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Study on the thermal performance and design method of solar reflective–thermal insulation hybrid system for wall and roof in Shanghai

Tong Qiu[a,b], Guojian Wang[a,*], Qiang Xu[b], Gang Ni[b]

[a] Tongji University, Shanghai 200092, China
[b] Shanghai Research Institute of Building Science, Shanghai 200032, China

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ABSTRACT

Solar reflective coating applied on roof/wall surface is becoming an important passive cooling technology for building energy efficiency. Shanghai is located in the climate of hot summer and cold winter, so the hybrid system of solar reflective coating combined with thermal insulation materials on roof/wall should be an efficient way for building energy saving. In this paper, the thermal performance and design method of the hybrid system was discussed. Equivalent thermal resistance for solar reflective coating was put forward for thermal performance evaluation and energy efficiency design for the hybrid system. Equivalent thermal resistance considers not only reflectance of the material, but also the weather conditions, demand for indoor comfort, orientation and thermal performance of base wall/roof. Equivalent thermal resistance in typical summer day and winter day of Shanghai were theoretically calculated and tested. Annual equivalent thermal resistance which integrated the benefit in summer and the penalty in winter was achieved by linear regression algorithm of simulated energy, and the results were 0.07–0.40 $m^2{\cdot}KW^{-1}$ for wall and 0.18–1.07 $m^2{\cdot}KW^{-1}$ for roof. This means solar reflective coating is energy saving equivalent and replaceable with 7–23 mm thermal insulation layer on wall, and 14–107 mm on roof. This method was useful and accepted in the energy efficiency design standard of Shanghai.

1. Introduction

Solar reflective coating which reflects solar radiation and especially the infrared radiation (0.7–2.5 μm) on exterior building surface and emits long wave infrared radiation has drawn a lot of interest in recent years (Akbari, 2005; Levinson et al., 2005; Berdahl and Bretz, 1997; Zinzi and Fasano, 2009; Kolokotsa et al., 2012). The reflective materials with high solar reflectance & high emittance could tremendously decrease solar heat absorption of the building, lower indoor air temperature and reduce cooling energy consumption (Levinson and Akbari, 2010; Akbari et al., 2009; Synnefa et al., 2007; Levinson et al., 2009; Synnefa et al., 2006; Uemoto et al., 2010; Summan and Verma, 2003; Guo et al., 2012; Yew et al., 2013). The literature showed that indoor thermal comfort improvement and energy saving benefits by solar reflective material were widely verified by test, monitoring and simulation. Iván Hernández-Pérez summarized the reported studies on thermal performance of the reflective materials by means of cell test, on-site test, computational fluid dynamics analysis, building simulation, and mesoscale modeling (Hernández-Pérez et al., 2014). Haberl and Cho presented a literature review about cooling energy savings from cool roofs based on 27 articles and concluded that cooling energy savings in residential and commercial buildings varies from 2% to 44% and averaged about 20% (Haberl and Cho, 2004). Yafeng Gao presented EnergyPlus simulations of standard compliant office building and residential building prototypes of seven cities in China (Harbin, Changchun, Beijing, Chongqing, Shanghai, Wuhan, and Guangzhou) and the results showed that substituting the white roof (albedo 0.6) for a gray roof (albedo 0.2) yields positive annual load, energy, and energy cost savings in all hot-summer cities (Chongqing, Shanghai, Wuhan, and Guangzhou) (Gao et al., 2014).

In China, the mandatory standard of building energy efficiency has been enforced for more than 10 years, and insulation materials are popularly applied on exterior surface of wall/roof for building energy saving. However, for high-rise buildings in Shanghai, fire, drop down and crack accidents occurred (see pictures in Fig. 1). The safety hazard for exterior wall insulation system became a big problem. Qi (2012) researched the fire safety of organic insulation materials such as extruded polystyrene (XPS), expanded polystyrene (EPS), rigid polyurethane foam (RPUF), which have better insulation performance but worse burning behavior. The fire classification of organic material by BS EN 13501-1 (2009) could reach class B or class C, but only noncombustible materials (class A1 and A2) are not restricted in application on exterior wall of high rise buildings in China. Inorganic materials such as mineral wool, foamed glass, foamed concrete and insulation

* Corresponding author.

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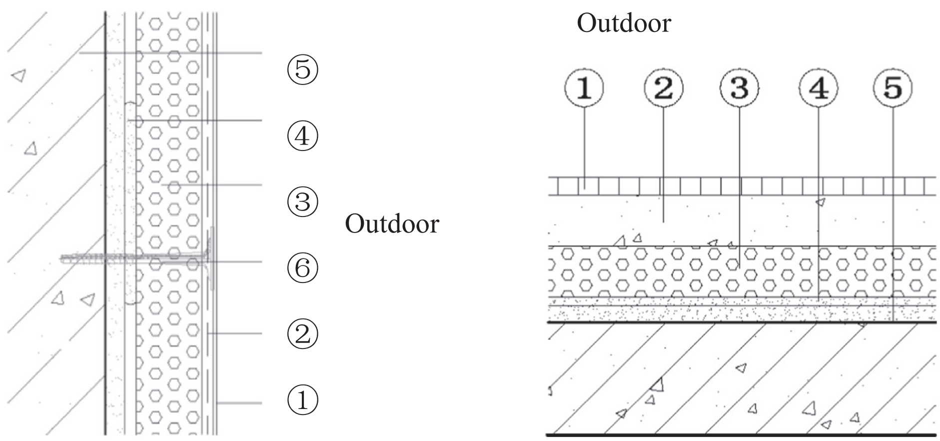
Fig. 1. Accidents for exterior thermal insulation system in Shanghai (fired, dropped, cracked).



(a) External wall system (b) Roof system

Fig. 2. Hybrid system of insulation with reflective coating (① solar reflective coating; ② rendering layer/guard layer; ③ insulation layer; ④ boundary layer/water proof layer; ⑤ base layer (wall/roof); ⑥ anchor).

mortar are non-combustible but have worse thermal insulation and worse waterproof performance.

Shanghai is located in the climate zone of hot summer & cold winter of China. For heating energy saving in winter, insulation is the best way, but for cooling energy saving in summer, reflective materials should be the optimum solution. Reflective coating could raise safety and durability of exterior insulation system by reducing the surface temperature in summer and reduce the design thickness of insulation material to the minimum value required with regard to winter heating. As a result, the hybrid system of solar reflective-thermal insulation shown for external wall and roof (shown in Fig. 2) could be a prospective solution for building energy saving in Shanghai.

Investigation of energy consumption in hot summer & cold winter zone showed that cooling energy consumption in summer was much higher than heating consumption in winter (Hu et al., 2013). However, only the thermal insulation parameter of U value was required in the mandatory standard of building energy efficiency design. Even if reflective coatings were proved effective for cooling energy saving, solar reflectance and emittance of roof/wall has not been taken into account by the design code of building energy efficiency (National standard of China, 2015, 2010).

The results of experiments, simulation and theoretical analysis confirmed the benefits of reflective materials on energy saving and thermal performance in summer and disadvantages in winter (Akbari, 2005; Levinson et al., 2005; Berdahl and Bretz, 1997; Zinzi and Fasano, 2009; Kolokotsa et al., 2012; Levinson and Akbari, 2010; Akbari et al., 2009; Synnefa et al., 2007; Levinson et al., 2009; Synnefa et al., 2006; Uemoto et al., 2010; Summan and Verma, 2003; Guo et al., 2012; Yew et al., 2013; Hernández-Pérez et al., 2014; Haberl and Cho, 2004; Gao et al., November 2014). Several studies have analyzed the change of energy consumption using reflective material on building surface in different climates (Shariah et al., 1998; Balaras et al., 2000; Wang et al., 2008; Yu et al., 2008; Shi and Zhang, 2011; Yu et al., 2008; Cheng et al., 2005). Thermal and energy saving performance of solar reflective coating is affected not only by the reflectance parameter, but also by weather conditions, as well as by surface orientation and inclination. None of the previous research integrated the complicated influences into a simple and quantified parameter for energy efficiency design. On the view of application in building construction, a simple and precise design and evaluation method is needed.

In this work, equivalent thermal resistance for solar reflective coating ΔR_{eq} was put forward for thermal performance evaluation and energy efficiency design for the hybrid system. The parameter of ΔR_{eq} for reflective coating considers not only solar reflectance of the surface, but also the weather condition, demand for indoor comfort, orientation and thermal performance of base wall/roof. Different ways for achieving ΔR_{eq} were discussed: