Reflective Technology for Roof Applications in Malaysia

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***Abstract*— Malaysia is in the Equatorial region with annual average daily solar irradiation up to 5.6 kWh/m^2. Building insulations played a vital role in reducing the heat gain and cooling load of a building. Reflective insulation in buildings is commonly used in this region. Different configurations of reflective insulation have different thermal resistance values. The main objective of this research is to determine the RSI (m^2·K/W) of various types of reflective insulation materials used in different roof assemblies in a hot climate. Three test huts of the same design were constructed with various roofing and insulation materials to record thermal performance. Thermocouples and heat flux transducers were installed on different positions on the roof with the data used for RSI calculations. The findings from this research will include RSI for the roof systems with different configurations and insulation materials. Field measurements of the RSI for the un-insulated test hut was 0.4 m^2·K/W. Test huts with reflective insulation assemblies provided thermal resistances up to 3.1 m^2·K/W, whereas the Malaysia Uniform Building Code (UBBL) requirement for roof assembly is RSI ≥ 2.5 m^2·K/W.**

***Keywords*— hot and humid climate, reflective insulation, thermal resistance, field study, thermal insulation.**

I. INTRODUCTION

Malaysia's climate is categorized as equatorial, with copious rainfall, temperatures of 26.6 - 32.4°C and high relative humidity throughout the year. Annual average daily solar irradiation ranges from 4.2kWh/m^2 to 5.6kWh/m^2 [1]. A large percentage of the incoming solar energy is absorbed by exposed roof surfaces and much of this energy is transferred to the interior of the building.

Solar heat enters the building through conduction, convection and radiation. Research work carried out by Nahar et al. [2] found that up to 50% of the thermal load of buildings in hot climates is through the roof. Of the total heat energy that enters the building through the ceiling, 87% is by radiation and balance by conduction and convection as shown in Fig. 1 [3]. Medina [4] reported that summer ceiling heat flows into a building could be reduced up to 45% with suitable attic radiant barriers.

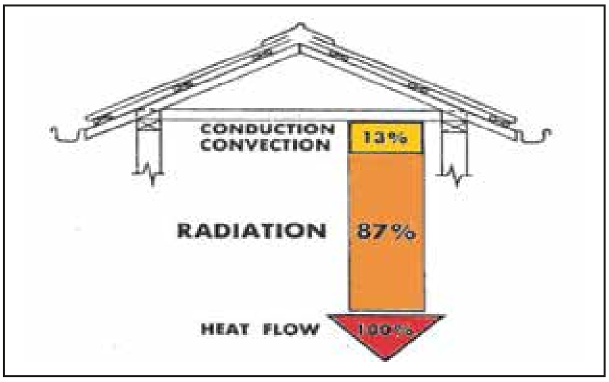

Fig 1: Heat Flow Mechanisms

Materials with mass such as mineral fiber or cellular plastics are commonly used to insulate buildings around the world. In hot climates, where heat flow downward predominates, attic radiant barriers and reflective insulation systems are effective options to consider.

II. BACKGROUND OF STUDY

To maintain a comfortable temperature in a building, incoming solar energy needs to be prevented from entering work spaces or living areas. Heat that enters occupied spaces is typically removed using conditioning equipment that consumes electrical energy. As the cost of electrical energy increases, energy conserving ideas such as highly efficient air-conditioning equipment, better building design with improved use of ventilation and materials with higher insulation properties become more urgent.

Ideally, buildings should be designed and constructed to have high energy efficiency, thermal comfort, be affordable and be ecologically friendly. An example of such a building is the Passive House [5, 6, 7] where heating and cooling savings, compared with conventional structures, of up to 90% can be achieved. Proper use of insulation above ceilings, in walls and below floors are essential to attain high energy efficiency. Using ECOTECT software coupled with actual field measurements, Sadafia et al. [8] demonstrated that with the introduction of an internal courtyard in a terrace house in a hot and humid climatic will improve the natural ventilation and thermal comfort. In their extensive study on wind-induced natural ventilation towers, Lim et al. [9, 10, 11, 12] found that such a tower is an effective option to consider for hot air removal, hence better dwelling conditions.

The Active House is another example of a high energy efficiency dwelling [13]. Such house is based on optimization of energy use to provide excellent indoor conditions. An Active House incorporates all the outstanding features of a Passive House plus the ability to generate energy through, for example, the use of photovoltaic panels with the possibility of generating more energy that it uses. Thermal insulation materials slow down the flow of heat energy across the building envelope.

Terminology such as reflective insulation and radiant barrier are defined in ASTM C168, a useful source for definitions associated with thermal insulations and related building materials. [15] Terms used in this paper are discussed below for convenience.

A) U-value

The U-value ($W/m^2 \cdot K$) is a measure of heat transmitted in unit time through a unit area of a building element resulting from a temperature difference between the air spaces on both sides of the element. The surface air film resistances are included in the U-value.

$$U = (Q/A)/\Delta T \quad (1)$$

where:
Q/A is the steady-state heat flux, W/m^2
ΔT is a temperature difference, K or °C

B) Thermal Resistance

RSI ($m^2 \cdot K/W$), is a measure of resistance to heat flow, at steady state, through a given thickness, l, of material with apparent thermal conductivity λ_a.

$$R = l/\lambda_a \quad (2)$$

Heat is transmitted by three mechanisms: radiation, convection and conduction. The amount of heat transferred by each mechanism varies according to the situation and the insulation material used. For example, a reflective material with emittance of 0.1 or less with an adjacent enclosed air space (no infiltration) will have a good thermal resistance value because of the low thermal conductivity of the adjacent air. The thermal conductivity of air at 23°C is 0.0259 W/m·K and increases as the temperature increases [16, 17]. The purpose of the low-emittance surface is to reduce heat transfer by radiation. Enclosed air space surfaces prevent air infiltration and surface friction opposes internal natural convection. In the absence of heat transfer by convection and radiation, the RSI for a 25-mm air cavity is 1.0 $m^2 \cdot K/W$ at 23°C. This RSI is the maximum value for a thermal insulation based on air as the low thermal conductivity component.

III. RESEARCH STATEMENT

Use of reflective insulation materials to create an enclosed reflective insulation assembly to reduce heat flow into building has been discussed and reviewed in the literature [4, 14, 18,19]. The performance of reflective insulation materials in buildings are determined by material emissivity, boundary temperatures, heat-flow direction, roof configuration, construction materials and climatic conditions. Direct comparison of published data from different parts of the world, therefore, is a challenge. In Malaysia, published information about the performance of reflective insulation materials is limited. The field study reported in the following sections was undertaken to contribute to an understanding of the thermal performance of reflective insulation in Malaysia.

IV. OBJECTIVES

The objectives of this field evaluation are as follows:

1) To determine the thermal performance of selected roofing materials with different reflective insulation materials below the roof.
2) To evaluate the influence of different air space dimensions on the thermal performance of reflective insulations.
3) To establish comparative thermal performance of different configurations of reflective insulation materials and fibrous mass insulation.

V. METHODOLOGY

A) Test huts

Small test huts were constructed to study the performance of reflective insulation under actual environmental conditions. Three identical test huts were designed and built in an open field in Melaka, Malaysia (North 2° 12' 20.466" and East 102°, 15' 22.158"). The dimensions of the test huts are 2.2 m (width) x 2.5 m (length) x 2.5 m (ceiling height) with distance between the test huts of 1.9 m. The test huts face west to prevent interference from self-shading. Fig. 2 shows the three test huts with masonry tile roofs with 30° slope. Fig. 3 shows the three test huts with 10° slope metal roof panels.

Fig. 2: Photograph of test huts with tile roofs

Fig. 3: Photograph of test huts with metal roofs

The walls, including the attic area, consist of hollow metal frames with 6-mm cement board on the exterior side and 12-mm gypsum sheathing on the interior side. The floors are 12-mm plywood on both sides of rock wool insulation. The walls and floor are insulated with 100 mm thick – 80 kg/m^3 rock wool insulation.

The project consisted of seven phases completed over a period of 12 months to complete. Each phase involved three insulation configurations tested concurrently. Roof materials commonly available in Malaysia were used, i.e., concrete tile, clay tile and metal deck. For insulation materials; woven foil, bubble foil, foam foil and mass insulation were evaluated.

B) Data monitoring and acquisition system

The equipment used included a pyranometer, thermocouples and heat-flux transducers. The pyranometer was placed above the roof of the middle test hut to measure solar flux. Twelve thermocouples were installed in each hut used to measure surface temperatures. The thermocouple locations consisted of six locations underneath the roof tiles or metal deck, three locations underneath the insulation material below the roof and above the ceiling, and three locations on top of the ceiling for Phases 1 - 5 as shown in Fig. 4 for Phases 1-5 and in Fig. 5 for Phases 6 and 7. Average temperatures were obtained for each of the three key locations. Each test hut contained a transducer on the ceiling to measure the heat flux across the ceiling.

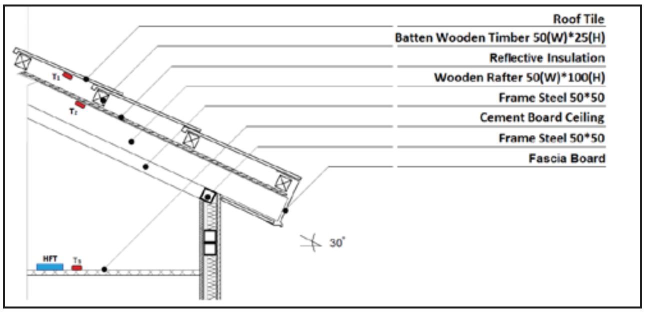

Fig. 4: Locations of Thermocouples for Phases 1-5 (Dimensions in mm)

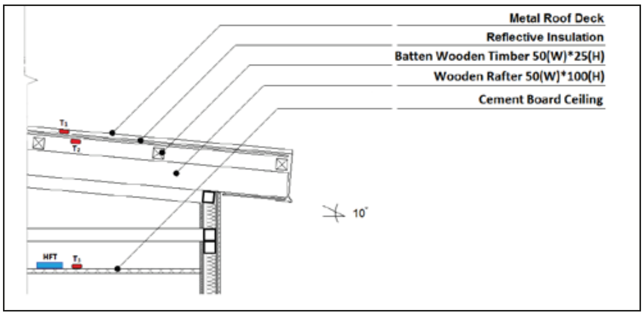

Fig. 5: Locations of Thermocouples for Phases 6-7 (Dimensions in mm)

C) Calculation of RSI from transient data

Temperatures, heat fluxes, and solar flux from the instrumentation described above were recorded every two minutes for 10 days. Fig. 6 is an example of the average temperature for roof tiles (red line), woven foil (blue line) and ceiling (grey line) during the 10-day period. It is interesting to note that the ceiling temperatures for Test Hut 1 and Test Hut 3 are significantly lower than Test Hut 2 during day time as shown in Fig. 7.

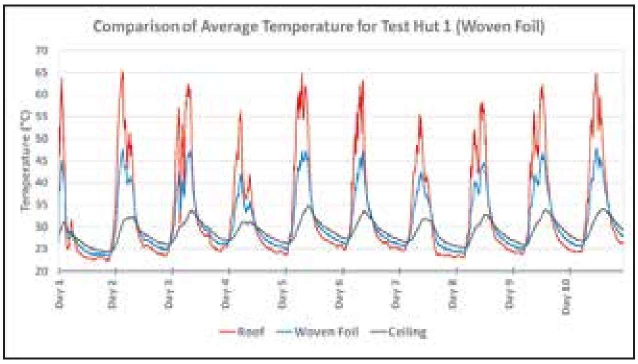

Fig 6: Average temperature for roof tiles, woven foil and ceiling

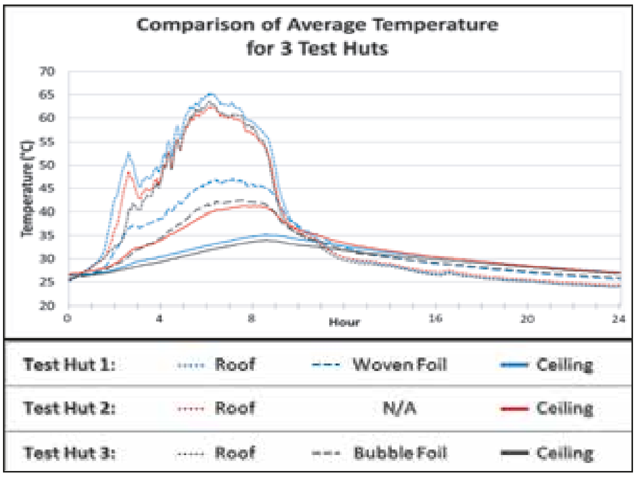

Fig 7: Comparison of temperatures

RSI are calculated for a single airspace using

$$RSI = \Delta T/q \tag{3}$$

where q is the stead-state heat flux.

ΔT and q vary with time, so we develop time-average values over 10 equal time increments: t_1 to t_{10}.

$$\overline{\mathrm{RSI}} = \frac{1}{(t_{i+1} - t_i)} \int_{t_1}^{t_{10}} \Delta T(\tau) / q(\tau)\, d\tau \approx \frac{1}{10} \sum_{i=1}^{10} \left(\Delta T_i / q_i \right) \quad (4)$$

where,
t is time
T is temperature

The transient data are filtered according to the following criteria to avoid weather-related spikes. Failure to meet any one of the criteria results in deletion of the data point.

1) Data are for heat flow down
2) Irradiance at least 600 W/m²
3) Heat Flux at least 1W/m²
4) Temperature difference across an air space is at least 0.1°C
5) Each block average must be within 25% variation of running average

A combination of RSI across the two air spaces present in some cases is based on an assumption of heat flow at a specific time is constant. The thermal mass of the material separating the air spaces is small. The areas, however defining the air spaces are different making heat flux different as shown by (6). The overall thermal resistance between the roof and the ceiling is calculated using (5).

$$\begin{aligned} RSI_{overall} &= RSI_A + RSI_B \\ &= (T_1 - T_2)/Q_A + (T_2 - T_3)/Q_B \end{aligned} \quad (5)$$

where,
RSI_A is the RSI for air space between roof and insulation material.
RSI_B is the RSI for air space between insulation material and ceiling.
T_1 is the average temperature of roof (refer to Fig. 4).
T_2 is the average temperature of insulation material (refer to Fig. 4).
T_3 is the average temperature of the ceiling top (refer to Fig. 4).
Q_A is the heat flux across the roof.
Q_B is the heat flux across the ceiling.

Only one heat flux transducer was placed on the ceiling to obtain Q_B. Q_A can be obtained by,

$$Q_A = Q_B * \left(\frac{\text{Area of Ceiling}}{\text{Area of Roof}} \right) \quad (6)$$

For example, in Fig. 8, the RSI values for test hut with bubble foil (green symbol) comprised of 24 sets of averaged $RSI_{overall}$ that fulfilled the above five criteria. Each block was an average of 10 intervals and it was plotted in green. The vertical error limits show +/- 25% from the average $RSI_{overall}$. The subsequent averaged $RSI_{overall}$ must be within the 25% variation range from the preceding $RSI_{overall}$ and so on for all the data measured throughout the test period. This would ensure a reasonable representative RSI performance by excluding weather spikes. Then the average of the averaged $RSI_{overall}$ was then calculated for each test hut. For the case of 'Bubble Foil', the average of 24 blocks of averaged $RSI_{overall}$ was 2.69m²·K/W.

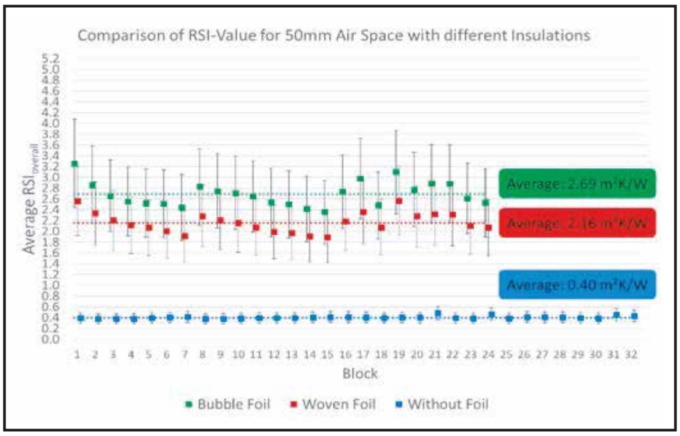

Fig. 8: RSI results for 3 test huts

VI RESULTS AND DISCUSSION

A) Phases 1 & 2:

For roof assemblies without radiant barriers, the enclosed air space has RSI of 0.37 m²·K/W. This allows heat to move across the attic space into the interior of the building. With the use of woven foil, the RSI of the enclosed air spaces increased to 2.16-2.37 m²·K/W as shown in Table 1. This is because the addition low-emittance foil has reduced thermal radiation across changing the enclosed air space in the roof assembly into a reflective enclosed air space. This reduction of the heat flow into the building, which agrees with published findings [4, 20]. With the use of bubble foil, the RSI of enclosed air spaces showed a greater RSI of 2.69-2.93 m²·K/W. This is partly due to the intrinsic RSI of 0.13 m²·K/W for the bubble foil insulation and its tendency to sag more as compared to woven foil which has created additional reflective air space.

B) Phases 3 & 4:

When the reflective enclosed air space height was increased from 25 to 75 mm, the RSI increased from 2.15 m²·K/W to 3.08 m²·K/W for woven foil and 2.41 m²·K/W to 3.09m²·K/W for bubble foil. This finding agrees with the general understanding that for downward heat flow the RSI increases as the distance across the air space increases.

C) Phase 5:

The uninsulated clay-tile roof assembly with RSI of 0.40 m²·K/W increased to RSI of 2.40m²·K/W when woven foil was installed to create a 25-mm enclosed reflective air space. The uninsulated concrete-tile roof with a similar installation has a RSI of 2.26m²·K/W which is approximately equivalent to insulated clay roof.

D) Phase 6:

Results in this phase were obtained based on metal deck structure. The RSI of reflective enclosed air space for roof assembly with foam foil is 2.37m²·K/W, which is comparable to mass insulation supported with woven foil which had RSI of 2.23m²·K/W.

E) Phase 7:

Based on results in Phase 7, roof assemblies each with bubble foil and mass insulation has RSI of 2.02m²·K/W and 1.61m²·K/W, respectively. Despite the lower intrinsic RSI of bubble foil compared to mass insulation (1.20m²·K/W), the thermal performance of reflective enclosed air space created by bubble foil is better than mass insulation combined with enclosed air space. An addition of a layer of woven foil supporting the mass insulation can further increase the RSI to 2.77m²·K/W. This increase in RSI is due to the contribution of both the reflective enclosed air space and mass insulation.

All the RSI's derived from this study are summarised in Table 1. With such results, it showed that reflective insulation materials with proper installations are able to improve the roof assemblies to achieve the UBBL requirement of RSI ≥ 2.5m²K/W [21]. Besides, reflective air space is recognized and included in MS 2680 [22].

TABLE 1: Summary of Measured RSI for the test hut project

Phase	Type of roof	Config-uration	Test Hut 1 (RSI)	Test Hut 2 (RSI)	Test Hut 3 (RSI)
1	Concrete tile	25mm air space	Woven foil 2.37	Without foil 0.37	Bubble foil 2.93
2	Concrete tile	50mm air space	Woven foil 2.16	Without foil 0.40	Bubble foil 2.69
3	Concrete tile	Woven foil	50mm air space 2.31	25mm air space 2.15	75mm air space 3.08
4	Concrete tile	Bubble foil	50mm air space 2.41	25mm air space 2.41	75mm air space 3.09
5	Clay/ Concrete tile	25mm air space (Woven Foil)	Concrete tile 2.26	Clay tile (Without foil) 0.40	Clay tile 2.40
6	Metal deck	No air space	Woven foil/ Mass insulation 2.23	Foam foil 2.37	Bubble foil 1.77
7	Metal deck	No air space	Woven foil/ Mass insulation 2.77	Mass insulation 1.61	Bubble foil 2.02

VII. CONCLUSION

Reflective Insulation materials when used to create an enclosed reflective air space under concrete roof-tile assemblies increased the RSI from 0.37m²·K/W to 3.09m²·K/W for a 75 mm air space. The enclosed air space was increased from 2.15m²·K/W to 3.09m²·K/W when the air space was increased from 25 to 75 mm. Metal deck structure with mass insulation had a RSI of 1.61m²·K/W while with the bubble foil assembly had RSI of 2.02m²·K/W. The addition of a layer of woven foil under the mass insulation further increased the RSI to 2.77m²·K/W. Roof assemblies with reflective insulation, or combined with mass insulation for metal roof, is able to meet UBBL requirement of RSI ≥ 2.5m²K/W.

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