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Effect of retro-reflective materials on building indoor temperature conditions and heat flow analysis for walls

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ABSTRACT

Reducing the solar heat gain of buildings is an effective way to improve the building thermal conditions in summer and reduce the energy consumption. Although highly reflective materials can reduce the heat gain of the target building by specular reflection, they also increase the heat gain of the surrounding buildings owing to the fact that the reflected radiation is only transferred, not eliminated. In this situation, this study considers retro-reflective materials, which can improve the building temperature conditions by reflecting the solar radiation back in the opposite direction. Comparative experiments were conducted without any conditioning in summer, and the experimental results show that due to the covering of the retro-reflective materials, the peak temperatures of the indoor air and the inner surfaces were decreased up to 8 °C and 10 °C, while the outer surface peak temperature was reduced up to 25 °C. Through a comparison of the walls in different orientations, the top, south and east walls were found to be better choices for covering with the retro-reflective materials. To explore the influence of retro-reflective materials on the inner surface heat flow, a one-dimensional wall heat transfer model was built for four typical walls with an indoor constant temperature of 25 °C, and this model was verified by the experimental data. The numerical results showed that, due to the addition of the retro-reflective materials, the inner surface heat flow can be reduced by more than 30%, and the outer surface peak temperature can be reduced by 10–20 °C, clearly demonstrating that retro-reflective materials can reduce the outer surface temperature effectively.

1. Introduction

Due to the high population density, the large number of buildings, the high energy consumption, and the lack of green, water and land spaces in cities, building outdoor thermal environments have become increasingly worsened [1] and one obvious phenomenon observed is the urban heat island, whose main characteristic is the systematic increase of the air temperature in the urban environment, compared to the rural one [2]. The main outcomes caused by the urban heat island are a deterioration of the outdoor climatic conditions [3] and the indoor thermal environment [4] in summer, an increase of energy consumption in cooling [5] and an increase of polluting emissions [6]. With the continuous improvement in living standards and comfort requirements, a vast amount of air-conditioning and heating equipment is widely used. Due to the urban heat island effect, more energy will be consumed for the improvement of the thermal environment and such energy consumption will worsen this effect. Therefore, a vicious circle is being built between the worsening of the urban heat island effect and the increase of energy consumption. It is therefore a very urgent task to improve the exterior thermal environment of buildings and reduce building energy consumption.

Heat island intensity measurement in certain cities is gaining attention. Busato et al. [7] experimentally researched the urban heat island intensity in Padua, Italy for three years, and showed that the presence of an urban heat island in urban zones can increase the outer temperature by 6 °C. The experimental results of Lokoshchenko [8] showed that the heat island intensity in Moscow was as high as 14 °C, usually at night or in the early morning. Similar research by George et al. [9] showed that the urban heat island intensity in winter was stronger than that in summer.

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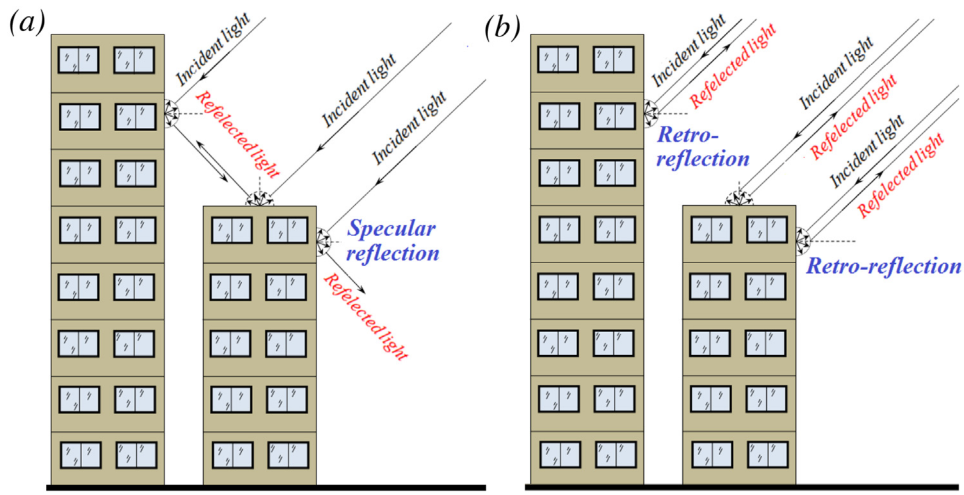

Fig. 1. Example of solar radiation reflected by outer building surface covered by (a) highly reflective materials and (b) retro-reflective materials [20,21].

In addition, Eduardo [10] researched the urban heat island and its effects on the indoor comfort at the social housing dwellings in Curitiba (25.5°S), located within a region of subtropical climate in elevation, and showed that there was an increase in the heat stress, especially in low-cost houses, and that the urban heat island was responsible for the more substantial effect on the indoor thermal discomfort in summer. Wu et al. [11] assessed the spatial structure effects of land use on the urban heat island effect in Wuhan, China, and showed that urbanization played a major role and that water resources can alleviate this effect significantly. Moreover, the research of Rizwan et al. [12] showed indirect solar heating, the heat re-radiated by the urban structures and anthropogenic heat, plays an important role, especially in the urban heat island. Specialized urban design can promote the urban heat island reduction, but it is so complex that it is not yet a practical approach.

From the above research, a reasonable urban layout and increase of water and green spaces are the main methods to alleviate the urban heat island effect, but these methods often have poor feasibility owing to fixed urban layouts and planning, and the high cost of municipal reform. Urban areas are growing rapidly and urbanization is an inevitable trend, especially in developing countries such as China [13,14]. Therefore, there is an urgent need for a simple and feasible technology to alleviate the urban heat island effect. In addition, due to the rapid growth of urbanization, high-rise buildings with light-weight envelopes are widely built due to the shortage of both available urban building area and construction materials [15]. However, due to the low thermal resistance and the small thermal inertia of such building envelopes, the indoor air temperature varies with large amplitude, and the building energy consumption is high [16].

Absorbed solar radiation by the building outer surfaces is an important part of the wall heat gain and reducing the heat gain from solar radiation can be an effective method to alleviate the urban heat island effect and reduce the air-conditioning load caused by wall heat transfer. At present, the highly reflective materials (or cooling materials [17]) are the predominant choice to reduce the heat gain of the opaque enclosure from solar radiation due to the fact that they are optically functional materials which are characterized by a high solar reflectance and high infrared emittance values [18]. There are currently a number of highly reflective materials commercially available for buildings and other surfaces in the urban environment, having a high solar reflectance values ranging from 0.4 to 0.85. The thermal emissivity of these materials was measured to be about 0.9 [19]. Their main function is to reflect the solar radiation by the diffuse reflection in a thin layer. However, this diffuse reflection only reduces the heat gain of the target building but increases the heat gain of the surrounding buildings. So highly reflective materials behave differently in reducing the comprehensive urban heat gain.

To overcome this shortcoming of diffuse reflection for highly reflective materials, retro-reflective materials are proposed due to the fact that they can reflect the solar radiation back in the opposite direction, also in a thin layer, which is different from the specular reflection of highly reflective materials [20]. Retro-reflective materials are optically functional ones which have a high solar reflectance values ranging from 0.5 to 0.85, including the retro-reflectance values of about 0.2–0.45[20].

Fig. 1 shows the examples of solar radiation reflected by outer building surface covered by (a) highly reflective materials and (b) retro-reflective materials comparatively [20,21]. As shown in the figure, retro-reflective materials can reflect light back along the incident direction, thus it can partially solve this problem by preventing the reflected light from reaching neighboring buildings and roads. Therefore, retro-reflective materials can decrease the urban comprehensive heat gain, thereby improving the building temperature conditions.

However, there is lack of relative research on retro-reflective materials. Sakai et al. [22] and Nishioka et al. [23] were the first to research these retro-reflective materials and measure their retro-reflective properties. Yuan et al. [20] proposed a method to measure the retro-reflectance and durability of retro-reflective materials for building outer walls and measured the changes in solar reflectance and retro-reflectance of retro-reflective materials exposed to the outdoors over about 25 months. Meanwhile, Yuan et al. [21] studied the accuracy of the method proposed in Yuan et al. [20] on determining the retro-reflectance of retro-reflective material by means of a heat balance. In addition, Yuan et al. [24] researched the effect of retro-reflective materials on building cooling loads. Rossi et al. [25,26] assessed the angular reflectance of retro-reflective films for several inclination angles of solar radiation and the urban heat island mitigation of capsule retro-reflective materials. The above research paid more attention to the retro-reflective properties, and however, the effect of the engineering application is still lacking. Therefore, it is necessary to do systemic research on the influence of retro-reflective materials on building temperature conditions and energy consumption in cooling.

According to the above problems, two building models were built, one of which covered retro-reflective materials and the other taken as a comparative one, without any conditioning in Chengdu, China. And numerical research was then done on the reduction