Energy Proceedings
Vol 32, 2023
ISSN 2004-2965

Design Analysis of Building Radiative Cooling Windows in Infrared Band: Regularity Exploration and Universality Verification

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ABSTRACT

Research on radiative cooling windows suitable for hot climate regions is a hot topic of building energy conservation. Most existing researches default that windows should be ideal radiators with high emissivity($\varepsilon_{\lambda} \sim 1$) in wide infrared band ($2.5 \sim 20\mu m$). However, the universality of such an assumption is unproven. To explore the optimal design scheme of emissivity of radiative cooling windows in infrared band, Comsol Multiphysics software was used to simulate the building with radiative cooling windows, and the reliability of the model was verified by experiments. First, based on the spectral properties of ordinary glass, the window with different outer surface emissivity in the atmospheric window (AW, $8\text{-}13\mu m$) and remaining infrared bands (RIB, $2.5\text{-}8\mu m \,\&\, 13\text{-}20\mu m$) were simulated by traversal. Second, the influence of emissivity in the above two bands on radiative cooling effect of the window and the building was studied. Finally, the radiative cooling potential of the window in these two bands was compared. The results show that the lower the RIB emissivity ($\bar{\varepsilon}_{RIB}$) of the window outer surface in daytime, the more favorable the radiative cooling of the window. As the solar radiation decreases, it gradually changes to the larger the $\bar{\varepsilon}_{RIB}$ is, the more favorable the radiative cooling of the window. At different time periods, the adjustment trend of the $\bar{\varepsilon}_{RIB}$ to radiative cooling may be reversed. Through data analysis, compared with the high emissivity in wide infrared band design, it is more beneficial to reduce the window and indoor air temperature by reducing the $\bar{\varepsilon}_{RIB}$ of the window outer surface as much as possible. Smaller $\bar{\varepsilon}_{RIB}$ reduces the heat flow into the room and extends the time that the window becomes a "cooler" during the day. In addition, the temperature regulating effect of the window emissivity in AW is almost 8-9 times that in RIB, and the energy regulating effect is almost 9-11 times that in RIB. This work clarifies the default assumption of non-universality of building radiative cooling windows in infrared band and quantifies the importance of the atmospheric window in radiative cooling of building windows, which can provide valuable guidelines for material developers.

Keywords: Radiative cooling windows, Infrared emissivity, Building energy conservation, Numerical modeling

NONMENCLATURE

Abbreviations	
AW	Atmospheric window
RIB	Remaining infrared bands
VTRC	Visible transparent radiative cooling
Symbols	
T_w	Window temperature
T_{air}	Indoor air temperature
$\bar{\varepsilon}_{RIB}$	The RIB emissivity of the window
$\bar{\varepsilon}_{AW}$	The AW emissivity of the window
ΔT_{WR}	Window temperature regulating effect
ΔT_{AR}	Air temperature regulating effect
ΔE_R	Energy regulating effect

1. INTRODUCTION

It is reported that more than one third of the world's final energy consumption is attributable to the construction industry. Especially in hot climates, the vast majority of a building's operating energy consumption is used for cooling. As an important channel for heat

This is a paper for Applied Energy Symposium 2023: Clean Energy towards Carbon Neutrality (CEN2023), April 23-25, 2023, Ningbo, China.

exchange between indoor and outdoor environments, windows are the weakest link in the building envelope. Special structures or films have been developed to regulate the spectral properties of windows, such as visible transparent radiative cooling (VTRC) films. This kind of film uses the atmospheric window (AW, 8-13 μm) to transfer the thermal radiation from the window to the cold outer space (~3K), taking into account the photothermal regulation of the window and realizing the passive cooling of the building[1, 2].

In order to enhance the passive radiative cooling (RC) effect of windows, the design of the infrared spectral (2.5-20 μm) emissivity of the outer surface is crucial. The spectral emissivity in AW is usually pursued close to the design standard of 1. However, in the remaining infrared bands (RIB,2.5-8 μm &13-20 μm) of non-atmospheric windows, in order to pursue more radiative cooling power, in most application scenarios, material designers default to the design criteria for ideal radiators with high emissivity (~1) in the wide infrared band [1, 2]. Some studies have also adopted another design criteria for ideal radiators with high emissivity only in AW and low emissivity only in RIB[3]. At present, high emissivity in the wide band is a widely adopted design idea, which is also assumed to be optimal and universal by default. However, its universality is unproven, and there may be counter-examples.

In addition, the few design discussions on the emissivity in RIB are confined to steady-state analysis and theoretical assumptions, and are isolated from the building as a whole. There are few studies on the overall effect after it is embedded into the building as a component[4]. Thus, the "unspoken rules" for the design of the emissivity in RIB are vague and ill-considered.

Therefore, for the window, whose transient temperature fluctuates up and down the ambient temperature, it is particularly necessary to conduct a detailed analysis of the characteristics of the emissivity of its outer surface in RIB, combined with its characteristics in the operation of the building.

Based on the above analysis, the authors focus on the influence of the RIB emissivity of the RC window outer surface on radiative cooling effect. First, COMSOL Multiphysics software was used to establish a 3D architecture model based on the finite element method, and the correctness of the model was verified by experiments. Then, aiming at Haikou, China, a typical hot climate city, the infrared emissivity of the outer surface of the building window was calculated through traversal in two bands: AW and RIB. Through the analysis of the regularity of the temperature and heat flow, the optimal design scheme of the RIB emissivity of the window outer surface is obtained by simulating the hourly variation trend and variation degree of radiative cooling performance of actual building windows. Finally, given that the AW has been a major concern band of RC, the radiative cooling potential of the window outer surface in AW and RIB is quantified and compared.

2. NUMERICAL MODELING

2.1 Building model

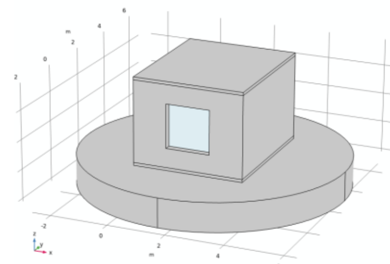

Fig. 1. Schematic diagram of the building model.

In this paper, COMSOL Multiphysics software was used to establish a three-dimensional building model based on finite element method, as shown in Fig. 1. The geometric dimensions of the building are: depth of 4 m, width of 3.3 m and height of 2.8 m. There is a 1.5m ×1.5m window in the centre of the west wall. The basic thermal parameters of each building envelope and soil are shown in Table 1. The emissivity of the inner surface of all walls is 0.96 and that of the remaining surface is 0.90. The solar absorptivity of the inner and outer surfaces of the wall and the roof are 0.21, 0.60 and 0.69, respectively. Since the research in this paper focuses on the spectral properties of glass windows, the spectral properties of ordinary 6mm glass as a reference are also experimentally measured.

Table 1. The thermophysical parameters of building envelopes and soil.

	Wall	Ceiling/Floor	Window	Soil
k / $W \cdot m^{-1} \cdot K^{-1}$	0.58	0.18	0.76	0.3
ρ / $kg \cdot m^{-3}$	1400	700	2500	800
c_p / $J \cdot kg^{-1} \cdot K^{-1}$	1050	1050	840	1500
δ / mm	240	100	6	1000

2.2 Selection of meteorological parameters

Considering the application background of radiative cooling, a city in the tropical region -- Haikou, China (20.03°N, 110.32°E) was selected for the simulation. The simulation study lasted for one week, from 6:00 am on July 6 to 6:00 am on July 13. The weather data for simulation are provided from the EnergyPlus website in a typical meteorological year format, including the temperature, solar radiation, relative humidity and wind speed.

2.3 Model settings

In Comsol Multiphysics, set indoor air exchange rate for 1 time/h. In surface-to-surface radiation module, several spectral bands are divided according to the infrared spectral properties of the ordinary glass. The surfaces of the corresponding envelopes of the building and the ground surface are set as diffuse surfaces, and the relevant settings are made according to the defined surface radiation properties. The atmospheric emissivity was set by relevant empirical formulas in the study of Kwan et al. [5]. The initial temperature value of the whole system is set as the ambient temperature value at the initial moment. The relevant governing equations and boundary conditions are shown in Table 2.

Table 2. Governing equations and boundary conditions.

Governing equations:	$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \boldsymbol{u} \cdot \nabla T + \nabla \cdot (-k \nabla T) = Q$ (1)
	$J = \varepsilon e_b(T) + \rho G$ (2)
Boundary conditions:	
Solar radiation absorbed by envelopes	$q_{abs} = \int \alpha_s(\lambda) I_{solar}(\lambda) d\lambda$ (3)
Convective heat transfer	$q_0 = h_0 (T_{ext} - T)$ (4)
Windowsill and building bottom	$-\mathbf{n} \cdot \boldsymbol{q} = 0$ (5)

2.4 Meshing

In this study, unstructured tetrahedral mesh was used, and the mesh size was customized by the user. Grid independence analysis was carried out to determine the minimum number of grids necessary to reduce the computational cost without loss of accuracy. Finally,the total number of meshes selected is 180,585 elements for further simulation analysis.

3. MODEL VALIDATION

In order to verify the accuracy of COMSOL simulation results, a full-scale outdoor experiment was conducted in Hefei, China in February 2023. The internal dimensions of the test room are 2.9m×1.8m×1.8m (length × width × height). The opaque envelope throughout the room is made of polyurethane, and the interior and exterior are wrapped in colored steel. The thickness of the walls and roof is 10cm, and the floor of the room is thickened to 15cm. The south direction of the test room is a glass curtain wall, the glass size is 1.66m×1.66m, and its thickness is 5.7mm. Its photograph is shown in Fig. 2 (a).

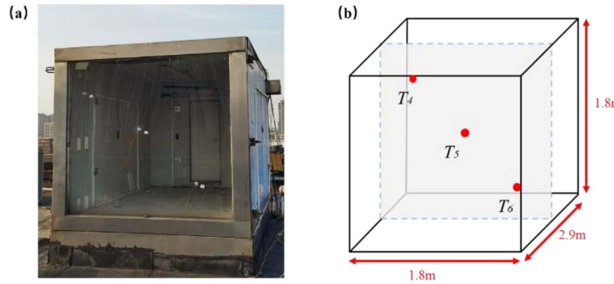

Fig. 2. (a) The photo of the test room. (b) Schematic diagram of indoor measurement point layout.

A total of 9 Type T thermocouples are arranged in three vertical planes equidistant in the room for measuring indoor air temperature. The position of measuring points is shown in Fig. 2 (b) (taking the central vertical plane as an example). The arrangement of glass measuring points is the same as that of the indoor vertical plane.

The window temperature (T_w) and the indoor air temperature (T_{air}) are selected as evaluation indexes. The experimental and simulation results of the two indexes are shown in Fig. 3. The CV (RMSE) values of the south window temperature and the indoor air temperature are 5.44% and 5.72%, respectively, far less than the 30% error upper limit stipulated in ASHRAE guidelines.

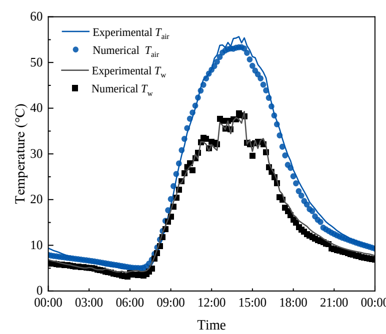

Fig. 3. Experimental verification of simulation results: Indoor air temperature and window temperature.

4. RESULTS AND DISCUSSIONS

This section will keep the remaining spectral properties of ordinary glass windows unchanged, and only perform traversal calculations (0-1 every 0.1) on the average emissivity of the outer surface of the window in RIB and AW ($\bar{\varepsilon}_{RIB}$ and $\bar{\varepsilon}_{AW}$), respectively. Focusing on the influence on the radiative cooling effect of the window itself and the radiative cooling effect of the building interior.

4.1 The window radiative cooling result of traversing the $\bar{\varepsilon}_{RIB}$

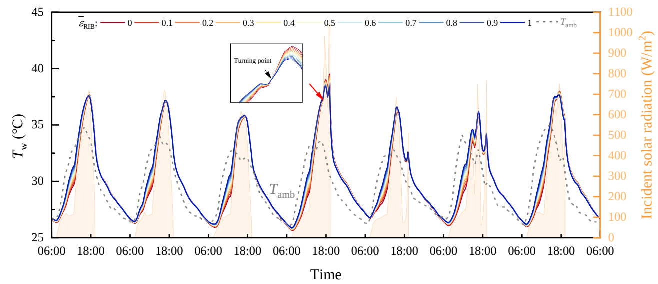

Fig. 4. Window hourly temperature under different $\bar{\varepsilon}_{RIB}$.

Fig. 4 shows the hourly variation of window temperature under different $\bar{\varepsilon}_{RIB}$. From the degree of density between curves, it can be seen that increasing $\bar{\varepsilon}_{RIB}$ (red curve - blue curve) has no significant influence on window temperature. However, the trend and magnitude of the influence vary from hour to hour. In different time periods, there may be two trends: the bigger the $\bar{\varepsilon}_{RIB}$, the more favorable the window temperature decreases and the smaller the $\bar{\varepsilon}_{RIB}$, the more favorable the window temperature decreases. The influence of the increase of $\bar{\varepsilon}_{RIB}$ on the window temperature is reversed (shown in the enlarged area in Fig. 4).

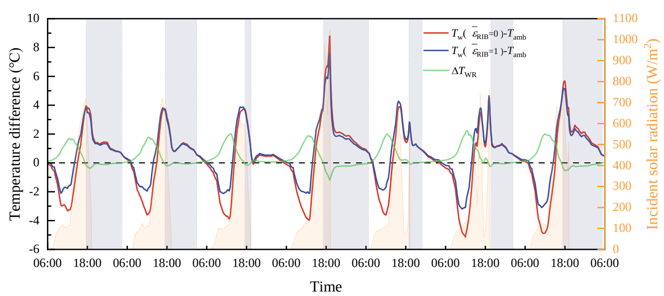

Fig. 5. Temperature difference between window and environment when $\bar{\varepsilon}_{RIB}$ decreases from 1 to 0 and ΔT_{WR}.

In order to investigate the influence degree of changing $\bar{\varepsilon}_{RIB}$ on window temperature under the above two trends. The index of window temperature regulating effect ΔT_{WR} is defined here, and the unit is °C. The index has positive and negative values. The positive value indicates that the temperature of the window decreases and its radiative cooling effect is enhanced. Negative values indicate that the temperature of the window increases and its own radiative cooling effect decreases. In addition, the larger the absolute value, the more obvious the enhancement/weakening effect. The specific expression is:

$$\Delta T_{WR} = \begin{cases} T_{w(\bar{\varepsilon}_{RIB}=1)} - T_{w(\bar{\varepsilon}_{RIB}=0)}, & \bar{\varepsilon}_{RIB}(1 \to 0) \\ T_{w(\bar{\varepsilon}_{RIB}=0)} - T_{w(\bar{\varepsilon}_{RIB}=1)}, & \bar{\varepsilon}_{RIB}(0 \to 1) \end{cases} \quad (6)$$

Fig. 5 shows the temperature difference between the window and the environment and the hourly change of ΔT_{WR} (green curve) when $\bar{\varepsilon}_{RIB}$ decreases from 1 to 0. Time periods when the larger the $\bar{\varepsilon}_{RIB}$ is, the lower the window temperature is (ΔT_{WR}<0) are marked with blue bars. It can be seen that in the period when ΔT_{WR} is negative, the value of ΔT_{WR} is close to 0, with an average value of -0.16 °C. That is to say, when $\bar{\varepsilon}_{RIB}$ increases from 0 to 1, it has weak regulating effect on window temperature. In the period when ΔT_{WR} is positive, the absolute value of ΔT_{WR} is larger, with a maximum value of 2.23°C and an average value of 0.68°C. Combined with the duration analysis, when $\bar{\varepsilon}_{RIB}$ decreases from 1 to 0, the duration proportion of ΔT_{WR} being positive (white bar area) is longer, and the absolute value of positive is larger. According to the specific data statistics, this period is 108.3 hours, accounting for about 64.5% of the total time of the study. Therefore, a smaller $\bar{\varepsilon}_{RIB}$ design is recommended to enhance the radiative cooling effect of the window for both the duration ratio and the degree of the effect.

The above results show that when the window temperature is higher than the ambient temperature in most of the time, not all design surfaces adopt a larger value of $\bar{\varepsilon}_{RIB}$ will be more conducive to the radiative cooling of the window. According to the data statistics, the window temperature was higher than the ambient temperature for a total of 108.5 hours under different $\bar{\varepsilon}_{RIB}$, accounting for 64.6% of the total time, but the simulation results still show that the use of smaller $\bar{\varepsilon}_{RIB}$ during the study period is more conducive to the radiative cooling of the window.

4.2 The indoor radiative cooling result of traversing the $\bar{\varepsilon}_{RIB}$

Fig. 6 shows the net infrared radiant heat flux between the inner surface of the window and each indoor wall, as well as the convective heat transfer flux between the inner surface of the window and indoor air. In Fig. 6, a positive heat flux means that the window absorbs the heat from the room, and a negative heat flux means that the window emits the heat into the room. It can be seen that the trend reversal phenomenon similar to Fig. 4 occurs in both heat fluxes. Among them, the period when the larger the $\bar{\varepsilon}_{RIB}$ is, the more favorable it is for indoor radiative cooling is still marked as the blue strip area. It is beneficial to indoor radiative cooling, which is manifested as more heat absorbed from the room or less heat released into the room. The conclusion that the effect of changing $\bar{\varepsilon}_{RIB}$ on the heat flow is similar to that of window temperature. In terms of both duration ratio and effect degree, smaller value of $\bar{\varepsilon}_{RIB}$ is recommended.

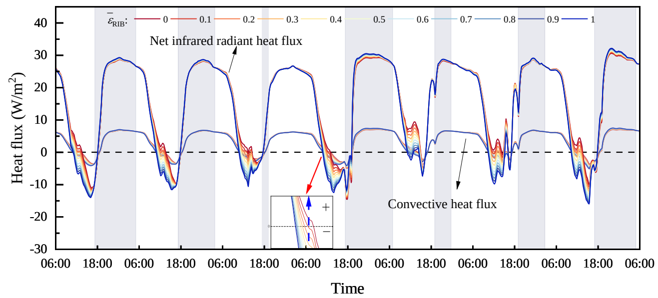

Fig. 6. Net infrared radiant heat flux and convective heat flux on the inner surface of window under different $\bar{\varepsilon}_{RIB}$.

More importantly, in many moments, the decrease of $\bar{\varepsilon}_{RIB}$ can reverse the direction of the infrared radiation heat flow and convective heat flow, changing the heat flux from the original negative value to a positive value, and from sending the heat to the room to absorbing the heat from the room. The smaller $\bar{\varepsilon}_{RIB}$ can extend the amount of the time that the interior radiates heat to the exterior through the window. According to the specific data statistics, in 168 hours of the simulation study, when $\bar{\varepsilon}_{RIB}$ =1 is raised on the outer surface of the window, the duration of infrared radiation heat dissipation to the window is 123.4 hours, and the duration of convection heat dissipation is 117.8 hours. When the $\bar{\varepsilon}_{RIB}$ of the outer surface of the window is reduced to 0, the duration of infrared radiation heat dissipation to the window is 142.3 hours, and the duration of convection heat dissipation is 135.3 hours. There is a significant increase in the duration of the heat dissipation. Thus, when the smaller $\bar{\varepsilon}_{RIB}$ is adopted, the window can be used as a "cooler" for longer periods during the day.

Similar to the definition of the window temperature regulating effect in Section 4.1, the indoor air temperature regulating effect (ΔT_{AR}) is used here to measure the comprehensive impact of changing $\bar{\varepsilon}_{RIB}$ on indoor radiative cooling of buildings. Fig. 7 shows the hourly changes of the indoor air temperature (T_{air}) and the ΔT_{AR} when $\bar{\varepsilon}_{RIB}$ decreases from 1 to 0. During the whole study period, the ΔT_{AR} was almost positive, with a maximum value of 0.23°C. In other words, during the simulation period, reducing $\bar{\varepsilon}_{RIB}$ from 1 to 0 is almost always conducive to the enhancement of the indoor radiative cooling effect. Therefore, it is more recommended to use smaller $\bar{\varepsilon}_{RIB}$ for both the radiative cooling performance of the window itself and its effect of radiative cooling on the interior of the building.

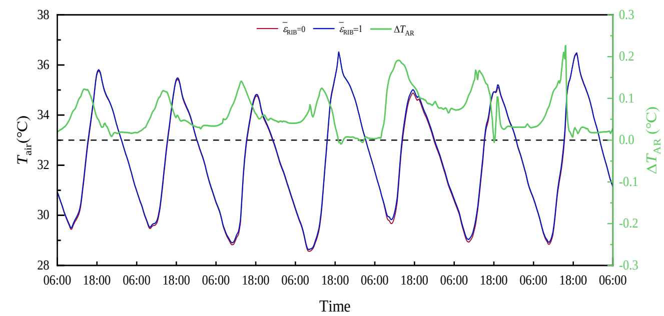

Fig. 7. The hourly change of the indoor air temperature and the ΔT_{AR} when $\bar{\varepsilon}_{RIB}$ decreases from 1 to 0.

4.3 Comparison of the radiative cooling potential between the AW and RIB

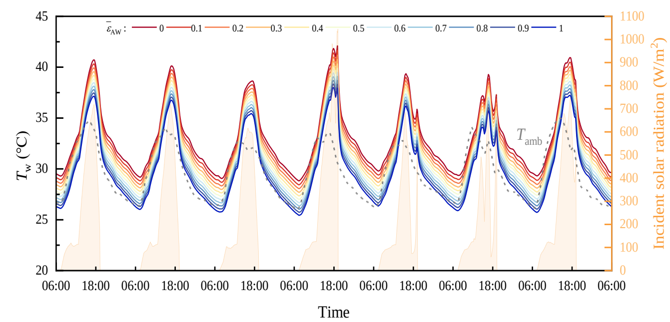

Fig. 8. Window hourly temperature under different $\bar{\varepsilon}_{AW}$.

In order to compare the radiative cooling potential of the window between the AW and RIB, similar assumptions were adopted in this section, and a 0-1 traversal calculation was performed for $\bar{\varepsilon}_{AW}$. Under different conditions of the $\bar{\varepsilon}_{AW}$, the change in window temperature over time is shown in Fig. 8. It can be found that, compared with changing $\bar{\varepsilon}_{RIB}$, changing $\bar{\varepsilon}_{AW}$ will have a more significant impact on window temperature. And the trend is consistent. The larger the $\bar{\varepsilon}_{AW}$ is, the lower the temperature of the window is, and the more favorable it is for radiative cooling of the window.

Table 3 summarizes the ΔT_{WR} , ΔT_{AR} and ΔE_R of the window and interior when $\bar{\varepsilon}_{RIB}$ is decreased from 1 to 0 and when $\bar{\varepsilon}_{AW}$ is raised from 0 to 1 respectively. Here, the ΔE_R is defined as the difference of the integral of the time and hourly heat flux within 7 days before and after the improvement -- energy regulating effect, which is used as an index to measure the improvement of the total heat transfer through the window inside and outside the room during the simulation period (unit: W·h). The index can be divided into positive and negative values. The positive value indicates that the energy emitted from the indoor to the outdoor becomes more, or the energy absorbed from the outdoor becomes less, indicating energy saving. Negative values, on the other hand, point to energy wasting. The formula is as follows:

$$\Delta E_R = \begin{cases} \int_0^t q(t)_{(\bar{\varepsilon}_{RIB}=1)} dt - \int_0^t q(t)_{(\bar{\varepsilon}_{RIB}=0)} dt, & \bar{\varepsilon}_{RIB}(1 \to 0) \\ \int_0^t q(t)_{(\bar{\varepsilon}_{AW}=0)} dt - \int_0^t q(t)_{(\bar{\varepsilon}_{AW}=1)} dt, & \bar{\varepsilon}_{AW}(0 \to 1) \end{cases} \quad (7)$$

Where the $q(t)$ represents the hourly infrared radiation or convective heat flux, and its unit is W/m^2. Under the suggestion of the optimal design scheme of the two bands, the ΔT_{WR}, ΔT_{AR} and ΔE_R are positive, pointing to energy saving and conducive to radiative cooling. The improvement of the AW brings greater radiative cooling enhancement effect. From the perspective of the $\Delta T_{WR,max}$ and $\Delta T_{AR,max}$, it is almost 2-3 times that of RIB, and from the perspective of the $\Delta T_{WR,ave}$ and $\Delta T_{AR,ave}$, it is almost 8-9 times that of RIB. On the other hand, from the perspective of indoor and outdoor energy regulation, the ΔE_R of AW is almost 9-11 times that of RIB. These results quantify the importance of the atmospheric window in improving the radiative cooling performance of windows in the entire infrared band.

Table 3. Comparison of the improvement effects of radiative cooling on the window and interior when $\bar{\varepsilon}_{RIB}$ and $\bar{\varepsilon}_{AW}$ are improved respectively.

Modified parameter	$\bar{\varepsilon}_{RIB}$ (1→0)	$\bar{\varepsilon}_{AW}$ (0→1)
$\Delta T_{WR,max}$ (°C)	2.23	4.17
$\Delta T_{WR,ave}$ (°C)	0.38	3.31
$\Delta T_{AR,max}$ (°C)	0.23	0.61
$\Delta T_{AR,ave}$ (°C)	0.06	0.53
$\Delta E_{R,rad}$ (W·h)	654.74	5780.14
$\Delta E_{R,conv}$ (W·h)	143.75	1645.81

5. CONCLUSIONS

In this paper, the influence of infrared emissivity inside and outside the atmospheric window on the radiative cooling effect of building windows is regularly explored. Through the simulation analysis of the temperature and the heat flow, the optimal design scheme of the window outer surface emissivity in infrared band is obtained by using the 3D building model verified by experiment. In addition, the radiative cooling potential of the outer surface of the window in the atmospheric window (AW) and the non-atmospheric window (RIB) is quantified and compared. The main conclusions are as follows:

(1) The adjustment tendency of the emissivity of the outer surface of the window to the radiative cooling of the window may be reversed. In the simulation period, compared with the broadband high emissivity design, reducing the emissivity of the outer surface of the window in RIB as much as possible is more conducive to enhancing the radiative cooling effect of the building window. Therefore, the widely adopted design idea of high emissivity in wide infrared band is not universal.

(2) The smaller $\bar{\varepsilon}_{RIB}$ can reverse the direction of part of the heat flow and reduce the heat flow into the room through the window, thus extending the time that the window becomes a "cooler" during the day.

(3) The AW is of great value in improving the radiative cooling performance of windows in the whole infrared band. Its temperature regulating effect is almost 8-9 times that of RIB, and its energy regulating effect is almost 9-11 times that of RIB.

This work clarifies that the default design of building radiative cooling windows in infrared band has a certain non-universality, and the exploration on the regularity of the two bands provides theoretical guidance for the material design of radiative cooling windows.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China (NSFC, Grant NO. 52130601).

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