Effects of modified near-infrared retro-reflective film on urban thermal environment

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Abstract. We investigated the specifications of a modified retro-reflective film for the window surfaces of buildings that reflects the near-infrared component of incident solar radiation upward toward the sky in order to reduce the indoor cooling load in the building and improve the thermal environment of the surrounding urban area. With the previous specifications, there were concerns that the near-infrared component, reflected upward away from one building, would strike the upper portions of neighboring buildings. To minimize this effect by reflecting as much radiation as possible back along the incident direction, we evaluated the modified film structure, replacing a saw-tooth section model with a pyramid-type microstructure model. In order to investigate its merits and quantitatively assess the impact of this technology on surrounding urban areas, annual simulations with this modified film were performed, using simple block model, actual city model and the results of an experimental study.

1. Introduction

In recent years, window glass that selectively reflects the near-infrared (NIR) components of incident solar radiation, such as Low-E (low-emissivity) double-glazed glass, has been widely used to reduce air-conditioning loads and improve indoor building environments. With such glass, however, much of the NIR component of incident solar radiation is simply reflected downward into the surrounding neighborhood, leading to significant deterioration in the thermal radiation environment. In response, we have proposed and developed a retro-reflective film for NIR solar radiation. Reflecting a higher proportion of incident solar radiation upward toward the sky should increase the reflectance of the city overall and decrease the total amount of thermal energy absorbed within it, thus alleviating the heat island phenomenon.

In the previous reports [1] [2], we addressed concerns that the NIR retro-reflective film with an embedded saw-toothed microstructure (“saw-tooth type film”) would adversely affect the upper floors of nearby buildings as a result of reflecting solar radiation upward toward the sky (opposite its direction of incidence). For a countermeasure, here we propose a film that has a pyramid-shaped embedded microstructure (“pyramid-type film”) capable of retro-reflecting incident solar radiation and thereby reducing the reflective load on nearby buildings (Figure 1). In this study, we constructed models of urban districts comprising medium- and high-rise buildings and, with reference to these models, we calculated the amount of upward reflected solar radiation when using saw-tooth type film and determined the impact of retro-reflection onto nearby buildings. We also experimentally investigated the ability of the pyramid-type film to alleviate this impact.
2. Investigation of the upward reflectivity of retro-reflective film

Retro-reflective film has a special embedded reflective structure and thus requires consideration of differing window specifications and angle of incidence characteristics. Here, to better accommodate arbitrary values for solar height and azimuth, we focused on the reflectivity characteristics of NIR components with consideration of angle of incidence (Figure 2), rather than profile angle. Using these reflectivity characteristics, we calculated the annual amount of reflected solar radiation for a saw-tooth type film.

We obtained the amount of direct solar radiation in Tokyo (latitude N35.6°) using the Bouguer equation and, from this, determined the direct solar radiation for clear days. The annual average of the upward NIR reflectance ratio was 0.20 for the south facade and 0.18 for the west face. The amount of upward reflectance of the retro-reflective film on these facade was large, suggesting a possibility of substantially reducing the amount of solar radiation absorption within the city.

3. Saw-tooth type film: impact of retro-reflective components on neighboring buildings

3.1. Overview of simulation

To investigate the impact on nearby buildings, we performed simulations using the saw-tooth type film. To ensure a degree of generality, we first conducted simulations with two types of simplified high-rise city block models (Figure 3). One type assumes square prism shaped buildings with a 60*60 m base, arranged on a grid. The variables in this model are building height and the spacing between adjacent buildings. The other type is a simplified representation of an existing high-density area in central Tokyo (Figure 4).

To create these models, we used Rhinoceros with the Grasshoppper plugin. For analysis of solar radiation, we used Radiance, a simulation program for lighting environments. Ladybug + Honeybee, which run on Grasshoppper, were used as an interface. Here, we define effective reflected rate as the proportion of solar radiation reflected upward toward the sky without striking a nearby building (Figure 5).
We calculated the effective reflected rate by dividing (i) the effective amount of reflected solar radiation with the saw-tooth type film (which reflects rays to the same height at a reverse angle of incidence by (ii) the effective amount of reflected solar radiation with a corner cube prism (CCP) which reflects solar radiation back in its direction of incidence; see Figure 5(a)). Each of these two effective amounts of reflected radiation is imparted to one evaluation surface, with an evaluation plane height set to correspond to the building height. The evaluation itself is of the amount of solar radiation reflected from a lower level toward a higher level. At this stage, we assumed that all façades, road surfaces, rooftops, and other objects in the urban environment other than the film-attached surfaces were ideal black bodies, thereby allowing us to limit our analysis to single reflections. Effective reflections from CCP and saw-tooth type surfaces are illustrated in Figure 5(b)(c).

3.2. Investigation with a simple block model

During summer, the influence of building height was comparatively small, and the effective reflected rate were between 0.95 and 1.0. In terms of the influence of building spacing, the value at a spacing of 120 m (gross building coverage of 11%) was very high, at about 0.95 throughout the year for the southern and western faces. Even at a building spacing of 35 m (gross building coverage of 40%, corresponding to a model of actual downtown Tokyo; Figure 4), the effective reflected rate declined only slightly in the winter for south faces and in summer and spring/fall for western faces. In the summer, when countermeasures against heat are particularly important, the value was high independent of building spacing. Figure 6 shows average effective reflected rates by time of day for representative summer and spring/fall months. While there are time periods when the value declines the results nonetheless show that a high effective rate is obtained overall, independent of building density. In other words, only a small proportion of upward reflected solar radiation strikes a neighboring building and most is reflected back into the sky.
3.3. Investigation with an actual city model

The actual city model (Figure 4) depicts the actual placement of buildings within an area of central Tokyo. For the surrounding areas, the same blocks are presumed to extend to infinity.

Figure 7 compares the effective reflected rates and amounts of solar radiation (vertical surface) between this model and the simple block model (which has a similar gross building coverage of 40%). When retro-reflection specifications were assigned to south and west facades, high effective reflected rates of 0.8 and above were maintained throughout the year. Little difference was observed in annual average values between the simple block model and the actual city model. This suggests that the saw-tooth type film could likely offer an effective solar radiation countermeasure even in situations where, as in actual city blocks, buildings of irregular shape are placed at non-uniform spacings.

Figure 6. Calculation results of effective reflected rate

Figure 7. Comparison of effective reflected rate between simple block model and actual city model

We also investigated effective reflectance in a manner that includes road surfaces, rooftops, and all other urban coverings. We assumed the reflective characteristics of road surfaces and rooftops to be uniform scattering. Then, we calculated the amount of effective reflected solar radiation by multiplying the amounts of reflected solar radiation at 5m grids by a sky factor at each grid point.

Figure 8 shows amount of incoming solar radiation (horizontal plane) for each surface and the effective reflected rates. Vertical surfaces account for the largest proportion of urban surfaces, showing the importance of taking measures for such surfaces. Vertical surfaces maintain high effective reflected rate values throughout the year but exhibit increases to particularly high values (0.9 and above) during the summer.
We calculated the amount of effective reflected solar radiation for each surface as well as the urban effective reflectivity with and without retro-reflective film. The results are shown in Figure 9. When all vertical faces of the buildings were covered with retro-reflective film, urban reflectivity increased by roughly 7% to 8%, indicating high effectiveness for reducing the amount of incoming solar radiation heat.

4. Experimental study of the interior/exterior thermal impact of pyramid-type film

We measured the spectral transmittance of solar radiation and solar heat gain coefficient of four glass specifications: (1) transparent single-glazed glass (FL) with saw-tooth type film (FL + saw-tooth type); (2) FL with pyramid-type film (FL + pyramid type); (3) solar-shading Low-E double-glazed glass (Low-E); and (4) transparent single-glazed glass (FL). Figure 10 shows measured solar heat gain coefficient. The two retro-reflective specifications selectively suppressed the transmission of solar radiation in the NIR. There was little difference in solar heat gain coefficients between the two. Compared with FL glass, the two retro-reflective specifications have a low solar heat gain coefficient of about 0.2, indicating a high level of solar-shading performance.

Assuming use on west-facing windows, we measured the amount of downward reflected solar radiation with each window specification and sol-air temperature (SAT) at points of solar radiation reflection. Both the saw-tooth type and the pyramid type acted to suppress the amount of reflected solar radiation to approximately one-third of that measured with Low-E glass (Figure 12(a)). Furthermore, SAT at those points improved to a value nearly 10°C lower (Figure 12(b)). The suppressive effect on downward reflected solar radiation of the two retro-reflective specifications was equivalent.
Next, we measured upward and downward reflections and transmission amounts under these two window specifications at varying elevations of the sun by means of a spectroradiometer, splitting upward and downward reflected solar radiation into hemispherical halves as viewed from the spectroradiometer. The results are shown in Figure 13. With both specifications, the NIR region is retro-reflected upward; and a comparison of the proportion of upward reflected solar radiation (NIR) of the two specifications indicates general agreement. Depending on the location of solar radiation incidence, the proportion of upward reflected solar radiation (NIR) was lower in some cases with the pyramid-type film than with the saw-tooth type film. This is presumably because the pyramid-type film reflects light back along its direction of incidence, and so the shadow cast by the measurement apparatus itself can prevent complete measurement. To obtain a more detailed understanding of reflection directions, we took measurements upon shading three-quarters of a hemisphere as viewed from the light detector. Figure 13 shows a diagram proportional direction of reflection by quadrant. Measurements showed that with the pyramid-type film, a comparatively high proportion of upward reflected solar radiation is reflected back toward the quadrant of the sun.

5. Conclusion
This paper focused on retro-reflective films for NIR components of solar radiation, and based on the results of simulations with an urban simple block model and an actual city model, we showed that with the saw-tooth type film, a comparatively small proportion of upward reflected solar radiation strikes neighboring buildings, with much of it being reflected into the sky. Calculations on the effect of applying retro-reflective film on the vertical surfaces of an urban area revealed that this would have a comparatively large effect on reducing the associated amount of solar radiation absorbed within that urban area and would mitigate the heat-island phenomenon. Through actual measurements, we showed that the pyramid-type film has the same degree of effectiveness as saw-tooth type film in terms of thermal performance and environmental improvement within surrounding areas, and furthermore, that the pyramid-type film retro-reflects light back in the general direction of incidence, and thus has a higher likelihood of reflecting incident solar radiation back to the sky.

References
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