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Integration of thermal insulation coating and moving-air-cavity in a cool roof system for attic temperature reduction

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ABSTRACT

Cool roof systems play a significant role in enhancing the comfort level of occupants by reducing the attic temperature of the building. Heat transmission through the roof can be reduced by applying thermal insulation coating (TIC) on the roof and/or installing insulation under the roof of the attic. This paper focuses on a TIC integrated with a series of aluminium tubes that are installed on the underside of the metal roof. In this study, the recycled aluminium cans were arranged into tubes that act as a moving-air-cavity (MAC). The TIC was formulated using titanium dioxide pigment with chicken eggshell (CES) waste as bio-filler bound together by a polyurethane resin binder. The thermal conductivity of the thermal insulation paint was measured using KD2 Pro Thermal Properties Analyzer. Four types of cool roof systems were designed and the performances were evaluated. The experimental works were carried out indoors by using halogen light bulbs followed by comparison of the roof and attic temperatures. The temperature of the surrounding air during testing was approximately 27.5 °C. The cool roof that incorporated both TIC and MAC with opened attic inlet showed a significant improvement with a reduction of up to 13 °C (from 42.4 °C to 29.6 °C) in the attic temperature compared to the conventional roof system. The significant difference in the results is due to the low thermal conductivity of the thermal insulation paint (0.107 W/mK) as well as the usage of aluminium tubes in the roof cavity that was able to transfer heat efficiently.

1. Introduction

Temperature rise increases the demand for air conditioning and energy consumption, leading to the increase of heat emission and further rise in temperature. Cool roof systems are an inexpensive method to save energy and to improve the comfort level in buildings located in hot climates. With today's high energy prices, various studies have been carried out to reduce energy consumption by increasing energy efficiency. Undeniably, most buildings incur a number of considerable impacts to the environment. The emission of greenhouse gases and the formation of microclimates within urban areas are among the most prevalent [1]. The consumption of operational energy emits the most greenhouse gases during the entire lifetime of a building [2]. As a tropical country, Malaysia's ambient air temperature and relative humidity lie in the ranges of 26–40 °C and 60–90%, respectively. This type of climate is non-conducive for human comfort and productivity since it leads to uncomfortable conditions [3].

In general, a common building is designed in such a way that roof tiles are at the uppermost region, followed by a gypsum board ceiling. The region between these two components is the attic space. Meanwhile, low cost houses and factories would have bare metal deck roofing. Concrete roof tiles are the most commonly used roofing material in Malaysia (85%) followed by clay tiles (10%) and metal deck (5%) [4]. Heat transmission through the roof can be reduced simply by providing insulation as a radiant and conductive heat barrier. In new roof constructions, aluminium foil glued to fibreglass or rockwool blankets are suspended directly under the roof with wire mesh.

The benefit of ventilation on the thermal load in roofs has been the subject of numerous studies. Airflow in the cavity effectively carries heat and moisture to the outside and keeps the internal part of the roof cool and dry [5–9].

Roofs contribute tremendously to building heat gain compared to vertical surfaces such as walls, mainly because the roofs are exposed to the sun throughout the daytime [10]. Residential buildings in Malaysia, especially the low rise buildings are found to undergo high intensity heat transmission from the building envelope, whereby the roof represents around 70% of heat gain [11].

Heat from solar radiation is absorbed by the roofs and is transmitted through and trapped in the attic, resulting in a hot ceiling.

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The hot ceiling then radiates heat to the occupants inside a building. In buildings without a ceiling, heat from the roof is exposed directly to the occupants below [3]. Overall, the increase in both the building surface temperatures and the air temperature inside the buildings cause thermal discomfort for users especially for those in buildings without air conditioning. This results in higher energy demand for cooling and ventilation systems [12]. Both systems create two major problems whereby air conditioning systems require enormous electrical energy and thus increase the utility bills.

Several research programmes have been carried out regarding insulation and reflective materials in roof designs. Ong concluded that insulation under the tile is preferred to above the ceiling from his field testing of several passive roof designs [13]. His study also proved that the roof solar collector (RSC) resulted in the coolest attic among his prototype, about 13 °C less than the standard non-insulated roof during the period from 2 to 3 pm (the highest temperature in the attic throughout the day). Investigation of the most suitable location of insulation on the roof was performed by Ozel and Pihtili. They found that the best load levelling was to place three pieces of the same thickness insulation at the outdoor surface, middle and indoor surface of the 20 cm thick roof construction (the gap between the insulation pieces was 10 cm) [14]. While minimizing heat transfer into the attic, the design of multi-layer green roof panel is proposed to induce the ventilation process of the building. Khedari et al. and Hirunlabh et al. have carried out an experimental study of a RSC towards natural ventilation [15,16]. The results of the study concluded that the optimum length of RSC of about 100 cm with a tilt angle of 30° was able to induce natural ventilation of 0.08–0.15 $m^3\,s^{-1}\,m^{-2}$. Akasaka and Takeda have intensively studied a practical heat transfer calculation method for development of roofs with ventilated air layers to evaluate quantitatively the shading and insulating effects of various combinations of techniques [17]. Al-Sallal [18], Taylor et al. [19] and Mathews et al. [20] showed that there are substantial energy savings in both winter heating and summer cooling with insulated ceilings. Hatamiour et al. have studied some useful ancient energy technologies that have been used for natural cooling of buildings during summer in a hot and humid province in the south of Iran [21]. Chong et al. have studied the moving air path in the air gap [22]. Based on their investigation into the mechanism of heat transfer of the multilayered green roof system, the movement of the surrounding air into the air gap space ensures no aggregation of hot air as well as draws out the interior hot air rapidly to prevent heating of the attic. Yokoyama et al. have investigated the prediction of energy demands using neural network with model identification by global optimization [23].

The use of reflective materials on the building envelope is one of the most efficient ways to reduce the roof temperature. According to Synnefa et al. [24], for peak solar conditions (about 1000 W/m^2) for an insulated surface and under a low wind condition, the temperature of a black surface with solar reflectance of 0.05 is about 50 °C higher than ambient air temperature. For a white surface with solar reflectance of 0.8, the temperature rise is about 10 °C. Surface temperature measurements demonstrated that a cool coating can reduce the concrete tile surface temperature by 7.5 °C and it can be 15 °C cooler than a silver grey coating.

This novel integrated cool roof design is more eco-friendly compared to other cool roof designs because it uses recycled aluminium cans and chicken eggshell (CES) waste. CES waste, a byproduct of the aviculture industry has been highlighted recently because of its reclamation potential. Most of it is discarded in landfills without further processing. It is known that CES waste contains valuable organic and inorganic components which can be utilized in commercial products to create new value in these waste materials. This study highlights a useful bio-filler derived from CES waste and its potential role in the coating industry. Although there have been several attempts to use CES components for various applications [25–27], its chemical composition and availability makes CES a potential source of filler for polymer composites [28–30]. The other advantages of using CES are that it is available in bulk quantity, inexpensive, lightweight and environmentally friendly.

The main objective of this study is to evaluate a system that combines TIC with aluminium tubes for cavity ventilation as well as to optimize the performance of the roofing systems in terms of heat reflection and heat rejection. The performance will be gauged by measuring the various temperatures of the roof and attic. The aim will be to obtain lower attic temperatures that will result in a more comfortable living environment.

Four small roof models representing the different roof system designs were constructed to evaluate the resistance to heat gain. Components that were tested included the TIC, cavity ventilation (MAC) and attic inlet. The performance of the four designs (i) roof coated with normal paint without MAC (Design A), (ii) roof coated with TIC without MAC (Design B) and (iii) combination of TIC and MAC with closed attic inlet (Design C) and (iv) combination of TIC and MAC with opened attic inlet (Design D) were studied and compared.

2. The green roof design

2.1. Mechanism of heat transfer of the cool roof system

The mechanism of heat transfer of the cool roof system is shown in Fig. 1. The temperature difference between the environment which is cooler than the aluminium tube on the underside of the roof causes the natural ventilation in the cool roof cavities. The thermal performance of the integrated cool roof system was analysed by estimating two control volumes by the following Eqs. (1) and (2).

The first control volume (CV_1): The heat transfer between the environment and thermal insulation coating and deck:

$$Q_s = Q_{\mathrm{Rad,Out}} + Q_{\mathrm{Conv,Out}} + Q_{\mathrm{Cond}} \quad (1)$$

where Q_s is the heat from the halogen light bulbs (W), $Q_{\mathrm{Rad,Out}}$ is the radiation heat reflected from top of roof (W), $Q_{\mathrm{Conv,Out}}$ is the convection heat transfer from top of roof (W), and Q_{Cond} is the conduction heat transfer into the roof deck (W).

The second control volume (CV_2): The heat transfer between the roof deck and aluminium channel and indoors (attic):

$$Q_{\mathrm{Cond}} = Q_{\mathrm{Rad,In}} + Q_{\mathrm{Conv,In}} + Q_{\mathrm{ve}} \quad (2)$$

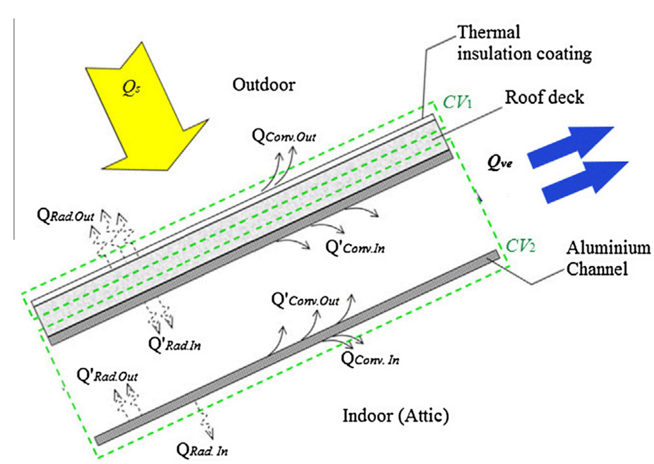

Fig. 1. Mechanism of heat transfer of the integrated cool roof system.