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EVALUATION OF THE THERMAL PERFORMANCE OF METAL ROOFING UNDER TROPICAL CLIMATIC CONDITIONS

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Summary

The assessment of the thermal performance was carried out on a low cost house mainly built from waste oil palm shell (OPS-Concrete) with galvanized steel-roof. It was noticed that reasonable thermal comfort took place during the night for the roof without ceiling and without insulation, and during the day at a peak temperature of a highly ventilated attic area. For such situation, it was recommended to install insulating horizontal plated surface under the roof, which should be turned into a vertical position during the night. Other alternatives may be creating small adjustable openings around building envelope just under the ceiling or making an open roof-ceiling system. This technique will reduce the heat flux from insulated ceiling by the flow of the cooling air at night, but the impact of surrounding microclimate on human thermal comfort should be considered. The mathematical model used to predict the attic temperature for a lightweight roof system was obtained by correlation, which can be used for a quick inspection. Insulation materials of 50 *mm* fibreglass and foil-aluminium were used with sealed attic, and found the ceiling temperature reduced by about 3 ^{o}C and 2 ^{o}C respectively. For the case of fibreglass of thickness beyond 50 *mm*, the reduction of ceiling temperature was recorded less than ½ ^{o}C, really not attractive.

1. Introduction

Kota Kinabalu city (the capital of the Sabah state of Malaysia) experiences a typical equatorial humid climate with heavy rainfall usually in the afternoon time, where the temperatures are uniformly high and extremely invariable throughout the year. A good thermal performance of any house in Kota Kinabalu has to have an indoor temperature between 25 ^{o}C and 28 ^{o}C (comfort range). The analysis of bio-climatic chart indicated that the ventilation should be considered for this type of climatic conditions. The utilization of active cooling system seems to be the only solution during the peak air temperature when no passive strategies could minimize the effect of radiation and air temperature to the acceptable indoor comfort range.

Metal roofing in Kota Kinabalu practically became the norm for low-cost houses, considerably contributing to heat gain and increasing the indoor temperature. A such roof system requires particular attention, since it is the most envelope building part exposed to solar radiation. Berdahl et. al. (1997) and Miller et. al. (2004) have studied the effect of roof colour in minimizing surface temperature, and found that high solar reflectance and infrared emittance of roofs surface reduce heat gain and also the *UV* radiation received by roofs. The utilisation of lighter colour is very highly recommended under Malaysia climate due to their high solar reflectivity, but it is less diffused and not well accepted by the population. Several solutions are possible to minimize the ceiling temperature such as the insulation of roof, attic ventilation, selection of roofing materials more suitable under warm humid conditions, the realisation of high-pitched roof, and may be other suitable and practical techniques.

The objective of the present study is to provide recommendations for the improvement of roofing design under Malaysia climate. Therefore, the assessment of the thermal performance of metallic roof system with sealed and ventilated attic will be considered. In addition to that, the impact of different thickness of fibreglass and foil- aluminium in reducing ceiling temperature will be studied. The model house used in this research is the low cost house built inside the campus of the Universiti Malaysia Sabah (5.93^{o}N, 116.05^{o}- about 2.3 *m* above sea level) using waste oil palm shells “OPS” as aggregate for the realization of walls, whereas the roof is made from galvanized steel.

2. Experimental Procedures

2.1 Description of the OPS House

The low-cost house used as a case study is a single story detached one family house which is considered as model house utilizing agricultural solid waste namely oil palm shell “OPS” in an innovative light weight concrete mix, based on financial and environmental design factors. This has double advantage of reduction in the cost of construction materials and solves the disposal of waste products generated at the palm oil mills. Mannan et. al. (2001, 2004) reported that the trend of behaviours of OPS concrete and control concrete is very similar construction and building materials. It was established that OPS performs as aggregate in concrete and possesses the potential of being used in building construction. The OPS concrete is also considered environmentally sustainable building materials, friendly product and does not have any health hazard since it is covered with cement paste and no deterioration is taking place. The model-house realised with the OPS concrete is considered socially acceptable for the low-income families. The roof system was built with red pre-painted galvanised steel sheet, and with ordinary plywood 6 *mm* in thickness used as ceiling without insulation, for all rooms. Table 1 describes the OPS building materials used and figure 1 shows the plan view of the house.

Table 1 Description of Materials Used in the OPS House

Description of material	Usage
• OPS concrete (G20) -Density = 1850 kg/m^3	Lean concrete, ground beam, Ground slab, Lintel, Roof capping beam.
• OPS hollow block - Size=420 *mm* (L) $\times$125 *mm* (W) $\times$ 190 *mm* (H) - Void/block=32% - Weight/block=12 *kg*	Walls- Attic ventilation.

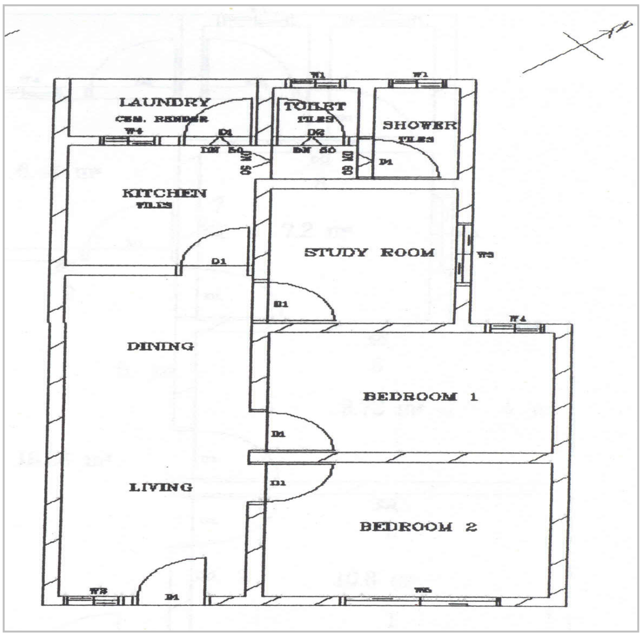

Figure 1 Ground floor plan of project.

The building consists as shown in figure 1, of one living dinning room, kitchen, shower, study room and two bedrooms, with floor to ceiling heights of 3.1 *m*, occupying an area of 58.68 m^2. The walls are constructed with small windows opening in most exterior walls except on the west-south side, which represents around 7.59% of the surface building envelope. These openings were covered with single plane glazing 6 *mm*, but no kind of sun shading was used for the openings. Solar radiation reaches the interior of the living and bedroom 2 during the sunrise and the kitchen during the sunset, which produces direct and immediate heating effect. The roof was built with narrow overhang of 0.9 *m* giving a little protection to the walls. The attic space is well ventilated as it appears clearly in figure 2. The external walls colours are beige and the house is located in an open area without landscaping. The vertical distance between the inlet and the outlet of the vent area facilitate the increase of the ventilation rate in attic space. However, the outlet vent area in this attic is less than the inlet vent area, which in turn minimizes airflow through the attic. The net free ventilating area in the attic space was about 1/13, which is higher than the minimum recommended of most codes at least a 1/150.

Figure 2 Ventilation gaps in the OPS house.

2.2 Data Monitoring

The field test includes mainly measurements of air temperature with the utilisation of data-loggers HOBO thermometer during two series of measurements, ventilated and sealed attic. The data-loggers were positioned in the centre of the house, outside the house, and at the centre of the attic space. The daily average monthly radiation was estimated on possible sunshine hours, nearly the same during these two periods about 20.22 *MJ/m²* from 8 July until 8 august 2004, and 20.77 *MJ/ m²* from 21 October 2004 until 22 December 2004. The assessment of different ceiling configurations was evaluated with sealed attic and summarized in table 2.

Table 2 Thermal Properties of the Evaluated Ceiling Configurations

Component	$U_{\text{Ceiling component}}$ ($W/m^2.K$)
6 mm plywood	0.99
Foil-aluminium + air space + 6mm plywood.	0.86
50 mm fibre glass + 6mm plywood	0.41
100 mm fibre glass + 6mm plywood	0.26
150 mm fibre glass + 6mm plywood	0.19

3 Results and Discussion

3.1 Temperature Prediction of Ventilated and Sealed Attic

Data reported in figure 3 shows a sequence of the indoor, mid attic and outdoor temperature from 8 July 2004 until 4 August 2004 with ventilated attic. The indoor temperature was recorded 1.5m above the floor.

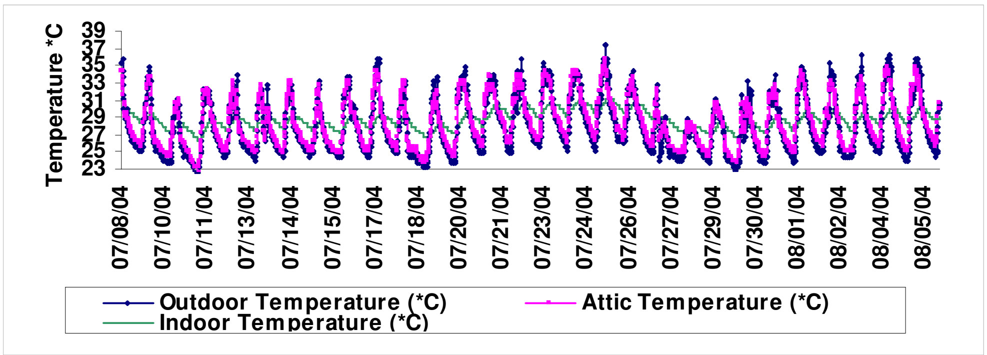

Figure 3 Indoor air, mid attic, and outdoor temperature

The thermal mass of the OPS house brought the maximum indoor temperature which is below the maximum daily outdoor temperature. The thermal capacity of walls has the effect of delaying the impact of external conditions on the interior of the building. The low thermal mass roof system, which is simply red galvanized steel and plywood for the ceiling, shows the tendency of similarity between the outdoor and attic temperature with slight variation during the daytime. This could be due to the roof surface temperature raised by absorption of solar radiation. The system of ventilation was judiciously chosen for this house in reducing the heat transfer through roofing materials. The hourly evolution of attic temperature for one hot sunny day's variation recorded on 25th July 2004 was slightly similar to the outdoor temperature, while the maximum indoor temperature was lower by about 4.58 ^{o}C below the maximum outdoor temperature. Note that the variation of attic air temperature during the night was lower than the indoor air temperature by about 3.16 ^{o}C. The outdoor temperature range (difference between maximum and minimum) recorded was about 10.14 ^{o}C. This means the utilisation of thermal mass under Malaysia climate to reduce the indoor temperature by about 7 ^{o}C or at least 4 ^{o}C during the peak indoor temperature could be quite acceptable. The correlation between hourly attic and outdoor temperature is shown in figure 4.

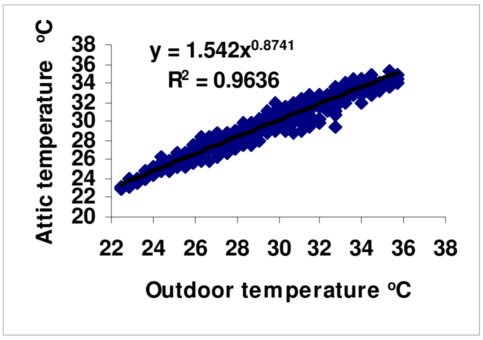

Figure 4 Correlation between hourly attic and outdoor temperatures with ventilated attic

An analysis of the hourly attic temperature was plotted versus outdoor air temperature. The daily maximum attic temperature was best predicted on the basis of the mean daily outdoor temperature as shown in figure 5, yielding good correlation between measured and calculated maxima.

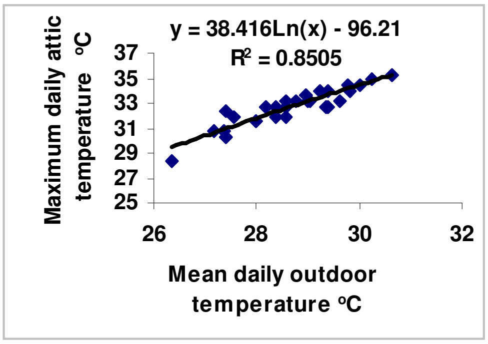

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Figure 5 Correlation between max. attic and mean daily outdoor temperatures with ventilated attic

The best curve fitting correlations for hourly and maximum daily attic temperature prediction, are as follows:

$$T_{h-attic} = 1.542 T_{h-out}^{0.8741} \quad (1)$$

$$T_{dmax-attic} = 38.416 \mathrm{Ln}(T_{dMean-out}) - 96.21 \quad (2)$$

Where;

$T_{h\text{-}attic}$: Predicted hourly attic temperature. $T_{h\text{-}out}$: Recorded hourly outdoor temperature.

$T_{dmax\text{-}attic}$: Predicted daily maximum attic temperature. $T_{dMean\text{-}out}$: Recorded daily mean outdoor temperature.

Figure 6 shows the measured and the computed maximum ventilated attic temperature based on Eq. (2), which are quite similar in terms of temperature. The difference between them was found statistically not significant using t-test (t-test = 0.04206) with total degree of freedom equals to 52, for the 2 samples (measured and computed), and each one contains 27-recorded data of temperature.

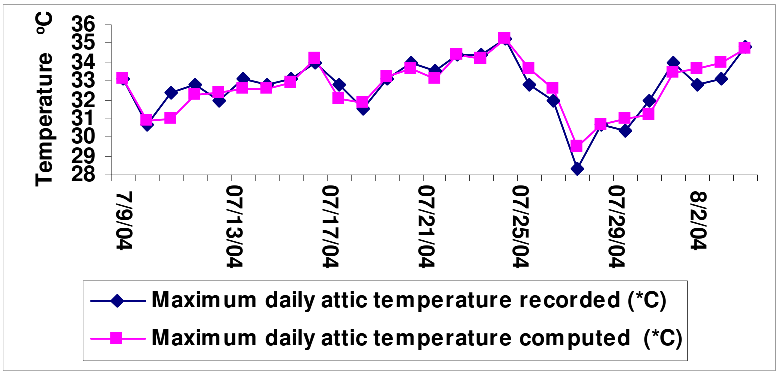

Figure 6 Comparison between computed and measured maximum attic temperature.

After the attic was sealed, the correlation between daily maximum attic temperature and maximum outdoor temperature was less predictable, conversely to the hourly prediction of attic temperatures plotted in figure 7.

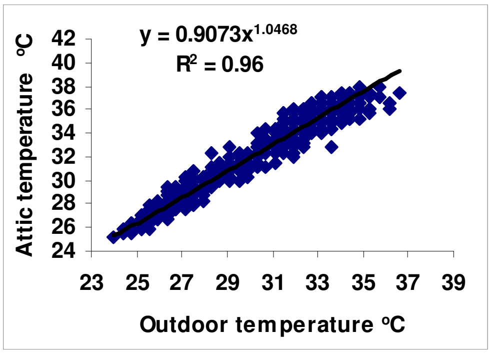

Figure 7 Correlation between hourly attic and outdoor temperatures with sealed attic

The predicted hourly attic temperature with sealed attic is expressed by the following formula;

$$T_{h-attic} = 0.9073 T_{h-out}^{1.0468} \qquad (3)$$

The predicted hourly attic temperature with ventilated and sealed attic for a possible outdoor temperature variation from 24 ^{o}C to 35 ^{o}C were computed using Eq. (1) and Eq. (3) respectively, and plotted in figure 8.

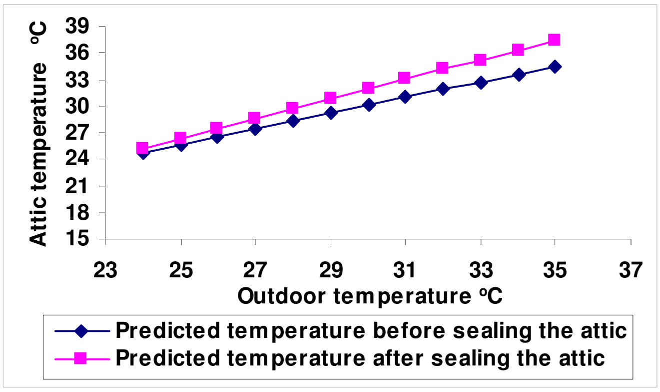

Figure 8 Computed attic temperature with sealed and ventilated attic

It is clear that the effect of ventilation in reducing attic temperature was more noticed with the increased outdoor temperature, and the difference between ventilated and sealed attic reached about 3 ^{o}C when the outdoor temperature attained 35 ^{o}C. The temperature with ventilated attic was always lower than the sealed one, and the difference between them becomes more significant when the outdoor temperature increases.

3.2 Thermal Performance of Metal Roofing and OPS Concrete Walls

The interior surface temperature of the OPS concrete wall as well as the temperature under metal roofing and the ceiling surface temperature were recorded and plotted against outdoor temperature as illustrated in figure 9. Inspection of figure 9 shown that the OPS concrete walls was always lower than the outdoor temperature, generally from 10 am to 15 pm. The OPS concrete wall rose after that and reached its maximum usually before 20 pm. The main issue of any building components particularly realised with concrete or bricks under tropical humid conditions, is the heat storage released during the early evening or before the outdoor temperature reaches its minimum. As for the case of the traditional building materials made with lightweight materials such as wooden, bamboo or thatched walls, used since the past in Malay architecture, are considered suitable under Malaysia climate, but could be warmer than concrete walls during the daytime since they follow greatly the outdoor temperatures. These traditional building materials are more suitable when the microclimate surrounding the building is modified with the plantation of trees or simply when the house is located in the jungle. Moreover, walls in traditional houses permit air to pass through gaps, which decreases the thermal sensation of the effect of temperature on human body. The problem of overheating was rather solved in the traditional houses in terms of human thermal comfort and not limited on building thermal performance. The designer under warm humid conditions should take into consideration not only the characteristic and the thermal performance of building materials but also the impact of surrounding microclimate on human thermal comfort.

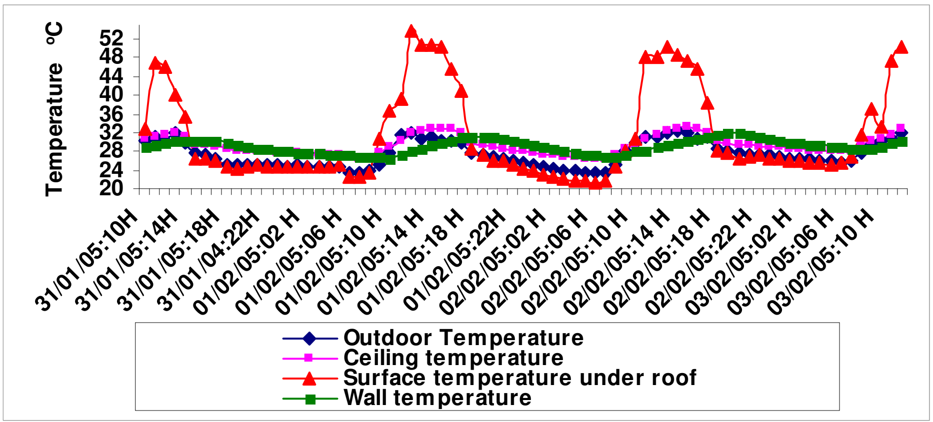

Figure 9 Hourly outdoor, ceiling, roof, and wall temperature

The hourly solar radiation and relative humidity are plotted with respect to roof surface temperature, and shown in figure 10.

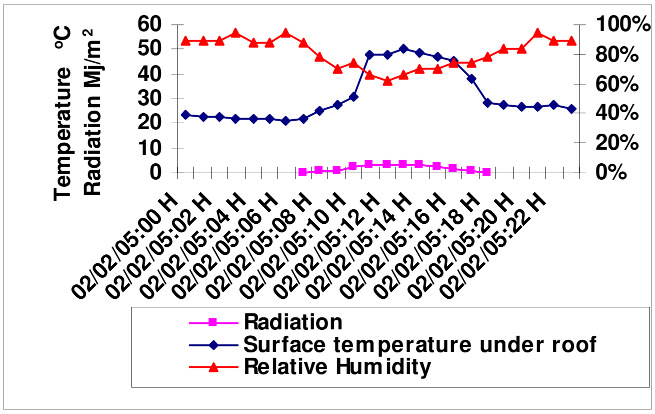

Figure 10 Hourly solar radiation and relative humidity versus roof temperature

It is evident from figure 10 when the roof surface temperature reaches its maximum limit the radiation attains its maximum level. This is not the case with the relative humidity, since the relative humidity increases when the outdoor temperature decreases which occurs during the nighttime. These results could be also encouraging for possible utilisation of evaporative cooling even under warm humid climate during the peak outdoor temperature when the relative humidity attains its minimum (Harimi et. al., 2005).

3.3 Thermal Performance of Insulation Materials

Thermal insulation is an important factor in minimizing the effect of heat absorbed and transmitted by metal roofing materials. When solar radiations as well as the roof surface temperature reach their maximum level, the radiant temperature from warm ceiling causes the greatest discomfort and increases the physiological heat stress as reported by Vecchia (2001). This could be reduced with the installation of insulation above the ceiling or just under the roof, and it may well reduce the energy consumption, which lowers utility bills in residential buildings under active cooling system. The role of fibreglass is to minimize conduction and convection, thereby decreasing the ceiling temperature, whereas, the principal function of reflective insulator (radiant barrier) is to reflect radiant heat rays and acts also as vapour barriers. Its capacity to insulate could be lost after a few years. The reflective insulation material is installed in general on a ceiling for more effectiveness. Figure 11 shows the variation of ceiling temperatures without insulation, and with different characteristics of insulation materials.

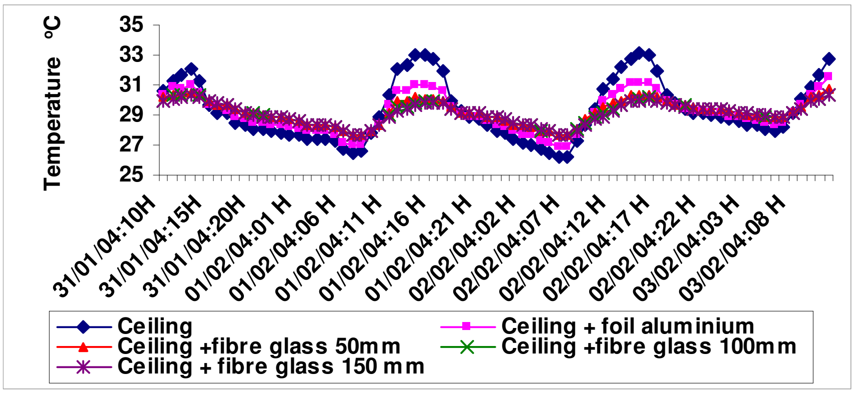

Figure 11 Impact of insulation materials on ceiling temperature

As it was expected, the fibreglass has more effect in reducing ceiling temperature in comparison to foil-aluminium. This is due to the low emissivity of metal roofing, which has the ability to minimize considerably the emitted radiation into attic before reaching the foil-aluminium. The efficiency of foil-aluminium could be more significant for a roof system made of concrete or clay tile with a ventilated attic space. The temperature difference between insulated ceiling with fibreglass and plywood ceiling could attain 3 ^oC; while the maximum difference recorded using foil-aluminium was about 2 ^oC. The increase of insulation thickness beyond 50 *mm* was not appreciated, because the maximum temperature reduction was found less than 0.5 ^oC. Table 3 summarize the ceiling surface temperature with different thickness insulation materials that was recorded on the second February 2005.

Table 3 Summary of Results for different types of insulation materials

Surface Temperature	Ceiling	Ceiling + Foil Aluminium	Ceiling + Fibreglass 50 mm	Ceiling + Fibre Glass 100 mm	Ceiling+ Fibre Glass 150 mm
Max	33.1	31.1	30.4	30.2	30.1
Min	26.2	26.9	27.6	27.6	27.6
Average	29.25	29.03	29.11	29	28.97

It comes into view from table 3, that the minimum surface ceiling temperature recorded during the night was always higher than the ceiling temperature without insulation. The ceiling insulated with fibreglass recorded the highest temperature. Givoni (1994), has recommended in such situation the installation of hinged interior insulating horizontal plated surface under the roof, and should be turned into a vertical position during the night. This special roofing design recommended by Givoni (1994) is more detailed in page 120 of his book and could be very useful under Malaysia climate particularly for low-cost houses. However, the application of such technique needs some improvements in the area of aesthetic and psychological side. Other possibilities could be simply making small adjustable openings all around building envelope and just under the ceiling to reduce the heat flux from insulated ceiling with the cooling air during the night, or by the realisation of an open roof-ceiling system as shown in figure 12.

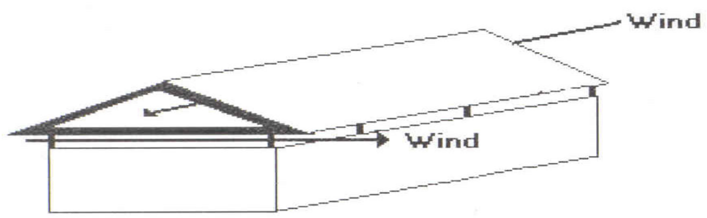

Figure 12 Roof design under warm humid conditions.

The overhang design should be large enough to protect the penetration of rain into ceiling floor and at the same time should allow the winds to penetrate easily in this area, which in turn can be slightly inclined to avoid the stagnation of rainwater in case.

4. Conclusions

From the thermal assessment of the OPS house, many observations have been recorded. It was noticed that during the night, roof without ceiling and without insulation performs thermally better than any roof system under tropical climate conditions. When the outdoor temperature reaches its maximum, the low-mass corrugated metal roof cools down rather quickly than the ceiling temperature, whereas, the highly ventilated attic area performs thermally better than the sealed attic area. This system is highly recommended under Malaysia climate with no additional cost, but the designer should take into consideration not only the characteristic and the thermal performance of building materials but also the impact of surrounding microclimate on human thermal comfort.

The prediction of attic temperature with lightweight roof system is possible and has been well established using a mathematical model correlation, which can be applied in the future for a quick inspection. The use of 50 *mm* fibreglass with sealed attic significantly lowers the ceiling temperature by about 3 ^{o}C, while for the case of foil-aluminium, ceiling temperature decreases by about 2 ^{o}C. It should be highlighted, that the advantage gained by increasing insulation thickness of fibreglass beyond 50 *mm* does not decrease ceiling temperature significantly, and the maximum temperature reduction was recorded less than ½ ^{o}C.

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