JEMMME (Journal of Energy, Mechanical, Material, and Manufacturing Engineering)
Vol. 7, No. 1, 2022

ISSN 2541-6332 | e-ISSN 2548-4281
Journal homepage: http://ejournal.umm.ac.id/index.php/JEMMME

Effect of roof and wall material on energy usage for house cooling system in hot-humid climate

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Abstract

A model of a typical townhouse in Surabaya is simulated using building energy simulation software to analyze the energy consumption for cooling due to a severe climate. The assessment focused on the internal heat effects caused by the wall and roof material to meet the thermal comfort in a hot-humid climate region. A baseline building was a one-story building for one family with the typical load profile in Surabaya applied. The insulation thickness and material composition of the wall and roof were varied, whereas the internal cooling system was maintained at 25.5^{o}C by the air-conditioning system. Results are presented and compared in terms of the annual energy consumption to meet the Indonesian standards for buildings. The best optimization shows that the implementation of the insulation in the model can lower the annual energy consumption and conserve the energy by 37%.

***Keywords**: building, energy efficiency, simulation.*

1. Introduction

Methods applied to maintain thermal comfort had been evaluated in the regions with hot and humid climate zone conditions. It shown that a cooling demand has been the main issue in several low attitudes and hot humid climates as evidenced through zero and low-energy buildings development (1).

In Singapore, a study investigated a hot humid climate passive house showed that the temperature and humidity were the main issues (2). The building was maintained at 26^{o}C indoor temperature with the HVAC system running continuously. Insulations were applied to the wall and roof. As a result, the cooling demand of the building was 38.7 kWh/m^{2}/year as the design reduced the exterior heat and applied a reflective exterior surface. Moreover, the window had solar glazing and an overhang shading of 1.5m is to prevent heat transmittance.

Chirarattananon et al. (3) investigated the role of wall insulation in Thailand regarding its thermal performance. The wall insulations analyzed were 25 mm, 50 mm, and 75 mm thick. The findings show that the thicker insulation, the lower the energy consumption of the building. The energy reduction was significantly shown compared with its baseline model without any insulation which was 58%, 69.8%, and 75% respectively.

On the other hand, Al-Obaidi et al. (4) explained the performance of the reflective and radiative roofs in the cooling effect. The roof was designed to prevent heat gain as the highest heat may be gained from the roof. A reflective roof strategy was used to slow the heat transfer into the building by implementing the right color for the roof. Another technique was performed through the calculation of the solar reflectance and thermal emittance.

However, it did not result well in the tropics. The preference of occupants still tended to choose a darker color, even though it gained more heat. Whereas the radiative roof was used to remove unwanted heat from the building. It proven that the issues lied in the evaluation of the roof performance, causing the failure of cost-effective and thermal performance of the building.

A study conducted in Jakarta dan Singapore investigated the usage of electronic appliance for cooling (5). It showed that 80% of the occupants were using a fan most of the time due to the need of thermal comfort. However, the fan effectivity for maintaining indoor temperature is lower than utilizing an air-conditioner.

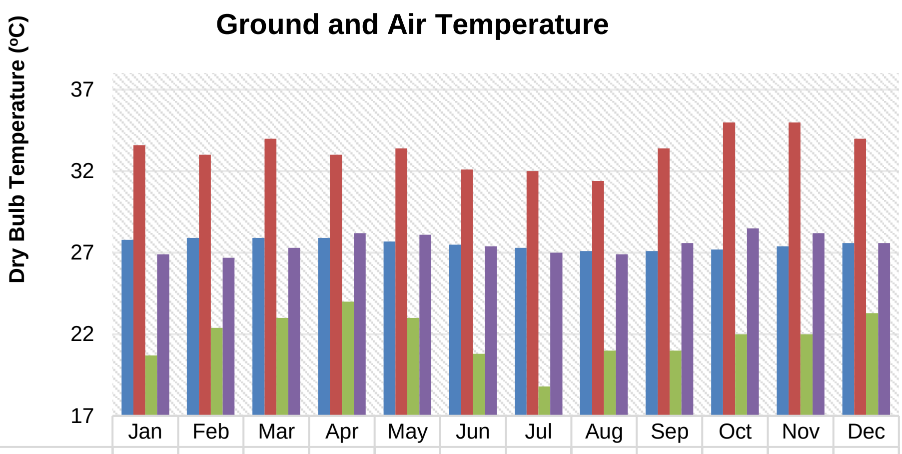
This paper covers the investigation of the roof and wall material to mitigate the high consumption of electricity in hot-humid climate areas, particularly in Sedati, Indonesia. A residential building was simulated with an air-conditioning system for maintaining the indoor temperature at 25.5°C based on the Indonesia National Standard of thermal performance (SNI 6390-2011) (6). Simulations were conducted by overseeing the anomaly of different U-value.

2. METHODS

2.1 Weather Profile

The building is located at 7°24'26.3" South and 112°46'49.9" East, Sedati, Kabupaten Sidoarjo. Based on the latitude, the climate condition of the area is hot and humid climate due to the Local Climate Zone (LCZ) (7). As daylight can be a significant variable influencing the thermal performance of the building, the measurement of the latitude and solar irradiance was necessary to analyse the most appropriate orientation and shape of the building.

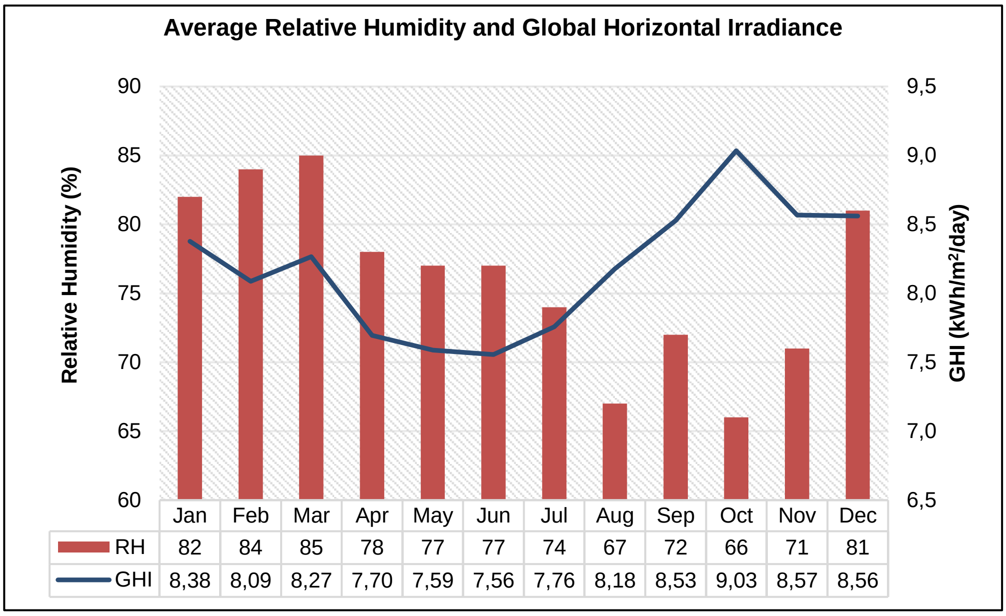
The weathering profile aims to reflect the real condition of the weather of the proposed area where Typical Meteorological Year (TMY) weather data is applied. The weathering profile was obtained from the meteorological station in Juanda airport located on the borderline between Surabaya and Sidoarjo with the dataset from 1986-2018 (8). This dataset was chosen due to its near location and similar terrain. The data includes the dry-bulb temperature, ground temperature, humidity, and solar exposure data.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ground DBT	27,8	27,9	27,9	27,9	27,7	27,5	27,3	27,1	27,1	27,2	27,4	27,6
Maximum DBT	33,6	33	34	33	33,4	32,1	32	31,4	33,4	35	35	34
Minimum DBT	20,7	22,4	23	24	23	20,8	18,8	21	21	22	22	23,3
Average DBT	26,9	26,7	27,3	28,2	28,1	27,4	27	26,9	27,6	28,5	28,2	27,6

Graph 1. TMY data of monthly ground, average, maximum, and minimum dry-bulb temperature of Juanda Airport weather station in Sedati.

Graph 1 indicates the average temperature, maximum temperature, and minimum temperature varies between 26-29°C. However, the maximum temperature varies and reaches the maximum temperature at 35°C. On the other hand, the minimum temperature is 19°C. It is also noticeable that all the temperature datasets above show a slight variation throughout the year due to insignificant temperature differences between the wet and dry seasons. The ground temperature shows a similar trend to the average dry-bulb temperature.



Graph 2. Average relative humidity and Global Horizontal Irradiance of Juanda Airport weather station in Sedati.

The datasets in Graph 2 indicate the trend of the relative humidity, showing a stable condition at high humidity throughout a year and frequently above 70%. Thus, the design must meet the humidity requirement to obtain human comfort as occupants tend to avoid over-sweating inside the building. On the other hand, the average solar exposure is 6.56 kWh/m²/day. The lowest solar exposure is in June. Thus, the building design should tackle the solar exposure issue to avoid the over-exposed condition.

Based on its characteristics, the building for hot and humid climates requires a well-insulated cooling system where daylight control significantly affects the comfort aspect inside the building (9). Moreover, the material requirements must include the possibility to prevent the hot air infiltrates the building. It is essential to consider the mass and energy balances in the building with the constant flow to overcome the purpose of energy reduction.

2.2 Baseline Building

The building has a total floor area of 60 m². It orientates to the is north with the largest proportion of windows facing west to avoid the over-exposed sunlight. The HVAC system continuously maintained the indoor temperature at 25.5°C. The building size is 10 meters long and 6 meters wide.

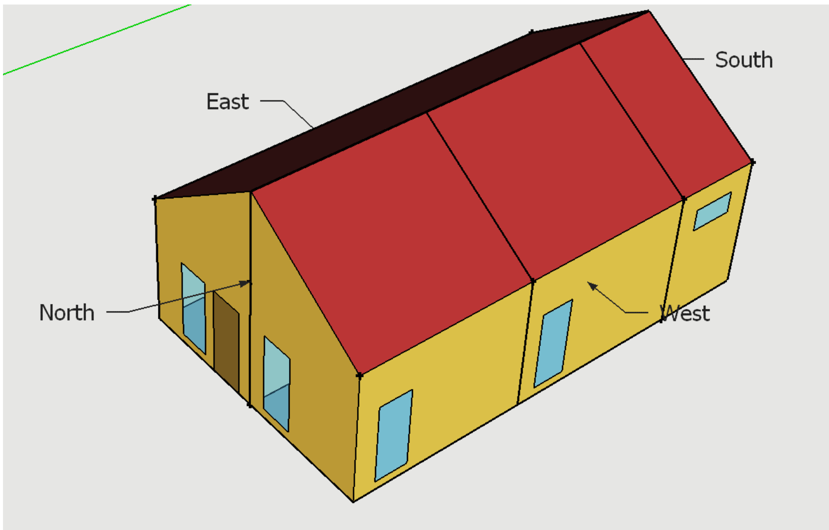


Figure 1. The building envelope of the residential building proposed.

Figure 1 presents the baseline building design and layout. This design is a typical residential building design for Indonesian mono-family. North, west, and south walls are exterior where the walls contact the outdoor environment. Whereas the east wall is indoor as it contacts the neighboring wall as an adiabatic wall. Thus, no contact occurred between the east wall and the outdoor environment.

The construction set of the baseline building was prepared to obtain the simulation result. Thus, the material applied for the baseline building is based on the research of the recent journal and typical material utilized in recent residential building design preferences (3, 10).

Table 1. Baseline construction set.

Construction Set	Definition	
	U-value (11) (W/m^2.K)	Layer
Wall	2.83	Cement plaster and brick
Door	1.61	Wood and plywood
Window	5.89	Single clear glass and timber frame
Roof 20^o Sloped	3.07	Clay tile, metal decking, and gypsum
Floor	1.17	Concrete block, cement plaster, and ceramic tiles

Table 1 presents the construction set for the baseline building. The total U-value was calculated by implementing the thermal resistance network approach obtained from OpenStudio. In this case, no construction had a U-value less than 1 indicating the layer could not reduce the heat gain optimally.

2.3 Optimization

It is noticeable that the energy usage in a hot and humid climate used more than doubled energy usage in a warm and humid climate. Thus, several construction improvements were conducted to optimise the thermal comfort and minimize the energy usage of the building. The main difference lies in the insulation due to the similarity of the external building design. This setup focused on tackling the cool air inside the building leaks and hot air outside flows into the building.

Wall construction of the baseline building only consists of the plaster, brick, and plaster from the outside layer to the inside layer which has a 2.83 W/m^2.K U-value. Based on the Passive House proposed by Schieneders et al. (2), a wall construction with a 0.2 W/m^{2}K U-value was utilized.

The wall construction used opaque material and lightweight material due to its low thermal mass (12). Moreover, the insulation method was utilized to prevent the effect of weather variation. Thus, insulation is the key. For the wall optimization, two options of wall construction layer were chosen with its insulation and lightweight construction.

Table 2. Wall construction set optimization.

Construction Set	**Wall**	
	U-value (11) ($W/m^2.K$)	**Layer**
Option 1	0.35	Cement plaster Light concrete Insulation 88.9 mm Light concrete Cement plaster Gypsum
Option 2	0.16	Cement plaster Light concrete Insulation 203.2 mm Light concrete Cement plaster Gypsum board

Table 2 shows the wall construction sets. The lightweight concrete was utilised between the insulation. Mineral fibre batt was used as this material is easy to install and good at avoiding mixture better than mineral wool. The thickness of the insulation is 88.9 mm in Option 1, while Option 2 has thicker insulation with 203.2 mm. It is obvious that Option 2 has a lower U-value than Option 1.

The roof applied reflective material to tackle the overheated condition. The roof was designed with a high-pitched angle to prevent heavy rainfall leaks into the building. The low emissivity reflective insulation was also implemented. Well-designed roof space can help to avoid the heat that goes inside the building and works the same as a cavity. Reflective foil insulation has been investigated as the alternative method for blocking heat with its 100% effectiveness. It is desired to layer the surface and make it waterproof and avoid condensation.

Table 3. Roof construction set optimisation.

Construction Set	**Roof**	
	U-value (11) ($W/m^2.K$)	**Layer**
Option 1	0.55	Asphalt shingles Roof membrane Metal decking Insulation 38.1 mm Gypsum board
Option 2	0.18	Asphalt shingles Roof membrane Metal decking Airspace Insulation 101.6 mm Gypsum board

Table 3 shows the complete construction layer from the outside to the inside layer of the roof. These two options used cellular polyurethane as it provides better U-value and vapor retardant. This material is also suitable for the structural consistency of the building. Option 2 provided thicker insulation causing the U-value to be better than Option 1. Moreover, the reflective layer is also applied to the Option 2 to prevent radiation. As the reflective layer was added, the airspace was also constructed to avoid the heat trapped inside the building.

3. RESULT AND DISCUSSION

By simulating the baseline building, 429.58 kWh/m^2/year were obtained as the energy consumption. This value was taken by maintaining the indoor temperature at 25.5^{o}C. The optimization simulations were taken by changing the wall and roof construction set in terms of the insulation and material. The simulations were conducted on two different U-values to analyze the reduction of the energy consumption per area per year. Wall and roof construction show a significant effect on energy-saving.

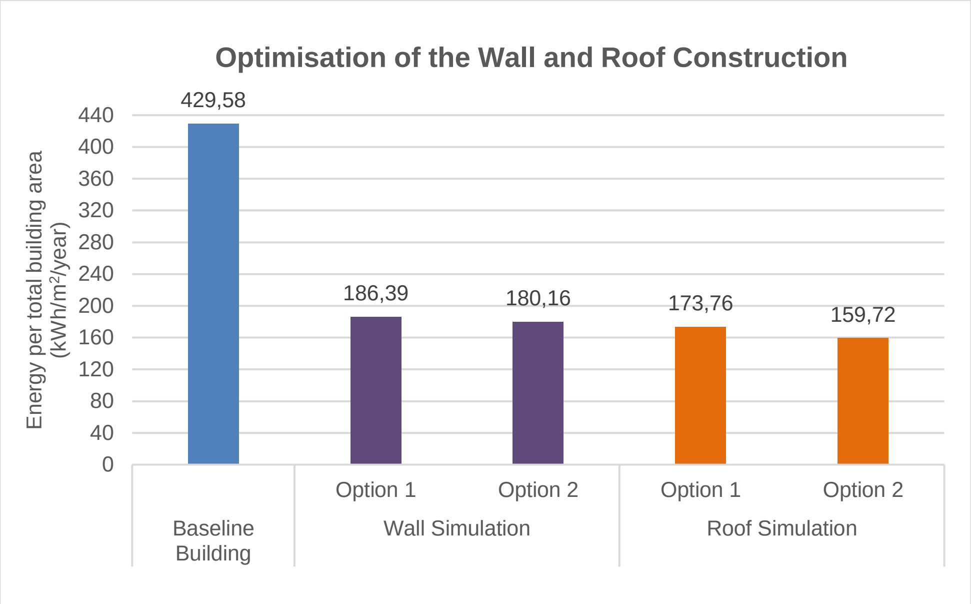


Figure 3. Energy consumption simulation results.

Regarding the results in Figure 3, a discussion has been noted to support the evidence. The wall reduces energy consumption by 27% (186 kWh/m^2/year) by applying Option 1 and by 29% (180 kWh/m^2/year) by applying Option 2. As the wall is the largest area of the building, the insulation works effectively in preventing heat transfer to the building. As mentioned in the literature review, these results support the role of wall insulation in regard to reducing energy consumption significantly. The study in Thailand found that energy consumption could be reduced proportionally by increasing the thickness of the insulation (3).

Furthermore, the roof shows the biggest improvement by 32% (174 kWh/m^2/year) in applying Option 1, and 37% (160 kWh/m^2/year) in applying Option 2. These results support the findings that applying insulation could prevent the radiative and convective effect flow inside the building as the building (4) as well as the application of the high pitched roof (13). Thus, applying insulation to the wall and roof can be a good way to improve the building's performance. It also concludes that building performance is improved better by utilising the lower U-value of wall and roof construction.

As the first simulation shows that the contribution of energy usage improvements primarily occurred in the roof, the energy reduction by changing the roof construction of the building is higher than applying new construction of windows and wall. Furthermore, changing the whole construction layers based on the material simulation results contributes significantly to reducing the energy consumption.

4. CONCLUSION

Typical residential mono-family building in Indonesia was investigated. The building achieved thermal comfort at 25.5ºC indoor temperature causing a high energy requirement. The wall and roof material assessments have been assessed. The findings show that wall and roof construction significantly reduce the energy consumption on thermal performance with a higher U-value. Wall construction is assessed based on the insulation thickness, which shows that the thicker insulation, the lower the energy consumption of the building. The lightweight and opaque material also contribute to building performance. Roof construction applies the reflective layer to avoid radiation and conduction through the roof layer.

This research provides insight into the residential building energy consumption improvement for wall and roof construction. However, the implication of the additional initial cost of construction should be assessed further. Therefore, the construction set could be a major factor to reduce energy consumption as it is noticeable that the U-value of the construction component affects the energy significantly.

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