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Theoretical and experimental studies on the daily accumulative heat gain from cool roofs

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A B S T R A C T

Cool roofs are gaining popularity as passive building cooling techniques, but the correlation between energy savings and rooftop albedo has not been understood completely. Here we theoretically model the daily accumulative inward heat (DAIH) from building roofs with different albedo values, correlating the heat gain of the building roof to both the rooftop albedo and the incident solar radiation. According to this model, the DAIH increases linearly with the daily zenith solar radiation, but decreases linearly with the rooftop albedo. A small building cell was constructed to monitor the heat gain of the building under the conditions of non-insulated and insulated roofs. The observational DAIH is highly coincident with the theoretical one, validating the theoretical model. It was found that insulating the roof, increasing the rooftop albedo, or both options can effectively curtail the heat gain in buildings during the summer season. The proposed theoretical model would be a powerful tool for evaluating the heat gain of the buildings and estimating the energy savings potential of high-reflective cool roofs.

1. Introduction

The thermal performance of a building is affected by the solar absorptance from the rooftop. During clear sky conditions, up to roughly 1000 W/m^2 of solar radiation is incident on a roof surface, 20–95% of which is typically absorbed depending on surface texture and albedo. High-reflective cool roofs (hereafter noted simply as “cool roofs”) reflect most of this incoming sunlight to keep the roof surface cooler than standard designed roofing products. In summer months, a cooler roof conducts less heat into the building and hence, reduces air-conditioning requirements for the building. Due to this phenomenon, cool roofs are gaining momentum as an effective passive building cooling technique [1–5].

Several field studies have shown that cool roofs reduce the air-conditioned requirement and improve the thermal comfort of the buildings. Akbari et al. [6] monitored one house and two school bungalows in Sacramento, California and found that changing the rooftop albedo from 0.18 to 0.73 saved the cooling requirement by about −2.2 kWh/d and reduced the peak cooling demand by 0.6 kW. Likewise, Parker [7] measured the impact on the space cooling of Florida residences and found that increasing roof solar reflectance reduced the average cooling energy by 19%. Similar results have been found in other experiments in moderate and tropical climate regions, in which the applications of cool roofs increase the building's thermal comfort and reduce building-cooling demands [8]. Studies also have demonstrated that cool roofs curtail energy demanding for several other building types in different climates [9–11].

In addition to field studies, cooling-energy savings from cool roofs have also been simulated at the building scale [12,13], city scale [14–17], and regional scale [3,18,19]. For regional scale, simulations have found that increasing the albedo of roofs improves local air quality [20,21], reduces gas house emissions [18,19,22], and even can inhibit regional warming [23,24]. In city scale, cool roofs have been noted to be an effective mitigation strategy against the urban heat island effect [2,16,23,25,26]. Increasing the albedo of the roofs in an entire city reduces urban air temperature, surface temperature, smog, and sensitive heat flux [25,27,28] and also saves the air-conditioning load requirements in the summer [15]. At the building scale, both

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increasing the rooftop albedo and the roof's insulation can lower the building's cooling energy expenditures [12,13,29]. Zingre et al. [13] found that on a sunny day, a high-reflectance coating with a solar reflectance of 0.74 on a common concrete roof 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, respectively [13]. Zingre et al. [12] also found that a double-skin cool roof can further reduce the inward heat flux to the building up to 6%. Detailed benefits of cool roofs varies seasonally [4]. Kolokotsa et al. [30] revealed that the energy savings of a cool roof was depressed by 19.8% for the whole year and 27% for the summer period. The transient roof temperature and transmitted heat flux through the building roofs have also been studied using an analytical complex fast Fourier transform [31], periodic solutions of the heat conduction equation [32], computational fluid dynamics for ventilated roofs [33,34], and spectral approximation method [13].

While existing field experiments and numerical simulations have confirmed that cool roofs can save energy demands of buildings, the heat gains of cool roofs have been not fully understood theoretically. On the basis of a steady-state roof heat flux, Suehrche et al. [35] proposed an analytical model correlating the rooftop solar absorption with the temperature difference between inner and outer air temperatures. But in reality, the rooftop is rarely at a thermally-steady state. The reliability of these predictions on the potential benefits of a cool roof also depend highly on a proper estimation of the flux components of the roof, such as the heat transfer coefficient [36]. Considering the transient heat balance at the rooftop and the ceiling, Levinson [37] proposed a model that correlates the rooftop albedo with the solar heat gain from the roof by neglecting the thermal storage in the roof and by linearizing the exchange of the thermal radiation between the roof and its environment. However, these models did not consider any inertial effect, which is substantial for most roof products, such as a concrete roof. Therefore, the goal of this study is to refine these theoretical models and to develop a new model that can accurately and simply evaluate the building heat gain from roofs with different albedo values and different insulation. In this study, the inward heat projected from a roof is theoretically derived with a focus on correlating the rooftop albedo with the DAIH. To validate the theoretical correlation, a flat-roof building cell was constructed and painted to simulate different albedo values and measure the instantaneous heat gain of the roof.

2. Theory

2.1. Existing analytic models (sol-air temperature model)

A roof is heated by the sunlight, the sky, and the air. The rooftop rejects a portion of heat back to the surrounding air and the sky. The surplus energy conducts to the ceiling, warming up the building

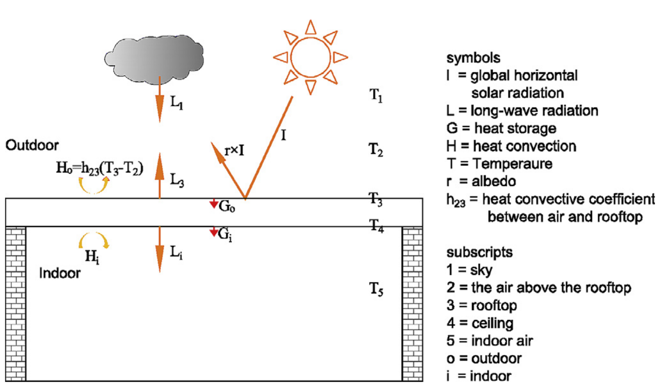

Fig. 1. Schematic showing the heat balance of a building roof.

interior walls and the indoor air. For convenience, in the following, digital subscripts of 1 = sky, 2 = air, 3 = rooftop, 4 = ceiling, 5 = indoor air are utilized respectively (Fig. 1). Symbols of G = heat storage, H = heat convection, L = long-wave radiation, T = temperature in °C, h = heat convective coefficient, and ε = emissivity are also used to represent energy balance factors (Fig. 1).

The heat transfer between building roofs and their surroundings is a transient heat balance process because the solar radiation and the ambient air temperature vary continuously. The solar absorption at the rooftop is the product of solar absorptivity (1-albedo) and incident solar radiation. One widely used model correlating the rooftop absorptivity with the rooftop temperature is the sol-air model [38].

$$\mathrm{T_{sol-air}} = \mathrm{T_2} + \frac{\alpha \mathrm{I} - \mathrm{L_{13}}}{\mathrm{h_{23}}} \tag{1}$$

where $T_{\text{sol-air}}$ (°C) is the sol-air temperature; T_2 (°C) is the air temperature; α is the rooftop absorptivity; h_{23}(W/m^2 K) is the heat convective coefficient between the air and the rooftop; I (W/m^2) is the incident global horizontal solar irradiance; and L_{13} (W/m^2) is the extra infrared radiation due to the difference between the external air temperature and the apparent sky temperature.

The sol-air temperature can be used to compute the incident heat inward, q (W/m^2), from the roof to the building

$$q = U(T_{\mathrm{sol-air}} - T_5) \tag{2}$$

where U (W/m^2 K) is the thermal transmittance or U-value; T_5 (°C) is the indoor air temperature.

Substituting Eq. (1) to Eq. (2) solves for the heat flux inward from the roof as

$$q = \mathrm{U(T_2 - T_5)} + \frac{\mathrm{U}}{\mathrm{h_{23}}}(\alpha \mathrm{I} - \mathrm{L_{13}}) \tag{3}$$

Eq. (3) appears to note that the incident inward heat (q) is proportional to the solar absorptivity (α) and to the incident solar radiation (I). However, the indoor air temperature T_5 varies with q so that Eq. (3) is an implicit function of variable q. Furthermore, Eq. (3) is derived on the basis that the heat storage on the roof is negligible, which may not be necessarily true especially for an uninsulated roof such as a concrete roof. Therefore, a correlation between the rooftop absorptivity (or 1-albedo) and the daily heat gain of a building cannot be found directly.

2.2. A new model for the daily accumulative heat gain from the roof

Here, a new model is introduced which considers the thermal balance at the rooftop, the thermal balance at the roof ceiling, and the heat storage in the roof. For many locations, a roof surface usually stays dry from proper drainage so that the evaporative heat flux is negligible.

The radiation incident on a rooftop includes short-wave radiation from the sun (I) and longwave radiation from the sky (L_1). Some of the incident radiation is reflected away from the rooftop, while the surplus is absorbed. The absorption heats up the roof and drains as sensible heat, long-wave radiation, and heat conduction. Therefore, the heat balance at a dry rooftop is (Fig. 1)

$$\alpha \mathrm{I} + \varepsilon_3 \mathrm{L_1} = \mathrm{h_{23}}(T_3 - \mathrm{T_2}) + \mathrm{L_3} + \mathrm{G_o} \tag{4}$$

where ε_3 is the emissivity of the rooftop; T_3 (°C) is the rooftop temperature; G_o (W/m^2) is the residual heat gain (or loss) at the rooftop, i.e., heat conduction; L_1 (W/m^2) is the downward long-wave radiation from the sky; L_3 (W/m^2) is the upward long-wave radiation from the rooftop.