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Design and performance of a novel innovative roofing system for tropical landed houses

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ABSTRACT

An innovative roofing system (IRS) is designed to deliver an abundant and uniform amount of cool natural light from the roof with reduced heat gain effect for tropical residential buildings (3 m height) in Malaysia. Studies revealed that several passive and active solar techniques can be integrated to form a roofing system to separate solar heat from useful natural light at the attic zone before heat reaches the occupied space. The IRS design is specified and proposed by using glazing technology (polycarbonate), pigment technique (reflective and radiative), as well as ventilation process (hybrid turbine ventilator) applied at the attic zone to represent a new model of sustainable roofing design. The aim of this research is to demonstrate the effectiveness of the design concept without the need for any chemical, complex, or expensive solar design techniques. The methodology was conducted on a series of field studies in a standard room model at Universiti Sains Malaysia. Three different roofing systems are investigated to identify the IRS performance in both dark and daylight conditions to determine the effect of natural light on the indoor environment. The outcomes of the design show that the IRS was able to reduce the indoor air temperature compared with conventional roofing system by approximately 2.1 °C under daylight condition. Results showed that the difference in the IRS (daylight–dark) condition was 0.31 °C compared to that in the conventional roofing system at 0.8 °C. Furthermore, the level of mean radiant temperature compared with indoor temperature under daylight condition was 2.61 °C for the IRS, whereas 4.05 °C for conventional roof. Moreover, the IRS successfully delivered an acceptable range of natural light below 2000 lux (Green Building Index) at daytime with a minimum level of 86% compared with 78% for conventional roofing design. As a result, these findings indicated that the IRS with light materials and without any insulation can separate solar heat from useful natural light under the climatic conditions in Malaysia. The system provides a new design paradigm based on the requirements of the Malaysian Green Building Index.

1. Introduction

Energy consumption is a serious issue in Malaysia. The Energy Commission [1] reported that the maximum demand for electricity increased dramatically. According to International Energy Agency (IEA) [2], the CO_2 emissions in Malaysia have increased critically since 1970, indicating that Malaysia is one of the largest emitters in Southeast Asia. Concerning the issue on a small scale, Malaysia had approximately 7.3 million residential dwellings in 2010, and the number is expected to rise by approximately 150,000 each year [3,4]. In 2010, the electricity generated has doubled compared to that in 2000 [5]. At present, the residential sector accounts for more than 20% of the energy consumption in the nation [2]. The urban population in Malaysia increased rapidly from 25% in 1960 to 72% in 2010. By 2030, more than three quarters of the total population in Malaysia are expected to settle in urban areas [6].

According to Al Yacouby et al. [7], approximately 75% of the Malaysian population relies on air conditioning to maintain a comfortable environment. Zain-Ahmed [8] showed that the average building energy consumption reached 233 kW h/m^2/year. Approximately 60% of the consumption is dedicated to air conditioning and approximately 25.3% to electric lighting. The problem is aggravated because modern residential buildings have been constructed based on airtight design, lightweight materials, and poor natural ventilation that consequently lead to the adoption of mechanical cooling systems [9].

The roofing system is the main source of heat build-up in residential and low-rise buildings, contributing approximately 70% of the total heat gain inside a building [10]. Roofing systems are

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affected directly by solar rays up to 1 kW/m^2. The heat absorption level is from 20% to 90% [11]. Unlike countries in temperate and cold climates, Malaysia is a tropical country exposed to substantial amounts of solar insolation. Malaysia has an uncomfortable climate zone characterized by prolonged summer in a typical year and excessive heat from solar radiation.

In reality, the roofing system in Malaysia is not sufficiently investigated and applied. Isa et al. [12] indicated that more than 1.6 million terrace houses in the country were inhabited by more than seven million people, and most of the roofs of these buildings were built with cement or clay tiles. Furthermore, most of these buildings have no insulation materials except for some with modified thin layer insulations beneath the roof tiles. According to a survey conducted by Allen et al. [13], roofing materials in Malaysia are classified as 85% concrete roof tiles, 10% clay tiles, and 5% metal decks. Al Yacouby et al. [7] indicated that the color of most roof tiles were dark. As a result, Malaysian houses have high solar radiation gains particularly from roofs, creating an uncomfortable environment for their occupants.

According to previous studies, most landed houses in the tropics rarely have a roof light element because it causes more thermal discomfort at human height level. Roof lights in the tropics heat up the interior quickly. Yu et al. [14] stated that heat gain through glazing openings represents 25–28% of the overall gain. The infiltration also reaches up to 40% in hot weather. Applying a roof light system in the tropics leads to more air conditioning load usage to cool the air mass [15]. In previous years, air conditioning was the method used to overcome thermal discomfort (heat accumulation). However, air conditioning is no longer considered as a tropical design element given the gradual increases in energy cost.

Stifling heat and glare are major problems in this region. Therefore, the main goal of this study is to design a special roofing system for a landed house, which allows for natural light while overcoming the heat accumulation problem. Previous studies showed that environmental boundaries in the tropics could force any building system to depend on certain approaches to overcome the severe weather [9,16]. To solve this problem, building professionals are advised to review the integration of building construction with sufficient knowledge and technological capacity in sustainability and energy efficiency. These strategies should address environmental restrictions by combining a number of solar design techniques to meet the requirements of the Malaysian built environment.

The review of literature found no specific standard to encourage the use of this type of approach in roofing systems, and no specific policy measure related to this technique is found in the building codes, such as Uniform Building By-Laws [17], Malaysian Standard MS1525-2007 [18], Green Building Index [19,20], and Building Sector Energy Efficiency Project [21]. For this reason, the effectiveness of the new roof design in existing buildings requires further investigation to obtain quantitative data on the performance of such a system in tropical climate.

2. Literature review

2.1. Sustainable roofs

Given the increasing public attention on climate change and global warming, international conferences are challenging the construction industry, and particularly the roofing industry, to translate the demands to reduce energy consumption through practical guidelines and systems [22]. Various conceptual definitions have been proposed to understand the relevance of sustainable roofs, but the most appropriate definition is from the proceedings of the *Sustainable Low-Slope Roofing Workshop*, Oak Ridge National Laboratory, USA in October 1996. According to this source, a sustainable roof is “a roofing system that is designed, constructed, maintained, rehabilitated and demolished with an emphasis throughout its life cycle on using natural resources efficiently and preserving the global environment.”

According to Hutchinson [23], this definition is difficult to understand and its values are complicated to implement extensively. To meet the requirements of sustainable development, an international committee (CIB W83/RILEM 166 RMS) summarized a document, *Tenets of Sustainable Roofing*, in 2002. This document has helped architects and designers to advance in three important sectors of sustainability, namely, (i) minimizing the burden on the environment, (ii) conserving energy, and (iii) extending roof system life spans [22]. Liu [24] stated that to support the idea of sustainable development, building owners demand more environment-friendly and low-impact roofing systems. Designers and manufacturers have responded by (i) using materials that are more compatible with environment, (ii) producing more durable products, and (iii) developing methods and system designs to enhance life-cycle costs.

Green roof systems (garden roof system), reflective roofs (cool roof), and roof photovoltaic are a few examples of sustainable roofs. However, this study proposes a new model of sustainable roofing design for landed houses in the tropics, which depends on several solar strategies to allow useful natural light to enter occupied spaces from the roof with reduced heat impact.

Ong [25], Ismail et al. [26], Al Yacouby et al. [7], Sheng [27], Ismail et al. [28], and Yew et al. [29] introduced a number of approaches to develop the roofing system in Malaysia. However, none of these studies combined daylighting and passive cooling techniques in one roofing design. The proposed design is a novel approach because no roofing system globally combines a roof light and ceiling light integrated with glazing technology, pigment technique, and attic ventilation approach as a design concept. Al-Obaidi et al. [15] proposed and recommended an innovative roofing system (IRS) design for Malaysia. However, the study was based only on simulation as an optimization study. Therefore, determining the actual performance is required.

2.2. Environmental conditions

To test a system in an existing building and validate the significance of this study, we have to identify weather conditions in the study area. Malaysia, a country with a tropical climate, is located at 3°N of the Equator, and has hot and humid climate characteristics. Malaysia has two seasons, dry and wet, which are characterized by high temperatures, exposure to substantial amounts of solar insolation, high level of humidity, plenty of rainfall throughout the year, and unpredictable wind movement. Generally, the air temperature in the humid tropics is high all the time. The temperature differences are negligible between seasons, and the differences in diurnal temperature are insignificant [30]. Temperature within places does not vary because the differences in the amount of net radiation received are negligible.

According to a 10-Day Agromet Bulletin issued by the Malaysian Meteorological Department (MMD) [31], the recorded normal temperature, particularly with diurnal air temperature, ranges from 20 °C to 36 °C, and the relative humidity is extremely high and normally exceeds 90% [32]. Fig. 1 [21] shows the general characteristics of Malaysian weather. Malaysia is exposed to a substantial degree of solar insolation, with an average of approximately 1643 kW h/m^2 per annum [33] and more than 10 h of sun exposure per day [34].

The position of the sun in Malaysia and particularly in Penang is at the zenith of the orbit from 1:15 pm to 1:30 pm all year, with a minimum altitude of 61° around December and January and a

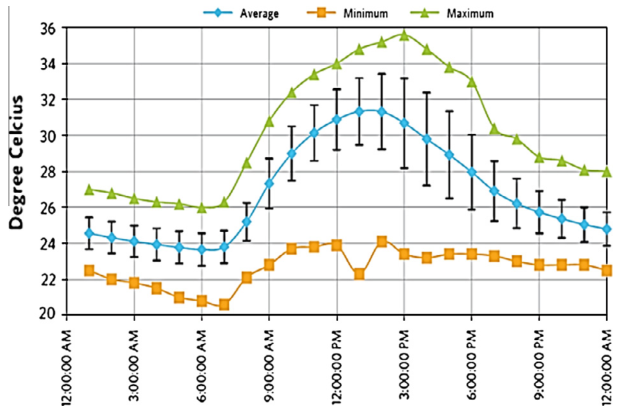


Fig. 1. Dry bulb temperature [21].

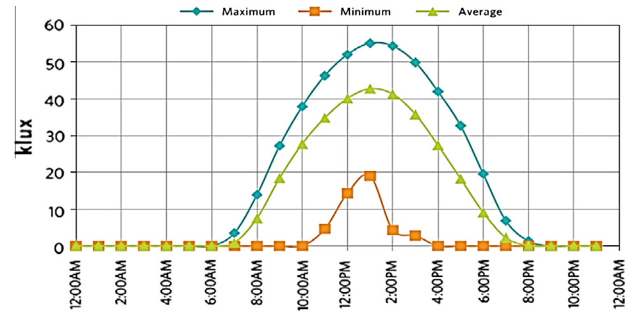


Fig. 3. Daylight level in Malaysia [21].

maximum altitude around 89° at the end of March, first of April, and September, depending on the location of the sun. Fig. 2 shows the typical solar radiation throughout the year.

Bittencourt [35] affirmed that the typical sky condition in warm humid climates is partially cloudy. Clear sky is rare (approximately 4.5% on average), whereas overcast skies are almost above 15%. Zain-Ahmed et al. [36] measured the Malaysian sky and classified it as intermediate mean and overcast sky with illumination between 60,000 to 80,000 lux at noon during the months with the highest solar radiation. Using field measurements, they found that the illuminance values could exceed 100,000 lux at Shah Alam and 140,000 lux at Bangi. Zain-Ahmed et al. [36] indexed the characteristics of Malaysian skies, indicating that 85.6% of the time, the sky is predominantly intermediate and 14.0% overcast. In addition, MMD [32] stated that a full day with totally clear sky even in times of severe drought is rare. Fig. 3 shows that the level of diffuse daylight availability during a year exceeds 50,000 lux [21].

Moreover, humid tropics are distinguished by light and variable wind movement. This climate is a sensitive issue as different places in the humid tropics provide different values. According to the MMD [32], Malaysia is a maritime country. The general wind flow pattern is dependent on the effects of land and sea breezes. According to Azusa [37], this parameter is considered only in coastal and mountain areas, but not in urban areas. Akorede et al. [38] indicated that Malaysia is generally a low-profile wind speed country. Abdul Rahman [39] concluded that Malaysian wind condition is unpredictable, multi-directional, and with insufficient velocity at ground level.

Such conditions require any building system in this region to adopt a combination of several approaches of passive and active solar methods. For these purposes, reviewing several solar design strategies associated with roofing systems is significant in investigating their performances in the Malaysian environment so that a new roof system design can be designed.

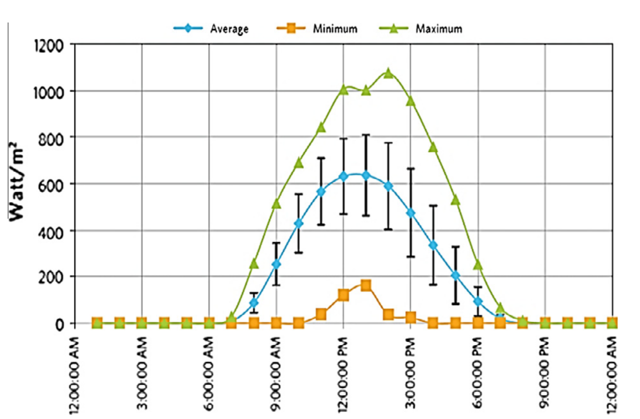


Fig. 2. Horizontal global radiation [21].

3. Design overview

Meeting the objectives of this study first requires understanding the performance of passive cooling systems. Generally, common systems are classified using methods proposed by Cavelius et al. [40], Hatamipour and Abedi [41], and Kamal [42]. Geetha and Velraj [43] developed a clear framework for passive cooling. This framework is broadly categorized according to three sections: (i) heat prevention/reduction (reduction of heat gains), (ii) thermal moderation (modification of heat gains), and (iii) heat dissipation (removal of internal heat). The various methods used for each of these sections are further classified and shown in Fig. 4. The most significant and comprehensive strategies related to the proposed system in this study are highlighted with red dashed lines.

Based on the classification presented by Geetha and Velraj [43], this study discusses three important design aspects: controlling, reducing, and rejecting heat from solar rays using roofing systems to provide cooler natural light in landed houses. This study also discusses two main strategies to develop an IRS, a combination of daylighting and passive cooling systems, as shown in Fig. 5.

According to the classification for review and application, the proposed design is divided into (i) daylighting incorporating rooflight system (skylight) and glazing material (polycarbonate), and (ii) passive cooling system incorporating the pigment technique (reflective and radiative) and attic ventilation (hybrid turbine ventilator). For the thermal mass, attic space functions as a space gap that controls the system behavior. The combination of these techniques results in an IRS.

3.1. Daylighting

3.1.1. Skylight systems

From an architectural point of view, the daylighting approach is defined as the controlled admission of natural light (direct sunlight and diffused skylight) into a space to save energy [44]. In fact, toplighting systems, a targeted element in this study, deliver significantly more suitable illumination using smaller openings than side-lighting. In addition, top-lighting systems provide three times more light than vertical glazing with the same area [45]. A skylight system is a light-transmitting fenestration placed horizontally on flat or sloped roofs to form all or a part of the roof structure, and can deliver a uniform level of illumination over an interior space. This system is an effective approach for illuminating one-story buildings. However, the performance of this system varies under overcast and clear skies, particularly given the concern for thermal impact in hot regions [46–49].

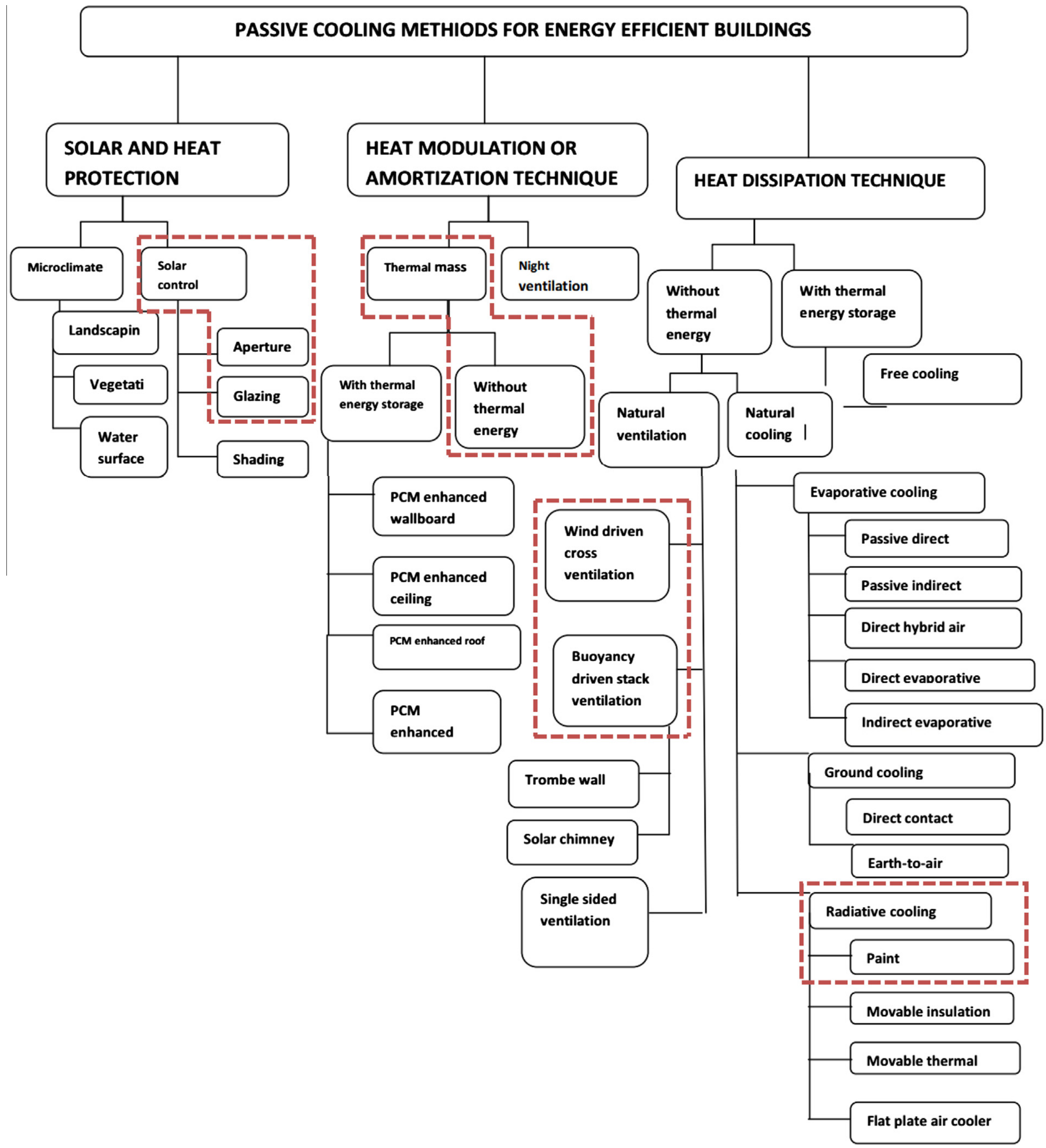


Fig. 4. Classification of passive cooling methods used in energy-efficient buildings [43] with highlighted target variables (Red dashed lines highlight the targeted approaches used in this study). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

According to Ruck and Aschehoug [46] and Heschong and Resources [50], in most cloudy conditions, skylight system designs require the distribution of natural light in indoor places when direct sunlight is unavailable. Therefore, to deliver a sufficient amount of daylight, the system has to be relatively large. On the other hand, under sunny conditions, direct sunlight is extremely bright and intense because the quantity of incident light entering a small opening is enough to deliver sufficient daylight levels in large indoor spaces. However, the design of this type of opening is considered a weak point because of glare and overheating, particularly in the tropics [51–53].

A number of factors determine skylight design, such as size, orientation, placement, amount of shading, and glazing type. In reality, glazing type is considered as the most essential factor in skylight design [54]. Therefore, understanding the properties of the glass material is critical to minimize cooling loads and maximize use of natural light. According to Edward [55], the incident of sunlight rays on 1000 square centimeters of horizontal glass on sunny days can deliver almost twice as much light as a fluorescent lamp.

3.1.2. Skylight glazing materials

Several types of glazing materials are used in the building design, particularly skylight systems. Both glass and plastic products can support modern buildings while meeting environmental and structural standards. However, choosing between glass and plastic depends on several factors, including climate, building location, and cost. Several different types of glass are available, such as

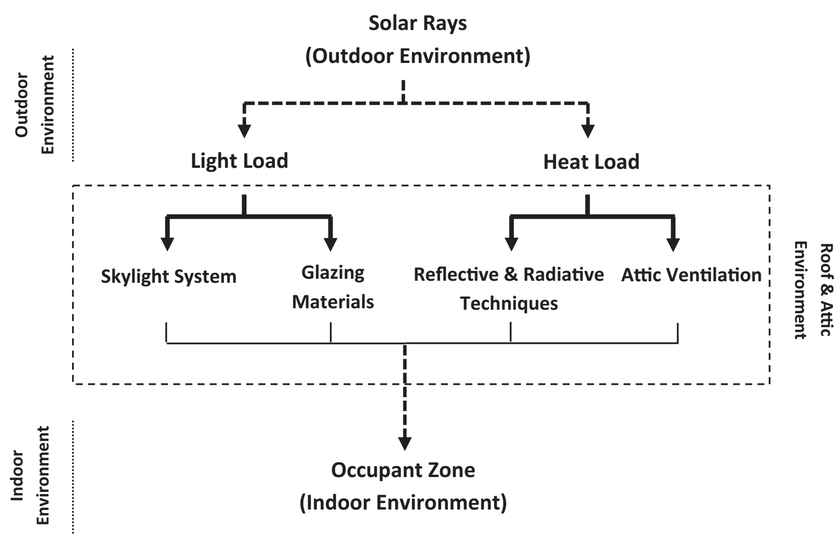


Fig. 5. Framework for solar design techniques used in IRS.

clear glass, tinted glass, wavelength-selective coatings, insulating glass, high-tech glazing, and miscellaneous glazing. However, these are generally costly and place additional loads on the roof. Plastic material used in skylight systems are polymers available in numerous forms, such as glass reinforcement plastics, polyvinyl chloride, polycarbonate, acrylic, fiberglass, and copolyester [54]. Al-Obaidi et al. [15,54] found polycarbonate to be one the most valuable materials for roofing systems, particularly for the tropics. Polycarbonate is designed for use in a wide range of roofing and cladding applications, and offers clarity, high-impact resistance, and UV coating protection that eliminates up to 99% of UV, thereby protecting materials and people beneath. According to Bristol Daylighting Systems [56], polycarbonates are 100% recyclable material and it has been used in most projects of Leadership in Energy and Environmental Design. Additionally, polycarbonates offer highly diffused light transmission and low U-factor, making them effective daylighting materials.

3.2. Passive cooling

3.2.1. Reflective and radiative techniques

According to a Malaysian study by Al Yacouby et al. [7], the majority of roof tiles colors are dark (red 38%, brown 25.9%, white 9.5%, beige and blue 7.8%, black 4.9%, and gray 2.9%). Their survey indicated that 68.8% of the respondents did not object to changing their roof color to white to cut down on air conditioning bills. Given the current interest in reflective roofs, the technique of approach is highly important in this region, and has to be clarified with the occupants and designers.

The effect of the external roof color has been studied by Givoni and Hoffman since 1968 at the Technion in Haifa [57]. Reflective roofs are a design concept intended to reduce heat gain impact on building roofs to a greater extent than conventional systems during sunny days [58]. Reflective roofs consist of a single layer or multiple layers of different materials. Generally, the physical properties of the material surfaces are the major factors that determine roof behavior as either cool or hot. According to a study by Urban and Roth [59], the temperature of normal dark roofs reaches 66 °C or more during hot days. By contrast, a reflective roof in similar environmental conditions stays approximately 28 °C cooler. Urban and Roth [59] and Energy Design Resources [60] specify different types of reflective roofs, such as cool roof coatings, modified bitumen sheet membranes, spray polyurethane foam roofs, shingled roofs, tile roofs, and metal roofs. Santamouris and Asimakopoulos [61] and Akbari and Matthews [62] agreed that the best cool-roof products for tropical climates considerably decrease maximum solar heat gain by reflecting approximately 90% of solar radiation.

The radiative cooling approach is another technique based on the process by which any object or surface at temperatures higher than 0 K emits energy in the form of electromagnetic radiation. Generally, radiant cooling methods work in a reverse manner to radiant heating methods, which absorb heat from hot surfaces inside a building and transfer it to cooler surfaces exposed to the external environment to decrease the heat gain effect [57]. Techniques used in radiative cooling include movable insulation, moveable thermal coolers, and flat plate air coolers. The pigment approach, which is considered as a cost-effective solution, can be used either above or under the roof. Radiative systems work day and night: during the day, the roof absorbs heat from the room below [63]; at night, the roof is exposed to the night sky, losing heat through long-wave radiation and convection [42]. Given that the roof absorbs the greatest part of solar radiation during hot days, the amount of heat that reradiates from hot roof surfaces in the summer can reach 750 W/m^2 when the roof surface temperature is approximately 65 °C [64]. According to the Building Sector Energy Efficiency Project [21], the effective sky temperature in Malaysia takes effect when the temperature drops below 20 °C. Thus, from 12:30 am to around 09:00 am, the effective sky temperature in Malaysia can be lower than 20 °C.

3.2.2. Attic ventilation (turbine ventilator)

The ventilation of attics has been recommended by building practices for energy-conscious design and construction. Ventilation cannot stop the transference mechanism of heat from the roof to the attic, but can reduce this effect. To achieve this reduction, an optimally designed system should deliver a constant flow of cool air under the roof surface to expel solar-heated hot air before it reaches the attic floor [65]. However, studies in different regions propose that a well-designed attic system might differ considerably according to the climatic conditions.

The actual impact of the thermal performance of an attic on the entire building has been less researched, particularly in Malaysia. Al-Obaidi et al. [66,67] provide a clear description of using attic ventilation in tropical climates, particularly using a hybrid turbine ventilator. Currently, different hybrid strategies, such as hybrid photovoltaic thermal systems, can be used to increase energy efficiency in buildings [68,69]. However, studies on hybrid turbine ventilator (HTV) system are still uncommon, particularly in Malaysia. Ismail and Abdul Rahman [70] tested a turbine ventilator that fabricated 450 mm (18″) on the roof level, with a Ø20 cm inner duct, Ø35 cm aluminum ventilation duct, and a solar-powered extractor fan with a Ø30 cm fan blade at the bottom. Their findings indicated that the HTV substantially lessened the interior air temperature and relative humidity by up to 0.7 °C and 1.7%, respectively. In addition, Ismail and Abdul Rahman [71] discovered that the same HTV configuration used as an attic strategy reduced the attic air temperature by approximately 0.9 °C and 1.0 °C compared with indoor HTV (fan at ceiling level) and not having HTV, respectively.

According to Al-Obaidi et al. [66,67], the Malaysian environment cannot rely only on the natural climate to induce the extraction of heat from the attic, and the hybrid system provides a better solution for this region. Thus, one preferable option is to adopt a system consisting of an inlet vent from the gable and an outlet vent using the turbine ventilator with curved vanes of 450 mm (18″) to 500 mm (20″) diameter comprising an internal duct, with an opening cap at the top with a 40–50 W solar panel. This combination creates constant air flow and provides uniform distribution to extract heat effectively. Al-Obaidi et al. [67] tested the attic ventilation in Malaysia with HTV through the aforementioned specification mentioned, and the results show that the system was able to reduce attic temperature by approximately 5 °C compared with unvented attic.

4. Proposed model

Based on previous studies, the combination of several design strategies in one roofing design has not been studied in a single system, particularly when used in real buildings in a hot-humid region. Therefore, based on the literature review, this study proposes that combining these specific methods in such a design can enhance the effectiveness of the separation and provide cooler natural light. According to the previous section, the IRS specifications used in this study are shown in Fig. 6 and listed as follows:

(i) Skylight (double polycarbonate): two units.
(ii) Roof (aluminum sheets): outdoor surface (reflective) and indoor surface (radiative).
(iii) Attic space ceiling light (double polycarbonate) 4 m × 2 m + plaster gypsum board.
(iv) Two openings: inlet at the gable side (350 mm × 350 mm, square shape) and outlet as the HTV on the sloped roof (Ø350 mm), both are in the opposite direction.

5. Experimental procedure

To examine the actual potential and effectiveness of this system in the specific climate conditions of Malaysia, the authors have selected several physical experimental methods. This method was adopted because from the architectural point of view, based on the work of Wouters et al. [72], full-scale field measurement research represents the ideal approach to obtain better evaluation and understanding of the building function and performance because it can deliver real conditions under real weather environments. A full-scale field study was conducted to evaluate the applicability of the IRS design under actual climatic conditions in a constructed building model in Penang, Malaysia. For this purpose, three types of roofing systems determined through empirical study were applied physically on the model at actual size. Ambient, attic, and indoor microclimatic conditions were measured to

(i) explore the effectiveness of the IRS in terms of improving indoor climatic conditions in comparison with different roofing systems, and
(ii) investigate the possibilities of using the IRS to separate solar heat from useful natural light in comparison to different roofing systems and different conditions (dark and daylight).

5.1. Experimental model

The test bed was a single-floor building located at the school of Housing, Building, and Planning in the main campus of the Universiti Sains Malaysia, Penang (latitude 5°2′N, longitude 100°2′E). This building was built using conventional construction techniques and had a concrete floor slab, plaster brick walls, plaster boards for a ceiling, and corrugated metal pitch roof, as shown in Fig. 7 and Fig. 8. However, the roofing system used a double polycarbonate glazing for a skylight as an innovative approach.

The model had no fenestration for daylight penetration from the walls. This configuration is believed to be the worst-case condition and is better for interior illumination and thermal studies. Therefore, to investigate the performance of the IRS in real climatic conditions, the field study was divided into three experimental stages, as shown in Fig. 8.

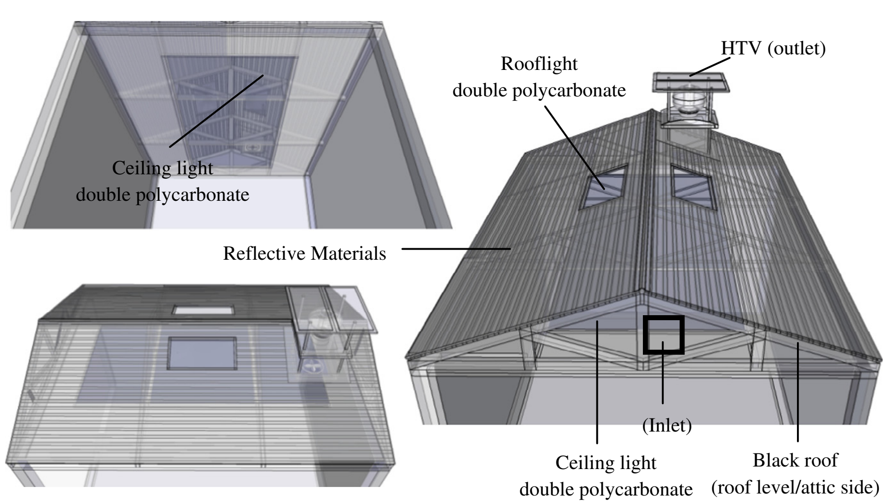


Fig. 6. Proposed model of IRS.

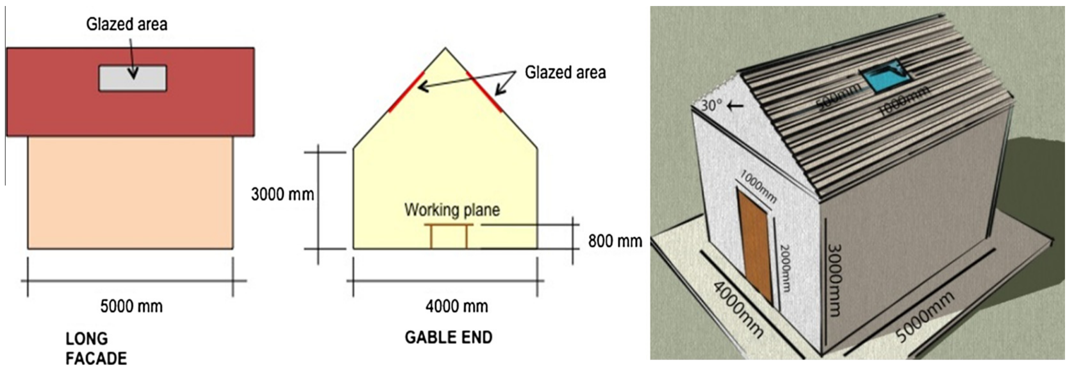


Fig. 7. Graphical representation of the test bed.

5.2. Roofing systems

The actual impact of the IRS on indoor climatic conditions and the possibility of separating solar heat from useful natural light was investigated, and the performance of the IRS was compared to that of other roofing designs. This field work involved investigations in closed conditions (no windows) in the occupied zone to determine the optimum situation to evaluate the performance of the roofing system. The study investigated every strategy in both dark and daylight conditions for roof without an attic, roof with an attic, and the IRS. The specifications for each strategy are listed as follows:

5.2.1. Roof without attic

This strategy was used as a control case for comparison purposes. The parameters used in the roofing system are shown in Fig. 9 and as follows:

(i) Roof (aluminum sheets) 0.8 mm.
(ii) Roof color: outdoor surface (white) and indoor surface (black).
(iii) Skylight: (double polycarbonate) 28 mm.

5.2.2. Roof with attic

For this strategy, the design had the same specifications as Strategy 1. However, an additional element was introduced to the ceiling to create a new zone, which is called the attic. The objective of this investigation was to evaluate the performance of the modified design depending totally on the performance of existing building materials. The parameters used in this roofing system are shown in Fig. 10 and as follows:

(i) Roof (aluminum sheets) 0.8 mm.
(ii) Roof color: outdoor surface (white) and indoor surface (black).
(iii) Skylight (double polycarbonate): 28 mm.

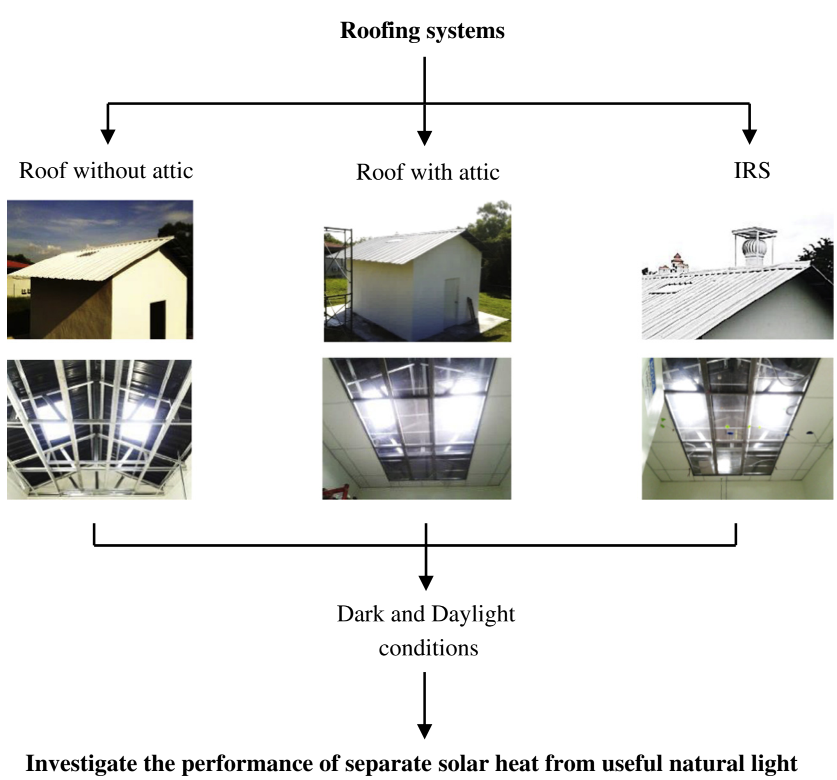


Fig. 8. Summary of different field study strategies used to investigate the performance of the IRS in a real building.

Fig. 9. Model design for roof without attic (Strategy 1).

Fig. 10. Model design for the roof with attic (Strategy 2).

(iv) Attic space ceiling light (double polycarbonate 4 m × 2 m): 28 mm thickness + plaster gypsum board (2 mm).

5.2.3. Innovative roofing system

The proposed design represents the complete configuration of the IRS and is the major focus of this study. This system is the same as Strategy 2, with the addition of new parameters: an inlet at the gable side and an outlet as an HTV. The specifications used in this roofing system are shown in Fig. 11 and as follows:

(i) Roof (aluminum sheets) 0.8 mm.
(ii) Roof color: outdoor surface (white) and indoor surface (black).
(iii) Skylight (double polycarbonate): 28 mm.
(iv) Attic space ceiling light (double polycarbonate 4 m × 2 m): 28 mm thickness + plaster gypsum board (2 mm).
(v) Two openings: a square-shaped inlet at the gable side (350 mm × 350 mm) and an outlet as the HTV on the sloped roof (Ø350 mm); both are in the opposite direction.

5.3. Measurement set-up and instrumentation

All field studies were conducted on the same premises in March 2013, April 2013, and May 2013, which is considered as the hottest period during the dry season in Penang [32]. Generally, this investigation was conducted in three stations and locations; outdoor, attic, and occupied zone for dark and daylight conditions. Given that each strategy was conducted on different days corresponding to similar weather conditions (hot and clear), the outdoor data were taken for comparison with indoor conditions. The outdoor station was connected to a group of sensors and associated with computer software to record the data. A data acquisition system was connected to four newly calibrated sensors for solar radiation, illuminance, ambient temperature, and wind speed. This station was located beside the model house at a height of approximately 3 m, the same level as the rooflight, as shown in Fig. 12. The specifications are presented in Table 1.

For the indoor conditions, the sensors and probes measured two zones. Three sensors were used in the attic space: one measured air temperature (DBT) and the other two measured air velocity. All sensors were placed at a height of 500 mm. The air velocity at the inlet and outlet was measured at a distance of 200 mm from the openings. Seven sensors were used in the occupied zone: one sensor measured the air temperature (DBT), one measured the globe temperature, and five were used as lux sensors at a height of 800 mm from the ground [19]. The details of the specifications and locations of these sensors are listed in Table 1 and shown in Figs. 13 and 14.

5.4. Data collection

Data from all sensors were recorded in the data acquisition system and a Babuc M data logger continuously at 10-min intervals from 07:30 am to 07:00 pm for three clear days per strategy and condition, as shown in Fig. 13. This measurement period of three "clear days," described by Dahlan et al. [73,74] as "days that are mostly dry, hot and have slightly cloudy sky," was considered to ensure that the performance of the different strategies were compared during fair-weather days. This three-day period was selected based on several studies conducted for the same environment (hot-humid), such as field studies by Ismail [16], Ismail and Abdul Rahman [71], Ong [25], Al Yacouby et al. [7], and Al-Obaidi et al.

(a) Inlet at gable end and the location of HTV

(b) Solar panel and Turbine Ventilator (c) View of ceili ng and daylighting system from inside the room (d) View of HTV from inside the attic

Fig. 11. Model design for the IRS.

Fig. 12. Measurement equipment for outdoor station.

[67], which considered the uniformly high outdoor temperature during the clear days in this climate.

5.5. Data analysis

To demonstrate the performance and effectiveness of the IRS in improving indoor climatic conditions in the hot-humid climate of Malaysia, this study conducted a simplified comparison of the average values of the maximum, mean, and minimum for air temperatures, globe temperature (mean radiant temperature), illuminance level, and air velocity for the three-clear-day period of each strategy and condition. However, comparing the performance of the different roofing systems during the various days indicated that each day had slightly different climatic conditions. Therefore, a simplified comparison using the relativeness index (RI) as an indicator was conducted to formulate general and subjective conclusions [16,71,75,76]. However, the situation was different for illuminance level, because the system considered the clear days as having sunny and clear skies. This study followed the recommendation of GBI [19,20] to control the level of illuminance to approximately below 2000 lux at a height of 800 mm from the floor.

6. Results and discussion

6.1. Occupied zone

6.1.1. Indoor air temperature

To clearly explain the performance of the IRS in decreasing indoor air temperature, the researchers conducted a comparison analysis with other roofing systems. However, because the measurements for each strategy were obtained on different days with varying climatic conditions, the RI, which depends on the data differences between indoor and ambient conditions (ΔT of temperature difference), was used as a comparison tool to frame general and subjective conclusions [16,71,76].

Moreover, the hottest days of each strategy were selected to perform a simplified comparison analysis, as demonstrated by the graphs. Fig. 15 presents the six days selected, which were clear and nearly had the same maximum peak temperature at around 02:00 pm to 04:00 pm.

Fig. 16 shows the comparison of indoor–outdoor temperature differences among the hottest days for all of the strategies. As shown in the graph representing both dark and daylight conditions, the IRS clearly decreased the indoor air temperature relative to outdoor air temperature than the other roofing systems and strategies at most times.

Fig. 17 shows the correlation between the levels of solar radiation and the value of indoor–outdoor temperature differences

Table 1
Sensor specifications.

No.	Sensor names	Models	Characteristics
(1)	Outdoor air temperature	NRG #110S	A six-plate radiation shield allows accurate measurement of ambient air temperature Applications: wind resource assessments, meteorological studies, and environmental monitoring Sensor range: 40–52.5 °C; Accuracy: +/−1.11 °C maximum
(2)	Indoor air temperature	TE Duct and Immersion	Can be used to monitor air or water temperature throughout a building management system or an air handler unit. For variable air volume applications: Temperature limits: operating temperature: −40 °C to 150 °C Accuracy: thermistor temperature sensor: ±0.2 °C
(3)	Black globe	A 1131	Measures the globe temperature with accuracy of ±0.5%
(4)	Outdoor wind speed anemometer	NRG #40	Sensor type three-cup anemometer Applications: wind resource assessment, meteorological studies, and environmental monitoring Sensor range: 1–96 m/s; Accuracy: within 0.1 m/s
(5)	Indoor air velocity transmitter	CTV100	Temperature and air velocity transmitter type Ranges from 0–5 m/s to 0–30 m/s; Accuracy reading ±0.3 m/s
(6)	Outdoor and indoor illuminance	Reinhardt	Ranges from 0 lux to 150,000 lux, in surrounding temperature from −50 °C to ±70 °C
(7)	Solar radiation pyranometer	Li-Cor #Li-200SA	Measures total solar radiation and cosine corrected for accurate measurement even at low sun angles Sensor range: 0–3000 W/m^2; Accurate maximum deviation of 1%

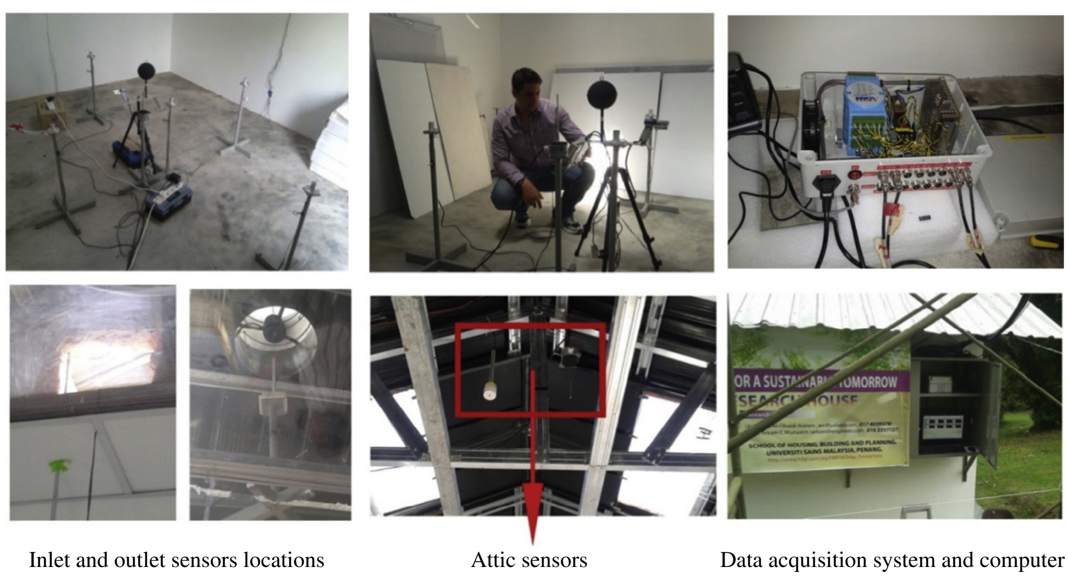


Fig. 13. Measurement equipment for data collection.

obtained when the IRS was used during the dark and daylight conditions. The results in Fig. 17 indicate that although the differences between dark and daylight conditions were not significant, the relation was higher under the daylight condition.

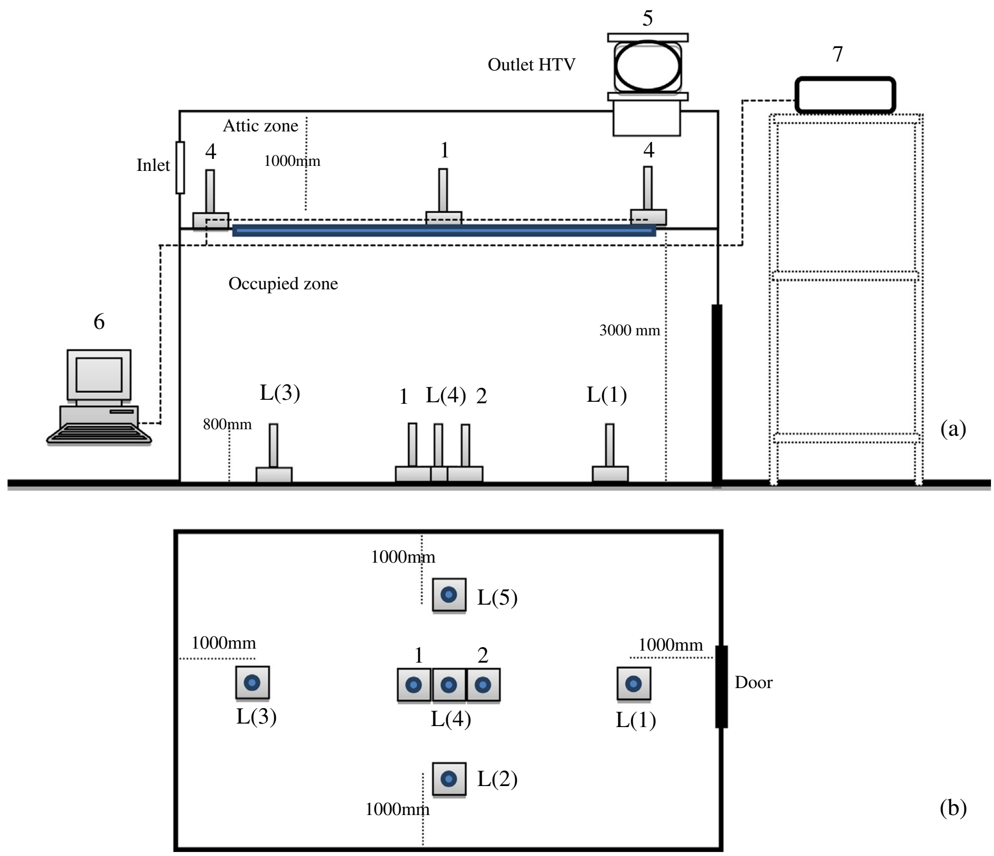
The mean maximum, mean, and mean minimum temperature differences for the three-day measurement period of each roofing system are represented in Table 2.

Table 2 shows that the occupied zone with the IRS had higher reduction in air temperature relative to ambient temperature compared with the other roofing system strategies. The mean minimum indoor–outdoor temperature difference recorded was −3.97 °C for the dark condition and −3.66 °C for the daylight condition. Compared with Strategy 1, the IRS obtained a higher difference of 1.52 °C for the dark condition and 2.01 °C for the daylight condition. In terms of percentage, this value is equal to 62% reduction for the dark condition and 121% reduction for the daylight condition. Compared with the results of using Strategy 2 and normal roofing systems, these values indicate a reduction of 37.55% and 80.60% for the dark condition, respectively.

However, although the mean maximum of indoor–outdoor temperature did not significantly differ among the strategies, applying the IRS resulted in the lowest values, which were 0.29 °C for the dark condition and 0.28 °C for the daylight condition, which were lower than those obtained using Strategy 1. This finding indicates the contribution of the IRS in minimizing the increased peak temperature in relation to the outdoor temperature. Table 2 shows that the maximum indoor temperature obtained using the IRS strategy under daylight was 33.22 °C compared with the maximum indoor air temperature of 34.55 °C and 34.08 °C obtained using Strategies 1 and 2, respectively.

6.1.2. Mean radiant temperature

To demonstrate the performance of the IRS in decreasing the indoor mean radiant temperature, the researchers conducted a



L= Illuminance, 1 = Temperature (DBT), 2 = MRT, 4= Air velocity, 5= Solar panel and HTV and 6= DAQ system
7= Outdoor station (air temperature, solar radiation, illuminance and wind speed)

Fig. 14. Schematic of the field study measurement set-up; (a) sectional view (internal condition) and (b) plan view of the test bed and measuring points.

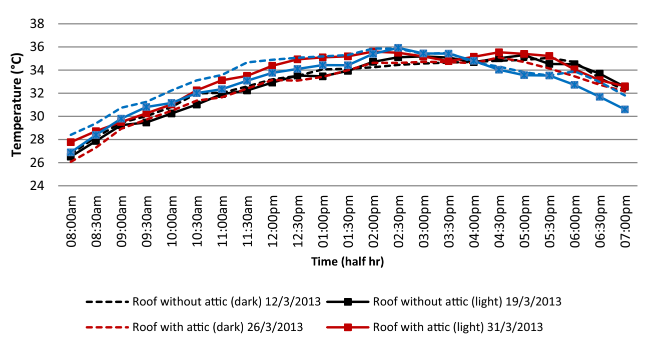


Fig. 15. Half hourly variations of the outdoor temperature during the hottest day for each strategy given the dark and daylight conditions.

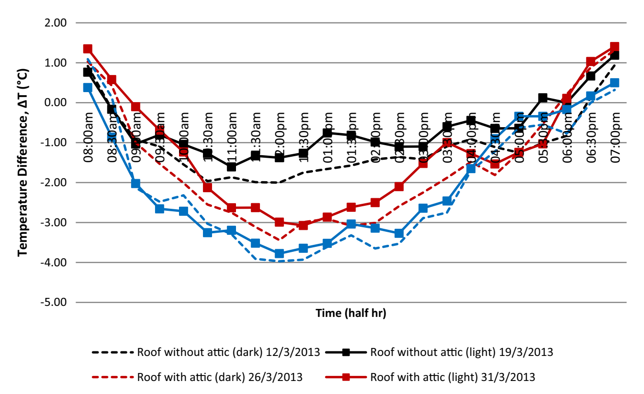


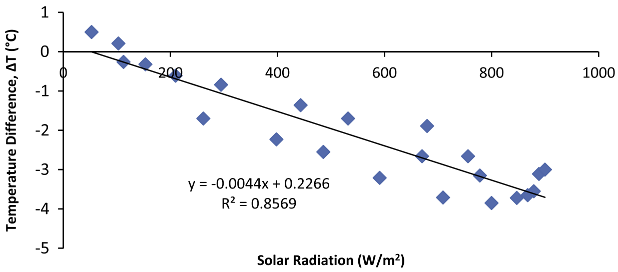
Fig. 16. Comparison of the difference between indoor–outdoor temperatures for different roofing strategies under dark and daylight conditions. (a) Dark condition. (b) Daylight condition.

comparison analysis with other roofing systems. However, the analysis of mean radiant temperature–indoor air temperature was used to identify the differences because the measurements for each strategy were conducted on different days with varying climatic conditions.

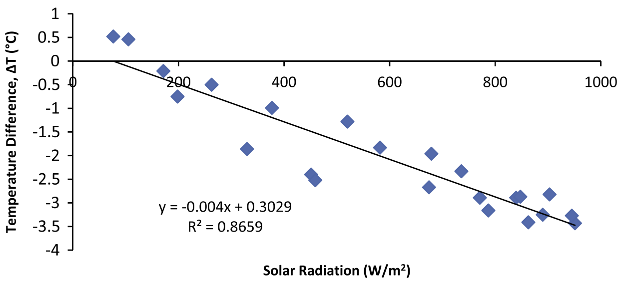
In addition, the hottest days for each strategy were selected for the simplified comparison analysis, as demonstrated in the graphs. Fig. 18 shows that the six days selected were clear and nearly had the same maximum peak solar radiation. The readings on solar radiation show that it was nearly stable as it gradually increased from 08:00 am to around 12:00 pm. However, solar radiation fluctuated in the afternoon as clouds covered the area due to weather conditions in Penang.

Fig. 19 illustrates the comparison of mean radiant temperature–indoor air temperature differences among the hottest day for the strategies. The graphs representing the dark and daylight conditions show that the IRS was more capable of decreasing the mean radiant temperature relative to the indoor air temperature than the other roofing systems at most times. The mean maximum, mean, and mean minimum temperature differences of each roofing system over the three-day measurement period are shown in Table 3.

Table 3 shows that the occupied zone with the IRS has higher reduction of mean radiant temperature relative to ambient



(a) Dark condition



(b) Daylight condition

Fig. 17. Correlation between solar radiation intensities and indoor–outdoor temperature difference when the IRS is used.

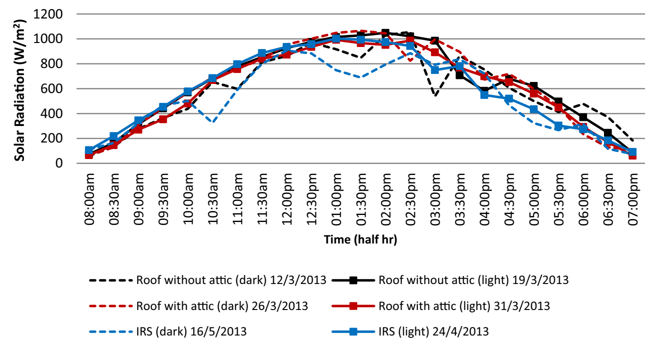


Fig. 18. Half hourly variations of solar radiation during the hottest day under the dark and daylight conditions for each strategy.

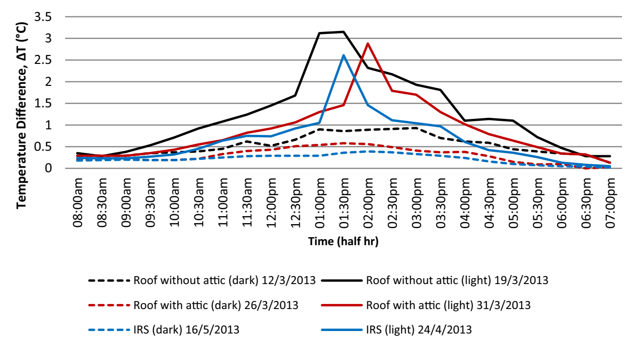


Fig. 19. Comparison of the differences in the mean radiant temperature–indoor air temperature of the different roofing strategies under the dark and daylight conditions.

compared to that in other roofing system strategies, with the mean minimum MRT–outdoor temperature difference recorded at −3.83 °C for dark condition and −2.87 °C for daylight condition. The comparison of the Strategy 1 – IRS shows that higher difference was 2.14 °C for dark condition and 2.35 °C for daylight condition. Compared with results of Strategy 2 (roof with attic), these values showed that the reduction was 1.48 °C for dark condition, and compared with results of Strategy 1 (roof without attic), the reduction was 1.52 °C for the respective cases.

Although the mean maximum of the mean radiant temperature–outdoor temperature did not significantly differ among the strategies, using the IRS resulted in the lowest values, which were 0.5 °C for the dark condition and 0.81 °C for the daylight condition, lower than the values resulting from Strategy 1. This finding indicates that the IRS contributed to minimizing the increased peak temperature in relation to the outdoor temperature.

Table 3 indicates that the maximum difference between the main radiant temperature–indoor temperature obtained using the IRS under sunlight was 2.61 °C lower than the maximum difference in air temperature obtained using Strategies 1 and 2, which were 4.05 °C and 2.85 °C, respectively. In addition, the maximum main radiant temperature obtained using the IRS under sunlight was 33.91 °C, which was lower than the maximum indoor air temperatures of 37.16 °C and 35.74 °C obtained using Strategies 1 and 2, respectively.

6.1.3. Illuminance (daylight level)

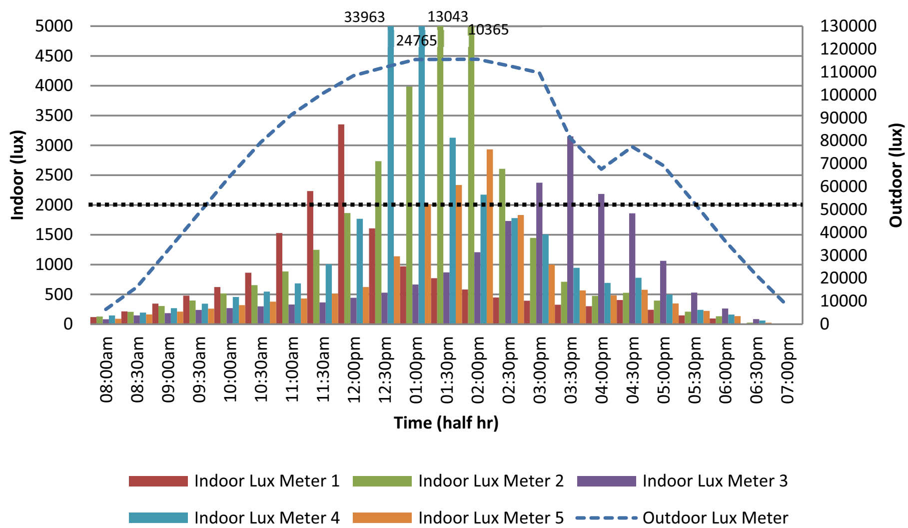
Fig. 20 shows the performance of the five lux sensors used in Strategy 1 and the IRS during the clearest days, March 19 and April 24. The readings show that Strategy 1 obtained a maximum value of approximately 33,963 lux whereas the IRS reached 20,850 lux. Fig. 21 shows only the clear days with less cloud cover during the measurement days. The indoor illuminance (daylight level) resulting from Strategies 2 and 3 was not considerably lower than that from Strategy 1. Fig. 21 shows that the levels of outdoor illuminance were nearly similar during the measurement days, particularly from 11:30 pm to 02:00 pm. The differences in the average illuminance level of the five sensors in the indoor at these peak times fluctuated from 3,600 lux to 8,000 lux for Strategy 1, and from 3,600 to 6,000 lux for Strategy 2, and then fluctuated from 3,600 lux to 5,300 lux for the IRS. These differences indicate the maximum illuminance level that could occur in one year as the altitude of the sun between March and April reached approximately 80–90°.

Table 2
Outdoor and indoor air temperatures for three days using the different roofing systems.

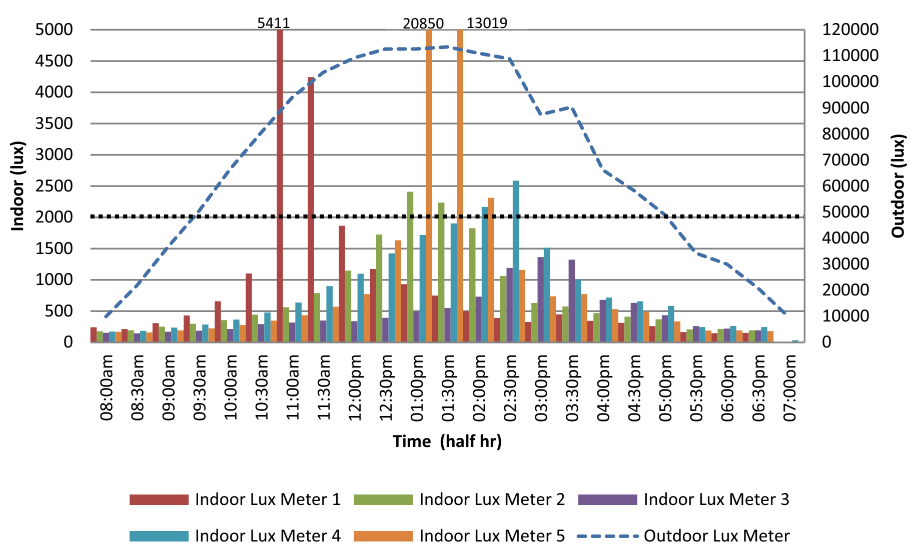
Opening	Outdoor air temperature (°C)			Indoor air temperature (°C)			Indoor–outdoor difference (°C)		
	Mean Max	Mean	Mean Min	Mean Max	Mean	Mean Min	Mean Max	Mean	Mean Min
Dark									
Roof (no) attic	35.16	32.55	26.26	33.91	31.58	27.09	0.84	−0.97	−2.45
Roof (with) attic	35.59	32.85	26.49	33.58	31.21	27.46	0.69	−1.64	−3.37
IRS	35.34	33.36	28.67	33.13	31.23	28.88	0.55	−2.13	−3.97
Daylight									
Roof (no) attic	35.30	32.48	26.29	34.55	31.79	27.28	1.16	−0.69	−1.65
Roof with attic	35.97	33.28	27.84	34.08	31.97	28.96	0.95	−1.31	−2.98
IRS	35.59	32.93	27.23	33.22	30.91	27.69	0.88	−2.01	−3.66

Table 3
Mean radiant temperatures of the different roofing system strategies over three days.

Opening	Mean radiant temperature (°C)			MRT – outdoor difference (°C)			MRT – indoor difference (°C)		
	Mean Max	Mean	Mean Min	Mean Max	Mean	Mean Min	Mean Max	Mean	Mean Min
Dark									
Roof (no) attic	34.39	32.09	27.36	1.10	−0.45	−1.69	0.91	0.51	0.12
Roof (with) attic	33.60	31.50	27.66	1.59	−1.35	−3.00	0.62	0.29	0.03
IRS	33.20	31.44	28.06	0.60	−1.92	−3.83	0.39	0.21	0.02
Daylight									
Roof (no) attic	37.16	33.07	27.67	2.29	0.59	−0.52	4.05	1.27	0.26
Roof with attic	35.74	32.81	29.22	1.76	−0.47	−2.03	2.85	0.84	0.12
IRS	33.91	31.51	28.14	1.48	−1.37	−2.87	2.61	0.65	0.05



(a)



(b)

Fig. 20. Performance of the five lux sensors in (a) normal roof without an attic on March 19, 2013, and (b) IRS on April 24, 2013 (*dotted horizontal line represents the 2000 lux GBI criteria).

Tables 4 and 5 show that the maximum illuminance level above 2000 lux for Strategy 1 was approximately 21.73% with the maximum indoor level around 33,963 lux at the center, and was 78.27% below 2,000 lux. For Strategy 2, the maximum illuminance level above 2000 lux was approximately 17.39% with maximum indoor level around 16,055 lux, while 82.61% was below 2000 lux. Finally, the maximum illuminance level above 2000 lux for the IRS was around 13.04% with maximum indoor level around 20,850 lux and was 86.96% below 2000 lux.

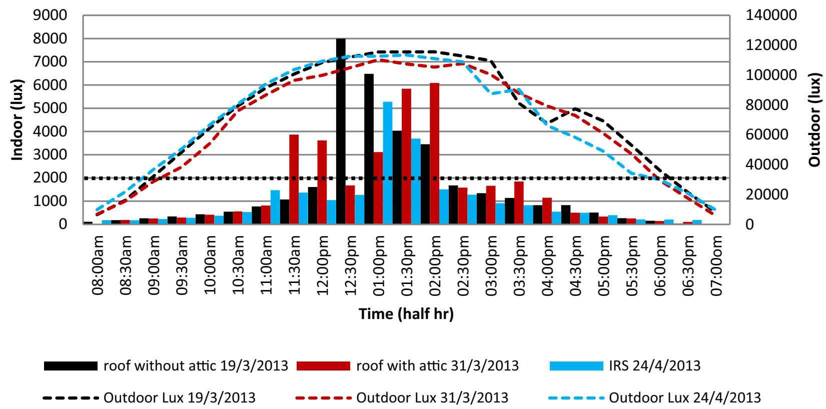


Fig. 21. Half hourly variations in the illuminance of the five sensors (average) for three different roofing systems over 13 h (daytime) (*dotted horizontal line represents the 2000 lux GBI.

Table 4
Half hourly maximum, average, and minimum illuminance of the five sensors from 08:00 am to 07:00 pm in three days using the different roofing systems.

	Roof without attic (lux) 19/3/2013			Roof with attic (lux) 31/3/2013			Roof with HTV (lux) 24/4/2013		
	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min
Outdoor	115565	71416	6471	110278	66945	5804	113420	68586	9624
Sensor 1	3352	697	0	16055	1732	0	5411	885	0
Sensor 2	13043	1864	0	14279	1872	0	2409	719	0
Sensor 3	3151	820	0	6299	1013	0	1364	462	0
Sensor 4 (center)	33963	3309	0	3040	1000	0	2587	844	33
Sensor 5	2932	721	0	19388	1842	0	20850	1980	0

Table 5
Percentage of daylight levels (lux) of the five sensors from 08:00 am to 07:00 pm in three days using the different roofing systems.

	Roof without attic (%) 19/3/2013			Roof with attic (%) 31/3/2013			Roof with HTV (%) 24/4/2013		
	>2000	<2000	<1000	>2000	<2000	<1000	>2000	<2000	<1000
Sensor 1	8.69	91.31	82.61	8.69	91.31	78.26	8.69	91.31	78.26
Sensor 2	21.73	78.27	69.56	17.39	82.61	65.21	8.69	91.31	73.91
Sensor 3	13.04	86.96	78.26	13.04	86.96	73.91	0	100	86.95
Sensor 4 (center)	17.39	82.61	65.21	21.37	78.63	60.86	8.69	91.31	65.21
Sensor 5	14.03	85.97	73.91	13.04	86.96	73.91	13.04	86.96	78.26

Strategies 2 and 3 (IRS) can deliver below the 2000 lux level during daytime with a minimum of 82.61% and a maximum of 86.96% during the peak date of the year because they share the same daylight concept.

6.2. Attic zone

6.2.1. Attic air temperature

The RI strategy was used to identify the differences between Strategy 1 and IRS because the measurements for each strategy were conducted on different days with varying climatic conditions. Fig. 22 presents the comparison of attic air temperature–outdoor air temperature differences among the hottest day for all of the strategies. The graph representing the dark and daylight conditions illustrates that compared with Strategy 2, the IRS was more capable of decreasing the attic air temperature relative to the outdoor air temperature at most times. The mean maximum, mean, and mean minimum temperature differences over the three-day measurement period of each roofing system are listed in Table 6.

Table 6 shows that the attic zone with the IRS had increased reduction in air temperature relative to the ambient temperature, and the maximum attic temperature–outdoor temperature difference recorded was 2.29 °C under the dark condition and 2.67 °C under the daylight condition. The differences between Strategy 2 and the IRS increased by 5.64 °C under the dark condition and 5.4 °C under the daylight condition.

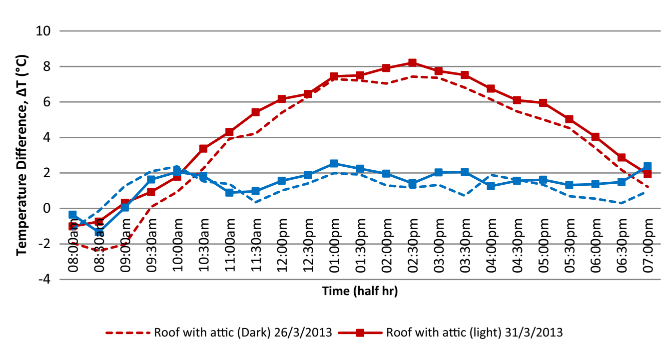


Fig. 22. Comparison of the difference between attic air temperature–outdoor air temperature obtained using Strategies 2 and 3 under dark and daylight conditions.

Table 6
Outdoor and attic air temperatures obtained in three days using the different roofing systems.

	Outdoor air temperature (°C)			Attic air temperature (°C)			Attic – outdoor difference (°C)		
	Mean Max	Mean	Mean Min	Mean Max	Mean	Mean Min	Mean Max	Mean	Mean Min
Dark									
Roof (with) attic	35.59	32.85	26.49	43.02	36.52	25.12	7.93	3.67	−1.76
IRS	35.34	33.36	28.67	36.90	34.26	27.39	2.29	0.9	−1.78
Daylight									
Roof with attic	35.97	33.28	27.84	43.87	37.84	26.87	8.07	4.56	−0.97
IRS	35.59	32.93	27.23	37.75	34.09	27.29	2.67	1.16	−0.98

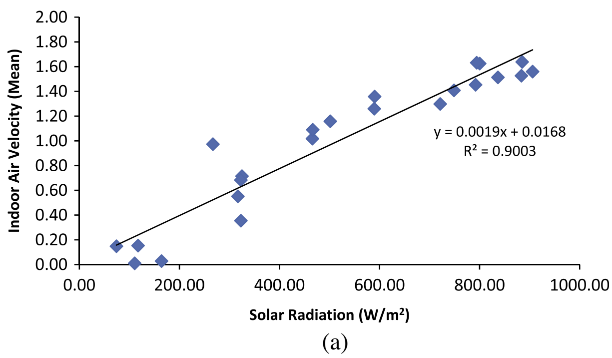


Fig. 23. Correlation between solar radiation intensities and indoor air velocity (mean) in the attic zone when IRS is used; (a) dark condition and (b) daylight condition.

6.2.2. Air velocity

Regarding the attic air velocity in the IRS, air velocity was significantly higher during daytime, particularly at the peak hours of solar radiation given the dark and daylight conditions. This study found that outdoor wind speed did not significantly affect the attic air velocity, unlike solar radiation. Fig. 23a and b shows the correlation between solar radiation intensities and attic air velocity (mean) when the IRS was used given the dark and daylight conditions. The results show that the correlation was high and reached $R^2 = 0.9$ in both conditions, which proved that a turbine ventilator in conjunction with a solar panel as (HTV) performed positively in relation to the air circulation at the attic space.

Table 7 depicts that the attic air velocity in the daylight condition was higher than that in the dark condition. The results in Table 7 show that attic air velocity was higher in daylight condition by approximately 0.28 m/s for inlet and outlet openings, with 0.22 m/s on average. These findings show that the maximum (mean) air velocity was 1.31 m/s for the inlet (dark condition) and then reached 1.59 m/s (daylight condition). However, the outlet speed reached 2.17 m/s (dark condition) and then 2.45 m/s (daylight condition). Moreover, analyzing the frequency results of mean air velocity exceeding 0.2 m/s would indicate that the daylight condition was higher at 92.75% compared to the dark condition, which was 81.15%, for 13 h.

7. Conclusions

In the present study, the performance of the IRS in improving the indoor climatic conditions of a landed building and in separating solar heat from useful natural light in such a building (3 m height) was evaluated experimentally. The performance of the IRS was compared with that of several roofing systems. The conclusions are summarized as follows:

- The findings show that the IRS decreased the effect of indoor air temperature and main radiant temperature without any insulation while maintaining a high level of natural light compared with different roofing strategies in the occupied zone.
- The results of the comparison between the IRS and the conventional system (Strategy 1) show a reduction in the indoor air temperature of up to 2.01 °C under the daylight condition. These results indicate that the difference in (daylight–dark) conditions was 0.31 °C, which was then compared with 0.8 °C obtained using the conventional roofing system (Strategy 1).
- The level of MRT in relation to the indoor temperature under the daylight condition was 2.61 °C for the IRS and 4.05 °C for the conventional roof. The IRS exhibited reduction with 1.44 °C.
- The IRS passively delivered an acceptable range of natural light below 2000 lux (Green Building Index) during daytime. These findings show that using the IRS controlled around 86% to 100% of illuminance below 2000 lux, whereas Strategy 1 delivered around 78% to 86% below 2000 lux.
- In the attic zone, the results show that compared with using Strategy 2, the IRS decreased the attic temperature by 5.4 °C under the daylight condition without using any insulation.

Table 7
Solar radiation and attic air velocity values obtained in three days using the IRS.

Solar radiation (W/m^2)			Inlet air velocity (m/s)			Outlet air velocity (m/s)			Mean air velocity (m/s)		
Mean Max	Mean	Mean Min	Mean Max	Mean	Mean Min	Mean Max	Mean	Mean Min	Mean Max	Mean	Mean Min
Dark											
952	541	52	1.31	0.71	0.00	2.17	1.33	0.04	1.71	1.02	0.03
Daylight											
1061	583	66	1.59	0.64	0.00	2.45	1.51	0.02	1.93	1.06	0.02

The attic air velocity had significant speed given both conditions; the maximum ventilation speed at the outlet was approximately 2.17 m/s under the dark condition and 2.45 m/s under the daylight condition. The mean air velocity at the attic space was up to 1.93 m/s under the daylight condition.

- This study provided ample evidence of the tremendous potential of using the IRS. The results confirmed that the IRS for landed houses (3 m height) can significantly improve the indoor climatic conditions and separate solar heat from useful natural light. As a result, these findings provided a new design paradigm in view of the requirements set by the Malaysian GBI.

Acknowledgment

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