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ScienceDirect

Procedia Engineering 169 (2016) 392 – 399

Procedia Engineering

www.elsevier.com/locate/procedia

4th International Conference on Countermeasures to Urban Heat Island (UHI) 2016

Life Cycle Analysis of Cool Roof in Tropical Areas

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Abstract

In this work, the Complex Fast Fourier Transform (CFFT) method is introduced to predict the roof temperature and heat gain in the tropical country of Singapore. The cost-effectiveness of cool paint and roof ventilation are evaluated through life-cycle analysis. Cool paint and roof ventilation can provide annual cooling energy savings of 33-57 USD/m^2 for the top-floor residential units. The payback period of cool paint is shorter than 2 months in unventilated roof and shorter than 6 months in ventilated roof. Both cool paint and roof ventilation are very energy-efficient and cost-effective in tropical climate.

Peer-review under responsibility of the organizing committee of the 4th IC2UHI2016

Keywords: Cool roof, Life cycle analysis, tropical climate

1. Introduction

The geographical location of Singapore is 1° north of the equator having hot and humid climatic conditions throughout the year. In order to maintain thermal comfort inside buildings under this climate, air-conditioning is so widely used that space cooling load accounts for nearly 40% of energy use in buildings. The Building Construction Authority (BCA) of Singapore launched a green building master plan in 2006, aiming to turn at least 80% buildings into "green" by 2030. Both passive and active design strategies have been implemented on green buildings depending on whether the external mechanical or electrical devices are required. In general, due to the high electricity demand

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Peer-review under responsibility of the organizing committee of the 4th IC2UHI2016
doi:10.1016/j.proeng.2016.10.048

and implementation cost coming along with active technologies, passive techniques are more recommended as the primary way to achieve thermal comfort and energy savings in buildings.

In recent years, the potential benefits of using cool roofs or coatings that have high solar reflectance and high infrared emittance were reported in many experimental studies. For example, from the field measurement on a 700 m^2 roof during the cooling season in Sicily of Italy, Romeo and Zinzi [1] found that the application of cool paint reduced the cooling energy demand by 54%, and reduced the peak temperatures of roof surface and indoor air by 20°C and 2.3°C respectively. In United States, Akbari *et al*. [2] monitored the effects of cool roofs and found that increasing the solar reflectance of roof by 0.33-0.60 reduced the peak temperatures by 33-42°C in six types of commercial building roofs in California. Moreover, the daily cooling energy consumption was reduced by 4% in a cold storage facility, 18% in a school building and 52% in a retail store building. In nine Florida houses, Parker and Barkaszi [3] found that the application of reflective coatings on the gray roofs reduced the electricity use for air-conditioning by 19% on average, and reduced the peak cooling load by 12-38% in summer. Hildebrandt *et al*. [4] reported that the daily cooling loads were reduced by 17%, 26% and 39% in an office, a museum and a hospital building respectively, after the application of white roof coatings in Sacramento. Akridge [5] reported that the cooling energy use was reduced by 28% after applying the white acrylic coatings on the galvanized roofs of a school building in Georgia. Under the hot humid climate in Hong Kong, Cheng *et al.* [6] found that the peak air temperature in a black scaled test room was 12°C higher than that in a white test room. Simpson and McPherson [7] measured the temperatures of four scaled roofs with different colors, and they found that increasing the solar reflectance of roof surface may not reduce the roof surface temperature if the infrared emittance was also reduced. Although the benefits of using cool roofs or coatings were revealed in many experimental studies, one major disadvantage of cool material is that its solar reflectance tends to degrade over time due to the aging and weathering [8, 9].

Theoretical studies were also conducted to analyze the impacts of solar reflectance and infrared emittance on the thermal performance of roofs. For example, cooling energy savings of 10-20% were estimated if the solar reflectance of roofs was increased in United States [10-12]. Shariah *et al.* [13] simulated the building energy performance using the computer program ANSYS. They found that increasing the solar reflectance of roofs from 0 to 1 reduced the energy loads by 32% and 26% in the buildings with un-insulated and insulated roofs respectively in the mild climate, and the reductions increased to 47% and 32% in the hot climate. In addition, several online tools were developed to estimate the energy savings as a function of the solar reflectance, building characteristics, local climate and cooling equipment, such as Energy Star Roofing Comparison Calculator [14] developed by the U.S. Environmental Protection Agency, and Cool Roof Calculator [15] developed by U.S. Department of Energy. Although these studies demonstrated the potential benefits of using passive roofing technologies, few works were dedicated to evaluate the cost-effectiveness.

In this work, the Complex Finite Fourier Transform (CFFT) method developed by Yumrutas *et al.* [16] is adopted to predict the transient roof temperature and transmitted heat flux across the multilayer roofs. Based on the predictions, life cycle analysis is also conducted to evaluate the cost-effectiveness of using cool paint in the unventilated and ventilated concrete roofs under the tropical climate in Singapore.

Nomenclature

α	thermal diffusivity of roof layer
COP	coefficient of air-conditioning system
C_{enr}	energy cost (USD)
C_{ini}	initial cost of roofing technology (USD)
C_{el}	electricity cost (USD/kWh)
E	solar irradiance (W/m^2)
g	inflation rate
h_o, h_i	overall heat transfer coefficients at the exterior and interior roof surfaces (W/m^2 K)
I, I^*	interest rate and adjusted interest rate
k	thermal conductivity of roofing material (W/mK)
L	length of roof layer (m)
PWF	present worth factor