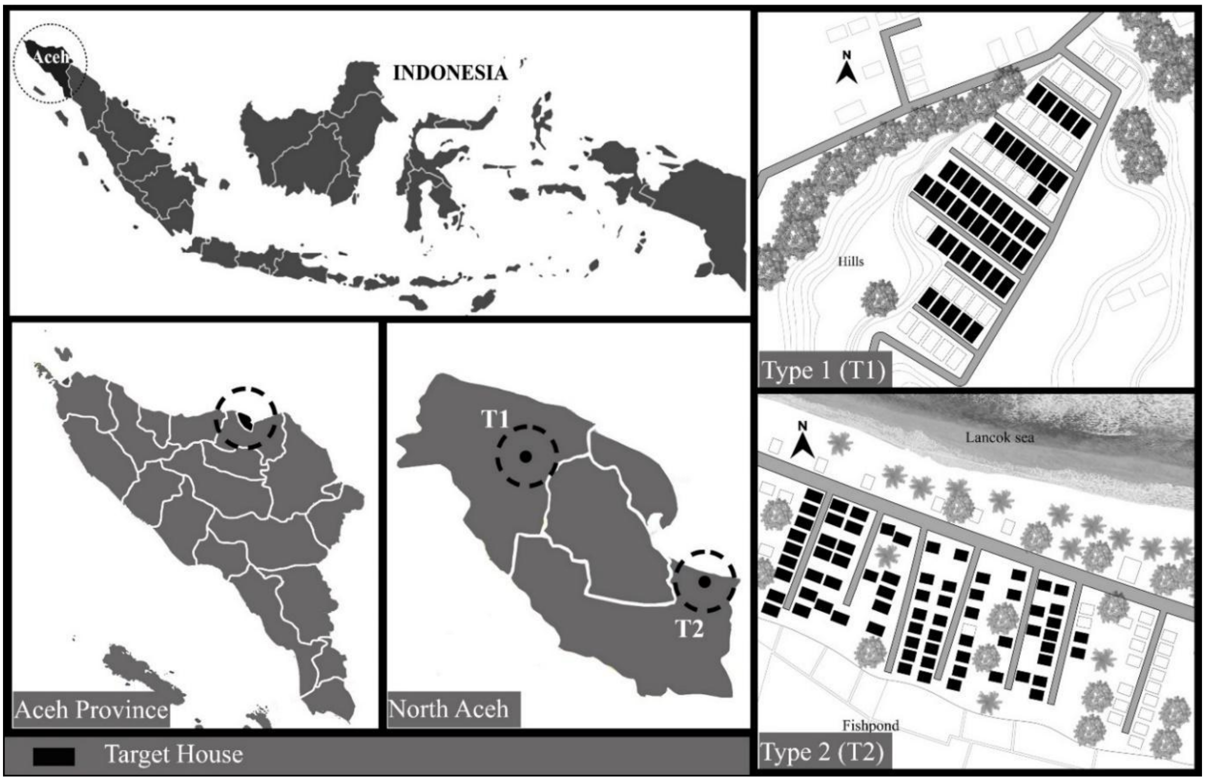


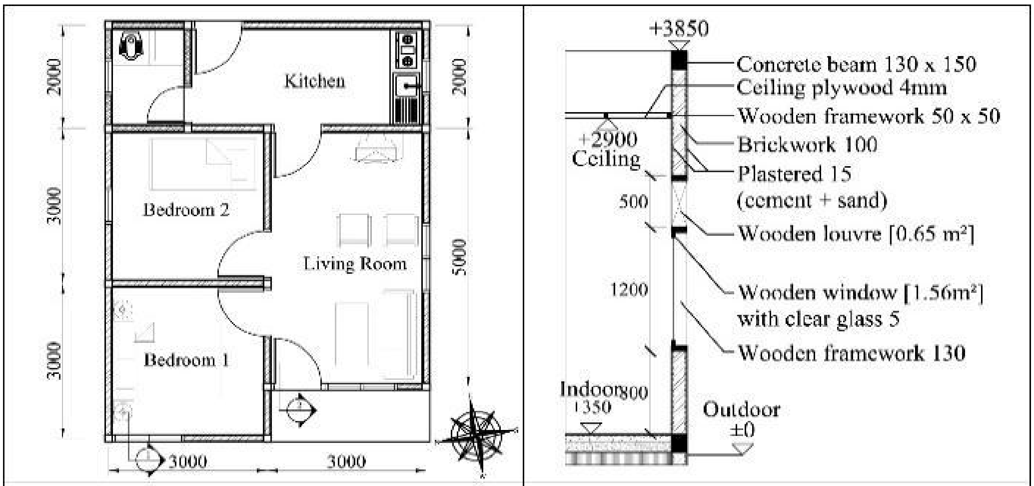
Figure 4 Site location of selected houses

2.1.1 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.

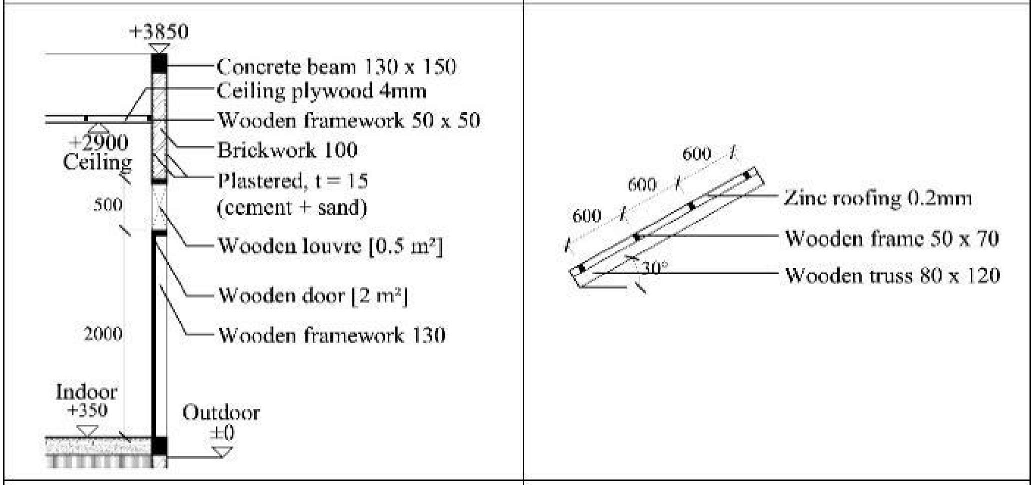
2.1.2 Type 2 (NGO house)

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 types have similar sizes 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 WWR) and WFR are 5.58 % and 9.06 %, respectively. Therefore, compared to type 1, type 2 is less than type 1.



(a) Floor plan 48 m²

(b) Detail 1

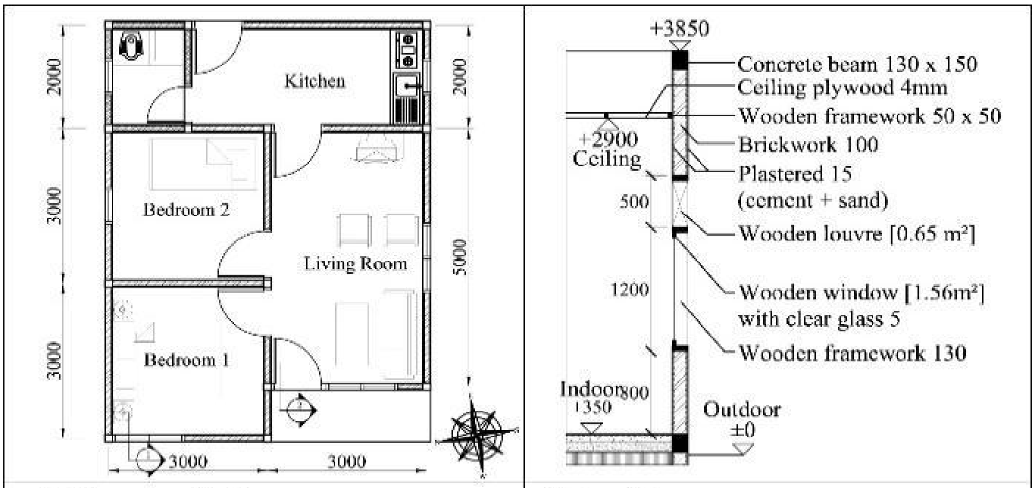


(c) Detail 2

(d) Roofing Detail

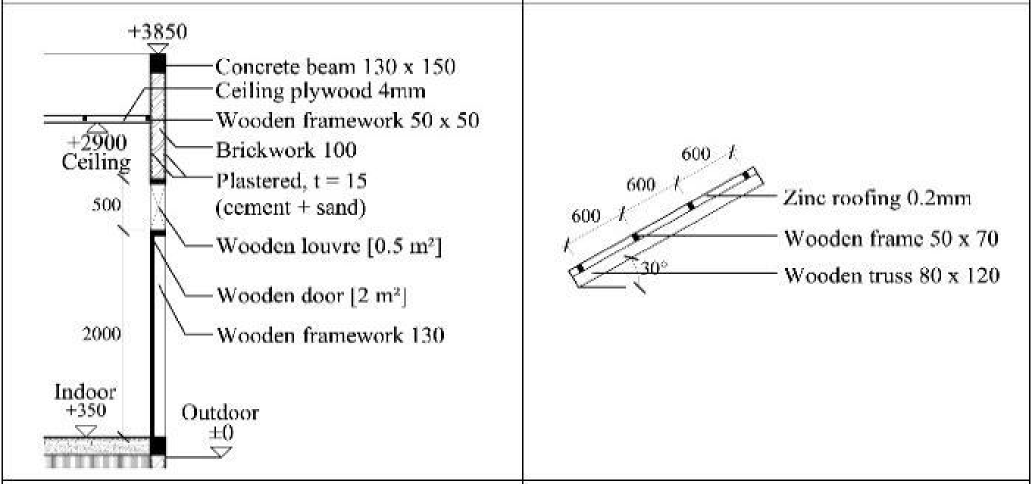
Figure 5 Floor plan of type 1

Figure 6 Exterior and interior appearance of type 1



(a) Floor plan 48 m²

(b) Detail 1



(c) Detail 2

(d) Roofing Detail

Figure 7 Floor plan of type 2

Figure 8 Exterior and interior appearance of type 2

2.2 Methods

2.2.1 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, representing 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 were distributed 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 subject was initially 90 and 160 respondents for type 1 and type 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 were 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.

2.2.2 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 to this survey. Therefore, common questions have been used to investigate thermal sensation and comfort votes. In order to evaluate the whole thermal perception, 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

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

In addition, the other questions will ask about 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.

2.2.3 Calculation Condition

The calculation condition for numerical simulation THERB for HAM is shown in Table 2. Standard weather data for North Aceh Regency is taken from the Malikussaleh BMKG (Meteorological and Climatological Agency) Indonesia. The temperature set point for the conditioned room was 22 degrees with natural humidity (no humidification) and constant indoor ventilation of 0.5 times/hour applied all day. In order to analyze the actual performance of the house, the occupants' thermal performance and moisture content are ignored. In addition, the windows opening of each room is only utilized in the daytime during occupancy.

Table 2. Calculation condition

Weather data	**Run-up**	**Calculation interval**	**Set-point of temperature**	**Window openings time**	**Space conditioning time**	**Air change rate**
Standard weather data in North Aceh, Indonesia	One month	10 minutes	22 degree	Daytime	None	0.5 times per hour

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 3 presents the respondent information of this study.

Table 3 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 4 presents the TSV (ASHRAE scale) and TCV (Bedford scale) between the 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 at 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 occupant's vote was dominated by too warm and much too warm at 54.55 %, followed by comfortable warm at 45.45%.

Table 4. 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	

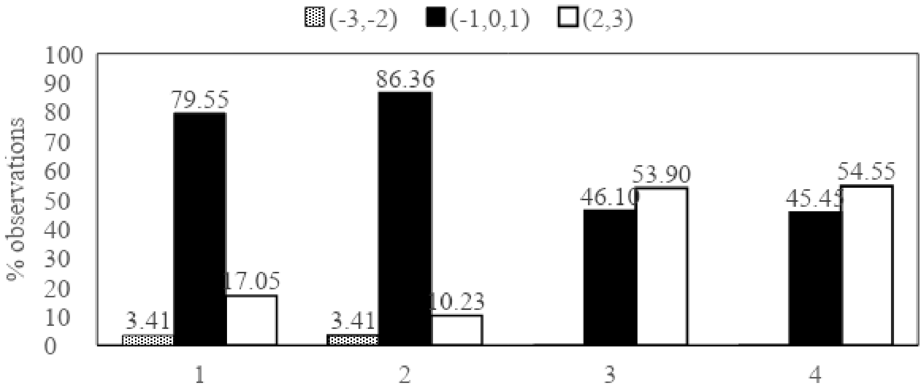


Figure 9 TSV and TCV on the central three categories

3.3 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 10 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 want to be cooler 66.23 %, followed by just right 33.77%, and no one wants to be warmer.

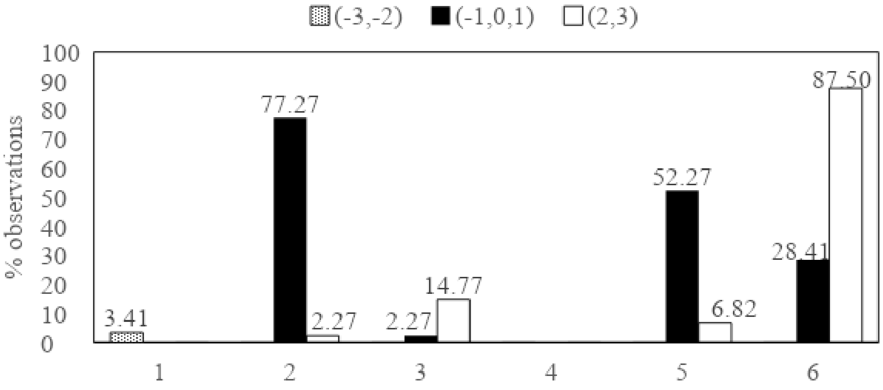


Figure 10 Thermal preference vote

3.4 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 the 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 moderately. 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 11.

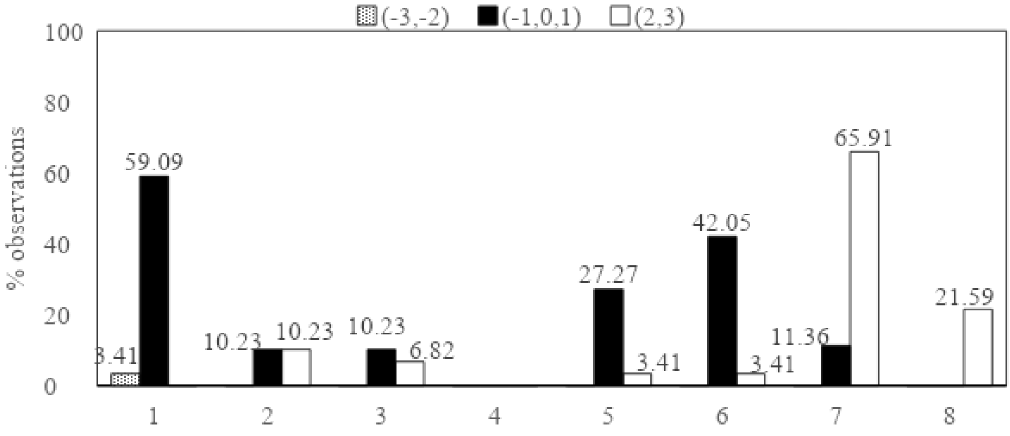


Figure 11 Body response vote

3.5 Indoor Environment Condition

Indoor environment condition was simulated by numerical simulation THERB for HAM in order to predict the indoor temperature and relative humidity for the cases tested during the survey period. The result is demonstrated in Figure 12-15. The air temperature and relative humidity continue to change according to outdoor conditions. Figure 12 shows the outside and inside air temperatures of type 1. The tendency of air temperature among the room tested was similar, with an average of 24.86 ℃ and the highest temperature in bedroom 2. The maximum and minimum air temperatures were 27.74 ℃ and 23.02 ℃, respectively. Compared to type 2, as shown in Figure 14, the air temperature was higher at 2.65℃ than type 1. The air temperature of type 2 starts from 25.37 ℃ to 29.81 ℃. Moreover, relative humidity in an indoor environment also fluctuated according to outdoor conditions, as illustrated in Figure 13 and Figure 15. The average relative humidity for both types was 69.42 % and 80.95 %, respectively. This result was similar to air temperature conditions where type 1 is more satisfied than type 2 in this study. The highest relative humidity occurred in the kitchen, followed by bedroom 1 of type 2 and the lowest in the living room of type 1. As a result, we confirm that the questionnaire filled by occupants during this survey corresponds to the simulation result. However, this simulation result should be verified for accuracy by measurement of indoor conditions with employs real-time outdoor weather data.

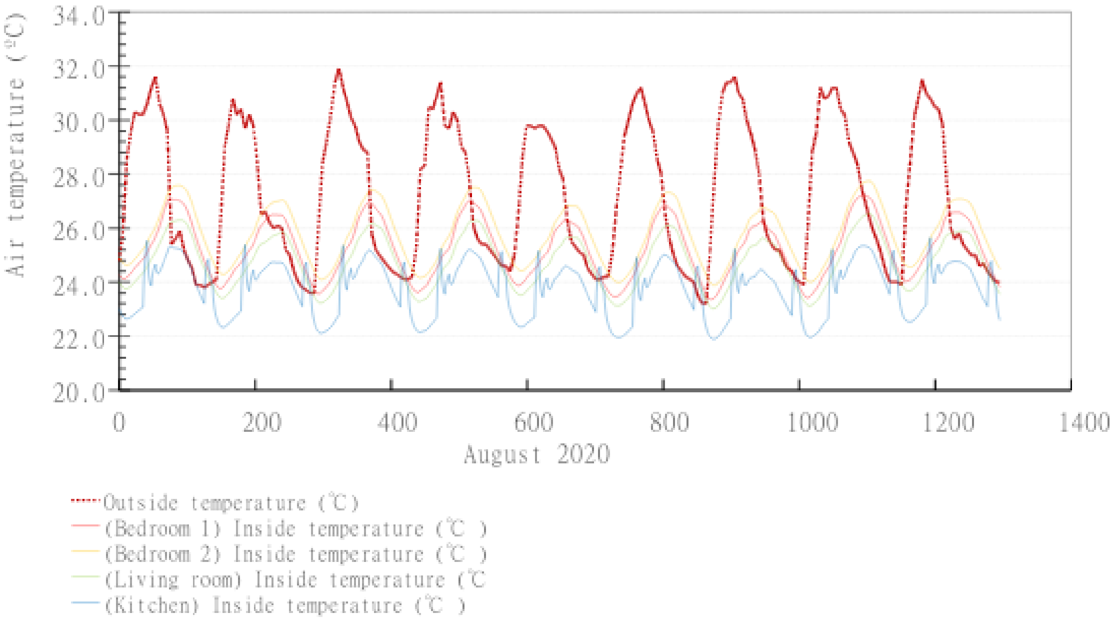


Figure 12 Outside and inside temperature on type 1

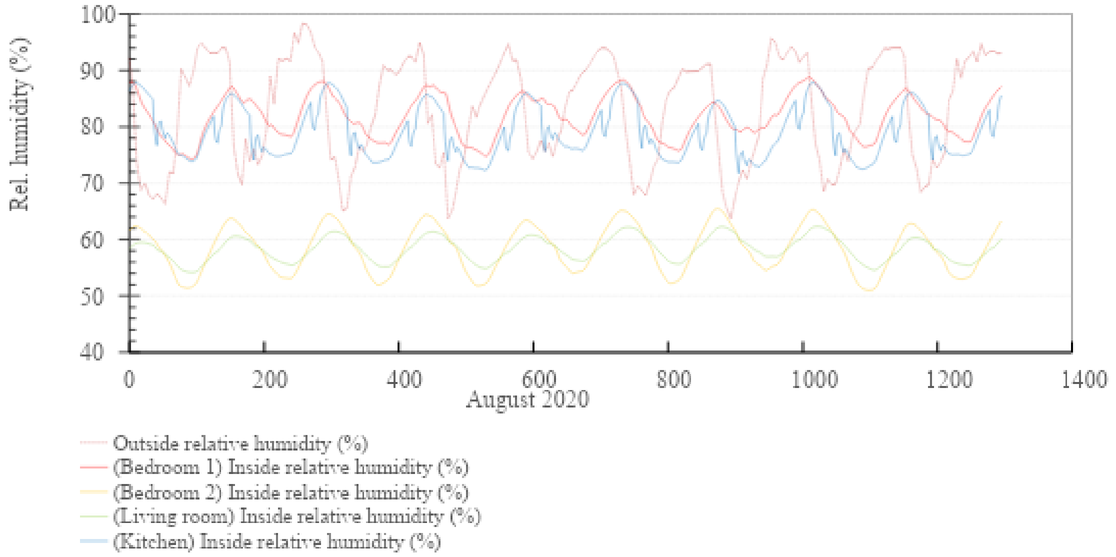


Figure 13 Outside and inside relative humidity on type 1

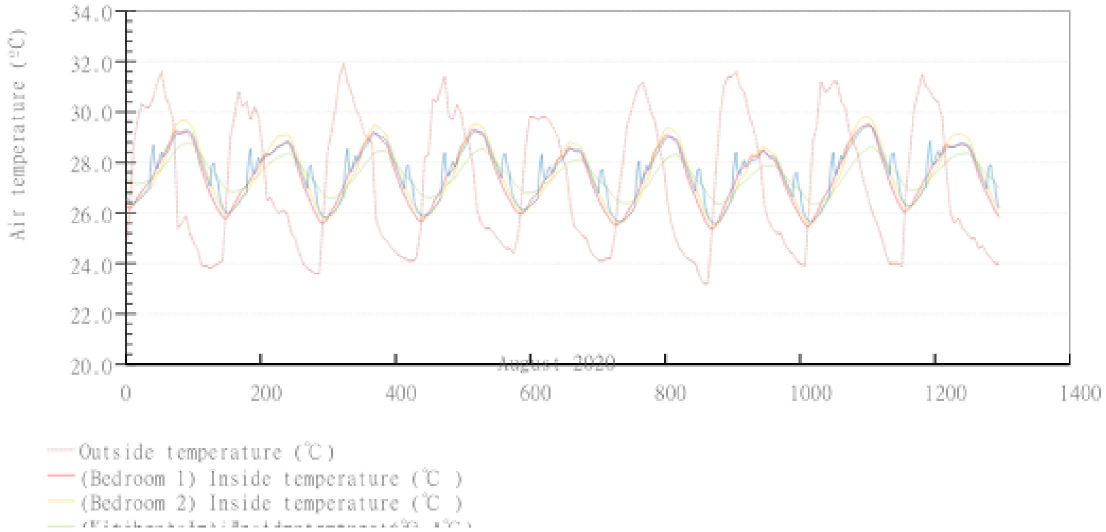


Figure 14 Outside and inside temperature on type 2.

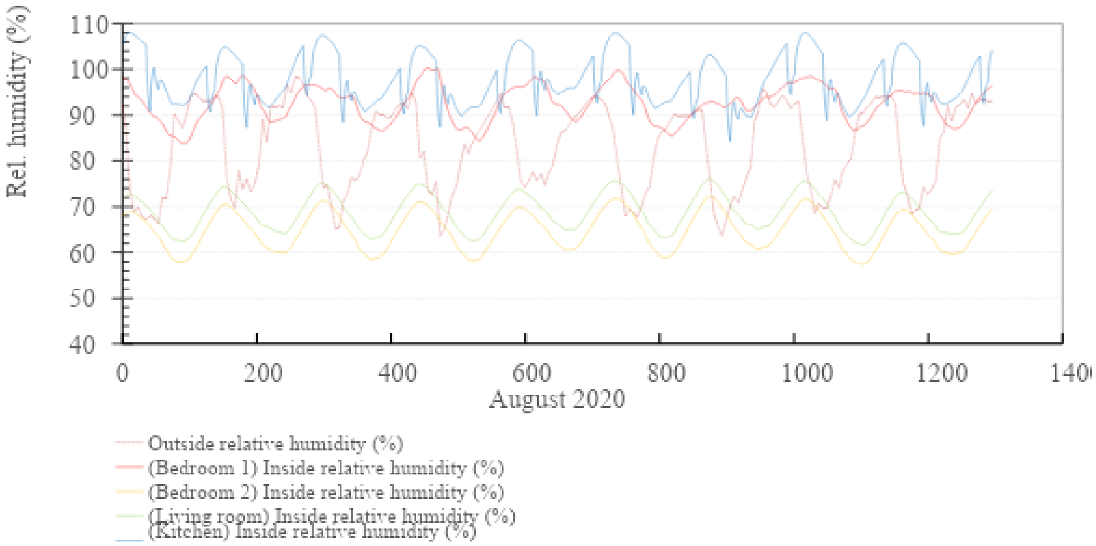


Figure 15 Outside and inside relative humidity on type 2.

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 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 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 am), afternoon (1–6 am), evening (7–12 pm), and night (1–6 am). Generally, the comparison of body action due to uncomfortable conditions between turning on the fan and using bedroom windows is 55.74 % and 44.26 %, respectively. 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 was reported at noon and morning at 20.99 % and 19.72 %, respectively. Therefore, it can be said that most of the occupants prefer to operate the fan together by opening the window at noon. Therefore, 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 votes 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 (1)
TCV = 0.9261 TSV + 0.3363 (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 Bedford scale's comfortable range (TCV = 0) 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.

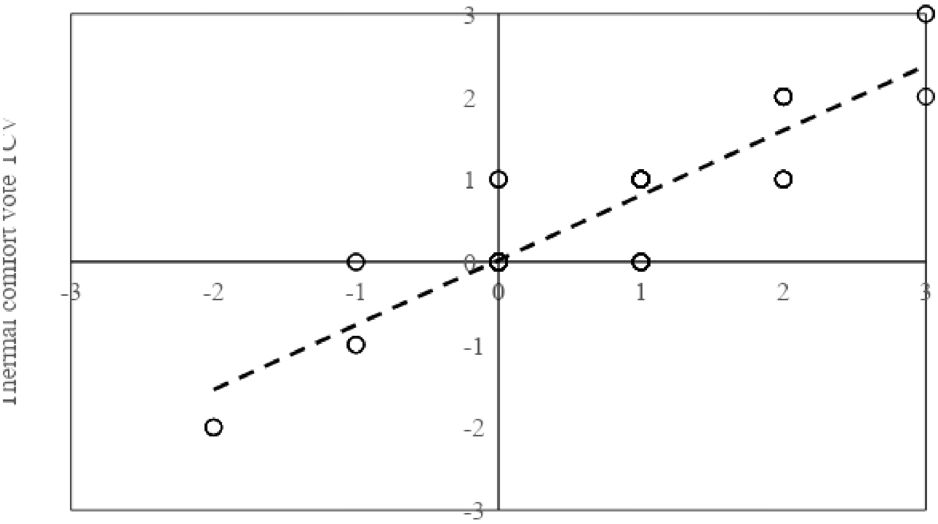


Figure 16 Regression linear of TSV against TCV for type 1

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).

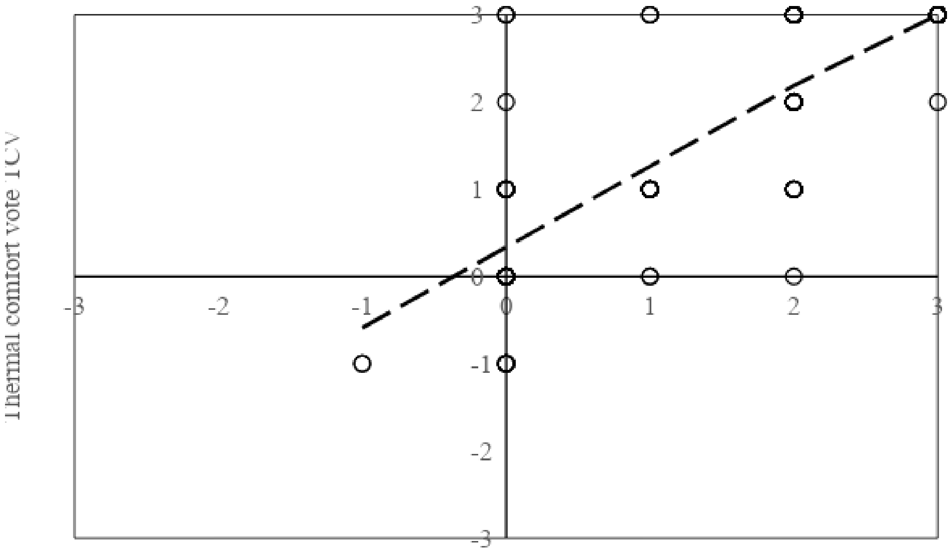


Figure 17 Regression linear of TSV against TCV for type 2

4. CONCLUSION

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

- Type 1 performs better thermal comfort than type 2 based on ASHRAE and Bedford scale and some questions related to thermal preference and body response.
- 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.
- Numerical simulation THERB for HAM confirmed the indoor environmental condition, where type 1 is better than type 2 according to air temperature and relative humidity.
- It is necessary to study natural ventilation design factors, especially the effect of opening ratio on ventilation rate and thermal comfort for naturally ventilated houses in tropical climates, as further research.

AUTHORS' CONTRIBUTIONS

All authors contributed equally to all parts of the report.

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