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Thermal Comfort Analysis of Residential Home in Coastal City Based on Physiological Equivalent Temperature (PET) Index and Operative Temperature Zone

Qurrotul A’yun¹, Riky Tri Yunardi², Satrio A. N. Rizqillah¹, Ucik N. Hidayati¹

¹ Architecture Department, Science, and Technology Faculty, Universitas Islam Negeri Sunan Ampel
² Department of Engineering, Faculty of Vocational, Universitas Airlangga
qurrotul_ayun@uinsby.ac.id

Abstract. Hot and humid tropical conditions in the coastal city have specific problems with the building thermal comfort. An important fact in creating thermal comfort is strongly influenced by two main factors that are the thermal environment and thermal balance of the human body. The differences in physical adaptation, physiological adaptation, behavior, and expectation of each human make thermal comfort varied as well. This research aim is to find out the level of thermal comfort for living home in the coastal city based on physiological equivalent temperature (PET) index and operative temperature zone. The research used simulation methods with RayMan software to analyze the thermal comfort of outdoor space and CBE Thermal Comfort to analyze the thermal comfort of indoor space. There are 4 (four) different subjects simulated in this research. The results showed that the condition could be categorized as comfortable if the thermal sensation is in a neutral position with a PET index of 20.5 – 27.0 and operative temperature zone at 22.8 – 28.8°C. Effective thermal comfort only happened in a short period. The 2nd floor is more comfortable for activity, and old female subjects need special attention to reach thermal comfort.

Keywords: CBE, PET, RayMan, operative temperature, thermal comfort

1. Introduction
In recent years, the attention of the world community on the issue of building thermal comfort [1]. The tropical country usually has hot and humid temperatures—one of the areas tropical country like Indonesia. Indonesia is considered the biggest tropical country in the world that has a problem with thermal comfort [2]. Cities on the coast have a particular problem with the thermal comfort of the building [3]. Research conducted by Prianto [4], states that the timber-framed house in the coastal region has a comfort level, but has yet to show results in concrete buildings. Inside a building, the air velocity makes it possible to solve the problem of indoor comfort [5], but its application requires additional electrical devices like fans. Based on the number of occupants of the building are also factors affecting the level of thermal comfort. Among studies on the thermal comfort level of students at the junior high school in the tropical city of [6-7] and subtropical [8-9], based on survey results, students are able to receive the air temperature between 28.2 to 33.6 °C at noon, with the condition of sitting in the classroom. The important fact in creating thermal comfort is strongly influenced by two main factors, namely the thermal environment and thermal equilibrium of the human body [10]. According to Lee [11], in general, people spend 90% of their time indoors, so they require comfortable air in the space in which they move. Differences in physical adaptations, physiological adaptation, behavior, and expectations of every human being make thermal comfort also vary.

There is a lot of research on different ways to evaluate thermal comfort to know the condition of the thermal environment appropriate for comfort in the room. These conditions can be categorized based on...
the thermal sensation with PET index [12-13] and the operating temperature zone [14-15]. Design criteria for thermal comfort have influenced the design of buildings and adaptive measures. ASHRAE 55 may identify and verify the physical measurement of thermal variables within reach of comforts, such as indoor thermal parameters [16]. This study aims to determine the level of thermal comfort of residential houses in the coastal city based on an index of physiological equivalent temperature (PET) and the operating temperature zone. This research used Rayman simulation software to analyze the thermal comfort outdoor space and CBE Thermal Comfort to analyze the thermal comfort of indoor space.

2. Method
The research used 2 (two) simulation methods. First, using RayMan software (Figure 1) to analyze the thermal comfort of outdoor space, and second, using CBE Thermal Comfort software (Figure 2) to analyze the thermal comfort of indoor space. Residential homes become the research object, which stands on hook land. The direction of this building is to the west. (Figure 3)

| Figure 1. RayMan Software | Figure 2. CBE Thermal Comfort Software | Figure 3. Residential home as a research object |
|---------------------------|---------------------------------------|-----------------------------------------------|

Simulation performed with location setting in Surabaya city. Research data was taken on September 28, 2020, for 24 hours, with geographic longitude 112°4’, latitude -7°. Horizon limitation 0.0%, sky view factor 1.000. Sunrise on 5:17 and sunset on 17:20. A more detailed picture about location conditions related to air temperature (Ta), surface temperature (Ts), and average radiation temperature (Tmrt) per hour, shown in Table 1.

Table 1. Location condition

| Time (h:mm) | Sact (W/m²) | Dact (W/m²) | Ts (°C) | Ta (°C) | Tmrt (°C) |
|-------------|-------------|-------------|---------|---------|-----------|
| 0:00        | 0           | 0           | 0       | 22.3    | 23.9      |
| 1:00        | 0           | 0           | 0       | 21.7    | 23.2      |
| 2:00        | 0           | 0           | 0       | 21.1    | 22.7      |
| 3:00        | 0           | 0           | 0       | 20.9    | 22.4      |
| 4:00        | 0           | 0           | 0       | 20.7    | 22.3      |
| 5:00        | 0           | 0           | 0       | 20.6    | 22.2      |
| 6:00        | 0           | 0           | 0       | 22.8    | 24.5      |
| 7:00        | 182         | 83          | 99      | 29.5    | 28        |
| 8:00        | 442         | 285         | 157     | 36.1    | 30.3      |
| 9:00        | 672         | 502         | 169     | 41.8    | 32.2      |
| 10:00       | 850         | 683         | 166     | 46      | 33.9      |
Thermal comfort analyzes in outdoor by using RayMan software, conducted on terraces (1st floor) and balconies (2nd floor). (Figure 4) Thermal comfort analyzes in indoor by using CBE Thermal Comfort software, conducted in the living room. (Figure 5)

| Time  | Temperature (°C) | Humidity (%) |
|-------|------------------|--------------|
| 11:00 | 962              | 801          |
| 12:00 | 1000             | 842          |
| 13:00 | 962              | 801          |
| 14:00 | 850              | 683          |
| 15:00 | 672              | 502          |
| 16:00 | 442              | 285          |
| 17:00 | 182              | 83           |
| 18:00 | 0                | 0            |
| 19:00 | 0                | 0            |
| 20:00 | 0                | 0            |
| 21:00 | 0                | 0            |
| 22:00 | 0                | 0            |
| 23:00 | 0                | 0            |

RayMan simulation used 4 (four) subjects for this research. The subject's personal data are listed in Table 2. But in CBE, Thermal Comfort only uses one subject that is Subject 1.

Table 2. Subject personal data

| Subject | Height (m) | Weight (kg) | Age (a) | Sex   | Clothing (clo) |
|---------|------------|-------------|---------|-------|----------------|
| 1       | 1.75       | 75.0        | 55      | Male  | 0.8            |
| 2       | 1.65       | 55.0        | 52      | Female| 0.8            |
| 3       | 1.75       | 60.0        | 20      | Male  | 0.8            |
| 4       | 1.65       | 50.0        | 18      | Female| 0.8            |
### Findings And Discussion

The discussion of this study is divided into two main topics, that is: (1) thermal comfort analyzes in outdoor space by using RayMan simulation, and (2) thermal comfort analyzes on indoor space by using CBE thermal comfort simulation.

#### 3.1 Thermal Comfort Analyzes in Outdoor Space by Using RayMan Simulation

RayMan helps to calculate the Predicted Mean Vote (PMV) index, Physiologically Temperature Equivalent (PET), and Standard Effective Temperature (SET). Table 3 and Table 4 describe RayMan simulation in terraces (1st floor) and balconies (2nd floor).

**Table 3. RayMan simulation in terraces (1st floor)**

| Time (h:mm) | PMV   | PET (°C) |
|-------------|-------|----------|
|              | SUBJ 1 | SUBJ 2 | SUBJ 3 | SUBJ 4 | SUBJ 1 | SUBJ 2 | SUBJ 3 | SUBJ 4 |
| 0:00        | -0.8   | -2.8   | 0.5    | -1.9   | 19.1   | 19     | 18.7   | 18.6   |
| 1:00        | -1.1   | -3.2   | -0.7   | -2.2   | 18.4   | 18.2   | 17.9   | 17.9   |
| 2:00        | -1.2   | -3.5   | -0.8   | -2.4   | 17.8   | 17.6   | 17.3   | 17.3   |
| 3:00        | -1.3   | -3.6   | -0.9   | -2.5   | 17.4   | 17.3   | 17     | 16.9   |
| 4:00        | -1.3   | -3.6   | -0.9   | -2.5   | 17.4   | 17.3   | 17     | 17     |
| 5:00        | -1.4   | -3.6   | -0.9   | -2.6   | 17.3   | 17.2   | 16.9   | 16.8   |
| 6:00        | -0.6   | -2.5   | -0.3   | -1.6   | 19.7   | 19.6   | 19.3   | 19.3   |
| 7:00        | 1.3    | 0.5    | 1.4    | 1.1    | 27.9   | 27.8   | 27.9   | 27.8   |
| 8:00        | 2.8    | 2.8    | 2.8    | 3.1    | 35.5   | 35.4   | 35.6   | 35.4   |
| 9:00        | 3.8    | 4.4    | 3.6    | 4.3    | 40.4   | 40.3   | 40.5   | 40.3   |
| 10:00       | 4.4    | 5.3    | 4.1    | 5.1    | 43.6   | 43.2   | 43.4   | 43.2   |
| 11:00       | 4.5    | 5.4    | 4.2    | 5.2    | 43.3   | 43.2   | 43.4   | 43.2   |
| 12:00       | 3.9    | 4.5    | 3.7    | 4.4    | 40.4   | 40.2   | 40.4   | 40.2   |
| 13:00       | 4.6    | 5.5    | 4.3    | 5.3    | 43.6   | 43.4   | 43.6   | 43.4   |
| TIME (h:mm) | PMV | PET (°C) |
|------------|-----|---------|
|            | PMV | PET     |
| SUBJ 1     | SUBJ 2 | SUBJ 3 | SUBJ 4 | SUBJ 1 | SUBJ 2 | SUBJ 3 | SUBJ 4 |
| 0:00       | -3.8 | -7.7    | -3     | -6     | 19     | 18.8   | 18.5   | 18.5   |
| 1:00       | -4.2 | -8.3    | -3.4   | -6.5   | 18.2   | 18.1   | 17.8   | 17.7   |
| 2:00       | -4.5 | -8.8    | -3.7   | -7     | 17.7   | 17.5   | 17.2   | 17.2   |
| 3:00       | -4.8 | -9.2    | -3.9   | -7.2   | 17.3   | 17.2   | 16.8   | 16.8   |
| 4:00       | -4.7 | -9      | -3.8   | -7.1   | 17.3   | 17.2   | 16.9   | 16.8   |
| 5:00       | -4.7 | -9.1    | -3.8   | -7.2   | 17.2   | 17     | 16.7   | 16.7   |
| 6:00       | -3.4 | -7.1    | -2.7   | -5.4   | 19.6   | 19.5   | 19.2   | 19.1   |
| 7:00       | 0.1  | -1.7    | 0.4    | -0.8   | 27     | 26.8   | 26.5   | 26.5   |
| 8:00       | 3    | 2.8     | 2.9    | 3      | 35.5   | 35.3   | 35.6   | 35.3   |
| 9:00       | 4.9  | 5.7     | 4.6    | 5.5    | 41.5   | 41.2   | 41.5   | 41.2   |
| 10:00      | 6    | 7.5     | 5.6    | 7      | 44.7   | 44.3   | 44.7   | 44.4   |
| 11:00      | 6.3  | 7.9     | 5.8    | 7.4    | 45.2   | 44.9   | 45.3   | 44.9   |
| 12:00      | 5.1  | 6       | 4.8    | 5.8    | 41.6   | 41.2   | 41.6   | 41.2   |
| 13:00      | 6.4  | 8.1     | 6      | 7.6    | 45.7   | 45.3   | 45.7   | 45.3   |

Table 4. RayMan simulation in balconies (2nd floor)
The definition of PMV value describes in Figure 6. After compiling simulation data in Table 3 and 4, data processed into a graphic to analyze its thermal comfort phenomenon. (Figure 7-10)
For the resident, the outdoor 2nd floor (balconies) is colder than the 1st floor (terraces). The PMV value always shows < -3. At the same time and same place, female subjects (subject 2 and 4) are more feel overheated or cold at the existing temperature than the male subject (subject 1 and 3). Young male subject (subject 3) is the most resistant people in existing temperature. PMV value in -1 < x < 1, happened during 12 hours at 6 p.m until 6 a.m. The old female subject (subject 2) is the weakest people in existing temperature. PMV value in -1 < x < 1, only happened in 1 hour at 6 p.m.

Based on SNI 03-6572-2001, the temperature can be said to be comfortable if it is in the range of 20.5°C until 27.1°C, with the most optimal thermal comfort temperature in 22.8°C until 25.8°C. The thermal comfort in the house can only be felt between 6 p.m. until 9 p.m., Especially on the 2nd floor, the resident also in the thermal comfort range when at 7 a.m. The most optimal thermal comfort temperature happened at 7 p.m. on the 1st floor and from 6 p.m. until 7 p.m on the 2nd floor. The most overheated temperature (>40°C) happened from 9 a.m until 3 p.m. The change of temperature occurs significantly between 6 a.m until 6 p.m.
Figure 9. PMV Data Analysis on 2nd floor

Figure 10. PET Data Analysis on 2nd floor
3.2 Thermal Comfort Analyzes in Indoor Space by Using CBE Thermal Comfort Simulation

Indoor Thermal comfort analyzes conducted in the living room that shown in figure 5. The result of simulation by using CBE thermal comfort, shown in Table 5.

Table 5. CBE Thermal Comfort Simulation in the living room.

| Time (h:mm) | Illustration | PMV  | PPD (%) | Sensation | Relative air speed (m/s) | SET (°C) | Complies with ASHRAE Standard 55-2017 |
|-------------|--------------|------|---------|-----------|--------------------------|----------|--------------------------------------|
| 0:00        |              | 0.15 | 5       | Neutral   | 2.58                     | 27.2     | √                                     |
| 1:00        |              | 0.04 | 5       | Neutral   | 2.63                     | 26.6     | √                                     |
| 2:00        |              | -0.05| 5       | Neutral   | 2.68                     | 26.1     | √                                     |
| 3:00        |              | -0.10| 5       | Neutral   | 2.80                     | 25.8     | √                                     |
| 4:00        |              | -0.07| 5       | Neutral   | 2.52                     | 26.0     | √                                     |
| Time | Value | Wind | Type       | Temperature | Humidity |
|------|-------|------|------------|-------------|----------|
| 5:00 | -0.08 | 5    | Neutral    | 2.50        | 26.0     |
| 6:00 | 0.30  | 7    | Neutral    | 2.44        | 28.2     |
| 7:00 | 0.79  | 18   | Slightly Warm | 3.12        | 30.7     |
| 8:00 | 1.08  | 30   | Slightly Warm | 3.18        | 31.8     |
| 9:00 | 1.32  | 41   | Slightly Warm | 3.21        | 32.7     |
| 10:00| 1.31  | 41   | Slightly Warm | 3.39        | 32.4     |
| 11:00| 1.43  | 47   | Slightly Warm | 3.79        | 32.8     |
| Time  | Temp | Hum | Weather | Wind | MinTemp | MaxTemp | Rain |
|-------|------|-----|---------|------|---------|---------|------|
| 12:00 | 1.41 | 46  | Slightly Warm | 4.07 | 32.7    | X       |
| 13:00 | 1.65 | 59  | Warm    | 4.28 | 33.5    | X       |
| 14:00 | 1.45 | 48  | Slightly Warm | 4.30 | 32.8    | X       |
| 15:00 | 1.37 | 44  | Slightly Warm | 4.30 | 32.5    | X       |
| 16:00 | 1.40 | 45  | Slightly Warm | 4.30 | 32.6    | X       |
| 17:00 | 1.19 | 35  | Slightly Warm | 4.30 | 31.8    | X       |
| 18:00 | 0.74 | 17  | Slightly Warm | 4.30 | 29.9    | X       |
| Time  | Temperature | Dew Point | Neutral | Airspeed | Operative Temperature Zone |
|-------|-------------|-----------|---------|----------|-----------------------------|
| 19:00 | 0.60        | 13        | Slightly Warm | 3.65 | 29.3 | X |
| 20:00 | 0.49        | 10        | Neutral  | 3.32    | 28.8 | √ |
| 21:00 | 0.39        | 8         | Neutral  | 3.27    | 28.4 | √ |
| 22:00 | 0.30        | 7         | Neutral  | 3.10    | 27.9 | √ |
| 23:00 | 0.22        | 6         | Neutral  | 2.94    | 27.6 | √ |

The operative temperature zone is 22.8°C until 30°C. The living room temperature in thermal comfort situation at 8 p.m until 6 a.m with neutral thermal comfort sensation. The most optimal thermal comfort temperature happened at 3 a.m. The most overheated temperature happened at 1 p.m. The highest airspeed occurs at 2 p.m until 6 p.m, then continues to decline until 12 a.m and rises again until 2 p.m.

4. Conclusion
In Coastal City, such as Surabaya, with two floors residential home as a case study, it has a different character about thermal comfort. From this research, it can be concluded that thermal comfort in this area correlated with 3 (three) aspects that is time, position, and subject. About time, thermal comfort only happened in a short period at night for 3 hours. The comfortable position for the activity is on the 2nd floor. A subject that needs special attention to reach thermal comfort is an old female subject. From
this, we can emulate a recommendation due to maximalize the thermal comfort by modifying building façade and spatial planning as well.

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