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Thermal analysis of roofs with thermal insulation layer and reflective coatings in subtropical and equatorial climate regions in Brazil

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ABSTRACT

This article presents a comparative analysis of the thermal performance of large metal roofs like those found on exhibition halls, airports, and malls located in subtropical and equatorial climates regions in Brazil. The focus of the investigation was the suitability of the use of white paints, selective coatings, and thermal insulation layers in those regions. The survey was based on a model of heat transfer through a roof where solar radiation and ambient air-temperature were studied as functions of time. The results showed that in cities with an equatorial climate, the roof with the thermal insulation layer and selective coating is the best option because it saves more energy and reduces the effects of urban heat island (UHI). Otherwise, in cities with a subtropical climate, the application of white paint on a roof without a thermal insulation layer is the best solution for both a reduction in energy consumption and a decrease in the formation of UHI.

1. Introduction

The ambient air-temperature in large cities increases in part from solar radiation being absorbed by the urban construction and by the exposed soil at a higher rate than what is reflected and emitted. This fact raises the average temperature of the city, creating a temperature difference between the urban area and the countryside. For instance, on very hot days some Brazilian' cities have an average temperature of 12 K warmer than the surrounding areas. This is the urban heat island (UHI) effect. The contribution to UHI from urban construction comes mainly from pavement and building roofs.

A building component that deserves more attention is the roof, especially in non-residential construction such as malls, factories, and exhibition halls. These buildings are characterized as having large roof surfaces (e.g. flat roofs) in comparison to their external wall surfaces. Also observe that roof surfaces are always exposed to solar radiation between sunrise and sunset. Therefore, they are responsible for a considerable part of the thermal load of the building and consequently the electrical energy consumption required for cooling. According to Brazil's Mining and Energy Ministry [1], the electrical energy consumption of buildings in 2012 accounted for 26.3% of the total electrical energy used in the country. It is estimated that at least one quarter of this amount is used for cooling.

In a previous work, Brito Filho et al. [2] showed that while it is possible to reduce heat gain through roofs by adding an even-greater thermal insulation layer, a more effective and adequate way is to combine a traditional thermal insulation layer with reflective surface coatings. This approach makes it possible to balance two competing effects, namely: cooling energy saving (i.e. lower the heat flux across the roof) and mitigation of UHI (i.e. lower the roof's external surface temperature). The climatic data used in [2] was for the city of São Paulo (latitude 23°30′ S, longitude 46°37′ W, and altitude of 792 m). The analysis was based on a model of heat transfer that includes solar radiation and external ambient air-temperature as a function of time, convection and radiation heat transfer, roof thickness, and thermophysical and optical properties of the materials. The dependent variables of the model are the time-dependent outside surface temperature of the roof and the heat flux that crosses it. The applicability of the model equations is for comparison of the thermal performance between roof configuration taking into account their impacts on UHI and heat flux that reach the indoor environment.

The objective of the present study is to extend the research [2] in two ways. First, showing the versatility of the mathematical model proposed regarding the analysis of a roof's thermal behavior. Secondly, applying the model to show the thermal effect of white

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Nomenclature

Latin letters

h	heat transfer coefficient ($\mathrm{W\,m^{-2}\,K^{-1}}$)
H_h	monthly average daily global solar radiation for a horizontal surface ($\mathrm{MJ\,m^{-2}}$)
k	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
L	thickness (m)
q	heat flux through the roof ($\mathrm{W\,m^{-2}}$)
q_s	solar radiation on the plane of the roof ($\mathrm{W\,m^{-2}}$)
R	thermal resistance ($\mathrm{K\,W^{-1}}$)
t	time (h)
T	temperature (°C)
v	wind speed ($\mathrm{m\,s^{-1}}$)

Greek letters

α	absorptivity of the roof
δ	thickness (m)
ε	hemispherical emissivity of the roof
ρ	reflectivity of the roof
σ	Stefan–Boltzmann constant ($\mathrm{W\,m^{-2}\,K^{-4}}$)

Subscripts

a	external ambient air
ave	monthly average daily
c	convection
e	external face of the roof (facing the sun)
i	internal face of the roof (facing the interior ambient)
ir	infrared region of the thermal radiation spectrum
min	monthly average daily minimum
max	monthly average daily maximum
o	internal ambient air
r	radiation
s	solar radiation

paints, selective coatings, and a thermal insulation layer for the first time on the external surface temperature of roofs and the heat flux through them in subtropical and equatorial climates regions in Brazil, and that the effectiveness of a particular roof's configuration will depend on the site's climate conditions. In forthcoming research, this model will be extended to include a building electrical energy saving estimation taking into account the roof type and climate region in Brazil.

The next section presents a literature review aiming to show case studies that support the findings reported and what is missing that this research intends to fill in. In particular: (a) the two relevant dependent variables of the roof heat transfer problem are the external surface temperature and heat flux because they are responsible for UHI and energy saving, respectively; (b) our model reproduces the qualitative results obtained by other authors, i.e. the effect of thermal insulation, paints, and selective coatings; and (c) the role of climate on roof thermal performance.

2. Literature review

Heat transfer in roofs has been investigated in many technological fields due to its importance in the thermal load of a building and the mitigation of the UHI effect. Current technologies of energy conservation and mitigation of UHI range from the use of shading objects such as trees [3], covering roofs with a layer of plants [4–6] and even more sophisticated solutions such as roof ponds [7] and roof water sprayings [8].

Another powerful technology is based on the use of reflective roof coatings. Several articles have reported energy savings and the mitigation of the UHI effect that results from the application of reflective coatings on buildings.

Sproul et al. [9] reported an economic comparison of white, green, and dark colored flat roofs in the USA using a 50-year life cycle cost analysis. The authors found that relative to dark colored roofs, white roofs provide a 50-year net savings of $25/m^2 and green roofs have a negative net savings of $71/m^2. Additionally, the annualized cost premium of white roofs compared to green roofs is small. Santamouris [10] conducted a comprehensive literature review of green and reflective roof technologies to mitigate UHI and improve comfort levels in urban environments, taking into account over 180 published studies. The author reported that when green roofs are applied on a city scale, the average ambient air-temperature is reduced to between 0.3 and 3 K. Otherwise, considering a global increase of the city's albedo, the expected mean decrease of the average ambient air-temperature is close to 0.3 K per 0.1 rise of the albedo, while the corresponding average decrease of the peak ambient air-temperature is close to 0.9 K. However, when only cool roofs are taking into account, the expected depression rate of the average urban ambient air-temperature varies between 0.1 and 0.33 K per 0.1 increase of the roofs albedo with a mean value close to 0.2 K. Rosado et al. [11] experimentally investigated two similar single family, single story homes (initial albedo of 0.51 and of 0.07) for one year which were built in Fresno, California (USA) aiming to assess the benefits of cool roofs. The authors calculated the cool roof energy savings in the cooling and heating seasons. They reported an annual cooling, heating fuel, and heating fan site energy savings per unit ceiling area of 2.82 kWh/m^2 (26%), 1.13 kWh/m^2 (4%), and 0.0294 kWh/m^2 (3%), respectively.

Rosenfeld et al. [12] found that the electricity consumption savings were 40% in a house in Sacramento, California (USA) with the walls and roof painted white. The albedo rose from 0.18 to 0.73. Simpson and McPherson [13] carried out a study in Tucson, Arizona (USA) based on three ¼-scale model buildings. They found that white roofs were up to 20 K cooler than that of gray or silver roofs, and up to 30 K cooler than brown roofs. Additionally, the authors estimate an air-conditioning energy reduction by approximately 5% for the house with a white-colored roof compared to the houses with gray and silver-colored roofs. Parker and Barkaszi Jr. [14] experimentally investigated the cooling energy savings provided by reflective roofing coatings in nine occupied homes in Florida (USA). They verified an air-conditioning energy reduction average of 19% after application of high-reflectivity coating. Akbari et al. [15] also reported a significant peak power and cooling energy savings (up to 52%) and a reduction of the daily peak surface temperature of the roof (33–42 K) from high-reflectivity coatings on six California (USA) buildings. Akbari et al. [16] monitored peak power and cooling energy savings from high-reflectivity coatings on two school bungalows and on one house in Sacramento, California (USA). These authors found that changing the reflectivity of the roof from 0.18 to 0.73 might result in seasonal savings for the house of 2.2 kWh/d and of 3.1 kWh/d for the school bungalows. Romeo and Zinzi [17] documented the results of the application of a cool, white paint with high solar reflectance and thermal emissivity on a 700 m^2 roof in an office/laboratory building in Trapani, Sicily (Italy). The authors observed a roof surface temperature reduction of up to 20 K, and a cooling energy demand decrease of 54%. Santamouris et al. [18] observed that for a group of representative buildings in Athens (Greece), the UHI intensity exceeded 10 K and increased the cooling load by about 100%, while the peak electricity load may have tripled. Bretz and Akbari [19] reported that cooling energy savings of 10–70% have been achieved by applying high-albedo coatings to residential buildings in California (USA) and Florida (USA). Kolokotroni et al. [20] analyzed the impact from the application of a reflective paint on a flat roof in a naturally ventilated office building in London (UK). The simulations show that the