THERMAL COMFORT STUDY IN A NATURALLY VENTILATED RESIDENTIAL BUILDING IN A TROPICAL HOT-HUMID CLIMATE REGION

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ABSTRACT

This paper presents a thermal comfort study in a naturally ventilated residential building located in a tropical hot-humid climate region. The specific objective of this study is to investigate whether thermal comfort in this house can be achieved through a passive system only.

The methods used in this study included conducting hourly monitoring of the temperature and relative humidity; measuring the air velocities; and assessing occupants' thermal sensations through questionnaires and interview. The data from the questionnaires were matched to the monitored data to assess the acceptable range of comfortable condition. Then using an hourly simulation program, some components of the building were also "modified" to investigate whether the building can be made "more comfortable".

This study shows that it is possible to provide a thermally comfortable space in this region without

latitudes. The occupants sensed "neutrality" when the operative temperature in the house was about 27 degree Celsius (80°F). The occupants could also tolerate slightly warm conditions, that is up to 29 degree Celsius (84°F), and still never wanted to install any air-conditioning systems.

The simulation showed that using light wall materials would result in cooler indoor temperature at night but warmer during the day. If all windows were opened (25% the total floor area) the house could be more comfortable at night but less comfortable during the day. Findings of this study are important for architects and engineers in designing comfortable living spaces in these regions.

INTRODUCTION

This paper presents a thermal comfort study in a naturally ventilated residential house located in a tropical hot-humid climate region. This study is part of long-term research to investigate: (1) the thermal comfort range for people who live in tropical hot-humid climate regions and (2) the design factors that affect thermal comfort in the building. The research was initiated because standards that are currently used in these regions to achieve thermal comfort in buildings are those from the northern latitudes. As a result, many believe that mechanical air-conditioning systems are the way to achieve thermal comfort in buildings. *ANSI/ASHRAE 55-1992, Thermal Environmental Conditions for Human Occupancy* (ASHRAE 1992), for example, is used worldwide, despite the fact that this standard is based on data from climate chamber experiments performed in mid-latitude climates. Thus, this has presented a question as to whether it is true that people living in the tropics have the same levels of comfort as those in the mid or northern latitudes.

Background Research

Several thermal comfort studies in hot-humid climates have been conducted to develop a data base

1992, Thermal Environmental Conditions for Human Occupancy, is based on data from climate chamber experiments performed in mid-latitude climates (ASHRAE 1992). In 1991, de Dear et al. (1991a) conducted some field experiments on thermal comfort in Singapore. Busch (1990, 1992) conducted a similar study in Bangkok. Results from these studies showed that people in tropical regions can tolerate warmer temperature than predicted by comfort models and ASHRAE 55-1992 standards.

Later de Dear et al. (1991b) also performed climate chamber experiments on thermal comfort of 32 college students in Singapore. The result showed that the sample's mean temperature preference was 25.4°C (77.7°F). More thorough studies were performed by de Dear and Fountain (1994) in Townsville, at latitude 19°S on the northeast coast of Australia. The study sample sizes were 628 and 606 respectively for the dry and wet seasons. The studies were performed in a controlled office setting. A

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mobile measurement system was used, recording the air temperature, dew-point temperature, radiant asymmetry, air velocity, and illuminance. Questionnaires were also used to assess the subjects' thermal acceptability, preferences and sensations, clothing and activities, and other subjects' background. Results from this study showed that thermal neutrality, based on ASHRAE scale, occurred at about 24.4°C (76°F), with preferred temperature of 23.5°C (74.3°F). The subjects could tolerate excessive air movement but were less tolerable to air that was too still. These findings showed the importance of extending thermal comfort studies in climates other than mid-latitude climates.

Objective of the study

The objective of this study is to investigate whether thermal comfort in a house located in a tropical hot-humid climate region can still be achieved in a natural ventilation setting only, based on a hypothesis that people from this region are used to living in a warmer condition. The case study house is located in Depok, a suburb town near the capital of Indonesia, Jakarta. Depok, like Jakarta, is a hot-humid area, only with more rainfalls during the rainy season. The monthly average temperature throughout the year is 27°C (80°F). There is little variation between day and night temperatures, that is only from 25 to 32°C (77 to 90°F).

Before the study was conducted, the occupants had claimed that the house was comfortable, and there was always cross ventilation in the house. Therefore, this study was particularly aimed to investigate: (1) the thermal comfort range of the occupants, (2) the effects of the openings and wall structures on the thermal condition in the house, and (3) other design strategies that could be applied to create a more thermally comfortable space.

About The House

This house was designed with an interesting concept. Standing on a long lot, the house is "divided" into two zones. The front zone, facing south and the street, represents "primitiveness", while the rear zone, facing north, represents "contemporary" (Figure 1). Primitiveness is represented with a façade that makes the house seem to "grow" from the earth. The brick walls are covered with natural stones ($U = 1.57\ W/m^{2}{}^{o}K$, time lag = 8 hours, approximated from 1 hour per 2.5 cm for masonry materials), and only have few windows. Contemporary is represented with a "modern" structure and wall materials (i.e. concrete structure with painted plastered brick walls, $U = 3.66\ W/m^{2}{}^{o}K$, time lag = 6 hours). This side is more "transparent" with the presence of many windows and openings. No insulation is used both on the walls and under the clay-tile roof. All interior walls are plastered bricks with reinforced concrete structures. All floors are concrete slabs except the third floor (loft space) which is on wooden structure. The total floor area is 232.50 sq.m. (2,500 sq.ft.). All windows are clear glazing with wooden frames, totaling 50 sq.m. (537 sq.ft). The total exterior wall area is 95 sq.m. (1023 sq.ft.). The average ceiling height is 3 meter (9.8 feet), thus the total volume of the house is 785 cu.m. (27,728 cu.ft.).

As most of other houses in Indonesia, this house does not use any mechanical air-conditioning system. The main reason for not installing the system is because they do not like an air-conditioning system and believe that they can have a comfortable house with a passive system. Therefore, to cool the house, the owner, who is also the architect, applied several strategies. First, there are only few windows on the east and west walls. Second, most windows are shaded by 2 meter long overhangs. Third, natural/ cross ventilation is made possible continuously through permanent openings (i.e. the screened holes on the walls), operable windows, and high ceilings with cavities that allow warm air to rise and escape to the outside (Figure 2). Most of the times, however, all the windows are closed except for the kitchen windows that are opened when the kitchen is occupied. Thus, cross ventilation occurs through the wall openings and ceiling cavities.

METHODOLOGY

The methods used in this study included conducting hourly monitoring of the temperature and relative humidity; measuring the air velocities; and assessing occupants' thermal sensations through questionnaires and interview.

Hourly monitoring

Hourly monitoring was conducted in November and December 1997. Several calibrated data-loggers (Onset 1997) were used to monitor the indoor and outdoor temperature and relative humidity. Three spaces were monitored: the family room (first floor), the sitting /TV room (second floor), and the contemplation room (third floor, or loft of the second floor). The operative temperature, or the Mean Radiant Temperature (MRT), was monitored using modified temperature data loggers. The thermistor attached to the data logger was put inside a black painted ping-pong ball. The air velocities inside and outside the house were measured in different time of the day using a hand-held anemometer.

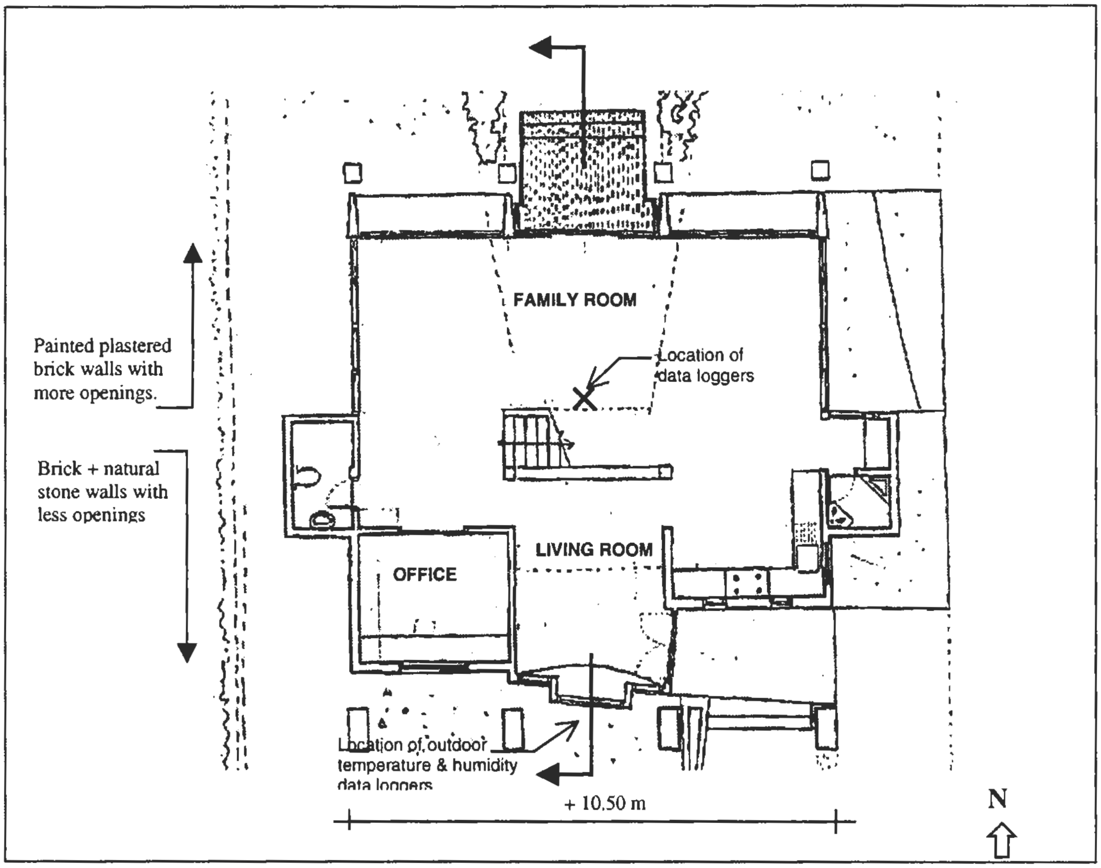

Figure 1. First floor plan of the house

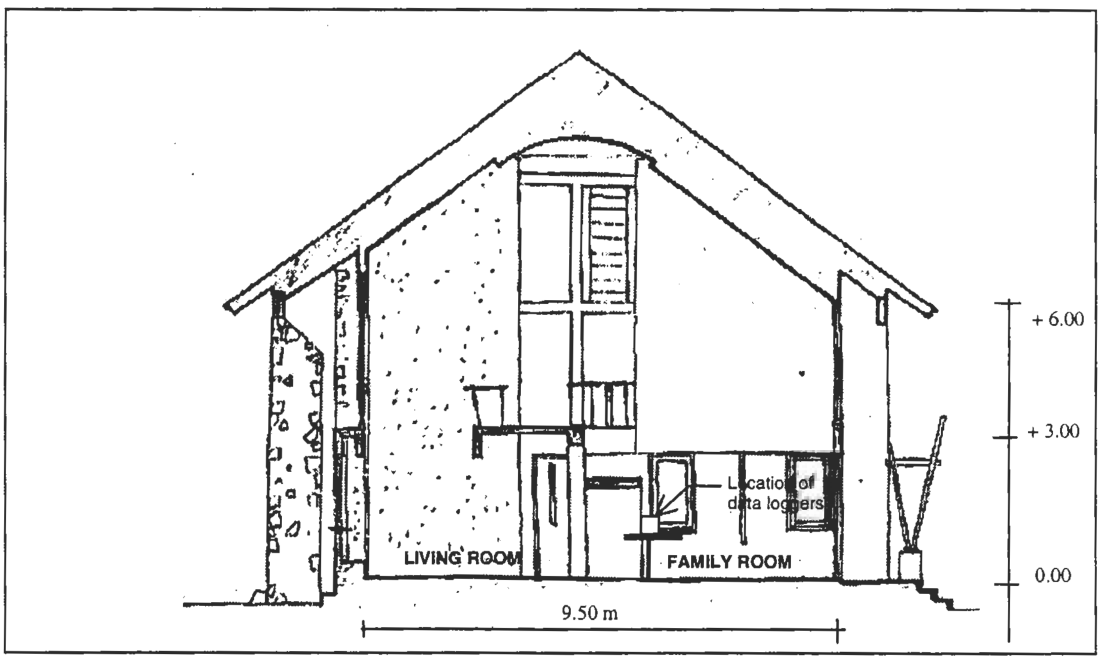

Figure 2. Cross section of the living - family room

Assessment of occupants' thermal preferences

During the period when the monitoring was conducted, the occupants were asked to record the thermal condition in the spaces where the monitoring devices were located. Using the provided form, the occupants recorded the time and date when they filled out the form, the thermal sensation, thermal comfort, their activity, and any special conditions that occurred while filling out the form (Table 1).

TABLE 1. Sample of questionnaire

Date	Time	Thermal sensation	Thermal comfort	Activity	Notes
11/ 28	6:30	Neutral	Comfort-able	Sitting	window closed
	10:00	Warm	Comfort-able	Watch TV	-

TABLE 2. ASHRAE Thermal Sensation Scale

Point	Scale
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
1	Slightly cool
2	Cool
3	Cold

The thermal sensation scale was from ASHRAE scale (PMV), ranging from hot to cold. The thermal sensation points were from 3, for hot, to -3, for cold (Table 2). Occupants are also asked to assess the thermal discomfort level, using DISC scale, from limited tolerance (4.7), very uncomfortable (3.9), uncomfortable (2.7), slightly uncomfortable (1.3), to comfortable (0 to 0.3).

The questionnaire did not include occupants' clothing because the occupants always wore light shirts or T-shirts with shorts or skirts, and either wore sandals or walked on bare feet (0.20 to 0.27 Clo). They were, however, asked to record their activity while filling out the form (e.g. sitting, watching TV, reading, walking). They were also asked to write down whether the windows were opened or closed, whether it was raining, or any other specific condition that they felt necessary to inform. Each day the occupants filled out the form at least four times (morning, noon, afternoon, and evening).

Applying this assessment approach was intended to obtain an objective result. In a controlled setting, as applied in many previous thermal comfort studies, the respondents knew that the thermal condition (temperature, relative humidity, and air velocities) was being varied to assess their thermal preferences. With the approach applied in the current study, the occupants wrote down their thermal sensation and comfort based on the condition that they experienced without knowing the actual temperature and relative humidity. The data loggers used did not display the measurement results until the data were downloaded into a computer.

After the monitored data were downloaded and put in a spreadsheet, the occupants' records were combined into the spreadsheet. The occupants' answers were placed at the appropriate time in the spreadsheet by matching the time when they were recording with the time interval in the spreadsheet. The results will be discussed later in this paper.

Interview

In addition to assessing occupants' thermal preferences through the questionnaires, an interview with the occupants were also conducted. Several questions asked include:

(1) What would you do if you feel that the air is (a) too warm, (b) too humid, (c) still or no air movement, (d) too breezy?
(2) Would you prefer or plan to install any mechanical air-conditioning systems?
(3) Is your house dusty because you have too many openings, is it bothering you?
(4) Is your house noisy because you have too many openings, is it bothering you?
(5) Is maintenance a problem because you have too many openings, is it bothering you? And
(6) What do "comfortable condition" and "comfortable house" mean to you?

As presented later in this paper, answers to these questions became an important piece of information in analyzing the occupants' thermal preferences.

Analysis of the data

After matching the monitored data with the answers from the occupants regarding the thermal sensation and comfort condition, the acceptable range of thermal comfort was analyzed by looking at the conditions when the occupant said that the temperature was at least neutral (scale = 0) and the thermal condition was at least comfortable. Then using the results, the number of hours during the

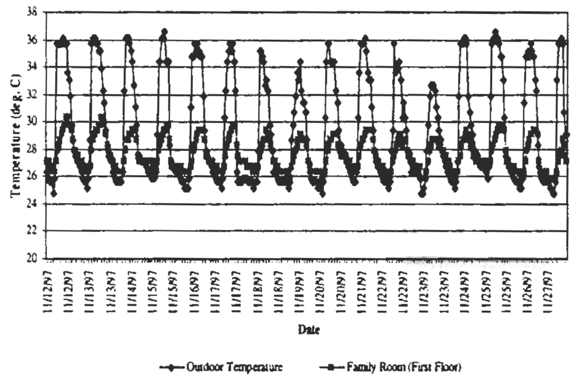

Figure 3. Family room temperature (first floor) and outdoor temperature

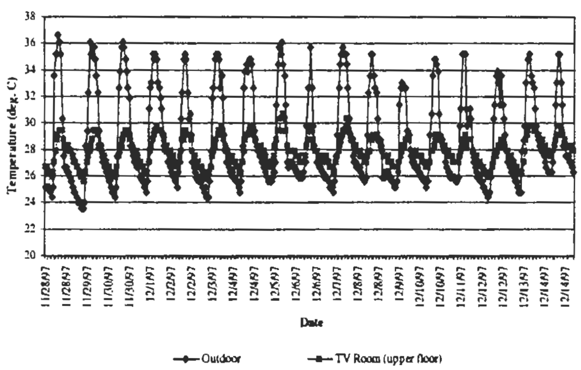

Figure 4. TV room temperature (second floor) and outdoor temperature

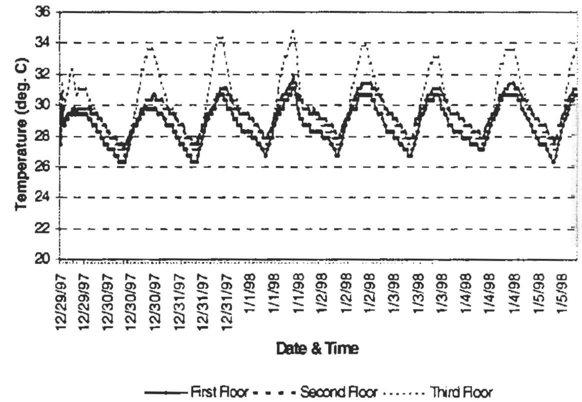

Figure 5. First, second, and third floor temperatures

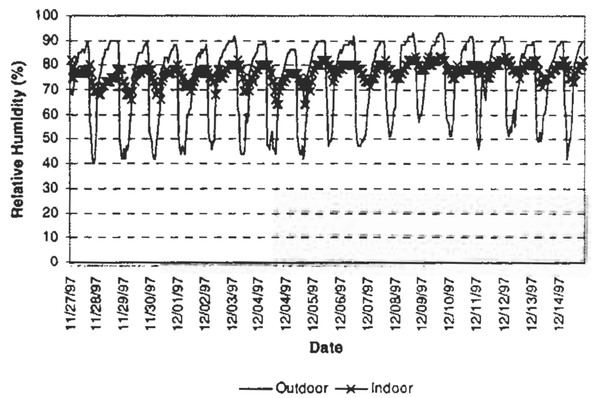

Figure 6. Indoor and outdoor relative humidity

entire monitoring period when the occupants may have sensed "neutral" and "comfortable" were predicted. This would indicate the percentage of the time when the occupants may have felt dissatisfied with the thermal condition in the house.

Simulation

An hourly simulation program (Degelman and Soebarto 1995) was used to predict the indoor operative temperature in the house throughout the year based on the thermal properties of the envelope, outdoor weather conditions, and internal loads. Using this simulation, the building was then "modified" to see whether a more comfortable condition can be achieved. This was done by: (1) changing the wall materials (from heavy to light structures), and (2) opening the windows until all windows were opened. From this we will see the impacts of opening all the windows and changing wall thermal properties.

RESULTS

Monitored temperature

The temperature data loggers measuring the indoor temperatures were placed in the family room (first floor), TV room (second floor), and a loft space. A temperature data logger was also placed outside, shaded from direct sun, to monitor the outdoor temperatures. Figures 3 and 4 show the monitored indoor and outdoor temperature. As shown in these figures, the indoor temperature at the peak hours was about 5°C lower than the outdoor temperature while at night the indoor temperature was about 2°C higher. This was shown both in the first and second floor even though the temperature on the second floor was slightly higher than the temperature on the first floor (Figure 5). These figures show the thermal mass effect of the heavy wall structure although the monitored time lags (lags between the outdoor and indoor peaks) were shorter than the previously approximated time lag of the walls due to the effect of the natural ventilation.

Monitored relative humidity

Figure 6 shows the outdoor and indoor relative humidity. The hourly indoor relative humidity was between 60 and 80% while the outdoor relative humidity varied from 45 to 90% (Figure 6). This also shows the impact of the less transparent walls. During this monitoring the windows were closed most of the times except the windows in the TV room which were opened in the afternoon.

Occupants' thermal sensations

To analyze the occupants' notes on thermal sensations, the occupants' notes were matched with the operative temperature and relative humidity when the notes were made. The occupants answered 106 times from the total of 1131 data points of monitored temperature and relative humidity. Their activities while answering the questionnaires were: sitting, reading, and watching TV, and walking (1 Met).

Figure 7 and 8 show that occupants' answers on thermal sensations were not too consistent. However, it can be summarized that the occupants felt "slightly warm" to "warm" (scale 1 to 2) between 26.3°C at 78.5% RH and 30.3°C at 60.9% RH. The occupants started to feel "neutral" (0) when the operative temperature was from 25.9°C at 82.1% RH to 28.7°C at 64.4% RH. The occupants also answered "slightly cool" (-1) when the temperature was from 25.9°C at 83.7% RH to 27.1°C at 73.3% RH. The average of 106 answers was 0.5 thermal sensation unit, which means in average the occupants' thermal sensation was between "neutral" and "slightly warm".

A regression line was then fitted to predict the thermal sensation of the entire data points of the monitored temperature. The fitted equation was:

$$y = 0.315\, t_o - 0.047 rh - 4.6855 \quad \text{eq. (1)}$$

where:

y = mean thermal sensation

t_o = measured operative temperature

rh = measured relative humidity

With this equation, the predicted average operative temperature when the occupants would sense "neutral" was 26.6°C (80°F) at 80% relative humidity. This is higher than what de Dear and Fountain found in their thermal comfort study in Townsville (1994). They found that the operative temperatures when neutralities occurred were 24.2°C (75.6°F) during the dry season and 25.8°C (78.4°F) during the wet season. This means that the occupants of this house can tolerate warmer temperature than most people in de Dear and Fountain's work.

Occupants' thermal comfort

Assessing the occupants' thermal comfort turned out to be a more difficult task. It had been expected that the answers to the thermal sensation would relate to the occupants' comfort and satisfaction to the thermal condition. For example, when the occupants answered "neutral" or "slightly cool", they would also answer "comfortable" or even "very comfortable".

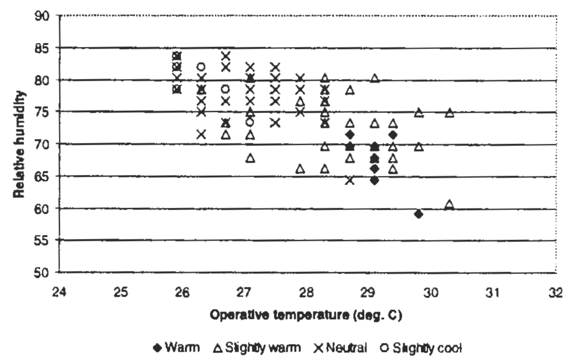

Figure 7. Relation of thermal sensation, operative temperature and relative humidity.

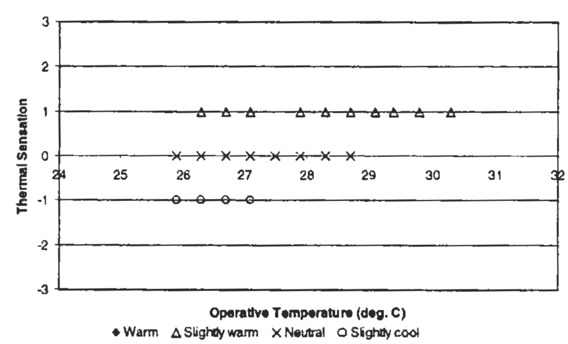

Figure 8. Relation of thermal sensation and operative temperature (RH between 60 to 80%)

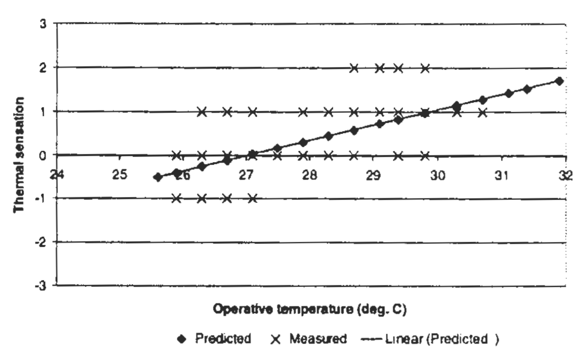

Figure 9. Measured and predicted thermal sensation

The results showed that the occupants' answers on thermal sensation did not necessarily relate to the thermal comfort and satisfaction. For example, even though the occupants did the same activities, many times they answered "comfortable" when they also answered "warm" or "slightly warm". But this once again shows that the occupants could tolerate warmer temperatures (compared to people living in the north or temperate climates). This is shown in Table 3. When they sensed "warm", for example, they could still feel comfortable 20% of the times, slightly uncomfortable 67% of the times, and only 13% of the times they felt uncomfortable. In average, they would feel very comfortable (0) when they sensed "slightly cool", comfortable (0.11) when they sensed "neutral", between comfortable and slightly uncomfortable (0.5) when they sensed "slightly warm", slightly uncomfortable (1.3) when they sensed "warm". Figure 10 also shows the relation between the thermal sensation and comfort.

TABLE 3. Occupants' thermal sensation and comfort

Therm. Sensation		Thermal Discomfort		%*
Slightly cool (ave= 26.7°C)	-1	Very comfortable	0	100
Neutral (ave= 27°C)	0	Very comfortable	0	65
		Comfortable	0.3	35
		Average	0.11	-
Slightly warm (ave= 28.3°C)	1	Very comfortable	0	4
		Comfortable	0.3	71
		Slightly uncomfort.	1.3	25
		Average	0.5	-
Warm (ave= 29°C)	2	Comfortable	0.3	20
		Slightly uncomfort.	1.3	67
		Uncomfortable	2.7	13
		Average	1.3	-

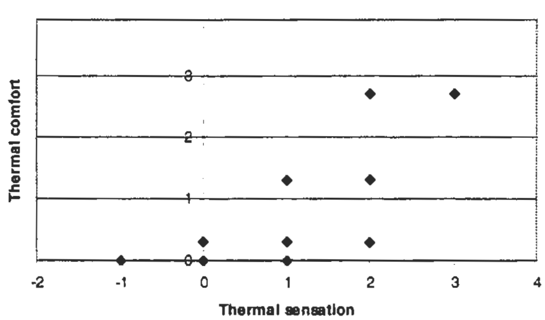

Figure 10. Relation between occupant's thermal sensation and thermal comfort

Air velocity

Notice that the discussion of the above results do not include a discussion on the air velocity in the space. This is because the measured air velocity when the occupants answered the questionnaires was too low, except when the windows were opened. The hand-held anemometer used in this study showed a zero reading (the lower limit of the meter was 0.1 mps) in the family and TV rooms when the windows were closed. The air movement could only be felt in the space when the windows were opened. During this time, the air velocities were between 0.2 and 0.4 mps (39 to 79 fpm) in the family room, between 0.2 and 0.35 mps (39 to 69 fpm) in the TV room, and between 0.2 and 0.9 mps (39 to 177 fpm) in the living room. The outside readings showed the same results: from 0.2 to 0.9 mps on the south of the house and from 0.2 to 0.4 mps on the north.

Since most of the times the windows were closed (the occupants would indicate in the questionnaire if they opened the windows), it can be concluded that the current occupants' thermal sensations and comfort were not influenced by air velocity. Thus, this also shows that the occupants of this house can tolerate much warmer and humid conditions than predicted by ASHRAE 55-1992 (Fountain and Huizenga 1995). If this standard was used, the occupants would feel comfortable at 27°C operative temperature and 75% relative humidity (with 0.27 Clo and 1 Met) if the air velocity was at least 0.1 mps. Once the temperature rises to 28°C, people would feel "too humid, warm" and "slightly uncomfortable". However, having an air movement was still an important strategy to achieve a comfortable condition for these occupants, as discussed in the next section.

Occupants' thermal preference

Despite the fact that they felt "slightly warm" in the space, the occupants indicated that they were quite satisfied with the thermal condition in the house. Their answer to the first question: "What would you do if you feel that the air is (a) too warm, (b) too humid, (c) still or no air movement?", was:

- Open the windows and doors
- Change clothes
- Go outside
- Turn on (portable) fans.

If there was too much air movement in the house, which almost never occurred except when all windows were opened, they would do nothing. However, answering to the second question: "Would you prefer or plan to install any mechanical air-conditioning systems?", they indicated that installing such systems was not necessary.

When answering to the third, fourth, and fifth questions: "Is your house dusty because you have too many openings, is it bothering you?", "Is your house noisy because you have too many openings, is it bothering you? ", and "Is maintenance a problem because you have too many openings, is it bothering you?", they indicated that those problems were present but they were used to having them. However, they indicated that they should have done something outside the house to reduce the noise from the street and the neighborhood.

Finally, the term "comfortable condition" and "comfortable house" to them meant "have a big house", "have a large garden", and "have cool spaces". These answers indicated that for the occupants having a thermally comfortable space is only one item from several other important needs. In summary, the occupants felt satisfied with the thermal condition in the house and did not want to alter anything they already had.

SIMULATION RESULTS

Effects of wall structure

Using an hourly simulation program, the effect of the current wall structure on thermal comfort was analyzed by studying the predicted indoor operative temperatures in January (representing the rainy season) and July (representing the dry season). To do this, the living room was used. Its existing wall structure (concrete structure with brick covered with natural stones, U = 1.57 W/m^2 °K, time lag = 8 hours) was then changed to a light structure (uninsulated wood siding, U = 3.42W/m^2 °K, time lag = 1 hour). This light structure is commonly found in many traditional homes in Indonesia.

The results as presented in Figure 11 showed that the existing wall structure would retain the heat in the afternoon, making the indoor temperature below the outdoor temperature. Late at night until early in the morning, this heat would be released to the interior space, making the space warmer than the outside temperature. This simulation result was proven by the monitoring results. Please note, however, that the monitored outdoor temperature at night, as previously presented in Figure 3 and 4, was about 5 degrees Celsius higher than the weather data used in the simulation. This is because the simulation used a weather simulator model (Degelman 1990) based on a 30-year of records. The monitoring was conducted in November 1997, in an unusual weather year in Indonesia predicted to be affected by El Nino.

Using the light wall structure, the indoor temperature would be lower than the temperature of the current condition late at night and early in the morning, but it would be higher during the day. Due to the higher heat transfer coefficient and shorter time lag period of this light structure, the heat would be transmitted faster during the day (from outside to the inside) and night (from inside to the outside).

This means that if the occupants preferred to have a cooler night while they were sleeping and a cooler morning, the existing wall structure was less beneficial. On the other hand, the existing wall structure made the evening indoor temperature slightly cooler than if light wall structures were used, even though the indoor temperature was still higher than outdoor temperature. However, since the occupants could still control the air movement in the house by opening the windows, the effect of this heavy mass could be compensated. The effect of alternating the area of the openings on the thermal comfort is presented in the next section.

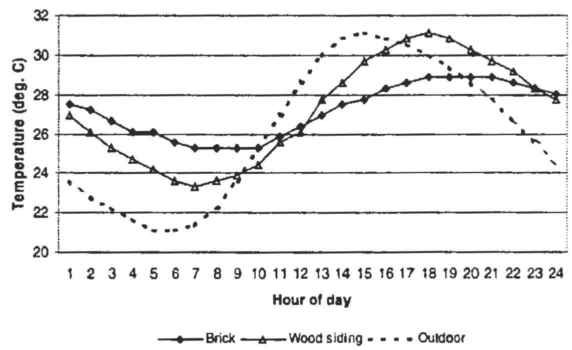

Figure 11. Predicted 24-hour average indoor temperature in January, using two wall materials

Effects of opening the windows

The effect of opening the windows on the indoor temperature was analyzed by simulating the same living room with the windows closed and opened. In the simulation, opening the windows was represented by increasing the ventilation rate in the space. This rate was estimated using the following equations:

$$Q = C_v \times A \times v \qquad \text{Eq. (2)}$$

(Stein and Reynolds, 1993)

where: Q = Ventilation rate, in cu.ft./min. (cfm)
A = Area of inlet (outlet has to be at least the same), in sq.ft.
C_v = effectiveness factor, 0.5 if the wind direction is perpendicular to the openings and 0.3 if diagonal
v = wind velocity, in ft/min (fpm).

To convert the units from SI (based on the measurements) into I-P units, the conversions are:

Area of opening (sq.ft.) = sq.m. / 0.0929 eq. (3)
Wind speed (fpm) = mps * 196.86 eq. (4)

And to convert the obtained ventilation rate in cfm into L/s (liter per second), the conversion is:

Ventilation rate (L/s) = fpm x 0.4719 eq. (5)

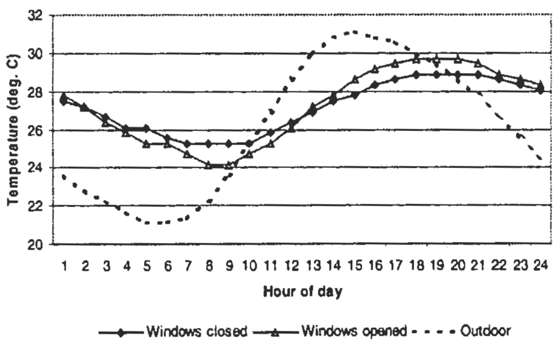

Figure 12. Predicted average indoor temperature in January, with closed and opened windows

As presented in Figure 12, opening all windows in the living room would lower the space temperature early in the morning when the outdoor temperature was low. In the afternoon, however, this would result in higher temperatures than those when the windows were closed because the warm outside air would be brought into the space. This makes the indoor temperatures stay warm until midnight, which also shows the thermal mass effect of the heavy walls. Similar results were obtained in simulating the house for other months.

This simulation, however, did not take into account the effect of the air movement on the occupants' skin that could shift the occupants' discomfort level. Therefore, to analyze the effect of the air movement from opening the windows the standard effective temperature (SET), which takes into account the radiative and latent heat transfer as well as the metabolic rate, was calculated (Fountain and Huizenga 1995). During the peak hours, the indoor temperature and relative humidity when the windows were closed were about 29°C (84°F) and 60% RH respectively. With air velocity of 0.1 mps, the standard effective temperature became 27.2°C (81°CF) and it is considered "slightly uncomfortable" by ASHRAE 55-1992, even though it could be considered "comfortable" by the occupants of this house as presented earlier. If the windows were opened, the predicted peak temperature and relative humidity would be about 30°C (86°F) and 60% RH respectively. With an air velocity of 0.7 mps as measured in front of the windows, the standard effective temperature became 25.3°C (77.5°F) and it is considered "comfortable" by ASHRAE, or could be considered "very comfortable" by the occupants based on the earlier result. At about 3 feet from the windows where the air velocity decreased to 0.4 mps as measured, the effective temperature would become 26.1°C (79°F). This is still considered "comfortable".

CONCLUSIONS

A thermal comfort study in a naturally-ventilated house in a tropical hot-humid climate was conducted. The study was conducted in November to December 1997. Indoor and outdoor climatic data were collected by several data loggers and hand-held measurement devices. There were 106 data points from the occupants with a total of 1131 points monitored data. Results from the study are as follow:

1. Occupants felt "neutral" at about 27°C operative temperature (80°F), 80% relative humidity. Below that temperature the occupants started to feel slightly cool. This indicated that the occupants of this house can tolerate higher temperature and relative humidity than the people in previous studies mentioned in this paper.

2. The occupants' thermal sensations did not necessarily coincide with their thermal comfort levels. They could feel "comfortable" or "uncomfortable" when they sensed that the space temperature was warm. In average, the occupants' range of comfort is as follow:
   25°C ≤ 27°C: very comfortable
   27°C ≤ t ≤ 28°C: comfortable
   28°C ≤ t ≤ 29°C: comfortable to slightly uncomfortable
   29°C ≤ t ≤ 30°C: slightly uncomfortable
   ≥ 30°C: uncomfortable

3. The occupants were satisfied with the existing thermal condition in the house and did not want to alter anything to make the house more comfortable. "Thermally comfortable" apparently was not the only thing that would make the occupants felt "comfortable" with the house.

4. The existing structure of the house (heavy, with brick walls covered with natural stones) was actually beneficial to the thermal condition in the house. This heavy structure delayed the heat

transmission from the outside, making the space during the day cooler than the outdoor temperature. Early in the morning, however, this heat would be released to the interior space (as well as to the outside), making the space warmer than if a light wall structure was used. Opening the windows could help decreasing the indoor temperature at night and early in the morning.

5. Using light wall structures could make the indoor temperature early in the morning 2°C lower than when using heavy structure. Using light materials, however, would quickly increase the indoor temperature during the day when the outdoor temperature was at peak; thus, making the house less comfortable before midnight.

6. To make the existing space more comfortable, the occupants could open the windows to have more air movement in the space. An example in January simulation showed that opening the windows of the living room could make the effective temperature 2 to 4°C lower than when the windows were closed. Considering that the existing house already has numerous operable windows in all the rooms, this condition can be easily achieved.

In summary, this study showed that a naturally-ventilated house can still provide a comfortable indoor environment even though the house is located in a tropical hot-humid climate region, a region often considered as "too humid" and "too warm". Appropriate strategies could include: having the right building and window orientations, having enough controllable openings to allow cross ventilation, and using the right building materials.

This study has shown the importance of assessing occupants' thermal comfort range and preference. It also shows a potential for further thermal comfort study for this region. This is a very important issue before applying any international thermal comfort standard in this region, knowing that the standard was developed in other climatic regions. Having local standards on thermal comfort will prevent designers and engineers from designing too cool or too warm indoor environment.

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