Reducing Heat Gains and Cooling Loads Through Roof Structure Configurations of A House in Medan

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Abstract. Heat gains and heat losses through building surfaces are the main factors that determine the building’s cooling and heating loads. Roof as a building surface that has the most exposed area to the sun, contribute most of heat gains in the building. Therefore, the amount of solar heat gains on the roofs need to be minimized by roof structure configurations. This research aims to discover the optimization of roof structure configurations (coating material, structure material, inclination, overhang, and insulation) as one of passive design strategies that reduce heat gains and cooling loads of a house in Medan. The result showed that case four, white-painted metal roof combined with 45° roof pitched, 1.5m overhang, and addition of insulation, indicates the minimum heat gains production and the less cooling loads during clear sky day but not in the overcast sky condition. In conclusion, heat gains and cooling loads of a house in Medan could be diminished during clear sky day by the addition of roof coating with high reflectance low solar absorbtance, the slope roof, the extension of wider veranda, and the addition of insulation in the roof structure.

1. Introduction

“The smaller the surface area of the house that is exposed to the sun, the smaller will be the total of the possible amount of radiation received” [1].

Cities near the equator experiences the high amount of solar radiation throughout the year. Medan, located in 3.6°N and 98.7°E, receives large portion of daily solar radiation from January to December (see Figure 1). Thus, the amount of heat transfer in the buildings are possibly high.

Heat transfer in the form of radiation occurred between outside and inside surface of the buildings and it causes heat gain in the buildings. There are two sources of heat gains in the building, from external (walls, windows, roof, and floor) and internal (occupants and equipment) building [2]. Roof as an element in the building contributes to heat gains production.

Roof as one of building surface that dominantly exposed to the sun is obviously caused most of heat gains in the building [1]. Excessive heat gains usually result in discomfort; thus, the cooling loads is also high. Therefore, solar heat gains through roof need to be controlled to minimize the cooling demand in the house.

Passive cooling strategy is an approach to control heat gains with low or zero energy consumption. This strategy attempts to prevent or remove heat transfer in the building by means of natural cooling
Hence, passive cooling system through roof structure configuration can be a strategy to reduce solar heat gains in the building and cooling demand in a house. This research aims to discover the optimization of roof structure configuration as one of passive design strategies that would reduce heat gains and cooling loads in the house. This research attempts to provide a solution for the climatic problem that could occur in the buildings in Medan.

![Figure 1. Sunpath Diagram of Medan](Source: Sunearthtools.com)

2. Literature Review

2.1. Heat Gains Prevention by Passive Cooling Means

Antinucci, et al. (1992) explained four different techniques of heat dissipations (see Table 1). Radiative cooling applies the cool color (color with high solar reflectance) into the building surface to give heat loss effect. Evaporative cooling provides cooling by means of evaporation. Ventilation delivers cooling by means of air to remove heat. Ground cooling offers cooling from the ground temperature and the atmospheric environment [4].

| No. | Process                        | Heat Sink | Main Heat Transfer Mode |
|-----|--------------------------------|-----------|------------------------|
| 1   | Radiative Cooling              | Sky       | Radiation              |
| 2   | Evaporation Cooling            | Air       | Evaporation            |
| 3   | Convective Cooling/ Ventilation| Air       | Convection             |
| 4   | Ground Cooling                 | Earth     | Conduction             |

According to Santamouris and Asimakopoulos (1996), there are three different stages of passive cooling strategies in the building.

1. Heat gain prevention/ protection in the building
2. Heat gain modulation
3. Heat rejection from the interior building heat sinks (natural or hybrid cooling)

Source: [3]

2.2. Passive Cooling Strategies through Roof Construction
Oakley (1961) said that parasol roof (see Figure 2) could be one of building’s solution in hot humid climates. Parasol roof serves as a large canopy towards the spaces and allowing air movement in sides between roof and ceiling [1].

![Figure 2 Parasol Roof Concept](Source: [1])

Al-Obaidi, Ismail, & Abdul Rahman (2014) stated that the use of reflective and radiative roofs gave a great reduction in building operational cost [5]. They suggested that the selection of colour and material properties should be taken into account as an approach to enhance the building thermal performance.

Chung, Park, & Ko (2015) proved that roof material with high reflectivity and emmissivity can decrease the urban temperature [6]. This cool roof also decreasing the cooling demand [6].

However, Sabzi, Haseli, Jafarian, Karimi, & Taheri, concluded that the most cooling reduction was provided by the application of water pond on roof, while the less reduction was shown by the use of water jacket on roof [7].

Arumugam, Garg, Ram, & Bhatia believed that two methods of making roof energy efficient are surface treatments (cool roof and radiant barriers) and thermal property modifications (roof insulation) [8]. They stated that the most suitable of roof in warm and humid climate were roof with R-value of 0.31 m2K/W, where it can be achieved by the addition layer such as Brick Bat Coba.

Roslan, Ibrahim, Affandi, Mohd Nawi, &Baharun argued that applying roofing passive design by reflective cooling with combination of optimum roof pitch and roof ventilated approach could contribute in the removal and reduction of heat gained on the roof [9]. They also added that the application of passive design in the roof could low the indoor temperature and the impact would less the energy demands by minimise the use of electricity for cooling purposes [9].

It is concluded that researches find some of passive strategies to reduce heat gains and cooling loads in the buildings. Researchers believe the application of cool roof, such as large canopy, cool coating colours, reflective roofs, evaporative roof, thermal properties modification, and combination of optimum roof pitch and ventilated roof can improve the building performance.

3. Methodology

This research included three stages in the process, consisted of solar radiation and sky cover range analysis of Medan, heat gains and cooling loads investigation of a house in Medan, and heat gains and cooling loads comparison by four different cases of roof structure configurations.

The research started with the analysis of solar radiation and sky cover range in Medan. This stage used Climate Consultant software to generate the weather data into charts and tables. This step determined the date for simulations. Because it was hard to determine the seasonal (rain and dry season) date in Medan, the date for simulations were selected based on the sky conditions, clear and overcast.

The second stage was the investigation of heat gains production and cooling loads of a house in Medan. This initial house was simulated by DesignBuilder. The heat gains simulation was based on two different sky conditions, clear and overcast. Then, the comparison between heat gains in the roof and cooling load in both sky conditions were discussed. This stage proved the performance of heat gains through building fabric occurred in the house.

The third step was the comparison of heat gains and cooling load improvement by four different cases of roof structure configurations. Four cases were simulated to observe the performance of heat gains and cooling loads. Then, the results were compared to analyse the reduction of heat gains and cooling loads from the original case.
In conclusion, the highest reduction of heat gains and cooling loads was indicated as the best performance of roof structure configurations. Then, this roof could be the parameters as the most suitable roof that could be applied in the house in Medan.

4. Results and Discussion

4.1. Solar Radiation and Sky Cover Range Analysis of Medan

Regarding solar radiation, the annual monthly average of daily hourly direct normal radiation was mostly dominated then its diffuse radiation (see Figure 3). Based on Energy Plus Weather Data, the highest monthly average of direct normal radiation was in July with 5315 Wh/m². While the lowest monthly average of direct normal radiation was 2398 Wh/m² in December. However, the maximum and minimum diffuse radiation was 3054 Wh/m² in October and 2313 Wh/m² in July, respectively.

![Figure 3](image)

**Figure 3** The Annual Monthly Average of Direct and Diffuse Solar Radiation of Medan

In terms of sky cover range of Medan, the monthly average high of cloud cover percentage was mostly near 100%, while the monthly average low was varied from about 35% to almost 70% of total cloud cover (see Figure 4). The average high demonstrates the overcast sky day, while the average low indicates the clear sky day. The huge gap between monthly average high and average low of sky cover percentage indicated that during one month the variation of sky condition could be occurred in Medan.

![Figure 4](image)

**Figure 4** Sky Cover Range of Medan

Source: Generated by Climate Consultant

However, at some point, the larger direct solar radiation was not always identify the clear sky condition in Medan. For instance, in July, the monthly average of direct solar radiation was high but the mean average of sky range cover was also high. This was probably due to the amount of sky pollutant, such as, vehicle emission, industrial emission, and forest fire smoke caused the cloudy sky condition. Consequently, it was hard to determine the seasonal (rain and dry season) date in Medan.

Theoretically, tropical cities has two seasons, rainy and dry season. But, the the amount of solar radiation was not subjective to the season period in Medan. Therefore, this research classifies the sample date of simulation by clear and overcast sky day. To simulate the heat gains and cooling loads
of the house, 15th December and 14th August were selected because they represented the most clear and overcast sky day.

4.2. Heat Gains and Cooling Loads of Existing House
In order to investigate heat gains and cooling loads of a house, computer simulation was conducted based on two different weather conditions, clear and overcast sky condition (15th December and 14th August). This research examined a landed house in Medan with the total ground floor area of 170.5m², including four bedrooms, two bathrooms, a living room, a family room, a dining room, and a kitchen (see Figure 5). All the building fabrics (roofs, walls, windows, and floor) were set according to the real condition.

![Figure 5. Layout of a house in Medan](source: Generated by Autocad)

The initial roof material contained 10mm of clay roof tile, 30mm of hard wood, 70mm of air gap, and 5mm of plywood as ceiling. The roof was constructed with 30° inclination, 0.6m overhang and without insulation.

The walls consisted of 120mm of brick and 15mm of plaster in both surfaces and the windows material was single glazing with painted wooden frame and the total opening was assumed as 30% of the walls.

The roof thermal properties are presented in Table 2. The total thermal resistance (R-value) was 0.36m²K/W, and the total thermal transmittance (U-value) was 2.7 W/m²K. The R-value is relatively high, and it is possible to reduced. However, the value of thermal absorptance and solar absorptance of clay roof tile were relatively high with 0.9 and 0.7, respectively. It is also noticeable that roof material is identified as lower heat reflection material, so it is easily absorbing heat from outside.
Table 2. The roof thermal properties of the house

Source: Generated by DesignBuilder

| Fabric                  | Thickness | Conductivity | Resistance (R-value) | Specific heat | Density | Emisivity | Solar Absorbance | Visible Absorbance |
|-------------------------|-----------|--------------|----------------------|---------------|---------|------------|------------------|-------------------|
| Clay Tile (Roofing)     | 0.01      | 1.00         | 0.01                 | 800           | 2000    | 0.90       | 0.70             | 0.70              |
| Wood Hard               | 0.03      | 0.18         | 0.17                 | 1255          | 721     | 0.90       | 0.78             | 0.78              |
| Air Gap                 | 0.07      | -            | 0.15                 | -             | -       | -          | -                | -                 |
| Plywood (Lightweight)   | 0.005     | 0.15         | 0.03                 | 2500          | 560     | 0.90       | 0.78             | 0.78              |
| Total                   | 0.115     | R-value      | 0.36                 |               |         |            |                  |                   |
| U-value                 |           | 2.78         |                      |               |         |            |                  |                   |

Regarding the heat gains production, the original roof construction presented the similar trend during clear and sky conditions. As described in Figure 6, the heat gains from roof material (red lines) was always dominated. It was reported that the roof contributed more than 4kW, while the rest of house elements produced less than 4kW of total heat gains in the house during both conditions. The second largest heat gains was generated by walls, where it reached maximum at 3.97kW and 3.77kW during clear-sky and cloudy-sky days.

Heat gains produced by roof was obviously started at 8 am and ended at 6 pm but the effect may remain at night. It began with 0.51kW and 0.47kW in clear and overcast day, respectively. Then, it was dramatically mounted into peak at noon with 4.76kW in clear day and 4.70kW in cloudy day. Last, it was significantly dropped into minus which means no heat gains was produced at 6 pm (see Figure 6).

Figure 6. Total heat gains from building fabric and ventilation during clear sky and overcast sky condition. Source: Generated by DesignBuilder

4.3. Heat Gains and Cooling Loads Reduction from Roof Structure Improvement

To predict the reduction of heat gains and cooling loads by passive cooling strategies, four cases of roof structure configurations were simulated based on clear and overcast sky condition (15th December and 14th August). The roof structure configurations were selected based on the combination of coating and structure material, inclination, overhang, and insulation (see Table 3)

Table 3 Roof Structure Configuration
As illustrated in Table 4, a gradual decrease of heat gains production was shown by four different cases. Case four is indicated the highest reduction of heat gains during both sky conditions. It is predicted that the maximum heat gains produced was decreased up to 3.68kW and 3.55kW during clear and overcast sky condition, respectively. It is also noticeable that the maximum heat gains of other building surfaces were also reduced but was not significant.

**Table 4** Comparison of heat gains production

Source: Generated by DesignBuilder

| Case | Material                                      | Slope | Overhang | Insulation |
|------|-----------------------------------------------|-------|----------|------------|
| Original | Clay roof tile                              | 30°   | 0.6m     | -          |
| 1     | Wood shingles, plain and plastic-film-faced | 30°   | 0.6m     | -          |
| 2     |                                               | 45°   | 1m       | -          |
| 3     | White-painted metal                          |       | 1.5m     | -          |
| 4     |                                               |       |          | Wood fibre |

However, it is predicted that the cooling loads of four different cases were also reduced during clear sky condition but not in cloudy sky day (see Table 5). This probably due to the roof improvement could not solve the high humidity during cloudy sky day result in discomfort, so the cooling loads was still high. Case four also obtained the best performance with the most reduction of cooling loads during clear sky days but not in overcast sky day. The maximum cooling loads of case four decreased 1.86kW during clear sky day but increased 1.32kW during cloudy sky day. Although the maximum cooling loads in case four was higher than the original case during overcast sky day, but the increase was least than three other cases of roof improvement.

**Table 5**. Comparison of cooling demand

Source: Generated by DesignBuilder

| Heat Gains | Original | Case 1 | Case 2 | Case 3 | Case 4 |
|------------|----------|--------|--------|--------|--------|
|            | Max (kW) | Max (kW) | Max (kW) | Max (kW) | Max (kW) |
| Glazing    | clear    | over cast | clear    | over cast | clear    | over cast | clear    | over cast | clear    | over cast | clear    | over cast |
|            | 1.89     | 1.75     | 1.89     | 1.75     | 1.91     | 1.73     | 1.89     | 1.66     | 1.89     | 1.66     |
| Walls      |          |          | 3.97     | 3.77     | 3.92     | 3.72     | 3.67     | 3.42     | 3.60     | 3.42     | 3.51     | 3.37     |
| Floors (int) | 1.39   | 1.44     | 0.89     | 0.92     | 0.86     | 0.87     | 0.78     | 0.79     | 0.36     | 0.36     |
| Floors (eks) | 0.2    | 0.20     | 0.12     | 0.12     | 0.19     | 0.20     | 0.33     | 0.34     | 0.19     | 0.20     |
| Roof       |          |          | 4.76     | 4.70     | 3.62     | 3.63     | 3.97     | 3.92     | 3.38     | 3.34     | 1.08     | 1.15     |

Based on the result, whited painted metal roof presented the best performance among others. This was probably due to the value of solar absorbance, visible absorption, and solar reflectance (see Table 6). Whited painted metal roof has the minimum solar and visible absorptance and high solar
reflectance. This material possibly absorb less solar radiation and reflect more solar radiation. Therefore, the value of heat gains and cooling load produced was also low.

The addition of insulation in the roof also provide a significant effect. Insulation provides high reduction of heat gains and cooling load. This is due to the U-value of wood fibre was minimum, with only 0.61 W/ m²K (see Table 7). This means that the heat transfer was also low, so it produced less heat gains. Thus, the cooling loads was also low.

Table 6. Thermal properties of roof outer layer

| Outer Materials                      | Emissivity | Solar Absorptance | Visible Absorptance | Reflectance |
|--------------------------------------|------------|-------------------|---------------------|-------------|
| Clay roof tile                       | 0.9        | 0.7               | 0.7                 | 0.3         |
| Wood shingles, plain and plastic-film-faced | 0.9        | 0.7               | 0.7                 | 0.3         |
| Whited painted Metal                 | 0.9        | 0.4               | 0.4                 | 0.6         |

Table 7. R-value and U-value of air gap and wood fibre as insulation

| Outer Materials            | R-value (m²K/W) | U-value (W/ m²K) |
|----------------------------|----------------|-----------------|
| Air gap                    | 0.15           | 6.67            |
| Insulation (Wood fibre)    | 1.63           | 0.61            |

Roof with higher inclination gave the big impact towards heat gains and cooling load reduction. In this case the maximum pitch was 45°, because the limitation of local material and the weather conditions. However, roof with higher inclination can give bad impacts to surrounding buildings. It gives glare and heat reflection, particularly in the metallic materials. Even though according to Antinucci et al. (1992) metallic materials gives the heat loss effect on a surface body due to its long wavelength radiation to the night sky, but it could reflect solar to other buildings. Hence, roof with high slope might not recommended and the suitable roof pitched for house in Medan should be less than 45°.

In addition, wider overhang was also obtained the most reduction of heat gains and cooling demand. This is probably because wide canopy can provide shading to house. Thus, the solar radiation would be decreased.

In general, the results assume that the best roof structure combination for house in Medan was whited painted metal roof with 45° roof pitched, 1.5m overhang, and addition of insulation.

5. Conclusion
In general, to solve the problem of heat gains and cooling demand in tropical cities, such as Medan, it can be solved by the arrangement of roof structure. Heat gains and cooling loads could be diminished during clear sky day by the addition of roof coating with high reflectance low solar absorbtance, the slope roof, the extension of wider veranda, and the addition of insulation in the roof structure.

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References

[1] D. Oakley, Tropical Houses, London: Batsford, 1961.
[2] R. McMullan, Environmental Science in Building, Basingstoke: Palgrave Macmillan, 2012.
[3] M. Santamouris and D. N. Asimakopoulos, Passive Cooling of Buildings, London: James & James, 1996.
[4] M. Antinucci, D. Asiain, B. Fleury, J. Lopez, E. Maldonado, M. Santamouris, A. Tombazis and S. Yannas, "Passive and Hybrid Cooling of Buildings - State of The Art," International Journal Solar Energy, pp. 251-271, 1992.
[5] K. M. Al-Obaidi, M. Ismail and A. M. Abdul Rahman, "Passive Cooling Techniques Through Reflective and Radiative Roofs in Tropical Houses in Southeast Asia: A Literature Review," Frontiers of Architectural Research, pp. 283-297, 2014.
[6] M. H. Chung, J. C. Park and M. J. Ko, "Effect of The Solar Radiative Properties of Existing Building Roof Materials on The Energy Use in Humid Continental Climates," Energy and Buildings, pp. 172-180, 2015.
[7] D. Sabzi, P. Haseli, M. Jafarian, G. Karimi and M. Taheri, "Investigation of Cooling Load Reduction in Buildings by Passive Cooling Options Applied on Roof," Energy and Buildings, pp. 135-142, 2015.
[8] R. S. Arumugam, V. Garg, V. V. Ram and A. Bhatia, "Optimizing Roof Insulation for Roofs with High Albedo Coating and Radiant Barriers in India," Journal of Building Engineering, pp. 52-58, 2015.
[9] Q. Roslan, S. H. Ibrahim, R. Affandi, M. N. Mohd Nawi and A. Baharun, "A Literature Review on The Improvement Strategies of Passive Design for The Roofing System of The Modern House in A Hot and Humid Climate Region," Frontiers of Architectural Research, pp. 126-133, 2016.