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Reflective Insulation for Energy Conservation in South East Asia

Khar San Teh[1,3], David W Yarbrough[2,4], Chin Haw Lim[1,5] and Elias Salleh[1,6]

[1]Solar Energy Research Institute (SERI), Universiti Kebangsaan Malaysia (UKM), Bangi, Malaysia
[2]R & D Services, Inc., Cookeville, TN, USA
[3]Corresponding author, Master Degree Candidate at SERI, UKM
[4]V. President of R&D Services, Inc.
[5]Senior Research Fellow at SERI, UKM
[6]Principal Research Fellow at SERI, UKM until November 2016; he has since moved to International Islamic University Malaysia as Professor of Architecture from December 2016.

ks.teh@sanmiguelwoven.com

Abstract. Thermal resistances have been measured for attic spaces insulated with reflective insulations. Three test units located in Malaysia were instrumented to provide heat flux and temperatures for the calculation of time-average RSI-values (RSI is representing R-value in SI units). The RSI for attics with enclosed reflective air spaces were in the range 2-3 $m^2·K/W$ while the uninsulated attics averaged about 0.4 $m^2·K/W$. The RSI-values determined in this project were for heat-flow down, the predominant heat-flow direction for attic spaces in Equatorial regions. The observed thermal resistances due to the installation of the reflective insulation results in an 80-90% annual decrease in the heat transfer across the ceiling. This reduces utility usage for air conditioned units and improved comfort for occupants. The research demonstrates the use of transient data for the determination of thermal insulation performance and usefulness of enclosed reflective air spaces for thermal resistance.

1. Introduction

Residential and commercial buildings in the countries located in South East Asia are excellent candidates for the use of reflective insulation in below-roof applications. The building energy consumption for air-conditioning systems in these countries is cooling-load dominated. This energy is costly and contributes to air pollution when fossil fuels are used for electricity generation. Reflective insulation makes use of low-emittance surfaces to reduce heat flow across open air spaces. When the air spaces are enclosed to prevent flow of air through the space, thermal resistances, R-value Systeme International or known as RSI-values ($m^2·K/W$), can be determined either by measurement or calculation.

A reflective insulation material has one or more surfaces with infrared emittances less than 0.1 resulting from the use of a metallic foil or film usually aluminum. The low-emittance surface is normally bonded to a substrate to facilitate handling and installation. These insulations materials usually have RSI- values from 0 to 0.25 $m^2·K/W$ based on the thickness and type of substrate material. The primary RSI-value attributed to a reflective insulation system, RIS, which is the reflective insulation material plus the adjacent enclosed reflective air space is provided by the air space. Heat transfer across an air space occurs because of thermal radiation, conduction, and convection. In cooling dominated regions, the heat flow direction is mostly downward across regions between the roof and the ceiling. This means that free convection is absent or minimal in many roof assembly applications. If the effective emittance of the air space is in the range 0.03 to 0.05, then the radiative component of heat transfer is small. The effective emittance, *E*, for parallel plane surfaces depends on the emittances, ε_1 and ε_2, of the surfaces emitting and receiving radiant energy is given by equation (1) [1]. Heat transfer by radiation across an air-space is directly proportional to *E*.

$$E = 1/(\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1) \quad \text{where } 0 < E < 1 \tag{1}$$

With heat flow by convection and radiation largely absent, conduction remains as the major mechanism for heat flow across an air space. The thermal conductivity of air at 23 ℃ is about 0.026 W/m·K [2]. This means that if convection and radiation are absent, then a 25-mm air space will provide RSI of 0.96 m^2·K/W. For air spaces with temperature differences less than 10 ℃, convection is predicted to be absent for air spaces less than 60 mm for heat flow down, 20 mm for horizontal heat flow, and 13 mm for heat flow up [3]. RSI of 0.96 for a 25-mm is an upper limit for air-based insulations are known as rock wool, fiberglass, expanded polystyrene, and reflective insulation.

2. Reflective insulations

Laboratory measurements of the thermal resistance for a RIS are made using a hot-box facility for testing building assemblies [4,5]. A hot-box test can provide RSI-values and U-values for a building element such as a RIS under steady-state conditions with specified boundary temperatures. Hot-box data are widely used for product labeling or comparisons. Additional product characterization can be obtained from field data that involve actual weather conditions. RISs have RSI-values that depend on heat-flow direction because the air in an enclosed space can exhibit convection when the heat flow direction is not downward. Figure 1 contains calculated RSI-values obtained using ISO 6946 for a single air space with an average air-space temperature of 25 ℃, ΔT of 6°C and an effective emittance of 0.03 [6]. Results for up, horizontal, and down show the variation of RSI with heat-flow down are much greater than the other heat flow directions when the air spaces are greater than about 30 mm. Enclosed air spaces can be partitioned with a reflective insulation to provide two or more enclosed reflective air spaces in series that provide substantially more thermal resistance than the same space with one low-emittance surface facing a single air space.

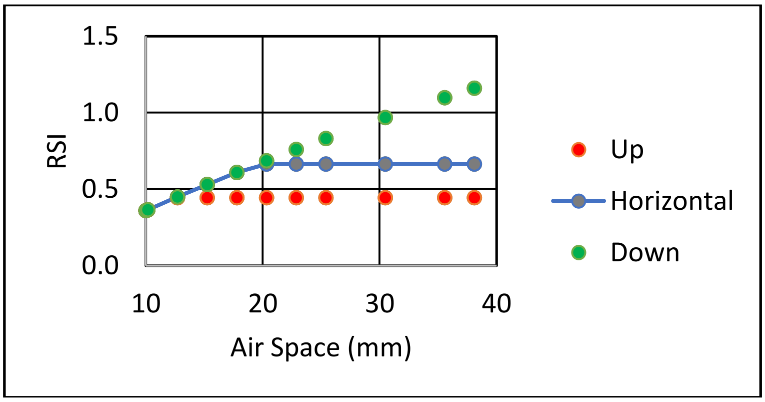

Figure 1. Calculated RSI-values for a single air space.

Thermal data obtained from reflective assemblies installed in structures (buildings) exposed to the environment provide transient performance data that can be more realistic than steady-state laboratory data. As a result, a study of field performance was undertaken.

3. Roof constructions

Concrete roof tiles are commonly found in South East Asia residential buildings and are well-suited for the use of RSIs. A layer of reflective insulation installed below battens creates an enclosed reflective air space below the roof tiles. This reflective air space provides thermal resistance and decreases the heat flow into the attic region. Metal roofing is also used in both residential and commercial applications. Reflective insulation installed below metal panels with a low-emittance surface facing downward provides thermal resistance and a reduction of heat flow into the structure.

4. The hut project

Figure 2. Picture of the three test huts.

The hut project pictured in Figure 2 was carried out to study the performance of reflective insulation under actual building and environment conditions. Three identical huts were built in an open area in Melaka, Malaysia and subjected to natural weather conditions. The dimensions of the huts are 2.2 m (width) x 2.5 m (length) x 3.3 m (height). The distance between the huts is 1.9 m. The huts face West to avoid shading.

The walls, including the attic area, are constructed using hollow metal frames and covered on the outside with 3-4 mm cement board and on the interior with 12 mm gypsum board. The floor cavity is faced with 12-mm plywood on the top and bottom. The wall and floor cavities contain 100 mm thick mineral wool with density of 80 kg/m^3 to reduce heat gain or heat loss through the walls and floor. As a result, temperature changes in the attic and interior of the huts are mainly affected by the roof insulation. The attic assembly for the tile roof huts uses a gable-roof design. Reflective insulation with low-emittance surfaces on both sides was laid on the rafters. Battens were used to create an enclosed reflective air space between the reflective insulation and the roof tiles. The attic enclosure was completed by fascia boards installed around the eaves. Figure 3 shows the attic region from the inside with the ceiling removed. A single pitch-roof design is used for the metal-roof structures. Reflective insulation and/or rock wool insulation is placed or draped above the battens with roofing panels installed above the insulation. The bottom side of the reflective insulation material creates an enclosed reflective air space.

Figure 3. Wall Insulation Material

5. Instrumentation

The huts were instrumented with a pyranometer, thermocouples, heat flux transducers and data loggers. The pyranometer was placed outdoor on top of the middle hut to record the irradiance during the day.

Type-K thermocouples with precision ±1 ℃ were positioned to monitor roof, ceiling, and reflective insulation temperatures. The surfaces being monitored represented the bounding surfaces for the enclosed reflective air spaces. Each hut has six thermocouples underneath the roof covering, three thermocouples attached below the insulation material, and three thermocouples on the top of the ceiling. Each hut contained a heat-flux transducer adhered to the ceiling to determine the heat flux across the ceiling. Temperature and heat flux data were recorded in order to calculate RSI for the attic assemble.

6. Calculate RSI from transient data

Temperatures, heat flux and irradiance were recorded at two-minute intervals for 10 days. Figure 4 shows an example of the average temperature for roof tiles (red line), woven foil (blue line) and ceiling (grey line) in the 10-day period. Figure 5 compares temperatures for the test huts for a 24-hour period. Test Hut 2 in this case did not have insulation in the attic space. Test huts 1 and 3 were insulated. As expected, the ceiling temperatures for Test Huts 1 and 3 are significantly lower than the temperatures in Test Hut 2 during the day.

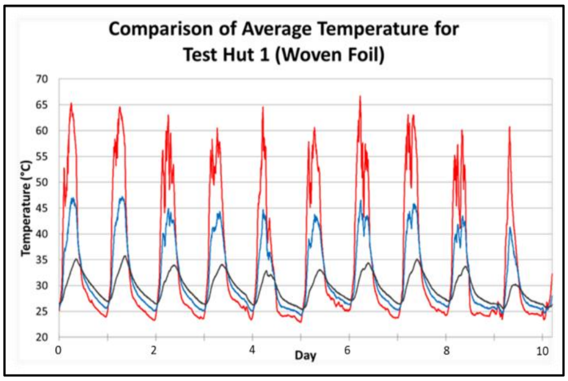

Figure 4. Average temperatures for roof tiles, woven foil and ceiling.

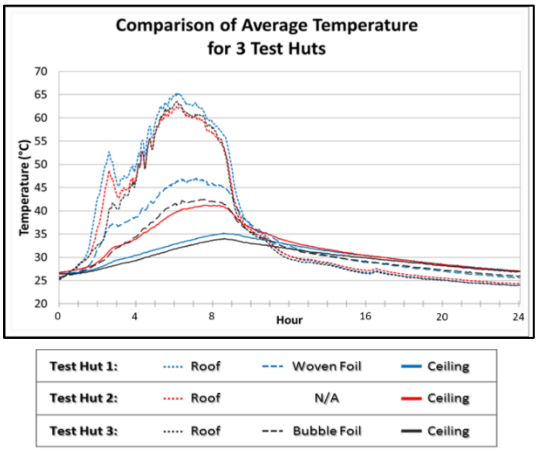

Figure 5. Comparison of average temperature for three test huts.

RSI_i in this study is the total thermal resistance of two enclosed attic spaces as indicated by equation (2). The heat fluxes for the upper attic region were obtained from the transducer mounted on the ceiling using equation (3). RSI_{block} is the average of ten consecutive two-minute readings with RSI_i calculated using equation (4). Equation (5) is for a running average of RSI-values.

$$RSI_i = RSI_A + RSI_B \tag{2}$$

$$Q_A = Q_B \cdot \left(\frac{Ceiling\ area}{Roof\ area}\right) \tag{3}$$

$$RSI_{block} = \sum_i \left\{\frac{(T_1 - T_2)}{Q_A} + \frac{(T_2 - T_3)}{Q_B}\right\}_i \cdot \Delta t_i / \sum_i \Delta t_i \tag{4}$$

$$RSI_{running-average} = \frac{\sum_n \{RSI_{block}\}_n}{n} \tag{5}$$

Where,

RSI_A is for the air space between the roof and the insulation material
RSI_B is for air space between the insulation material and the ceiling
T_1 is the average temperature of the roof
T_2 is the average temperature of the insulation material
T_3 is the average temperature of the top of the ceiling
Q_A is the heat flux across the roof

Q_B is the heat flux across the ceiling
Δt is the time interval
RSI_{block} is the average of ten RSI_i values

This reduction in heat flow translates to a reduction in electrical use when a conditioned space is maintained. Using the average CDD_{25} of 1311 from the data taken from www.degreedays.net and an air-conditioning coefficient of performance of 3, the estimated annual savings for a change in attic RSI from 0.4 to 2.4 is 109 kWh/y·m^2. The area in the result is for the ceiling.

7. Attic air temperature

Figure 6 shows attic air temperature results for Phase I. The results show that the attic with insulation is has attic air temperatures for a ten data period that are consistently lower than those of the uninsulated attic. The blue curve in the figure represents the uninsulated hut while the red and green curves are for huts containing reflective insulation that form enclosed reflective air spaces. Maximum attic temperatures during this ten-day period were reduced by about 10 ℃ as a result of the reflective insulation.

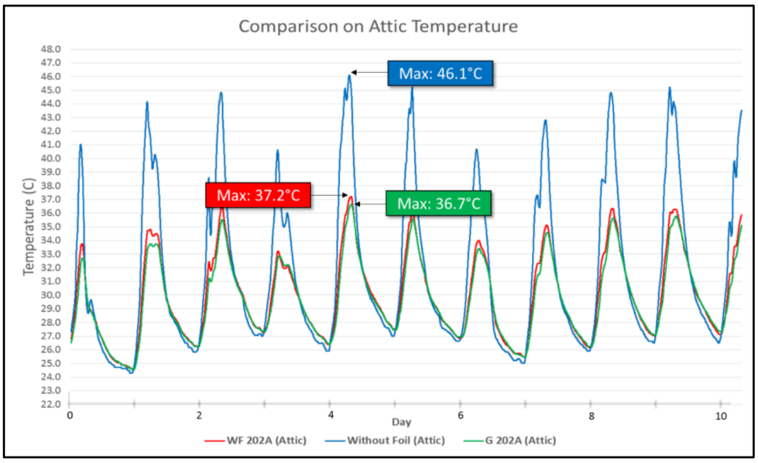

Figure 6. Results for attic air temperature.

8. Results for RSI

RSI values for three sets of tests are provided in table 1. Test hut 2 for all three tests showed RSI of about 0.40 m^2·K/W. The RSI for this configuration given in Table K2 in AS/NZS 4859 for heat flow down across an un-ventilated attic with high-emittance surfaces is 0.28 m^2·K/W.[7] The RSI for the insulated attic spaces are in the range 2 to 3 m^2·K/W. The percent reduction in ceiling heat flux (heat added to the occupied region of the hut) was found to be 80 to 90% using equation (6).

$$HFR\ (\%) = \left(1 - \frac{0.4}{RSI}\right) \cdot 100 \quad (6)$$

This reduction in heat flow translates to a reduction in electrical use when a conditioned space is maintained. Using the average CDD_{25} for S.E. Asia (data take from www.degreedays.net) and an air-conditioning coefficient of performance of 3, the estimated annual savings for a change in attic RSI from 0.4 to 2.4 is 109 kWh/y·m^2. The area in the result is for the ceiling.

Table 1. RSI for the hut project.

Phase	Type of roof	Air space	RSI (m²·K/W)		
			Test Hut 1	Test Hut 2	Test Hut 3
I	Concrete tile	25mm	2.37 [a]	0.37 [b]	2.93 [c]
II	Concrete tile	50mm	2.16 [a]	0.40 [b]	2.69 [c]
III	Clay/Concrete tile [d]	25mm	2.26 [a]	0.40 [b]	2.40 [a]

[a] Woven foil
[b] Without foil
[c] Bubble foil
[d] Concrete tile for Hut 1, clay tile for Huts 2 & 3

Table 2. Maximum attic air temperature.

Phase	Type of roof	Air space	Temperature (℃)		
			Test Hut 1	Test Hut 2	Test Hut 3
I	Concrete tile	25mm	37.2 [a]	46.1 [b]	36.7 [c]
II	Concrete tile	50mm	38.3 [a]	45.7 [b]	36.6 [c]
III	Clay/Concrete tile [d]	25mm	36.7 [a]	43.8 [b]	36.0 [a]

[a] Woven foil
[b] Without foil
[c] Bubble foil
[d] Concrete tile for Hut 1, clay tile for Huts 2 & 3

Table 2 shows the maximum attic air temperature for all the phases. It shows that there is about 9 ℃ difference for roof with and without insulation. The data in table 2 indicate that attic air temperature for clay tiles (without insulation) is cooler than concrete tiles.

9. Conclusions

RIS are effective as attic insulation in S.E. Asia where the predominant heat-flow direction is downward. Measured RSI for typical attic applications of reflective products showed results in the range 2 to 3 $m^2 \cdot K/W$. Measured thermal resistances for attics with reflective insulation are comparable to RSI for mass insulations in the same structure. Ceiling heat-flux reduction for attics with reflective insulation was determined to reduce ceiling heat flux by greater than 80% relative to an uninsulated attic. Small-scale field measurements using custom-built test huts can provide thermal resistance values from transient heat flux and temperature data.

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11. References

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