Evaluation of effects of retro-reflective window film on the outdoor thermal environment and cooling energy consumption using an urban canopy model considering the specular and retro reflections of solar radiation
鏡面反射・再帰反射を考慮した都市キャノピーモデルを用いた再帰反射フィルムによる屋外熱環境の改善効果及び省エネ効果の評価

2019年9月修了　環境システム学専攻　47-176818　方　儒玥（Fang Ruyue）
指導教員：井原　智彦　准教授

1. Introduction

The ongoing global warming and urban heat islands have resulted in a significant increase in the cooling energy consumption and the degeneration of urban thermal environment, especially in the central business district with a high density of population and buildings.

Recently, with the increasing window to wall ratio of office buildings, the heat shading window films (HSF) is spreading with the purpose of reducing the energy consumption of air conditioning in summer. However, the increase of the specularly reflected solar radiation from its surface will further degrade the thermal environment in outdoor spaces instead [1]. As its solution, the retro-reflective film (RRF), which allows to reflect the solar radiation back in the same direction of the incident radiation, is expected to be able to reduce building energy requirement for cooling and in the meanwhile improve the urban thermal environment during summer. In the previous studies, several field measurements have been conducted to estimate the effects of RRF on both indoor and outdoor radiant environments [2]. Besides, Yoshida and Mochida [1] evaluated the effects on the outdoor thermal comfort through CFD analysis on a simplified urban block model. However, the feasibility of the large-scale application of RRF to the exterior wall of buildings in actual urban areas has not been assessed, as well as its energy-saving potential.

What's more, for evaluating the effects on the outdoor thermal environment and on the cooling energy consumption simultaneously, a canopy model coupled with a building energy simulation model is necessary. However, most of them consider the window as a perfectly diffuse surface, which make it very hard to simulate the directional reflective behavior of retro-reflective films.

The main objective of this study to develop a new computational method of radiation heat transfer considering the specular and retro reflections of solar radiation in the CM-BEM model [3] first and then apply it to evaluate the impact of retro-reflective window films on the outdoor thermal environment and cooling energy consumption in the business district of Tokyo 23 wards.

2. Method

The numerical simulation system (WRE-CM-BEM) developed by Kikegawa et al. [3], which can explore the city-block-scale interaction between outdoor metrological conditions and energy consumption of air conditioning in buildings was utilized and improved in this study. A new calculation method of radiant heat transfer was established and incorporated into in the urban canopy model (CM) for calculating the directional reflection of solar radiation. The computational flow was shown in Figure 2

For radiant analysis, the window surface was assumed to be a perfect diffuse surface in the previous model. Of all the solar radiation incident on the ground and building walls, the amount of reflected solar radiation from the opposite window surfaces, indicated with R_{ref_w}, was calculated by the following equation.

$$R_{ref\_w} = \sum \left(R_{dir\_j} + R_{diff\_j}\right) \cdot P_j \cdot \rho \cdot a(j) \cdot \mu$$

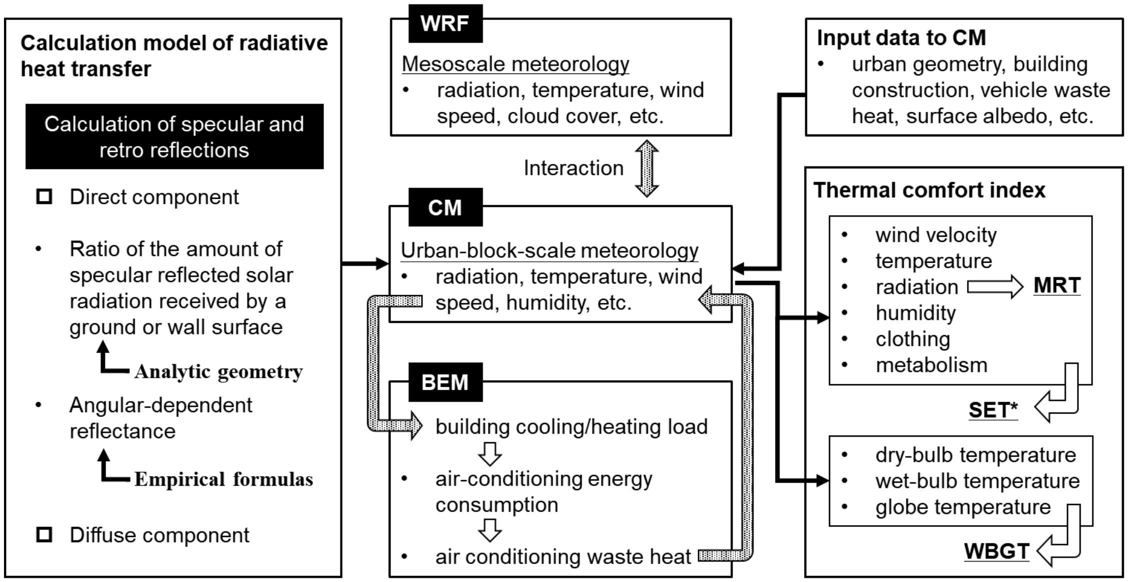


Figure 2. The computational flow

Where the subscripts j denotes the number of floors of adjunct building walls. $a(j)$ $(-)$ denotes the jth floor density, representing the building density at the vertical level. μ denotes the window to wall ratio. R_{dir_j} (W) and R_{diff_j} (W) denote the direct and diffuse solar radiation gains to the jth floor window surface, respectively. P_j denotes the proportion of the amount of reflected solar radiation reaching the receiving surface to the total amount from window surface. And ρ is the reflectance of window.

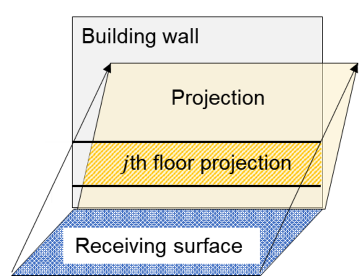
In the new model, with the consideration of specular and retro reflections of solar radiation, the calculation equation of R_{ref_w} was extended as follows:

$$R_{ref\_w} = \sum \left[R_{dir\_j} \cdot P_{d\_j} \cdot \rho_d(\theta) + R_{diff\_j} \cdot P_{df\_j} \cdot \rho_{df} \right] \cdot a(j) \cdot \mu$$

Where P_{d_j} $(-)$ and P_{df_j} $(-)$ denote the direct and diffuse components of P_j, respectively. ρ_s $(-)$ indicates the reflectance of the window surface generated by diffuse solar radiation with a constant value while $\rho_d(\theta)$ $(-)$ indicates the angular-dependent reflectance generated by direct solar beams. θ is defined as the angle between the sun's rays and the normal line to the window surface.

A method based on analytic geometry was established to calculate the value of P_{d_j} $(-)$. As illustrated in the right figure, the reflected solar beams from the wall areas where the projection is located, could reach the receiving surface. Thus, the ratio of the projection area on jth-floor (S_j) to the jth-floor wall area (A) is equivalent to the value of P_{df_j} as showed in the following equation.

$$P_{df\_j} = \frac{1}{A} S_j$$



In addition, the value of P_{df_j} $(-)$ was calculated using the method proposed by Kondo and Liu [4]. The values of $\rho_d(\theta)$ are obtained with the empirical formulas. And the ρ_s $(-)$ is average value of $\rho_d(\theta)$, being calculated through the equation proposed by Siegel and Howell [5].

Figure 2 and Table 1 show the optical properties of single float glass (SFG), heat shading film and retro-reflective film (RRF) used in this study.

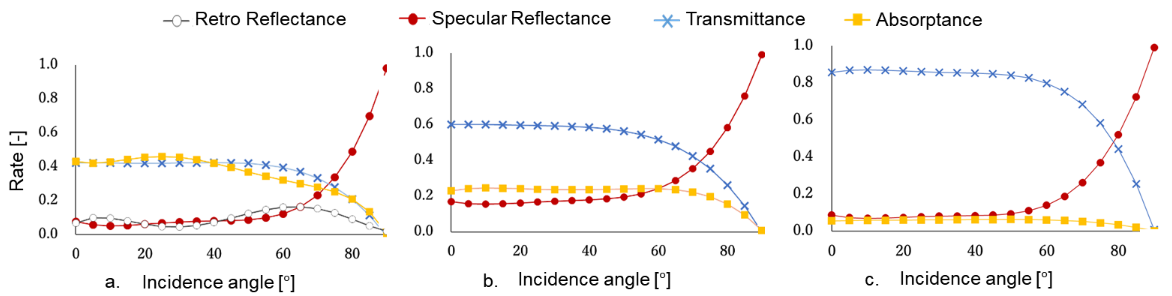


Fig 2. Variations of reflectance, transmittance and absorptance with incidence angles to window surface. (a) RRF; (b) HSF; (c) SFG

Table 1. The average values of the optical properties of each window surface

	Specular reflectance	Retro reflectance	Transmittance	Absorptance
Single-float glass	0.268	/	0.682	0.050
Single-float glass with HSF	0.350	/	0.446	0.204
Single-float glass with RRF	0.251	0.103	0.333	0.313

3. Simulation conditions

The evaluation was conducted in the business areas as 0.5-km grids in Tokyo 23 wards from July 27, 2006 to August 31, 2006 using the meteorological data obtained from WRF model. The total number of simulated blocks was 465. Two thermal indices were selected as evaluation indicators: mean radiant temperature (MRT) and wet bulb globe temperature (WBGT). The window to wall ratio (WWR) was set to 0.33 for typical office building and 0.9 for the building with glass curtain wall.

4. Results

For the effects on the outdoor thermal environment, the simulated results of a cloudless sunny day (August 5) was chosen to be analyzed. Figure 3 shows the time variation of average ΔMRT (HSF-RRF). The value maximized at 9:00 (0.29 °C) and 15:00 (0.26 °C), while it became not obvious at approximately noon when the outdoor thermal environment is worse. Figure 4 shows the distribution of ΔMRT (HSF-RRF) at 15:00. The values are larger in the central business areas near Tokyo station. By comparing with the heat disorder risk map obtained by Ohashi et al. [6], those areas with the high heat disorder risk also have larger value of ΔMRT (HSF-RRF). Subsequently, a strong positive correlation ($R^2 = 0.8$) was found between building coverage (BC) and ΔMRT (HSF-RRF) through the linear regression analysis. Furthermore, the effects on the heat illness risk were also evaluated in this work. The grades of heat illness risk are determined by maximum WBGT. Due to the installation of RRF, the number of "danger" blocks ($\mathrm{WBGT}_{max} > 31$°C) reduced by 14 and 24 in the case with WWR of 0.33 and 0.9, respectively.

For the effects on the cooling energy consumption, four cases with different BC and WWR were investigated. As shown in Table 2, for all windows, the cooling energy consumption increased with the reduction of BC and the increase of WWR. Both the installation of HSF and RRF reduced the energy consumption and the reduction effect of RRF was larger than HSF for all cases. Moreover, the value of Δ (RRF−HSF) and Δ (RRF−SFG) also increased as the BC decreases. It is indicated that energy-saving effect of RRF is more significant where the more energy is consumed (low density and high WWR).

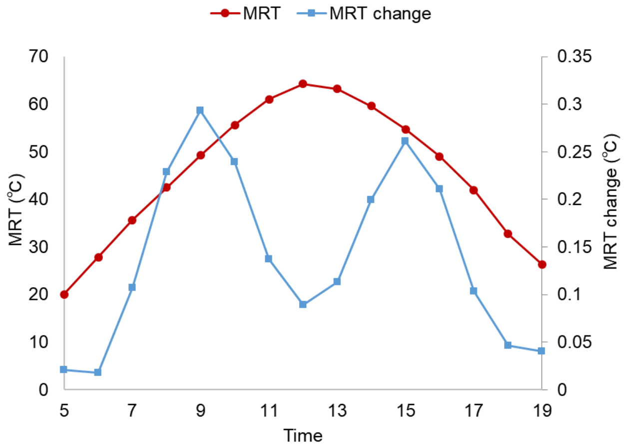


Fig 3. Time variation of ΔMRT (HSF-RRF)

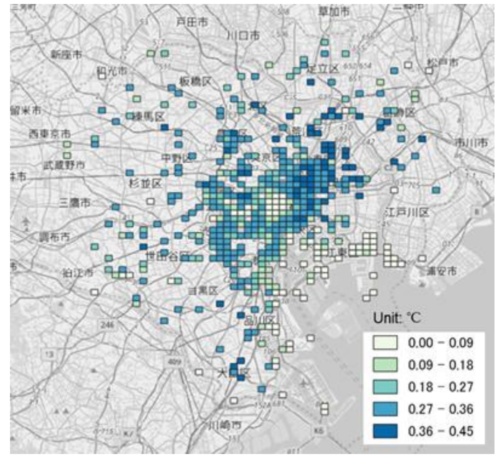


Fig 4. Grid map of ΔMRT (HSF-RRF) at 15:00

Table 2. Total amount of cooling energy consumption in August in each case (Units:kWh · m^{-2})

	SFG	HSF	RRF	Δ (RRF−SFG)	Δ (RRF−HSF)
BC=0.47, WWR=0.33	15.74	15.49	15.37	-0.37 (-2.3%)	-0.12 (-0.79%)
BC=0.33, WWR=0.33	16.70	16.41	16.28	-0.42 (-2.5%)	-0.13 (-0.82%)
BC=0.19, WWR=0.33	16.72	16.41	16.28	-0.44 (-2.6%)	-0.14 (-0.83%)
BC=0.47, WWR=0.9	17.82	17.12	16.74	-1.07 (-6.1%)	-0.38 (-2.2%)

Conclusion

In this study, the effects of retro-reflective window films both on the outdoor thermal environment and cooling energy consumption were assessed in the business district of Tokyo 23 wards. It is revealed that the improvement effects on the outdoor thermal environment become larger in the high-density areas with a worse thermal environment, and the energy-saving effects increase in the low-density areas where more cooling energy is consumed.

Since the retro-reflective film may cause the opposite effects in winter, the annual evaluation should be addressed. Moreover, as another important influence factor on urban thermal environment, the impact of urban orientation on the performance of retro-reflective film also need to be assessed in the future.

Reference

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