A thermal performance comparison of residential envelopes at the tropical highland for occupants’ thermal comfort

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Abstract. Climate change affects the thermal performance of buildings. A building’s thermal performance is influenced by its envelopes, such as roof, wall, and floor. A different building envelope may create a different thermal condition which may also influence its occupants’ comfort. This research aims at analyzing the residential thermal performance at the tropical highland areas by examining the deviation between the outer and inner space’s air temperature and humidity. The research employed a quantitative method by measuring the air temperature and humidity for 24 hours which were recorded every one hour. There were 15 houses with various building envelope materials as the samples. Since highland has colder air temperature, the differences between thermal variables of the outer and inner space’s of the residential were observed to figure out the longest warming. The warming process is associated with the occupants’ thermal comfort standards. The results showed there are two types of residential producing the longest warming (23 hours) which in accordance with the occupants’ thermal comfort standards. The first type is the house enveloped with roof tiles, wooden walls, and an earthen floor, while the second one is a residential house enveloped with a zinc roof, exposed stone walls, and an earthen floor.

1. Introduction

Many thermal comfort researches have been conducted and all of them lead to energy saving. Thermal comfort in regard to the building is currently associated with the occupants’ comfort. The thermal comfort theory is known with adaptive thermal comfort theory [1]. Adaptive thermal comfort is the occupants’ feeling of their environmental thermal condition. Researches propose that occupants feel inner space thermal condition influenced by outer space condition. In this case, the thermal variable is air temperature [2]. Tropical lowland’s temperature tends to be high. However, the tropical highland’s temperature tends to be low. The temperature may be 0.6°C lower in the higher area. The higher area may be cooler [3].

Thermal comfort researches on the building are always associated with a building thermal performance, known with passive thermal comfort [4]. The passive thermal comfort research aims at optimizing the architectural element to find a building design that may realize its occupants’ thermal
comfort [5]. A research conducted in Denmark finds that a naturally ventilated building may reduce artificial air conditioning up to 90.8% and save energy up to 42 kWh in 2009 [6]. A building’s passive thermal comfort is influenced by its envelopes, such as roof, wall, and floor. A research conducted in Italy finds that bricks may reduce discomfort for 30-50% [7]. The different material of a building’s envelope element may result in a difference in temperature inside the building. This is in line with material’s different property in absorbing and maintaining heat [8]. In addition to the material difference, natural ventilation also significantly influences thermal comfort. A naturally ventilated building is believed to realize its occupants’ thermal comfort [9].

Many thermal comfort researches have been conducted on lowland since, at high temperature, the occupants are deemed unable to do their activities well as the result of dehydration through sweat. However, the same occurs on the highland. A building’s occupants may not do their activities well when they are chilled [10]. Observing this issue, it is necessary to conduct a research of highland thermal comfort. Many thermal comfort researches employing air temperature variable have been conducted, especially those observing the difference of inner and outer space’s air temperature. However, only a few researches observe the difference of outer and inner space’s temperature in detail by observing how long a building lowers (cooling process) or raises (heating process) outer space’s temperature. During the heating or cooling process, we should also observe the highest, the lowest and average temperature in a building enveloped with different material.

The most frequently used thermal comfort theory is the Predicted Mean Vote (PMV) proposed by Fanger in 1972. In 1998, Fergus Nicol and Humphreys conduct a research to verify the PMV and find an adaptive thermal comfort theory which is based on the AMV (Actual Mean Vote). The adaptive thermal comfort theory is still based on the climate and personal variables of the PMV, however, a thermal sensation aspect taken through questionnaire is added [11]. The most frequently used thermal variable is air temperature, air humidity and mean sun radiation temperature. The personal variables are clothing and activity. The six variables form the basis of a thermal comfort research [12].

With regard to architecture science, the thermal comfort theory is used to predict occupants’ thermal comfort and forms the basis of a building’s thermal performance. A building’s thermal performance is the building’s ability to create its inner space condition thermally comfortable for its occupants [13]. A building’s thermal performance is analyzed using a thermal variable. From the four thermal variables, the air temperature variable is deemed to be the most influential variable in creating thermal comfort [14]. The air temperature variable is used to analyze a building’s thermal performance. To measure a building’s thermal performance, an air temperature analysis is conducted by comparing the outer and inner space’s temperatures. The difference between outer and inner space’s temperatures shows a building’s thermal performance [15]. The difference between outer and inner space’s temperatures is varied, considering that the difference is unstable at the certain time. The various temperature differences are, air temperature all-the-time difference, air temperature maximum difference, Air temperature minimum difference and air temperature average difference [16].

In addition, different results exist in the air temperature differences above during such times. When inner space’s temperature is higher than that of outer space, a building is considered to be able to cool the space (heating process). When inner space’s temperature is lower than that of outer space, a building is considered to be able to cool the space (cooling process) [17]. Research results will show the performance of the building for the comfort of its occupants.

2. Method
The research is conducted on 15 residential houses on the slope of Mount Prau, Banjarnegara Regency. The research employs a quantitative method by conducting a 24-hour measurement. A record is hourly made using a thermal tool. The tool used is RHT 20 Extech datalogger to measure temperature and humidity. The air temperature variable is measured in inner and outer spaces. Inner space measurement is conducted in a guest room, or, a family room for a house with no guest room. This measurement method has been used in relevant researches [18].
3. Result and Discussion
Most of the residential houses have no terrace considering their location with outer space’s low temperature. The selection of a building’s envelope is related to its occupants’ social activities. An occupant who has a farm and is near the stone source, such as a river or mountain, may use the stone wall. An occupant with no easy access to stone may use a non-stone wall material, such as wood or bricks. An occupant with high social status may plaster his house wall, however, the wall material is made of stone. Community social condition and climate condition influence the shape of a residential house. This is relevant to the other studies conducted in Malaysia. This research employs a simple residential object and finds that social and climate factors influence occupants’ thermal comfort [19].

Table 1. Residential Samples Display

| No | Envelope Material                                         | Photo | Figure |
|----|-----------------------------------------------------------|-------|--------|
| 1  | Zinc roof, exposed brick wall, lean concrete floor layered with carpet | ![Photo 1](image1) ![Photo 2](image2) ![Photo 3](image3) | ![Figure 1](figure1) |
| 2  | Zinc roof, wooden wall, lean concrete floor layered with carpet | ![Photo 4](image4) ![Photo 5](image5) ![Photo 6](image6) | ![Figure 2](figure2) |
| 3  | Roof tile, plaster wall, lean concrete floor layered with carpet | ![Photo 7](image7) ![Photo 8](image8) ![Photo 9](image9) | ![Figure 3](figure3) |
| 4  | Zinc roof, exposed stone wall, lean concrete floor layered with carpet | ![Photo 10](image10) ![Photo 11](image11) ![Photo 12](image12) | ![Figure 4](figure4) |
| 5  | Roof tile, wooden wall, earthen floor                     | ![Photo 13](image13) ![Photo 14](image14) ![Photo 15](image15) | ![Figure 5](figure5) |
| 6  | Zinc roof, exposed stone wall, earthen floor              | ![Photo 16](image16) ![Photo 17](image17) ![Photo 18](image18) | ![Figure 6](figure6) |
| 7  | Zinc roof, wooden wall, earthen floor layered with carpet  | ![Photo 19](image19) ![Photo 20](image20) ![Photo 21](image21) | ![Figure 7](figure7) |
| 8  | Zinc roof, plaster wall, lean concrete floor layered with carpet | ![Photo 22](image22) ![Photo 23](image23) ![Photo 24](image24) | ![Figure 8](figure8) |
A building’s envelope is one of the important design elements in architecture, for its occupants’ thermal comfort, beauty and to be the ground in a policy making. A residential house with a plaster wall is initially one with exposed stone but later modified to the plaster wall. This influences the building’s performance, pursuant to a research conducted in Bosporus, Istanbul stating that inappropriate modification of a building’s envelope structure to its original may reduce the building’s thermal performance [20]. A building’s envelope design is also deemed to realize a green architecture. On the residential houses observed it is building with wooden and exposed wall that may realize thermal comfort. Wood and exposed stone are environmentally friendly materials. The materials constitute one of the green architectural elements [21].

Highland condition with low air temperature is relevant to the thickened exposed stone wall with about 20 cm of thickness. Although the wood material may generate occupant’s thermal comfort, however, the exposed stone is more frequently used for wall, particularly by people near such material source. That stone is used as building’s envelope material constitutes a simple heating process. This heating process is also conducted to the ancient building of Anatolian historical hospitals by making a thick wall in order to create occupants’ thermal comfort [22]. Besides envelope, another architectural element constitutes a ceiling. The lower class community does not bother non-existence of ceiling.
The ceiling does not influence thermal comfort much in the cool area. The contrary applies to a hot area, that ceiling is closely related to a residential house’s thermal performance [23].

All of the residential samples apply natural ventilation. However, the highland residential houses do not apply window opening/closing since the low air temperature. However, the naturally ventilated residential houses provide their occupant's thermal comfort according to other researches, stating that natural ventilation successfully creates a building’s occupants’ thermal comfort [24]. The longest heating process occurs to samples 5 and 6, for 23 hours. House 5 is equipped with roof tile, wooden wall, earthen floor and house 6 is equipped with a zinc roof, exposed stone wall, earthen floor. This is in line with previous researches conducted on residential houses with wooden and exposed stone wall, proposing that they may warm their occupants [25].

The longest cooling process occurs in houses 3 and 9, for 16 hours. House 3 is equipped with roof tile, plaster wall, lean concrete floor. House 9 is equipped with thatch roof, ketapang wall (woven bamboo), and earthen floor. A plaster wall-house tends to maintain heat, which makes inner space cool [26]. Considering a highland residential house’s low air temperature, plaster wall may keep inner space cool, causing its occupants uncomfortable. House with ketapang wall (woven bamboo) indicates the longest cooling process as the result of gaps on woven bamboo flowing air temperature in through wind. This makes inner space’s air temperature lower.

**Table 2.** An analysis of house 1 to house 5

| Process | Residential 1 | Residential 2 | Residential 3 | Residential 4 | Residential 5 |
|---------|--------------|--------------|--------------|--------------|--------------|
| TP      | 16.00        | 8.00         | 13.00        | 11.00        | 8.00         | 16.00        | 20.00        | 4.00         | 23.00        | 1.00         |
| Ta-In Max | 21.50        | 20.40        | 25.30        | 23.20        | 23.10        | 21.20        | 25.40        | 24.40        | 26.60        | 21.90        |
| Ta-Out Max | 20.90        | 20.50        | 22.40        | 24.70        | 22.50        | 24.70        | 23.90        | 26.50        | 24.40        | 22.10        |
| DTa Max | 0.60         | 0.10         | 2.90         | 0.50         | 0.60         | 3.50         | 1.50         | 2.10         | 2.40         | 0.20         |
| Ta-In Min | 19.20        | 19.00        | 17.50        | 17.50        | 19.00        | 19.00        | 19.90        | 19.90        | 19.90        | 21.90        |
| Ta-Out Min | 18.60        | 19.50        | 17.30        | 18.50        | 20.20        | 20.00        | 16.70        | 16.70        | 17.60        | 22.10        |
| DTa Min | 0.60         | 0.50         | 2.10         | 1.00         | 1.20         | 1.00         | 3.20         | 3.20         | 2.30         | 0.20         |
| Ta-In Ave | 20.15        | 19.55        | 19.97        | 19.89        | 21.66        | 20.25        | 22.70        | 23.85        | 23.13        | 21.90        |
| Ta-Out Ave | 19.73        | 19.95        | 19.22        | 20.56        | 21.24        | 21.28        | 20.15        | 25.33        | 22.56        | 22.10        |
| DTa Ave | 0.42         | 0.40         | 0.75         | 0.67         | 0.41         | 1.03         | 2.55         | 1.48         | 0.57         | 0.20         |

**Table 3.** An analysis of house 6 to 10

| Process | Residential 6 | Residential 7 | Residential 8 | Residential 9 | Residential 10 |
|---------|--------------|--------------|--------------|--------------|--------------|
| TP      | 23.00        | 1.00         | 13.00        | 11.00        | 18.00        | 6.00         | 8.00         | 16.00        | 12.00        | 12.00        |
| Ta-In Max | 25.40        | 23.60        | 22.20        | 18.80        | 19.80        | 19.70        | 19.90        | 18.90        | 19.80        | 17.10        |
| Ta-Out Max | 24.10        | 24.40        | 19.80        | 19.50        | 19.50        | 20.00        | 19.70        | 21.20        | 19.20        | 16.90        |
| DTa Max | 1.30         | 0.80         | 2.40         | 0.70         | 0.30         | 0.30         | 0.20         | 2.30         | 0.60         | 0.20         |
| Ta-In Min | 19.30        | 22.40        | 18.30        | 18.00        | 18.10        | 18.40        | 17.40        | 17.10        | 17.80        | 17.10        |
| Ta-Out Min | 16.30        | 23.70        | 17.30        | 18.80        | 18.00        | 19.30        | 16.90        | 17.20        | 16.90        | 17.20        |
| DTa Min | 3.00         | 1.30         | 1.00         | 0.60         | 0.10         | 0.90         | 0.50         | 0.10         | 0.90         | 0.10         |
| Ta-In Ave | 22.41        | 23.00        | 18.97        | 18.52        | 19.35        | 19.20        | 18.48        | 18.06        | 18.78        | 18.31        |
| Ta-Out Ave | 20.79        | 24.05        | 18.32        | 19.07        | 19.11        | 19.59        | 17.98        | 18.91        | 18.03        | 18.74        |
| DTa Ave | 1.62         | 1.05         | 0.64         | 0.56         | 0.24         | 0.39         | 0.50         | 0.85         | 0.75         | 0.43         |
Table 4. An analysis of house 11 to 15

| Process | Residential 11 | Residential 12 | Residential 13 | Residential 14 | Residential 15 |
|---------|----------------|----------------|----------------|----------------|----------------|
|         | Ht  | Cl   | Ht   | Cl   | Ht  | Cl   | Ht  | Cl   | Ht  | Cl   |
| TP      | 14.00 | 10.00 | 15.00 | 9.00 | 21.00 | 3.00 | 19.00 | 5.00 | 16.00 | 8.00 |
| Ta-In Max | 20.30 | 18.70 | 20.30 | 18.70 | 19.80 | 17.80 | 19.70 | 19.70 | 18.70 | 22.50 | 22.70 |
| Ta-Out Max | 19.20 | 19.00 | 19.20 | 19.00 | 18.30 | 18.90 | 19.20 | 22.50 | 18.50 |
| DTa Max | 1.10 | 0.30 | 1.10 | 0.30 | 0.60 | 1.00 | 0.80 | 0.50 | 0.00 | 4.20 |
| Ta-In Min | 17.10 | 17.10 | 17.10 | 17.10 | 17.20 | 17.80 | 17.10 | 20.20 | 21.40 |
| Ta-Out Min | 16.70 | 17.50 | 16.70 | 17.50 | 16.70 | 17.60 | 16.90 | 18.00 | 17.80 | 23.40 |
| DTa Min | 0.40 | 0.40 | 0.40 | 0.40 | 0.70 | 0.40 | 0.20 | 0.90 | 2.40 | 2.00 |
| Ta-In Ave | 18.23 | 17.72 | 18.23 | 17.72 | 18.23 | 17.58 | 19.10 | 18.03 | 21.40 | 22.20 |
| Ta-Out Ave | 17.71 | 18.03 | 18.03 | 18.03 | 18.10 | 18.41 | 18.69 | 20.03 | 25.55 |
| DTa Ave | 0.52 | 0.31 | 0.20 | 0.31 | 0.58 | 0.52 | 0.70 | 0.66 | 1.38 | 3.35 |

Description:
- Ht = Heating
- Cl = Cooling
- TP = Time Period (hour)
- Ta-In Ave = Inner space’s average temperature (°C)
- Ta-Out Ave = Outer space’s average temperature (°C)
- DTa Ave = Average temperature difference (°C)
- Ta-In Max = Inner space’s highest temperature (°C)
- Ta-Out Max = Outer space’s highest temperature (°C)
- DTa Max = Highest temperature difference (°C)
- Ta-In Min = Inner space’s lowest temperature (°C)
- Ta-Out Min = Outer space’s lowest temperature (°C)
- DTa Min = Lowest temperature difference (°C)

According to the table, house 5 has an inner space’s maximum air temperature of 26.60°C during the heating process. House 5 is one with roof tile, wooden wall, and earthen floor. The inner space's lowest air temperature of 17.10 °C takes place in house 9 during the cooling process, house 10 during the cooling process, house 11 during cooling and heating processes, house 12 during cooling and heating processes and house 14 during the cooling process. The inner space's lowest air temperature takes place in 5 houses, indicating that the highland influences inner space’s air temperature, considering that the higher a location, the lower the air temperature may become.

4. Conclusion
Not all types of the residential house provide its occupant comfort. There are two types of residential house that provide their occupants comfort with regard to adaptation of environmental air temperature with residential house’s inner space, first, residential house with roof tile, wooden wall and earthen floor and, second, residential house with a zinc roof, exposed stone wall, and earthen floor. This is in line with a thermal comfort standard stating that highland occupants are comfortable at 24-25°C. The results of the study can be a convenient home reference to respond to uncertain climate change. The comparison between cold and heat becomes extreme which causes the occupants to feel uncomfortable.
Acknowledgments
Thanks to the Directorate of Research and Community Service (DRPM), Director General of Higher Education, Ministry of Research, Technology and Higher Education of the Republic of Indonesia for providing the applied research grant with contract number 027/K6/KM/SP2H/PENELITIAN/2018.

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