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Life-cycle cost analysis of roofing technologies in tropical areas

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ABSTRACT

Various technologies have been applied on roofs to reduce the air-conditioning load in buildings during summer or in tropical areas, including cool paint, roof ventilation, mass and reflective insulation. These technologies help to reduce roof temperatures or heat transmission effectively in summer at different economic costs. It is desirable to evaluate the cost effectiveness of different roofing technologies, especially in the tropical climate.

This work analyzes the heat gains of concrete-based roofs combined with different roofing technologies, as well as the cost effectiveness of these technologies in the tropical climate of Singapore. The transient roof temperatures and heat transmissions are predicted using Complex Fast Fourier Transform (CFFT) method, and the impacts of roof ventilation on heat gain are predicted using correlations proposed for convective resistance prediction via computational fluid dynamics (CFD) simulation. The daily heat gains of different roof components are hence predicted, and Life-cycle Cost Analysis (LCCA) is performed to evaluate the payback periods of different roofing technologies, including cool paint, expanded polystyrene foam (EPS), radiant barrier (RB), and roof (natural and forced) ventilation. It is concluded that the application of cool paint on unventilated roof shows the shortest payback period, and the combined use of RB and natural ventilation yields the largest energy savings in the long run. Compared with forced ventilated roofs, those passive roof technologies (cool paint, RB, air gap and EPS foam) without electricity requirement are more recommended, due to their cost effectiveness.

1. Introduction

The geographical location of Singapore is 1° north of the equator having the typical hot and humid tropical climate throughout the year. In order to maintain the indoor thermal comfort in this city state, air-conditioning is extensively used and responsible for nearly 50% of energy use in buildings [1]. The Building Construction Authority (BCA) of Singapore launched a green building master plan since 2006 for sustainable urban development, aiming to transform at least 80% of all buildings into "green" by 2030 [2]. Under the context of global warming, the energy efficiency of buildings becomes a major concern of urban designers and building engineers. Since a major part of spacing cool load results from the solar heat gain of building envelope in tropical climate, various technologies are applied to reduce the heat gain of building envelope components, including wall, roof, window, and shading devices. Among these envelope components, roof is most exposed to solar radiation with the incident solar irradiance reaching up to 1000 W/m^2 under the clear sky conditions [3].

A literature review shows that both experimental and theoretical studies were carried out to study the energy benefits of using various roofing technologies on concrete roofs, such as cool paint, roof ventilation, green roof and mass/reflective insulation. The common concrete surfaces have a low solar reflectivity (SR), and the potential benefits of using solar-reflective cool roof were studied. The application of cool coatings with SR of 0.73 reduced air-conditioning load by 19% during summer in Florida, and reduced peak cooling load by 12%–38% in nine concrete-roofed houses [4]. In addition, Levinson et al. proposed a prototype for the solar-reflective concrete tile to facilitate the application of cool roofs on concrete-based buildings [5]. Roof ventilation helps to reduce the roof heat gain in summer as well. Dimoudi et al. reported that a 6-cm naturally ventilated air gap reduced the heat gain of a flat concrete roof by 56% during the summer daytime in Greece, and the additional use of radiant barrier (RB) reduced the roof heat gain further to 68% [6]. Miranville et al. studied the field performance of a ventilated roof under different ventilation modes, such as unventilated, naturally ventilated and forced ventilated [7]. Thermal resistances of roofs were calculated based on the collected

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Nomenclature

$C_{1\varepsilon}, C_{2\varepsilon}, C_{3\varepsilon}, C_{\mu}$	Constants in the $k-\varepsilon$ turbulence model
E	Solar irradiance (W/m^2)
e_H, e_C	Infrared emittance of the upper and lower cavity surfaces, dimensionless
Gr_L	Grashof number based on the cavity length, dimensionless
g	Acceleration of gravity (m^2/S)
h_o	Convective heat transfer coefficient in the naturally ventilated roof cavity (W/m^2 K)
h_H, h_C	Convective heat transfer coefficients at the hot and cold cavity walls (W/m^2 K)
k	Thermal conductivity of roofing material (W/m K)
L	Length of roof or cavity (m)
p	Air pressure (Pa)
Pr	Prandtl number, dimensionless
q_{rad}	Radiative heat transfer between the upper and lower surface of cavity (W/m^2)
q	Transferred hourly heat flux across roof (W/m^2)
Q_c	Daily roof heat gain (Wh/m^2)
r_{rad}	Thermal resistance due to radiation between upper and lower cavity surfaces (m^2 K/W)
r_1, r_2, r_3	Transformed thermal resistances in ventilated cavity (m^2 K/W)
r_a, r_b	Thermal resistances of upper and lower slabs of ventilated roof (m^2 K/W)
r_e, r_i	Thermal resistances of exterior and interior air films (m^2 K/W)
r_H, r_C	Thermal resistances due to convection between air and the upper and lower cavity surfaces (m^2 K/W)
Re	Reynolds number, dimensionless
Ra_o, Ra_H, Ra_C	Rayleigh numbers in the cavity, at the hot and cold walls, dimensionless
S	Spacing between upper and lower roof slabs or cavity height (m)
t	Time, (s)
T_i, T_o	Indoor and outdoor air temperatures (K)
T_H, T_C	Surface temperatures of hot and cold cavity walls (K)
T_m	Introduced node temperature in the Y-mesh thermal circuit (K)
T_w	Average temperature of cavity surfaces (K)
u, v	Airflow velocities in the x and y directions (m/s)
z_n	Dimensionless distance within the *n*th roof layer

Greek letters

α	Solar absorptance of ventilated roof or thermal diffusivity
β	Thermal expansion coefficient of air
γ	Solar reflectance of exterior roof surface
ε	Infrared emittance of exterior roof surface or dissipation rate of turbulent kinetic energy (m^2/S^3)
τ	Dimensionless time
σ	Stefan-Boltzmann constant, 5.67×10^{-8} (W/m^2 K^4)
$\sigma_k, \sigma_\varepsilon$	Empirical constants in $k-\varepsilon$ turbulence model
λ	Thermal conductivity of air (W/m K)
ν	Kinematic viscosity of air (m^2/s)
μ	Dynamic viscosity of air (kg/ m s)
ρ	Density of air (kg/m^3)
θ	Inclination of roof from the horizontal plane (°)

Subscripts

n	Layer number of a multilayer roof
j	Fourier transform coefficient

long-term data, and a linear correlation was derived between airflow rate and overall thermal resistance of forced ventilated roof. Based on experimental data, Chang et al. proposed the correlations for the thermal resistances of naturally ventilated roofs, but the radiative heat transfer between the upper and lower cavity surfaces was neglected [8]. Furthermore, green roofs can contribute to reduce roof temperature and enhance indoor thermal comfort as well. Zhou et al. reported that a rooftop lawn can lower the peak indoor temperature by 3–4 °C of a concrete building [9], but Sfakianaki et al. observed a maximum indoor temperature reduction of merely 0.6 °C after planting vegetation on a residential roof in Japan [10]. In laboratory environment, Alvarado et al. measured the performance of a scaled concrete roof with a wide range of insulation types, and roof insulated with combination of aluminium reflector and polyurethane provided an 88% heat gain reduction compared with uninsulated concrete roof [11].

Theoretical studies were conducted to estimate the cooling and heating loads caused by building envelope solar gain as well. The degree-day method provides a simple and crude estimation using the average building U-value and static outdoor air temperature [12]. Some published studies employed this method to optimize the building insulation thickness [13–15], or evaluate the potential benefits of using cool paint with high solar reflectivity and infrared emissivity [16]. Some methods considered the transient outdoor conditions, heat capacity of building envelope, and heat loss rate inside buildings for estimation of building heating and cooling loads [17–19]. In this paper, the Complex Finite Fourier Transform (CFFT) method is used to predict the transient roof surface temperature and heat gain. This method was firstly used by Yumruts et al. to estimate the heat flow through multilayer walls or flat roofs [20], and applied to estimate the equivalent temperature difference [21] and optimal insulation thickness of building walls [22].

Although extensive studies have been conducted to study the energy savings of roofing technologies, fewer studies were dedicated to compare their cost effectiveness. Several methods were commonly adopted to perform life-cycle cost analysis (LCCA) of building system or components, including net present value (NPV) method, annual cost (AC) method and internal rate of return method [23]. For example, Sproul et al. [24] presented a 50-year LCCA for white, green and black roofs using data collected from 22 flat roof projects or studies in U.S. They found that white roofs provided a 50-year net savings of \$25/m^2 and green roofs had a negative net savings of \$71/m^2 compared to their black counterparts. The annual difference of \$3/m^2 between a white and green roof is sufficiently small, and both of them offered local cooling benefits to mitigate urban heat islands, which were partly caused by prevalence of dark roofs. Clark et al. [25] demonstrated a payback period of 11 years on a single green roof in Michigan when low green roof installation costs and high environmental benefits were considered. The NPV method was used to perform the LCCA of other building components as well. Hasan [26] optimized the thickness of external walls to cut down the total cost of wall insulation materials and space heating in Palestine. It was also applied to evaluate the various renewable energy sources for heating a greenhouse in Turkey, including solar collectors, heat pumps, biomass and cogeneration systems [27]. Fay et al. studied the primary energy use of a detached house in Melbourne, Australia, and found that the initial embodied energy cost of additional insulation is paid back in around 12 years [28]. Audenard et al. conducted an economic analysis of a passive house and compared it with a standard house [29]. They concluded that the passive house equals the cost of a standard house in 29 years if energy cost remains constant, and the payback period is reduced to 18 years if the cost of electricity would be with an escalation rate of 5%. Marszal and Heiselberg [30] made an LCCA of a multi-floor residential net-zero energy building in Denmark