Research Article

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Field evaluation of reflective insulation in south east Asia

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Abstract: The objective of this research was to obtain thermal performance data for reflective insulations in a South East Asia environment. Thermal resistance data (RSI, m²·K/W) for reflective insulations are well established from 1-D steady-state tests, but thermal data for reflective insulation in structures like those found in South East Asia are scarce. Data for reflective insulations in South East Asia will add to the worldwide database for this type of energy-conserving material. RSI were obtained from heat flux and temperature data of three identical structures in the same location. One unit did not have insulation above the ceiling, while the second and third units were insulated with reflective insulation with emittance less than 0.05. RSI for the uninsulated test unit varied from 0.37 to 0.40 m²·K/W. RSI for a single-sheet reflective insulation (woven foil) varied from 2.15 to 2.26 m²·K/W, while bubble-foil insulation varied from 2.69 to 3.09 m²·K/W. The range of RSI values resulted from differences in the spacing between the reflective insulation and the roof. In addition, the reflective insulation below the roof lowered attic temperatures by as much as 9.7°C. Reductions in ceiling heat flux of 80 to 90% relative to the uninsulated structure, due to the reflective insulation, were observed.

Keywords: Thermal resistance, reflective insulation, emittance, test hut, reflective air space, reflective technology

1 Introduction

Reflective technology in this paper refers to materials and assemblies designed to reduce heat transfer by thermal radiation. The reduction is accomplished in the building envelope by the use of low thermal emittance (high-reflectance) surfaces bounding air spaces. If, in addition, the air spaces are enclosed so that no air moves in or out of the spaces, the application is denominated a reflective insulation assembly (RI) and a thermal resistance (RSI, m²·K/W) can be measured or calculated [1, 2]. When the air space is ventilated, the assembly is denominated a radiant barrier (RB) [3, 4]. Radiant barriers are not commonly evaluated in terms of RSI partly because a wide range of values can occur within the assembly. Rather, radiant barriers are generally evaluated in terms of reduced heat flux (W/m²) [5, 6]. Reflective technology is also used on exterior surfaces to reduce solar gain, that is, the solar radiation from the sun that is absorbed by the exterior surface [7]. The exterior applications are generally characterized as having a high solar reflectance. Interior coatings with low thermal emittance are also used on interior surfaces to reduce the heat transfer between the interior space and the coated wall; these materials are referred to as interior radiation control coatings [8]. This paper will only focus on reflective insulation assemblies.

1.1 Reflective Insulations

An RI is an air-based thermal insulation. Hence, the thermal resistance of RIs is the result of the low thermal conductivity of air. The thermal conductivity of air at 23°C is approximately 0.0259 W/(m·K) and increases as the temperature increases [9, 10]. The purpose of the low emittance surface provided by an RI is to reduce heat transfer by radiation. The design of the enclosed space can also inhibit the movement of air in the cavity, reducing the transport of heat by convection. In the absence of heat transfer by radiation and convection, the RSI for a 25-mm air space is approximately 1.0 m²·K/W at 23°C [9]. This RSI is the maximum value for a thermal insulation based on air as the low thermal conductivity component. As shown by
the examples in Figure 1, a large number of thermal insulations used in buildings are air-based insulations.

RIs are made by attaching a low emittance metallic foil or metallized film to a substrate material for support. The substrate can be, for example, a plastic material, paper, cloth, metal or wood. The total hemispherical emittance of the exposed surface of the film or foil is generally in the range 0.03 to 0.06. The measured emittance [11, 12] of the RI surface is a property that is listed on product labels and technical bulletins. In many cases, the RSI of the substrate of an RI is small or negligible. The thermal performance of an RI is based on the reduction in the heat flow by radiation across the enclosed space.

Reflective technology represented by RIs (and RBs) are especially useful in hot climates since the heat flow direction is mostly downward. Free convection is generally a small factor when the heat flow is downward and heat transport across air spaces is dominated by radiation. The weather conditions that are favorable for the use of reflective technology will be discussed in the following section.

### 1.2 The climate in South East Asia

The climate in South East Asia is such that interior space conditioning is dominated by cooling. A review by Mourshed [13] clearly shows that cooling requirements expressed as Cooling Degree Days (CDD) are significant in South East Asia, while heating requirements expressed as Heat Degree Days (HDD) are largely negligible. Myanmar and Laos are the only countries showing HDD greater than 50. This is important in the present discussion about reflective technology because natural convection is minimized when the heat flow direction is down, hence radiant barriers and reflective insulation perform best when the heat flow direction is downward.

At present, the ten countries in South East Asia have a total population of over 600 million, which is increasing at a population-weighted annual rate of about 1.1%. The gross domestic product in these countries is also increasing, at a population-weighted average rate of about 5% per year (2015 data). The combination of increasing population and expanding economy translates to increased demand for housing and increased demand for conditioned space. As discussed above and documented in Table 1, given the HDD\textsubscript{25} (heat degree days, base temperature 25°C) and CDD\textsubscript{25} (cooling degree days, base temperature 25°C) for capital cities in South East Asia, the utility demand will be for cooling. Thus, reflective technology can reduce this demand.

### 1.3 Construction and Application of Reflective Technology

South East Asian countries have hot and humid climate throughout the year, except those countries (e.g., Myanmar and northern Vietnam) that are further north of equator, experience cooler year-end period. Buildings are generally constructed to reduce the solar heat gain, especially through the roof. There are two types of roof generally used in South East Asia – Tile roof (concrete/clay) and Metal roof.

#### 1.3.1 Tile Roof (concrete and clay)

The majority of the residential buildings roofs are constructed using concrete and clay tiles, probably due to its availability, aesthetic and inherent sound proof properties. Roof pitch is typically greater than 30° to prevent water leakage during heavy rain with strong wind. Ceiling is constructed between the living space and the roof to create a non-ventilated attic space. Often, there is no insulation material underneath the tiles. However, newer houses may be insulated using RI as illustrated in Figure 2.

#### 1.3.2 Metal Roof

Metal roofing is used in residential, industrial and commercial buildings. For residential buildings, metal roofing is gaining in popularity due to its versatile design, and is able to prevent water leakage even in heavy storms. Typical roof pitch is usually less than 10°. This results in
### Thermal Insulations Used in Buildings

<table>
<thead>
<tr>
<th>Air based</th>
<th>Gas other than air</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiberglass</td>
<td>Extruded Polystyrene</td>
<td>Aerogels</td>
</tr>
<tr>
<td>Rock wool</td>
<td>Polyisocyanurate</td>
<td>Vacuum panels</td>
</tr>
<tr>
<td>Cellulose</td>
<td>Closed-cell polyurethane</td>
<td></td>
</tr>
<tr>
<td>Perlite</td>
<td>Phenolic foam</td>
<td></td>
</tr>
<tr>
<td>Reflective</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expanded Polystyrene</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agglomerated Cork</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Figure 1: Examples of three categories of thermal insulation materials

#### Figure 2: Tiled roof with reflective insulation

Smaller non-ventilated attic spaces in comparison with concrete and clay tile roofs. Metal roofs are commonly insulated against sound and heat using insulation materials such as mineral wool and fiberglass, supported by reflective insulation material as illustrated in Figures 3 and 4. Figure 5 shows that the reflective insulation can also serve as a vapor barrier. Cellular plastic insulation, foams or bubble foil are also used when sound attenuation is not required.

## 2 Evaluation of Performance

The performance of reflective insulation assemblies is quantified as a thermal resistance (RSI with unit m²·K/W), similarly to other thermal insulations. The RSI for reflective insulation assemblies are measured under steady-state conditions with a hot-box facility [14, 15]. RSI can be calculated for enclosed rectangular regions for specific values of emittance, surface temperatures, and heat flow directions [1, 16]. The calculation methods are valid for single air spaces with known conditions. Variations from parallel plane surfaces can be accommodated in some cases by using an average value for the distance across the air space [14, 17]. The method for calculating RSI for an enclosed reflective air space generally starts with two equations. Equation (1) provides an effective emittance, $E$, for an air space bounded by hemispherical thermal emittances $\varepsilon_1$ and $\varepsilon_2$. Equation (2) is a general expression for thermal resistance.

$$ E = \frac{1}{\left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1\right)} \quad (1) $$

$$ RSI = \frac{1}{h_{rad} + h_{cc}} \quad (2) $$

Where: RSI is the thermal resistance in m²·K/W; $h_{rad}$ is the radiative coefficient; $h_{cc}$ is the conduction/convective coefficient.

When the radiation occurs between large parallel planes, the radiation transport is calculated using Equation (3). The radiation coefficient for finite parallel planes...
Legend:
1) Metal deck roof
2) Fixing clip
3) Mass insulation (50mm x 40kg/m³)
4) Double sided aluminium woven foil
5) Purlin

Figure 3: Metal deck with mass insulation and RI (Source: Swissma Roofing Malaysia)

Legend:
1) Metal deck roof
2) Double sided aluminium foam foil
3) Metal deck roof
4) Mass insulation (50mm x 40kg/m³)
5) Double sided aluminium woven foil
6) Purlin

Figure 4: Double skin metal deck with mass insulation and RI (Source: Swissma Roofing Malaysia)
separated by re-radiating surfaces is less than that predicted by Equation (3). In this case \( E \) is replaced by a “configuration factor, \( F_{12} \)” that includes the impact of the emittances of the surfaces 1 and 2 and re-radiation from the bounding surfaces [18]. The radiation transport is subtracted from the hot-box measurement of total heat transfer rate to determine the convective-conduction transport across an enclosed region [14].

\[
h_{\text{rad}} = 5.67 \times 10^{-8} \cdot E \cdot \left(T_2^4 - T_1^4\right) \approx 0.227 \times 10^{-6} \cdot E \cdot T_3^m
\]  

(3)

Where; \( E \) is effective emittance; \( T \) is surface temperature.

This partition of heat flows by type of mechanism may not be precise if the \( h_{\text{rad}} \) from Equation (3) is used in the present analysis. The conduction-convective term, \( h_{\text{cc}} \), can be estimated using the equations in ISO 6946 [16]. In addition, the dimensionless groups, Grashof (Gr) and Nusselt (Nu), are often used to describe \( h_{\text{cc}} \) [1, 13] as follows:

\[
Nu = h_{\text{cc}} \cdot d/\lambda = f(Gr)
\]  

(4)

\[
Gr = \Delta T \cdot d^3 \cdot g \cdot \beta/\gamma^2
\]  

(5)

Where; \( d \) is the distance across the air space; \( g \) is the gravitational acceleration; \( \lambda \) is the thermal conductivity; \( \beta \) is the gas expansion coefficient; \( \gamma \) is the kinematic viscosity of air.

ISO 6946 contains equations for direct calculation of \( h_{\text{cc}} \) for unventilated air spaces that are summarized as follows. The coefficient \( h_{\text{cc}} \) is the larger of \( h_{\text{cc}}^0 \) given by Equation (6) and \( h_{\text{cc}} \) for the heat flow direction of interest calculated, when \( d \) is less than 10% of both the length and width of the airspace. The numerator in Equation (6) is the thermal conductivity of air [8].

\[
h_{\text{cc}}^0 = \frac{0.02414 + 0.000074 \cdot T}{d}
\]  

(6)

If \( \Delta T < 5 \, \text{K} \), then \( h_{\text{cc}} = 1.25 \) for horizontal heat flow, 1.95 for heat flow up, and 0.12/d^0.44 for heat-flow down. Otherwise, \( h_{\text{cc}} = 0.73 \cdot \Delta T^0.333 \) for horizontal heat flow, 1.14 \cdot \Delta T^0.333 for heat-flow up, and 0.09 \cdot \Delta T^0.187/d^0.44 for heat-flow down. ISO 6946 recommends a reduction of calculated RSI by 50% for slightly ventilated airspaces and an assignment of zero RSI for a well-ventilated airspace [8]. Advanced methods for evaluating the performance of enclosed air spaces based on computer simulations are also available [19]. Computer simulations provide air-velocity profiles and heat flow calculated from the transport equations.

The performance of radiant barrier systems is not commonly evaluated in terms of RSI. RB systems are often ven-
The reduction in temperature in an attic space containing air handling ducts can reduce the air conditioning load. Reductions in load due to RB systems has been the subject of numerous scientific papers [6, 20] that involve primarily installations in North America. There is also an abundance of published information about reflective insulation systems [21].

The absence of field data for RI and RB systems for locations in South East Asia provided motivation for the present study, which is focused on performance in Malaysia.

2.1 The experimental test huts

Test huts were constructed to study the performance of radiant barriers and reflective insulations for actual environmental conditions. The test huts shown in Figure 6 were built in an open area with natural weather in Melaka, Malaysia. The dimensions of each hut are 2.2m × 2.5m × 3.3m (height). The distance between the test huts is 1.9m. The test huts face West to prevent self-shading.

The walls, including the attic area, are constructed using hollow metal frames and covered on the outside with 6 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/m³ to reduce heat gain or heat loss through the walls and floor. Hence, temperature changes in the attic and interior of the test huts are mainly affected by the roof insulation.

The attic assembly for the test hut uses a gable-roof design. Reflective insulation with low-emittance surfaces on both sides is laid on the rafters. Battens with specific dimensions are used to create an enclosed reflective air space between the reflective insulation and the roof tiles. The enclosure is completed by fascia boards installed around the eaves. Figure 7 shows the attic region from the inside with the ceiling removed. A shed-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.

The project was carried out in seven phases over a period of 12 months (May 2015 – April 2016). Each phase consisted of different insulation configurations in the three test huts. In this study, roof materials commonly found in Malaysia, i.e. concrete tile, clay tile and metal deck, were used. For insulation, woven foil (double sided Aluminium), bubble foil (8mm thick with double sided Aluminium), foam-foil (8mm thick with double sided Aluminium) and mineral wool (50mm thick with density 40kg/m³) were used.

2.2 Instrumentation

The test huts were instrumented with a pyranometer, thermocouples, heat flux transducers and portable data loggers. The pyranometer was placed in the exterior on top of the roof ridge of the test hut to record the irradiance throughout the day. Type-K thermocouples with precision ±1°C were installed and positioned as shown in Figure 8, and were used to monitor the material surface temperatures. Each of the test huts contained 12 thermocouples – six underneath the roof tiles or metal deck, three underneath the insulation material, and three thermocouples on top of the ceiling. Every test huts contained a transducer attached to the ceiling with silicon thermal adhesive (as shown in Figure 9) to determine the heat flux across the ceiling. Portable data loggers recorded the attic air temperature.

2.3 Calculation of RSI from transient data

Temperatures, heat flux and irradiance were recorded at two-minute intervals for 10 days. Figure 10 shows the average temperature for roof tiles (red line), woven foil (blue line) and ceiling (grey line) in the same 10-day time frame (29 May – 7 Jun 2015). The average outdoor temperature ranged from 25 – 38°C. Figure 11 is the temperature comparison of three test huts in the same 1-day time frame,
whereby Test Hut 2 was without any insulation material underneath the roof.

It is noted that the ceiling temperatures for Test Hut 1 and Test Hut 3 are significantly lower than Test Hut 2 during daytime. $R_{SI_t}$ is the total thermal resistance of two enclosed regions of the attic as indicated by Equation (7). The heat fluxes for the upper attic region were obtained from the transducer mounted on the ceiling using Equation (8). $R_{SI_{block}}$ is then calculated by averaging temperature and heat flux data for ten two-minute intervals, as expressed in Equation (9). For instance, if there are 1,000 two-minute intervals, then there will be 100 $R_{SI_{block}}$ values.

$$R_{SI_t} = R_{SI_A} + R_{SI_B}$$

$$Q_A = Q_B \cdot \left(\frac{\text{ceiling area}}{\text{Roof area}}\right)$$
The RSI (m² · K/W) for each roof configuration for each phase are contained in the Table 2.

The results for Test Hut 2 with no insulation show RSI 0.40 for the region between the roof and the ceiling. The corresponding value given in Table K2 in AS/NZS 4859 is 0.28 m² · K/W. The agreement seems reasonable given the wide variety of attic designs. The time-averaged RSI values in Table 2 for insulated attic spaces are significantly greater than the uninsulated value. The reduction in heat flow across the ceiling results in lower maximum air temperatures in the region below the ceiling when the space is not conditioned, or in reduced utility used for air conditioning in the occupied space. The reduction in interior air-space temperatures due to attic-space insulation was discussed in section 2.3. The % reduction in ceiling heat flux (HFR) is estimated using Equation (11), where RSI is
Table 2: RSI for the test huts

<table>
<thead>
<tr>
<th>Phase</th>
<th>Type of roof</th>
<th>Configuration</th>
<th>Test Hut 1 (RSI)</th>
<th>Test Hut 2 (RSI)</th>
<th>Test Hut 3 (RSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Concrete tile</td>
<td>25mm air space</td>
<td>Woven foil 2.37</td>
<td>Without foil 0.37</td>
<td>Bubble foil 2.93</td>
</tr>
<tr>
<td>2</td>
<td>Concrete tile</td>
<td>50mm air space</td>
<td>Woven foil 2.16</td>
<td>Without foil 0.40</td>
<td>Bubble foil 2.69</td>
</tr>
<tr>
<td>3</td>
<td>Concrete tile</td>
<td>Woven foil</td>
<td>2.31</td>
<td>25mm air space 2.15</td>
<td>75mm air space 3.08</td>
</tr>
<tr>
<td>4</td>
<td>Concrete tile</td>
<td>Bubble foil</td>
<td>50mm air space 2.41</td>
<td>25mm air space 2.41</td>
<td>75mm air space 3.09</td>
</tr>
<tr>
<td>5</td>
<td>Clay/Concrete tile</td>
<td>25mm air space (Woven Foil)</td>
<td>Concrete tile 2.26</td>
<td>Clay tile (Without foil) 0.40</td>
<td>Clay tile 2.40</td>
</tr>
<tr>
<td>6</td>
<td>Metal deck</td>
<td>No air space</td>
<td>Woven foil/Mineral Wool 2.23</td>
<td>Foam foil 2.37</td>
<td>Bubble foil 1.77</td>
</tr>
<tr>
<td>7</td>
<td>Metal deck</td>
<td>No air space</td>
<td>Woven foil/Mineral Wool 2.77</td>
<td>Mineral Wool 1.61</td>
<td>Bubble foil 2.02</td>
</tr>
</tbody>
</table>

Table 3: Maximum attic air temperatures

<table>
<thead>
<tr>
<th>Phase</th>
<th>Type of roof</th>
<th>Configuration</th>
<th>Test Hut 1 (°C)</th>
<th>Test Hut 2 (°C)</th>
<th>Test Hut 3 (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Concrete tile</td>
<td>25mm air space</td>
<td>Woven foil 37.2</td>
<td>Without foil 46.1</td>
<td>Bubble foil 36.7</td>
</tr>
<tr>
<td>2</td>
<td>Concrete tile</td>
<td>50mm air space</td>
<td>Woven foil 38.3</td>
<td>Without foil 45.7</td>
<td>Bubble foil 36.6</td>
</tr>
<tr>
<td>3</td>
<td>Concrete tile</td>
<td>Woven foil</td>
<td>37.3</td>
<td>25mm air space 38.4</td>
<td>75mm air space 35.8</td>
</tr>
<tr>
<td>4</td>
<td>Concrete tile</td>
<td>Bubble foil</td>
<td>50mm air space 36.7</td>
<td>25mm air space 37.8</td>
<td>75mm air space 35.4</td>
</tr>
<tr>
<td>5</td>
<td>Clay/Concrete tile</td>
<td>25mm air space (Woven Foil)</td>
<td>Concrete tile 36.7</td>
<td>Clay tile (Without foil) 43.8</td>
<td>Clay tile 36.0</td>
</tr>
<tr>
<td>6</td>
<td>Metal deck</td>
<td>No air space</td>
<td>Woven foil/Mineral Wool 39.2</td>
<td>Foam foil 38.7</td>
<td>Bubble foil 39.5</td>
</tr>
<tr>
<td>7</td>
<td>Metal deck</td>
<td>No air space</td>
<td>Woven foil/Mineral Wool 37.6</td>
<td>Mineral Wool 39.1</td>
<td>Bubble foil 38.1</td>
</tr>
</tbody>
</table>

for the insulated attic:

$$HFR \, (\%) = \left( 1 - \frac{0.4}{RSI} \right) \cdot 100 \quad (11)$$

Table 2 shows a reduction in heat flows across the ceiling ranging from 80 to 90%, which translates to a reduction in electrical use when a conditioned space is maintained. Using the average CDD$_{25}$ of 1311 from Table 1 and an air-conditioning coefficient of performance (COP) of 3, the estimated annual savings for a change from 0.4 to 2.4 in attic RSI is 109 kW-h/(y·m$^2$).

Table 3 shows the maximum attic air temperature for all phases. It shows that there is about 9°C difference for roof with and without insulation (Phases 1 and 2). There will be a reduction of attic air temperature of about 1.5°C with every increment of 25mm of enclosed reflective air space (refer to Phases 3 and 4). In general, attic air temperature for clay tiles (without insulation) is cooler than concrete tiles. However, there is no significant difference in terms of attic air temperature when clay tiles and concrete tiles are insulated (refer to Phase 5). For phase 6, Hut 3 insulated with Bubble Foil gave the highest attic air temperature. For phase 7, there is a 1.5°C attic air temperature difference for mass insulation with and without reflective insulation.

4 Conclusions

Reflective technology, RI and RB, are effective as attic insulation in South East Asia buildings, especially in locations where the predominant heat flow direction is downward. Measured RSI for typical attic applications of reflective products showed results in the range of 2 to 3 m$^2$·K/W.
Measured thermal resistances for attics with reflective insulations are higher than for mass insulations in the same structure. Ceiling heat-flux reduction for attics with reflective insulation were determined to exceed 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.

**Acknowledgement:** The authors acknowledge, appreciate and are grateful to Solar Energy Research Institute (SERI), Universiti Kebangsaan Malaysia and San Miguel Yamamura Sdn Bhd for the data obtained from the joint research collaboration, without which this research would not have been possible.

**Table of Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDD</td>
<td>Cooling Degree Days</td>
<td>[days]</td>
</tr>
<tr>
<td>CDD&lt;sub&gt;25&lt;/sub&gt;</td>
<td>Cooling Degree Days, base temperature 25°C</td>
<td>[days]</td>
</tr>
<tr>
<td>d</td>
<td>Length</td>
<td>[mm]</td>
</tr>
<tr>
<td>E</td>
<td>Effective emittance</td>
<td>[dimensionless]</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational acceleration</td>
<td>[m/s&lt;sup&gt;2&lt;/sup&gt;]</td>
</tr>
<tr>
<td>HDD</td>
<td>Heat Degree Days</td>
<td>[days]</td>
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<tr>
<td>HDD&lt;sub&gt;25&lt;/sub&gt;</td>
<td>Heat Degree Days, base temperature 25°C</td>
<td>[days]</td>
</tr>
<tr>
<td>h&lt;sub&gt;cc&lt;/sub&gt;</td>
<td>Conduction/convection coefficient</td>
<td>[W/m&lt;sup&gt;2&lt;/sup&gt;·K]</td>
</tr>
<tr>
<td>h&lt;sub&gt;rad&lt;/sub&gt;</td>
<td>Radiative coefficient</td>
<td>[W/m&lt;sup&gt;2&lt;/sup&gt;·K]</td>
</tr>
<tr>
<td>Q</td>
<td>Heat flux</td>
<td>[W/m&lt;sup&gt;2&lt;/sup&gt;]</td>
</tr>
<tr>
<td>RSI</td>
<td>Thermal resistance</td>
<td>[m&lt;sup&gt;2&lt;/sup&gt;·K/W]</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>[°C]</td>
</tr>
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**Greek Letters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>β</td>
<td>Expansion coefficient</td>
<td>[k&lt;sup&gt;−1&lt;/sup&gt;]</td>
</tr>
<tr>
<td>ε</td>
<td>Emittance</td>
<td>[dimensionless]</td>
</tr>
<tr>
<td>λ</td>
<td>Thermal conductivity</td>
<td>[W/m·K]</td>
</tr>
<tr>
<td>γ</td>
<td>Kinematic viscosity</td>
<td>[m&lt;sup&gt;2&lt;/sup&gt;/s]</td>
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**Dimensionless Groups**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>Gr</td>
<td>Grashof number, Equation 5</td>
</tr>
<tr>
<td>Nu</td>
<td>Nusselt number, Equation 4</td>
</tr>
</tbody>
</table>

**References**


[17] ibid 17, Annex C

