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Heat transfer through building envelope materials and their effect on indoor air temperatures in tropics

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Abstract: High thermal mass modern building materials are unsuitable to be used in the tropics due to their thermos-physical properties and the ability in absorbing solar radiation, storing and transferring heat into the building, affecting the high indoor air temperature, hence, reducing thermal comfort. However, due to the high demand for building, utilization of this material is avoidable. This study investigated the heat transfer through building envelope materials and their effect on the indoor air temperature of the building through field measurement using a thermal camera and a handle wind meter. The results found that the ceiling is the part of the building which gained the highest indoor surface temperature which reaches 38.6 °C at the apex point at 2pm but decreased significantly to 30.4 °C at 6 pm. Meanwhile, the inner of the northeast wall gained 33.1 °C at the peak temperature and stayed above 30 °C until 10 pm. The indoor air temperature of this unit housing was 36.3 °C at 2 pm with the temperature difference between outdoor and indoor was 2.5 °C. At night, the indoor air temperature was 3.8 °C higher than the outside temperature.

Keywords: *Heat transfer, building envelope, temperature, thermal comfort, tropical climate*

Introduction

As a product of culture, architecture has evolved, shifted, and changed over time. Shifts or changes in architecture had happened because of many things, such as changes in the order of human life, changes in patterns and types of activities, changes in the supply of natural resources, developments in building materials, developments in building technology, and also changes in human mindset which ultimately changes the culture and level of civilization.

The building that was originally made of wood and other natural materials has now changed to adapt to modern materials. The high demand for buildings and the increasing value of land leads to the increasing use of modern building materials as the main material for building from time to time, and it is unavoidable. Modern building materials such as bricks (concrete or earth), steel and glass have replaced traditional building materials such as wood and bamboo. The modern material which is a high thermal mass is unsuitable to be applied in tropical climates because of its ability in absorbing solar radiation, storing and transferring heat into the building [1]. The utilization of these materials will affect the thermal sensation for occupants in this region.

The tropical climate region which is lies between the tropic of Cancer (23°27'N) and the Tropic of Capricorn (23°27'S) has hot and humid climate characteristics. This region receives large solar radiation with long periods of sunny days throughout the year as well as high temperatures and high levels of relative humidity. The average monthly temperature in this area ranges from 1-3 °C, while the average daily temperature variation is about 8 °C and the average annual temperature is around 27 °C which exceeds the ASHRAE summer comfort limit of 26 °C for most of the year [2].

American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) [3] stated that the indoor air temperature is between 22.5°C to 25.58°C but Zain-Ahmad, et.al [4] found that people who live at the hot-humid tropical climate fell thermally comfortable with the optimum comfort temperature ranges between 24.5°C to 28°C, the higher temperature that ASHRAE standards. Maximum temperatures in the tropics are not as high as in hot arid climates, but nights often remain above the comfort zone [2].

Several factors that affect the thermal comfort of a building related to energy use include the orientation of the building, air circulation through ventilation, and thermos-physical properties of building envelope materials. Aside from a separator from the environment, the building envelope is also the protection from the climates, such as solar radiation, wind and precipitation that directly affects the building [5]. Heat by solar radiation is the prominent load transferred from the building envelope that affects the thermal sensation of occupants inside the building. The amount of heat that reradiate from the building envelope including wall and roof is diverse related to the climate condition and material properties [6].

The materials used to construct the building envelope determine the relationship between outdoor temperature and solar radiation conditions, and indoor temperature in non-AC buildings [7]. Poor quality building envelope results in less comfort for the occupants. Lack of comfort results in dependence on active systems such as air conditioning, which use more energy. [2]. The discomfort of the indoor environment encourages people to rely on air-conditioning inside the building. Aside from the effectiveness of the air conditioning system in increasing thermal comfort, these appliances consumed around 30-60 % of the total energy consumption in the building sector [8][9].

In addition, during the current COVID-19 pandemic, people are encouraged to stay at home and work from home. To be able to work with optimal performance, residents often feel uncomfortable thermally, especially in buildings with unfavorable physical and architectural conditions. A building located in Lampung; Indonesia was chosen as a cases study. This building consists of several housing units, each of which is occupied by several lecturers from a university in Lampung. During this pandemic, lecturers work from home. However, the conditions in the building are not comfortable because the orientation and environment of the building cause this building to receive full sunlight and results in high air temperatures in the building's rooms, especially the living room which is usually used as a workspace. Therefore, this study aimed to investigate the heat transfer through surface envelope materials of the building located in the hot-humid tropical climate and its effect on the indoor air temperature of the building.

Method

Case study

This research is a field experimental research that was conducted on a case study. A case study is a unit of a single floor terrace-house facing Northeast located at Bandar Lampung, Indonesia (5°22'19" S nd 105°17'54" E) (Figure 1). The front side of the building is adjacent to a large vacant lot with minimum vegetation. This spacious area is also functioning as a yard and parking lot. Meanwhile, the backside is next to a neighbor's vacant land which is used as a plantation area. These both empty spaces allowing the sunlight to hit the building freely.

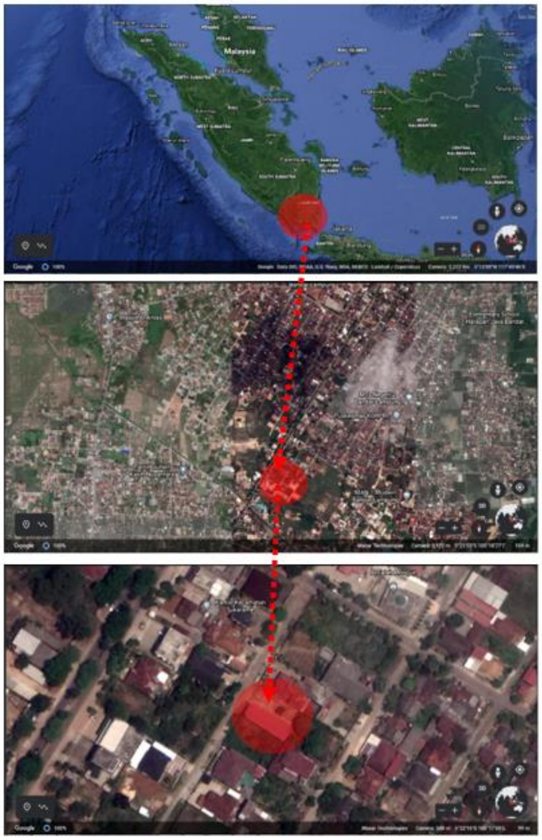

Figure 1. Location of the case study

The building consists of seven units which shares the sidewalls. The wall of the building was constructed using clay bricks with a thickness of 100-mm-thick. The wall was plastered and is painted in white. The wall facing northeast has the window-to-wall ratio (WWR) of 8.6 %. The building has a pitch roof with metal-zinc corrugated sheet roofing with attic and plasterboard ceiling and concrete floor with tiles. The thermal properties of the building envelope materials are shown in Table 1 while Figure 2 shows the existing condition of the building.

Table 1. U-value of envelope materials [10]

		U-value (W/m²K)
External Wall	Brick, single skin, plastered	3.28
Window	Wood frame, single 6 mm glass	5.0
Roof	Metal sheet (corrugated) roof with attic and plasterboard ceiling	2.54
Floor	Concrete floor	1.07

Figure 2. existing condition of the case study

Measurements

The field experiment was conducted to investigate the surface temperature of the outer wall of the building and the temperature of the internal surface under actual hot-sunny climatic conditions and its effect on the indoor air temperature of the building. The measurements were focused on the living room of the housing unit. This area is usually used as a workspace when the *Work from Home (WFH)* is enforced during the Covid-19 pandemic. Since it is used as a daily workspace, this area should have an adequate level of thermal comfort for the user.

The indoor air temperature was measured using a handle wind meter WeatherHawk WindMate (WM-300), while the surface temperature data was taken using a thermal imaging camera (FLIR C2). The thermographic camera will detect radiation in the long-infrared range of the electromagnetic spectrum and produces an image of that radiation. All data were taken in the one-hour interval from 6 am to 10 pm on 1st May 2021, which is categorized as the month with the highest annual average temperature level [11]. The outside average temperature and humidity was 27.75 °C and 81.74%, respectively.

The sun path diagram of Bandar Lampung as shown in Figure 3 depicts the collection of sunlight, which is relatively constant throughout the year, from 06.00 am to 06.00 pm. Since Bandar Lampung lies close to the equator, this area receives more than 10 hours of sunlight from the dawn to sunset.

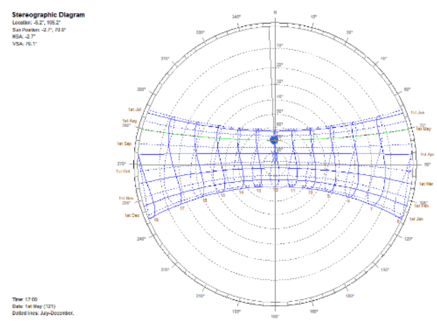

Figure 3. Diagram of the Sun Path in Bandar Lampung from Autodesk weather

Outdoor wall surface temperature was measured on the front wall of the building which directly receives solar radiation in the morning until noon. The internal surface temperature was measured in four directions of the living room walls (IW1-IW4), ceiling and the floor as shown in Figure 4. The measured data was recorded manually. Data analysis was performed using descriptive methods by explaining existing conditions through supporting graphics and pictures.

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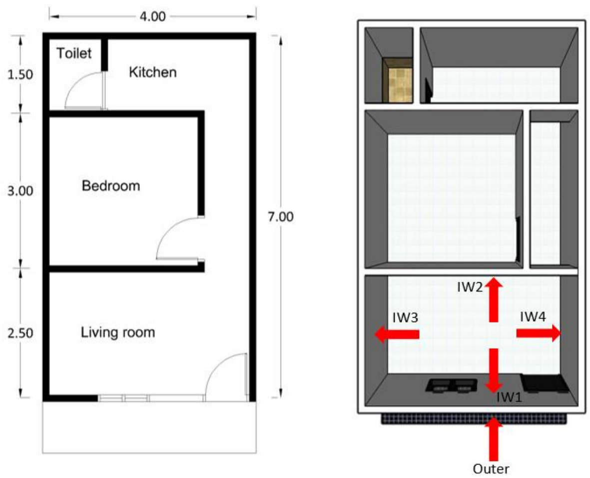
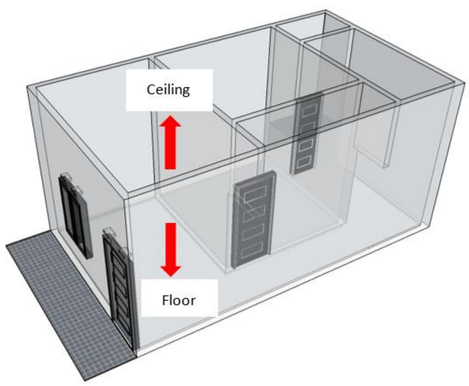


(a) Wall surface measurement points



(b) Ceiling and floor surface measurement point

Figure 4. Measurement point of thermographic camera

Results And Discussion

Indoor-outdoor Wall Surface Temperatures

The comparison between the surface temperature of the outer and inner walls (IW1) is illustrated in Figure 5. The measurement data shows that the outer wall surface temperature was 2 °C lower than the IW1 at 6 am in the morning. As the sun rises, the outer wall temperature increases significantly until it reaches the peak of 36.3 °C at 2 pm. At 6 pm when the sun is setting and the outside air temperature is dropping, the outer wall temperature was lower than the inner wall temperature. The outer wall surface temperature dropped drastically from 33.5 °C at 5 pm to 28.1 °C at 6 pm and continued to drop to 27.0 °C at 10 pm, meanwhile, the inner wall surface temperature only dropped from 32.5 °C at 5 pm to 31.8 °C at 6 pm and reduces to 30.8 °C at 10 pm. The temperature difference between the inner and outer surfaces was 3.8 °C.

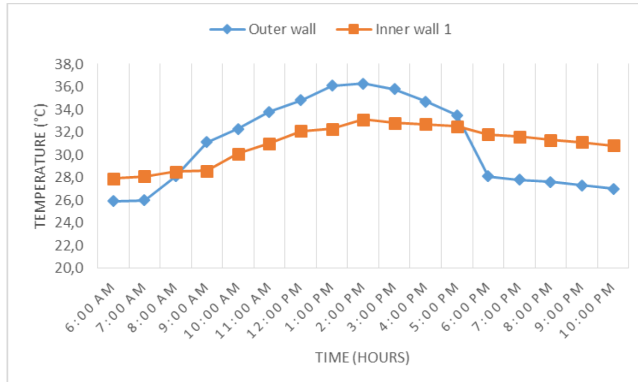


Figure 5. Surface temperature of outer and inner wall

In Figure 6 we can see the thermograms of the external and internal Northeast façade. The thermographic camera detected the amount of radiation in the long-infrared electromagnetic spectrum. Thermograms visually displays the amount of infrared energy emitted, transmitted and reflected by the object [12]. The amount of radiation emitted by the object increases with the temperature; therefore, the thermograms show variations in temperature.

The thermograms of the outer wall taken at 6 am and 6 pm (Figure 6a and 6c) is slightly uniform compared to the one taken at 12 pm (Figure 6b). This phenomenon can be related to the heat radiation emitted by the overhangs on the terrace which gives a lighter color to the top of the wall, indicating that it is hotter. When viewed through a thermal imaging camera, warm objects appear in brighter colors against a cooler background.

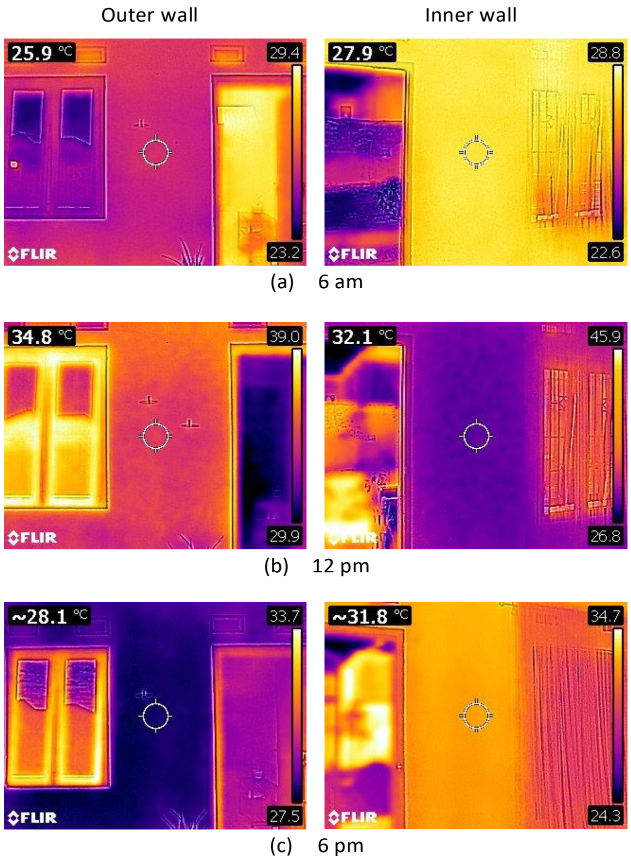


Figure 6. Thermograms of outer and inner wall surface

Surface Temperatures

The surface temperature of different directions of the inner wall (IW1, IW2, IW3, IW4), ceiling and floor is shown in Figure 7. It can be seen that IW1 gained the highest surface temperature of the wall area, followed by IW4 and IW3. Higher surface temperature of IW1 was due to it was directly adjacent with outdoor environment.

The high thermal mass material such as concrete, clay brick, and tiles requires a lot of heat to increase the temperature. As the solar radiation hit the outer wall surface, the heat was transferred into the building envelope structure and stored. However, since this kind of material slow in releasing heat. Hot and humid air is trapped in the structure, affects to the increasing indoor air temperature. At night, due to the delay in heat transmission caused by the high mass of the building walls, the internal space of the building tends to be warmer than the outside

In the other hand, roof is the part of the building that receives the highest amount of solar radiation. High solar radiation can be a cooling problem if it accumulates and then is transferred to indoor spaces. Hence, the ceiling becomes the part of the surface of the building that has the highest temperature, which is 38.6 °C at the peak point, but immediately drops when the outside temperature drops.

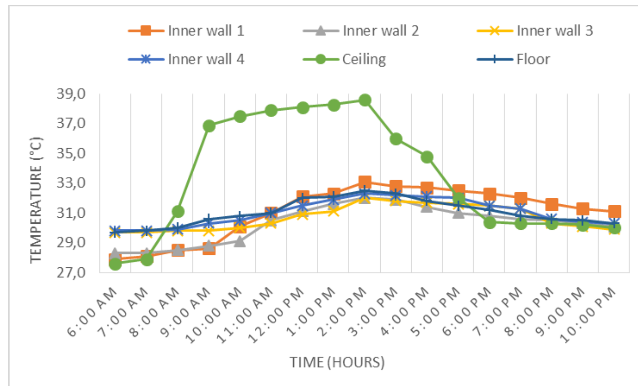
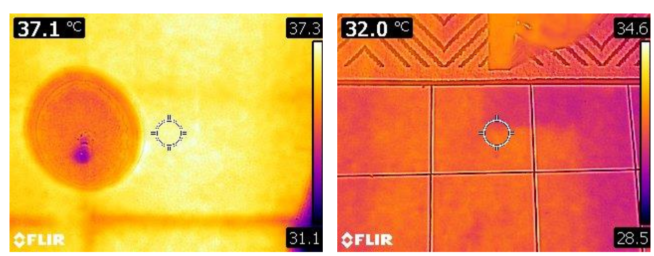


Figure 7. Surface temperature of 4 direction inner wall, ceiling and floor

This phenomenon might be influenced by the thermal properties of building materials. As already known that the thermal conductivity of metal-zinc roof has high value of thermal conductivity of 112 W/mK [10]. This thermal characteristic as well as the thin metal sheet makes the roof easily transfer the heat into the building. However, this type of material can release the heat easily. A least, the ceiling surface had the lowest temperature at night. Figure 8 shows the thermograms of the ceiling and floor of the building.



(a) Ceiling (b) Floor

Figure 8. Thermograms of ceiling and floor surface at the apex point

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The efficiency of envelope is often discusses in terms of its thermal properties in heat transfer by process of conduction, convection and radiation occures at the exterior surface of the building. The total surface area subject to thermal transfer is a function of the building shape and orientation. The solar irradiation from the building envelope was also simulated using the Autodesk Ecotect building simulation as shown in Figure 9 and 10.

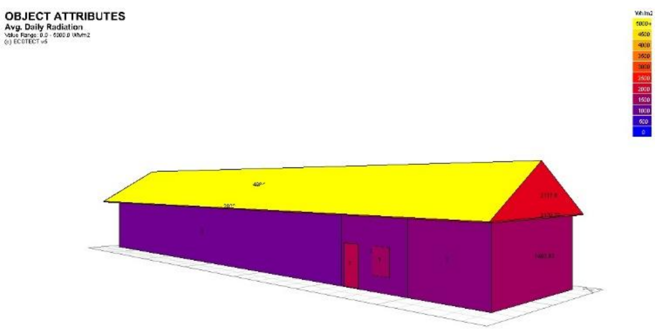

Figure 9. Solar irradiation

Because it was built with a long section facing east-west, this building receives a lot of solar radiation during the day, especially on the facade and roof of the building. In Figure 9, it can be seen that the wall facing the northeast has a lower irradiation than the wall facing the northwest, although it is still at a moderate level. While the roof emits the highest radiant energy incident on the surface. This is because at 12 noon, the sun has moved upwards, so that the roof is more exposed as shown in Figure 10.

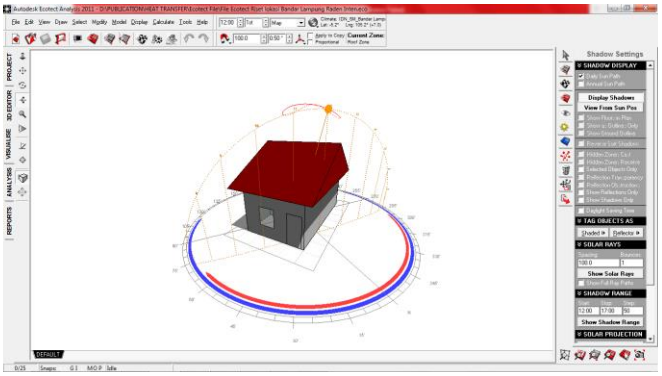

Figure 9. Daily sun path

Air Temperatures

The heat flow between the building and its environment occurs in several physical modes including conduction gain through envelopes, indirect solar gain through opaque such as wall and roof, direct solar gain through a transparent material such as windows, heat gains from ventilation and air infiltration, internal gains from human, and heat gains from inter-zone gains (adjacent zones) [13][7]. The high temperature of the external environment and the heat transmission through the building envelope provides a sauna effect, that creates an uncomfortable indoor environment [6].

Since the outdoor temperature and solar radiation followed diurnal cyclic patterns. Hence, the outdoor temperature has its minimum around sunrise, rises and reaches its maximum at an early afternoon hour, and then drops down as sunset. During the daytime hours, solar radiation striking and absorbed at the walls and roof surface causes an elevation of the indoor average temperature above the outdoor average [7]. The heat gain from the conduction through building materials, indirect solar radiation through wall and roof, direct solar gain through the window, heat flows from ventilation and air infiltration affecting the indoor air temperature [14].

Figure 11 shows the indoor and outdoor air temperature. As the outdoor air temperatures increases, the indoor temperature also increases and lasts a long time with only a slight decrease in temperature. It is seen that the indoor temperature has not had time to decrease but the outside temperature has started to increase, hence, the indoor air temperature was always higher than the outside temperature.

Indoor air temperature increases significantly at 8-9 am until reaches the maximum of 36.3 °C at 2 pm. The temperature difference between outdoor and indoor at the peak point was 2.5 °C. As the heat absorbed and stored in the building structures especially the wall and floor, the indoor air temperature was 3.8 °C higher than the outside temperature (26.2 °C) at 10 pm. The average indoor and outdoor temperature after sunset to 10 pm was 30.9 °C and 29.0 °C, respectively. The fact that this building has no cross ventilation adds to the reason for the high air temperature inside the building.

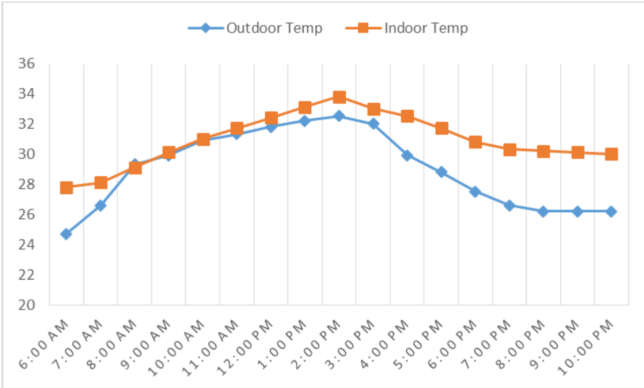

Figure 11. Outdoor and indoor temperature

Conclusions

This study was conducted to investigate the heat transfer through surface envelope materials of building in the tropics and the indoor air temperature of the building. The measurements found that the ceiling is the highest indoor surface temperature which reaches 38.6 °C at 2 pm but decreased significantly to 30.4 °C at 6 pm. The inner of the northeast wall gained 33.1 °C at the peak temperature and stayed above 30 °C until 10 pm. The indoor air temperature of this unit housing was 30.0 °C at 10 pm, about 3.8 °C higher than the outside temperature of 26.2 °C.

Meanwhile, the average indoor and outdoor temperature was 30.9 °C and 29.0 °C, respectively. Eventually, the building layout where the long part faces northeast, the absence of shading devices, minimum ventilation, integrated with poor building envelope materials leads to increasing indoor air temperature of this building, above the optimum comfort limit.

Conflicts of interest

There are no conflicts to declare

Acknowledgements

The acknowledgements come at the end of an article after the conclusions and before the references.

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