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Modeling of cool roof heat transfer in tropical climate

Kishor T. Zingre [a], Man Pun Wan [a, *], Shanshan Tong [a], Hua Li [a], Victor W.-C. Chang [b], Swee Khian Wong [c], Winston Boo Thian Toh [c], Irene Yen Leng Lee [c]

[a] *School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore*
[b] *School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore*
[c] *Building Research Institute, Housing and Development Board HUB, 480, Lorong 4 Toa Payoh, Singapore 310480, Singapore*

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ABSTRACT

Cool roof is gaining popularity as a passive building energy saving solution. A concise and easy-to-apply mathematical model is essential for building designers to evaluate the impact of cool coating on heat transfer and indoor thermal comfort. A novel cool roof heat transfer (CRHT) model was developed using the spectral approximation method. The CRHT model was verified against the conduction transfer function method and was validated against experiments performed in two identically configured apartments with concrete roofs in Singapore. The model predictions show that on a sunny day, a cool coating (solar reflectance of 0.74) reduces the peak roof temperature, indoor air temperature and daily heat gain by up to 14.1 °C, 2.4 °C and 0.66 kWh/m^2 (or 54%), respectively through the concrete roof. The model predictions match with experimental measurements with reasonable accuracy. Further model predictions suggested that significant daily heat gain reduction can also be achieved by cool coating on galvanized steel (metal) roofs. The daily heat gain reduction brought by the cool coating drops as the roof exposes to higher wind speeds. The proposed CRHT model largely simplifies the calculation of heat transfer of cool roofs, compared to existing methods, and is generally applicable to opaque solid surfaces (roofs and walls).

1. Introduction

Energy plays an important role in Singapore's economic growth, however, the ‘air-conditioned nation’ as quoted by Singaporean author Cherian George [1], lacks natural energy resources for the production of electrical energy and relies on the import of fossil fuels from foreign countries [2]. The building sector consumes about 57% of the total electrical energy production in Singapore [3]. Air-conditioning of buildings alone guttle about 60% of the electrical energy consumed by the building sector [4]. This suggests that about 34% of the country's total electrical energy production is being consumed for air-conditioning of buildings alone [4]. Building energy savings has become a huge concern in the city state.

In the tropical region, opaque envelope surfaces receive abundant solar irradiation throughout the year [5]. Chua & Chou [6] conducted computational simulation in a high-rise (12-storey), air-conditioned residential apartment building in Singapore. They reported that the heat gains through the opaque envelope surfaces constitute about 30% (including 19% through walls and 11% through roof) of the total power consumption for air-conditioning of the building [6].

A building surface exposed to solar irradiation is heated up by absorbing the radiation energy. Part of the absorbed thermal energy is stored in the material due to its thermal storage capacity and some other part is lost to outdoor by thermal emission and convection. The remaining is conducted into the building. The heat gain into buildings can be reduced by reflecting off more of the solar irradiation during day time and emitting off the stored heat in the opaque material to outdoor when the sky is clear [7]. The cool coating, which features high solar reflectance ($\rho > 0.65$) and high thermal emittance ($\varepsilon > 0.75$) provide passive cooling [8] based on such principle.

The potential economic and environmental benefits of cool coating [9,10] have attracted attention over the last few decades. A number of studies conducted in Europe and the U.S. [11–16] showed that cool coating contributes significantly in reducing heat gain through opaque envelope surfaces in these climate zones. It is hypothesized that the performance of cool coating would be more prominent where solar irradiation is abundant since cool coating works on the principle of high solar reflectance when it is exposed to solar irradiation. The tropical climate [17] of Singapore

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* Corresponding author. Tel.: +65 6792 5498; fax: +65 6792 4052.
E-mail address: mpwan@ntu.edu.sg (M.P. Wan).

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receives abundant annual-averaged solar irradiation of 1680 kWh/m^2 compared to other locations [10–19], as shown in Fig. 1. Air-conditioning of buildings is also sought throughout the year in the tropics, suggesting that the potential heating penalty [9] of cool coating does not exist in tropical climate applications. Cool coating is often applied on roofs, which are commonly referred as "cool roof".

Heat transfer through roof/wall is a mixed-mode heat transfer phenomenon. The roof/wall surface heat exchanges mainly consist of the radiation component (solar heat gain and thermal emission) and the convection component (heat exchanging with surrounding air). Cool coating affects the radiation component by providing high solar reflectance and high thermal emittance. The cool coating layer adds resistance to the heat conduction through the roof/wall, which is coupled with the surface heat exchanges. In order to quantitatively analyze the impact of cool coating on the roof/wall heat transfer phenomenon, a robust heat transfer model is essential.

Over the years, numerous analytical methods, such as response factor (RF) and conduction transfer function (CTF), and numerical methods, such as Finite Difference (FD) and Finite Element (FE) have been developed. These methods have been implemented in building energy simulations programs, such as EnergyPlus [5], TRNSYS [9,10], eQUEST [12], BEopt [20], roof/wall savings calculators [21,22], building load calculation software [23–25], as well as RF and CTF coefficient calculators [26]. In these implementations, RF method requires long series of history temperatures or heat flux data. CTF method requires a set of pre-calculated coefficients [27–29] which are tabulated for certain types of roof/wall assembly, building materials and certain climate conditions, limiting its potentials for general uses. FD and FE methods overcome the drawback of RF and CTF methods. However, for discretization of the transient heat conduction equation, FD and FE methods use low-order polynomials, and require small grid size in the slab material and small time step (15 min or less) to achieve sufficient accuracy [20]. This leads to heavy demand of computational resources. Due to the need for discretization, these methods resolve the detailed temperature distributions within the slab material which is unnecessary for air-conditioning load calculations.

Spectral approximation method [30–32], on the other hand, uses orthogonal functions or higher-order (trigonometric) polynomial to solve the partial differential equation for heat conduction. This leads to the system of equations that are very easy-to handle and substantially reduces the complexity of calculations [33]. It does not require a set of pre-calculated coefficients, history heat flux data or the use of tables. At the same time, it does not require small grid size in the slab material (hence no need to calculate the detailed temperatures within the slab material) and a time step of 1 h can be used [34]. Also, previous studies [35–39] showed that spectral approximation method is best suitable for the problems involving mixed mode heat transfer such as the building roof/wall applied with cool coating.

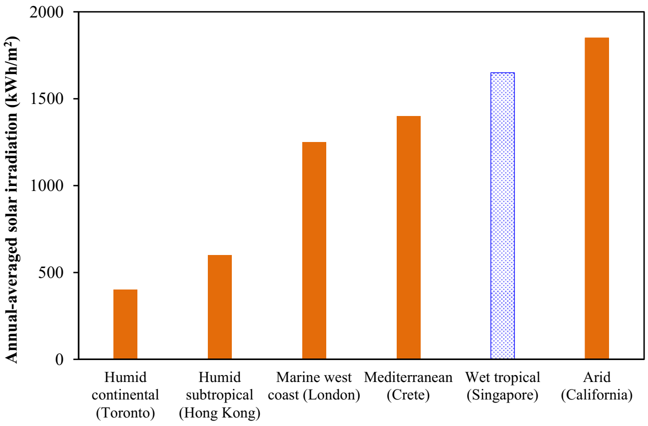

Fig. 1. Annual-averaged solar irradiation at different locations [10–19].

Despite the numerous advantages of the spectral approximation method, it has not yet been explored to develop a heat transfer model for the analysis of heat transfer through building envelope surfaces. This study proposed a novel cool roof heat transfer (CRHT) model for solid roofs (no air-gap between roof layers) applied with cool coating on the roof surface based on the spectral approximation method. It should be noted that the CRHT model is also applicable to opaque wall surfaces. The CRHT model can handle transient outdoor and indoor boundary conditions as experienced by naturally ventilated buildings. The CRHT model is advantageous over other existing building energy simulation models since the final solution of the CRHT model is very concise and, therefore, much easier to apply.

The CRHT model is verified against CTF method [26–29,40] and is further validated against real-scale measurements on a test building with concrete roof under the tropical climate conditions of Singapore, though the CRHT model is a general model that is applicable to other climate conditions and roof/wall materials.

2. Methodology

2.1. Cool roof heat transfer (CRHT) model

Building roofs experience transient heat transfer as the intensity of solar irradiation and ambient air temperature vary continuously. In a naturally ventilated building, the indoor air temperature also varies with the changing environments and the internal heat loads. In this derivation, it is assumed that the roof material has constant thermophysical (conductivity, specific heat capacity) and radiation properties (solar reflectance, thermal emittance). The roof material is homogeneous with constant material property (mass density). In case of multi-layered roof, good contacts between different layers of the roof material with negligible interfacial resistance are assumed. The indoor air is assumed to be well-mixed and there are no internal heat sources inside the apartments. Hourly-averaged values of overall (combined convection and radiation) indoor heat transfer coefficient (h_i) for ceiling and overall outdoor heat transfer coefficient (h_o) for roof are used [14,19] in this study since the inputs are hourly-averaged values.

2.1.1. Problem formulation and boundary conditions

Consider an opaque solid roof applied with a cool coating (or "cool roof") having its top surface exposed to solar irradiation as shown in Fig. 2. The incident radiation includes short waves in the wavelength range of 250 nm–3500 nm (SW_{in}, i.e., insolation and the radiation reflected by other objects on the earth surface) and long waves with wavelength >3500 nm (LW_{in}, i.e., thermal radiation emitted by clouds and other objects on the earth surface). The outgoing radiation includes SW_{out} (i.e., reflected radiation by the roof surface during day time) and LW_{out} (i.e., thermal radiation emitted by the roof surface to the sky and other objects on the earth surface). The radiation balance at the cool roof surface is given as follows:

Absorbed radiation by the cool roof surface (I_{abs}) = Incident radiation on the cool roof surface ($I_{in} = SW_{in} + LW_{in}$) − Outgoing radiation from the cool roof surface ($I_{out} = SW_{out} + LW_{out}$).

The diurnal heat transfer through the cool roof is assumed to be one-dimensional, i.e., in the direction perpendicular to the exposed surface. Assuming that the coordinate direction perpendicular to