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RESEARCH ARTICLE

Study on the influence of retroreflective materials on the "secondary reflection" on the room above the horizontal sunshade

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Abstract Existing studies on horizontal sunshade systems mainly focus on the influence of the sunshade on the room under or inside the sunshade systems. Meanwhile, the top surface of horizontal sunshade, especially those with mirror surface or made of metal, reflects solar radiation into the indoor and surroundings, resulting in "secondary reflection". This paper mainly focuses on the influence of secondary reflection on the room above the sunshade, using DesignBuilder software to conduct numerical simulation analysis and building architectural model for field measurement. Results from simulation and field measurement both prove that mirror materials increase secondary reflection reflected into the indoor. Moreover, results from experiments show that retroreflective materials decrease secondary reflection reflected into the indoor. At low latitude, the application of retroreflective materials on the top surface of horizontal sunshade effectively reduces the adverse influence of secondary reflection on the room above the sunshade.

1. Introduction

Building energy consumption accounts for a large proportion of national economic energy consumption. Results of the analysis based on the model of the decomposition of carbon emission factor indicate that the energy efficiency of China's building industry needs to be improved (Zhang et al., 2018). Research on building energy efficiency is important for the world and China to reach the carbon discharges peak value as soon as possible and achieve the goal of full carbon neutrality (Chi et al., 2021). Architecture designers often neglect the application of sunshade systems. Results of BIM-based simulation analysis of the

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impact of external shading equipment of various configurations on building energy consumption show that the most effective shading equipment reduces cooling energy consumption from 45,337.67 kWh without shading to 25,475.75 kWh with shading in March, saving energy of 19,861.92 kWh in total (Shahdan et al., 2017). Proper exterior sunshade systems can control the amount of solar radiation entering the room and affect the indoor temperature (Al-Tamimi and Fadzil, 2011). Valladares-Rendon and Lo (Valladares-Rendon and Lo, 2014) simulated the influence of seven different overhanging sunshade systems. The results indicate that the single edge layer shading system installed on the 18th floor obscured 21.5% of the solar radiation, and saved 8.92% of the cooling energy consumption eventually. Further research applied sunshade devices on the building elevation and performed parametric simulation analysis, confirming that the energy saving potential of sunshades can reach up to 8.0% when it's applied on apartments with exterior walls facing the west (Liu et al., 2019). Sunshade devices around the building degrade the outdoor insolation and further relieve the UHI effect (Qin, 2015). Existing studies of horizontal sunshade systems mainly focus on how the sunshade devices (balconies, sunshield, etc.) influence the room under or inside the structure. The top surface of horizontal sunshades, especially those with mirror surface or made of metal, while shading the buildings below, reflects solar radiation into the indoor and surroundings, resulting in "secondary reflection". Secondary reflection affects the surroundings and the building itself (the room above the sunshade, etc.) (Vallati et al., 2018). Solar Radiation from secondary reflection is beneficial for indoor thermal environment in cold weather while detrimental in hot weather. There are few current studies on the effects of secondary reflection.

Retroreflection is a reflection of reflected ray that returns in the direction close to the opposite of the direction where the incident ray enters (Fig. 1). Retroreflection technology uses microglass beads or microprisms to return the light by the route it originally entered. Retroreflective material can control the effect of secondary reflection (Yoshida and Mochida, 2018). Researchers have studied how much retroreflective materials depend on directions, so as to evaluate their influence on the solar energy load and the energy performance of the building envelope (Mauri et al., 2018). Researchers conducted experimental measurements to evaluated the distribution of retroreflection in accordance with the change of the incident angle of solar radiation. The results show that the retroreflection mainly happens when the incident angle is small, and that retroreflective material reflects about 4% energy back at summer and thereby improves the city's thermal environment (Rossi et al., 2015). Researchers measured the incident angle in accordance with the retroreflective intensity of the retroreflective material of microglass beads and microprism, and discovered that the retroreflective capacity of these two retroreflective materials is in inverse proportion to the incident angle of solar radiation, and that the retroreflective capacity of microprisms retroreflective material is stronger when the incident angle is smaller. When the incident angle increases to 60°, the retroreflective intensity deceases sharply. (Yuan et al., 2016b). Based on analysis of the retroreflective capacity of microglass retroreflective material in accordance with

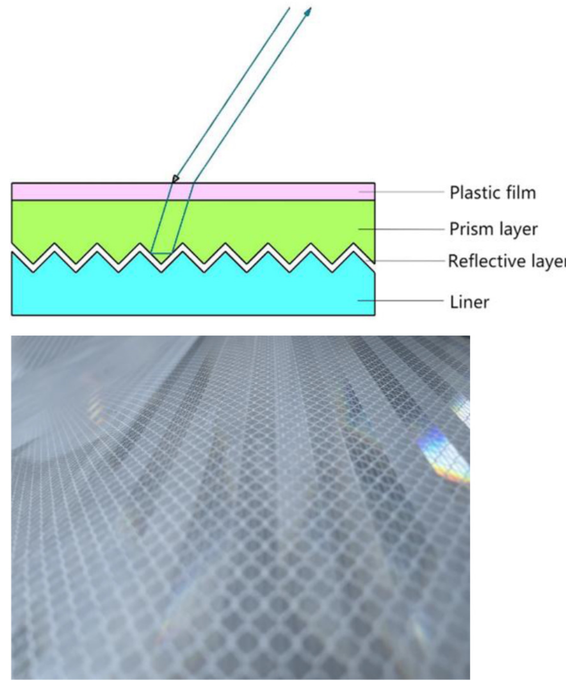

Fig. 1 Schematic Diagram of the Principle of Prism Microscopic Structure Retroreflection and Details of the Reflective Film Attached in the Experiment (the actual size:1.5 m Length × 0.8 m Width).

different incident angle, researchers discovered that the reflectance of the light upward and downward decreases and the specular reflectance increases when the incident angle increases, and that the correlation coefficient between reflectance upward and downward and the incident angle is about 0.92. (Yuan et al., 2021). Researchers applied the wavelength selective retroreflective film on the window, and confirmed the remarkable effect of how the wavelength selective retroreflective film increases the visible light introduced indoor while reduces the secondary reflection through analog calculation and field measurement (Ichinose et al., 2017). Further studies applied the retroreflective material on the building elevation. Results from simulation analysis indicate that the surface temperature of the adjacent buildings decreases sharply (Han et al., 2015). Studies show that comparing the samples of retroreflective microglasses with refractive index of 1.5 and 1.9, the retroreflective capacity of the latter is superior to the former, enhancing the city's albedo and reducing the absorption of solar radiation by urban street canyon. (Yuan et al., 2016a). Based on studies on the distribution of the incident angles of solar radiation that shines on the building exterior walls, researchers found that retroreflective walls are of little influence with big incident angle. Accordingly, researchers built dual-surface retroreflector with orthogonal mirrored groove to enhance the city albedo and increase the proportion of solar light reflected back to the sky. (Levinson et al., 2020). Researchers also improved the traditional external wall tiles, expanding their retroreflective capacity. Researchers found that the total reflectance of the original tiles is 36.5% while the of tiles covered with barium titanate glass balls reaches 39.1% and such tiles show outstanding retroreflective capacity with the incident angle is smaller than 60°. (Castellani et al., 2017). Through actual measurements in experiment, researchers have proved that retroreflective material can preferentially reflect the near-infrared components of solar radiation upward, and then reduce the secondary reflection between buildings and improve the outdoor thermal environment (Inoue et al., 2017). There are few research on the application of retroreflective materials on buildings and their influence on the surrounding environment, and even fewer on their influence on the building itself (especially the room above the sunshade).

2. Research objectives and methods

This paper mainly studies the influence of secondary reflection on buildings (the room above the sunshade). Firstly, this study applied numerical simulation to analyzed how the secondary reflection caused by sunshade made of mirrored reflective material influences the room above the sunshade.[1] Subsequently, based on contrast experiments of the influence brought by sunshade made of mirrored reflective material and the one brought by sunshade made of retroreflective material, this study concluded that while shading the rooms below, sunshades made of mirrored material caused higher indoor temperature in the room above because of secondary reflection, and that sunshades made of retroreflective material can control secondary reflection, suitable for hot summer and warm winter zone.

1) Simulation Analysis by DesignBuilder Software : this study simulated how the thermal environment of the room above was influenced under the circumstance where there was a sunshade made of mirrored reflective material and where there was no sunshade, and obtained how the secondary reflection brought by mirrored material influenced the thermal energy and indoor temperature of the room above through contrast analysis.
2) Actual Measurement in Experiments: the researcher built an architectural model of a two-storey building and applied mirrored reflective material and retroreflective material on the surface of sunshade (Fig. 1). The researcher measured the indoor dry bulb temperature and black globe temperature in the room above and conducted contrast analysis.

3. Simulation analysis

The simulated location is set in Guangzhou, China (113° E, 23° N), which is a low-latitude hot summer and warm winter zone in the subtropical zone. The researcher selected June 21st (the day of Summer Solstice) as the day of representative summer weather day and December 21st (the day of Winter Solstice) as the day of representative winter weather.

[1] Since retroreflective material cannot be set in the DesignBuilder software, the simulation in this study only built the model with mirrored sunshade and the one without sunshade, so as to analyze the solar energy entering the room above the sunshade by mirrored reflection (secondary reflection). Moreover, the researcher mainly conducted comparison experiments between the mirrored sunshade model and the retroreflective sunshade model.

3.1. Model building and simulation calculation

The researcher used DesignBuilder V6.1.8.021 software (the built-in calculation engine is EnergyPlus V8.9) to build the model. The only difference between these two two-story building models is that one is equipped with mirrored aluminum sunshade while the other is sunshade-free (Fig. 2), all other factors being equal, in order to analyze how the surface of mirrored reflective sunshade influences the indoor temperature of the room above.

These two architectural models are designed and built as follows: the first storey is a 3-m high viaduct (the four columns in the viaduct are set as heat insulator and are not considered in the simulation calculation); the second story is a 3-m-long, 3-m-wide and 3-m-high enclosed space, which is size of a standard single chamber, convenient for accurate simulation analysis and calculation. The south elevation is a 6 mm-thick single glazing and the other three elevations are all compound structure (the inside is a 3-mm-thick acrylic board and the outside is a 5-cm-thick polystyrene board); the rooftop and floor slabs are all 5-cm-thick polystyrene boards. The four elevations of the simulation model are made of transparent materials to simulate the transparent part of the actual building, convenient for comparison with the transparent acrylic board of the actual model. Polystyrene boards are set outside the three elevations except for the one facing the south. Polystyrene board is opaque thermal insulation material for exterior walls frequently used in building construction; it's also convenient for the construction of actual models. The simulation model used exterior thermal structure made of polystyrene board to simulate the opaque thermal insulation structure of actual building, which is convenient for comparison with the actual model. The material and structure of the computer simulation model is consistent with the actual model basically, so as to ensure the comparability between the simulation results and the field measured results. The left model in Fig. 2 is equipped with a 3-m-long and 2-m-wide mirrored aluminum sunshade. Specific parameters of applied material in the model are listed in Table 1.

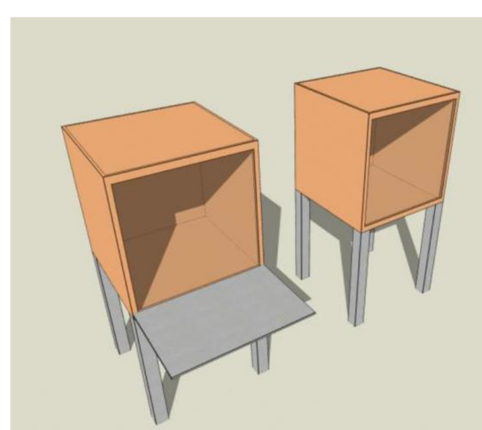

Fig. 2 Schematic diagram of computer simulation model.

3.2. Results and discussion

The researcher imported weather data and conducted simulation calculation, sorting out the differences of thermal energy and indoor temperature of the second floor in the models in the day of Summer Solstice (Fig. 3) and the day of Winter Solstice (Fig. 4). Average indoor temperature of the room with mirrored sunshade is higher than the one without sunshade. The variation trends of thermal energy (unit: kW) acquired by the exterior windows in the model with sunshade and the one without in the day of Summer Solstice are the same and they both reached peak value at 15:00. The room above the mirrored sunshade acquired more heat energy than the one without sunshade (the upper part of Fig. 3). The variation curves of indoor dry-bulb temperature (unit: °C) of the two models started to differ from the other at 8:00 and reached peak value at 16:00. The indoor temperature of the room above the mirrored sunshade (37.3 °C) is 1.7 °C higher than the one of the room in the model without sunshade (35.6 °C) (the lower part of Fig. 3).

In the day of Summer Solstice, the solar altitude angle is bigger and more solar radiation is casted upon the rooftop, exceeding the thermal energy entering the room by the south window. In the day of Winter Solstice, the solar altitude angle decreases, so the rooms in the models with sunshade and the one without both acquired more heat energy (unit: kW) by the south window in the day of Winter Solstice than in the day of Summer Solstice and the heat-energy-acquiring periods are more concentrated. The variation trends both reached peak value at 14:00. The room above the mirrored sunshade acquired more heat energy than the one without sunshade (the upper part of Fig. 4). Average indoor temperature of the room with mirrored sunshade is higher than the one without sunshade. The variation curves of indoor dry-bulb temperature (unit: °C) of the two models started to differ from the other at 8:00 and reached peak value at 16:00. The indoor temperature of the room above the mirrored sunshade (30.9 °C) is 1.5 °C higher than the one of the room in the model without sunshade (29.4 °C) (the lower part of Fig. 4).

Results from software simulation show that the indoor temperature in the day of Winter Solstice is lower but increases quickly than the one in the day of Summer Solstice. The temperature fluctuation in the model room is lagging behind the change of the indoor heat gain but their changing trends are mostly identical. The sunshade brings evident heat growth to the room above and results in the rise of indoor temperature, proving that the "second reflection" caused by the top surface of the sunshade has direct and significant influence of the room above, and that research of the top surface of the sunshade is of practical importance to the enhancement of indoor thermal environment.

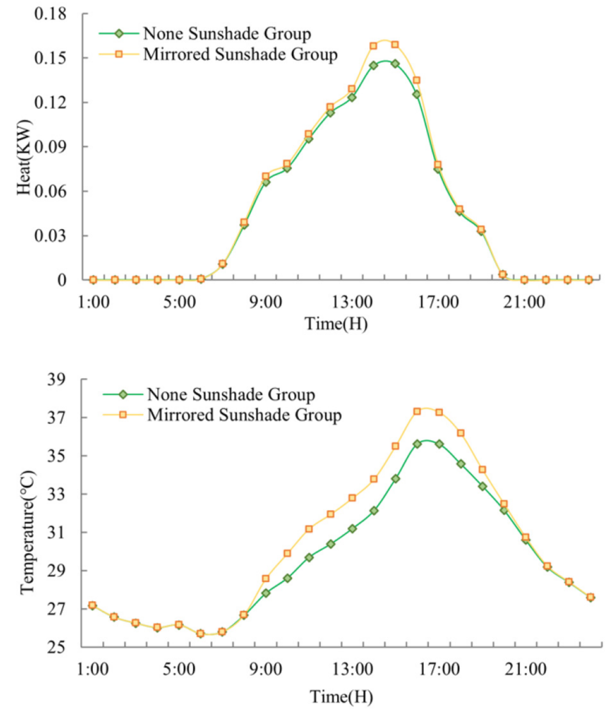

Fig. 3 Variation Trends of the Thermal Energy Acquired (unit: kW, the upper part) and Indoor Temperature (unit: °C, the lower part) in the Models in the Day of Summer Solstice.

4. Actual measurement in experiments

4.1. Building experiment models

The actual measurement in experiment is set in the same location as simulation in Guangzhou, China (113° E, 23° N, a low-latitude hot summer and warm winter zone). The experiment is carried out on the rooftop of Mong Man-wai Science and Engineering Building, Jinan University (Fig. 5). The two models are placed parallelly and their transparent

Table 1 Parameters of envelope structure and sunshade in the models.

	Material	Thickness/ cm	Heat transfer coefficient/ W/(m^{2}K)	Specular reflectivity
Exterior Wall	Polystyrene Foam Board (Outside)	5	0.696	—
	Acrylic Board (Inside)	0.3		—
	Glass	0.6	5.778	—
Rooftop	Polystyrene Foam Board	5	0.719	—
Floor Slab	Polystyrene Foam Board	5	0.685	—
Sunshade	Aluminum Board	3	6.667	0.85

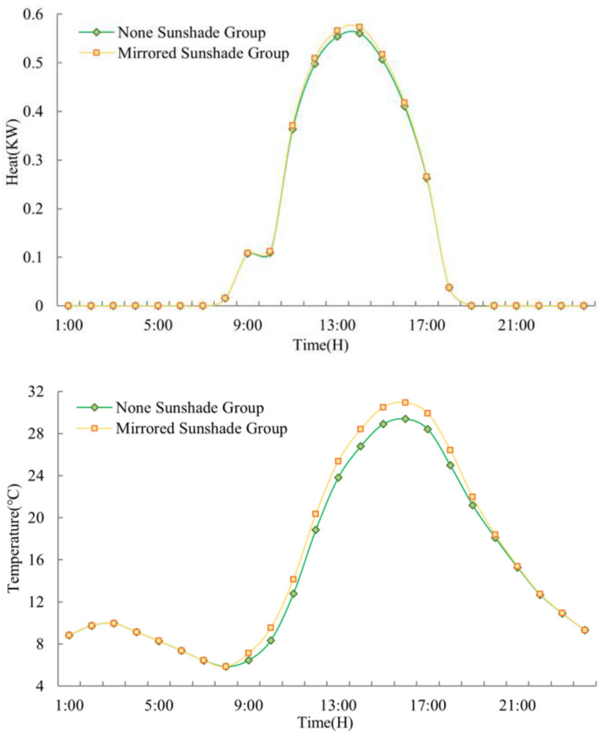

Fig. 4 Variation Trends of the Thermal Energy Acquired (unit: kW, the upper part) and Indoor Temperature (unit: °C, the lower part) in the Models in the Day of Winter Solstice.

exterior wall are set due south. The interval between these two models in the east-west direction is 1.5 m, as to avoid the surrounding and models blocking each other and the resultant shadow influencing the actual measurement.

The researcher built two model shelves of 0.5 m high to measure and collect data of the room above the sunshade. The model should be constructed indoor and transported to the rooftop for field measurement. Due to the limitation of the size of the entrance of the rooftop (1 m wide), the length and width of the actual model are scaled to half of the ones of the simulation model (1.5 m long and 1.5 m wide), while the height is 0.5 m. Since retroreflective material cannot be set in the DesignBuilder software, the researcher mainly conducted experiments for the comparison between the mirrored sunshade model and the retroreflective sunshade model. Except for the retroreflective sunshade, the material and structure of the computer simulation model is consistent basically with the actual model, so as to ensure the comparability between the simulation results and the field measured results. Both models were built as follows: the south exterior wall is a transparent acrylic board of 3 mm thick and the three other exterior walls are all compound structure (the inside is a 3-mm-thick acrylic board and the outside is a 5-cm-thick polystyrene board); the rooftop and floor slabs are both 5-cm-thick polystyrene boards. Both models are equipped with mirrored aluminum sunshade of 1.5 m long, 0.8 m wide and 1 mm thick. The only difference is that the mirrored aluminum sunshade of one model (left part of Fig. 5) was attached with a layer of retroreflective film (Fig. 1). The thermophysical parameters of the material of the models are listed in Table 2.

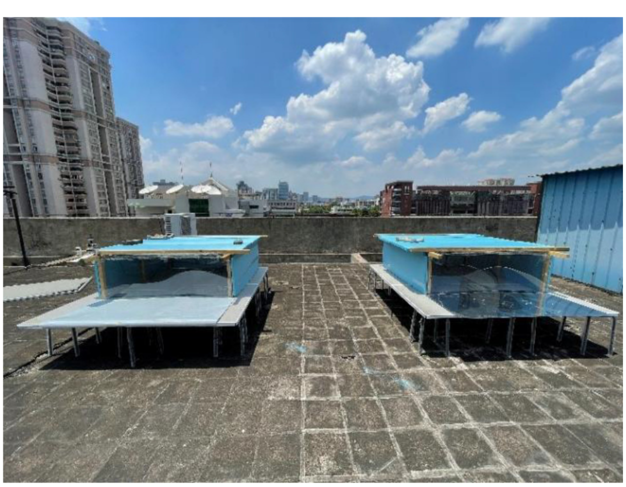

Fig. 5 The Rooftop for Experiment and the Models for Actual Measurement (Sunshade: the Left One is Made of Retroreflective Material and the Right One is Made of Mirrored Aluminum)

4.2. Actual measurement

Measuring Indoor Black Globe Temperature (Fig. 6 and Fig. 8): the researcher placed a black globe temperature automatic recorder at the shadow inside the model room. The recorder is HQZY-1 Black Globe Temperature Automatic Recorder made by TIAN JIAN HUA YI. Its parameters are measurement range between −20 and +80 °C, operating temperature range between 0 and +60 °C and operating humidity range between 10%—90% RH.

Measuring Temperature and Humidity (Fig. 7 and Fig. 9): the researcher placed a temperature and humidity recorder at the shadow inside the model room and an elevated point 1.5 m high from the ground outside the model room. The recorder is RC-4HC Temperature and Humidity Recorder made by Elitetech. Its temperature measurement parameters are measurement range between −30 and +60 °C (by the built-in probe), measurement accuracy of ±0.5 °C, and measurement resolution of 0.1 °C. Its humidity measurement parameters are measurement range between 0—99% RH, measurement accuracy of ±3% RH, and measurement resolution of 0.1% RH. The researcher imported the actual measuring data into the Elitetech Data Center software and obtained temperature and humidity charts.

Measuring Wind Speed: the researcher placed an anemometer at an elevated point 1.5 m high from the ground outside the model room. The anemometer is 16025 Anemometer made by JIA XING GUO HAO. Its parameters are: measurement range between 0—30 m/s, startup wind speed of the sensor of 0.8 m/s, measurement accuracy of ±(0.3 + 0.03*V, V as the actual wind speed, m/s) and measurement resolution of 0.1 m/s.

The actual measurement day at winter is January 17th, 2021, and the one at summer is July 14th, 2021. The time step interval of the black globe temperature automatic recorder and the temperature and humidity recorder was set as 10 min (that is to say that the recorders record data every 10 min automatically). The measurement was carried out from 11:00 a.m. to 16:00 p.m.

Table 2 Parameters of material used in the experiments.

Materials	Thickness/cm	Thermal Conductivity/W/(mK)	Specular Reflectivity/%	Minimum Coefficient of Retroreflection/cd·lx^{-1}·m^{-2}		
Polystyrene Foam	5	0.041	–	–		
Transparent Acrylic	0.3	0.18	–	–		
Mirrored Aluminium	0.1	138	0.85	–		
Super Retroreflective Film	0.05	–	–	Observation Angle	Incident Angle	White
				0.2°	−4°	360
					15°	265
					30°	170

4.3. Results from actual measurement

The researcher analyzed actual measurement data and obtained the comparison of the indoor black globe temperature as well as the indoor and outdoor dry bulb temperature of retroreflective sunshade model and mirrored sunshade model in winter (Figs. 6 and 7) and summer (Figs. 8 and 9).

Actual Measurement Day in Winter (January 17th, 2021): as Fig. 6 shows, the average indoor black globe temperature of retroreflective material sunshade is lower than the one of mirrored sunshade, the time-variant trend of black globe temperature of retroreflective sunshade model and mirrored aluminum sunshade model is the same and both reached the peak value at 13:10 p.m. The maximum value of the indoor black globe temperature of the room above the mirrored sunshade at the actual measurement day in winter is 38.1 °C, 2.6 °C higher than the one in the room above the retroreflective sunshade model (35.5 °C). As Fig. 7 shows, the average indoor dry bulb temperatures of retroreflective material sunshade is lower than the one of mirrored sunshade and the indoor dry bulb temperature of both sunshades is higher than the outdoor dry bulb temperature, the maximum value of the indoor dry bulb temperature of both models occurred separately around 13:30 p.m. The indoor temperature of the room above the mirrored sunshade model at the actual measurement day in winter reached the peaked value of 33.2 °C at 13:50, 2.4 °C higher than the one of the room above the retroreflective sunshade model (30.8 °C, recorded at 13:20). Meanwhile, the maximum value of outdoor temperature is 25.6 °C (recorded at 14:30). The temperature in the experiment model is rising faster and the maximum value occurs earlier than the outdoor temperature, because the heat storage capacity of the model is much small.

Actual Measurement Day in Summer (July 14th, 2021): as Fig. 8 shows, the average indoor black globe temperature of retroreflective material sunshade is lower than the one of mirrored sunshade, the time-variant trend of black globe temperature of both models is the same and both reached the peak value at 14:40 p.m. The maximum value of the indoor black globe temperature of the room above the mirrored sunshade is 50.5 °C, 1.7 °C higher than the one in the room above the retroreflective sunshade model (48.8 °C). As Fig. 9 shows, the average indoor dry bulb temperatures of retroreflective material sunshade is lower than the one of mirrored sunshade and the indoor dry bulb temperature of both sunshades is higher than the outdoor dry bulb temperature, the maximum value of the indoor temperature of both models both occurred at 14:40. The maximum value of the indoor temperature of the room above the mirrored sunshade model is 47.7 °C, 0.3 °C higher than the one of the room above the retroreflective sunshade model (47.4 °C). The outdoor temperature experienced more fluctuation with the maximum value of 46.6 °C (recorded at 15:00 p.m.). The temperature in the experiment model is rising faster and the maximum value occurs earlier than the outdoor temperature, because the heat storage capacity of the model is much small. Results from filed measurement show that compared with mirrored sunshade, sunshade with retroreflective material reflects a considerable amount of solar radiation back to the sky and reduces effectively the thermal energy entering the room

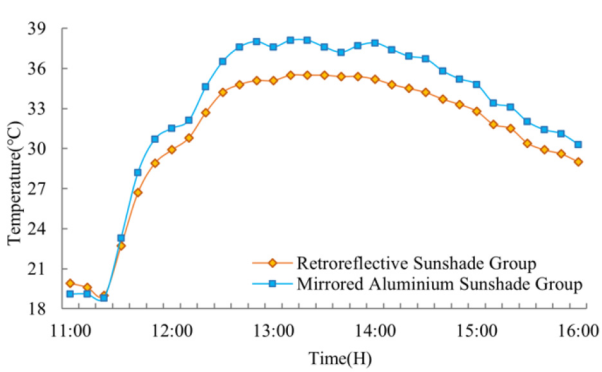

Fig. 6 Indoor black globe temperature in winter (January 17th, 2021).

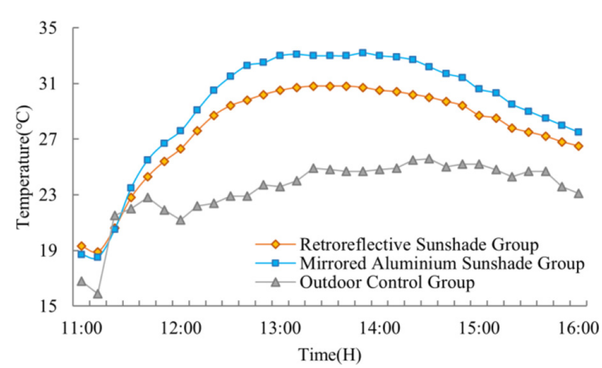

Fig. 7 Indoor and outdoor dry bulb temperatures in winter (January 17th, 2021).

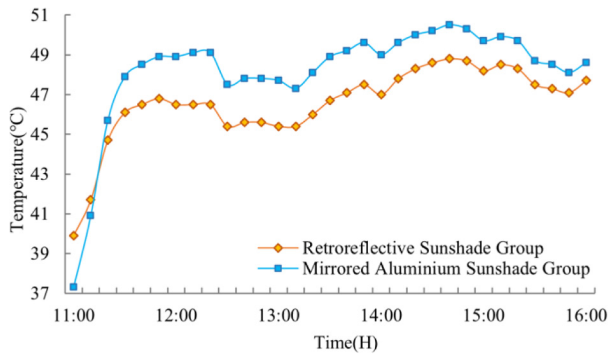

Fig. 8 Indoor black globe temperature in summer (July 14th, 2021).

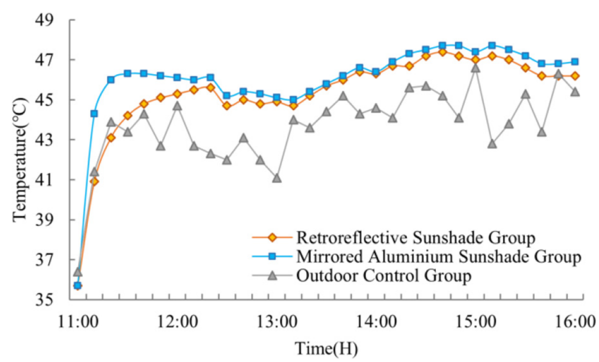

Fig. 9 Indoor and outdoor dry bulb temperatures in summer (July 14th, 2021).

above and decreases the indoor temperature, solving the secondary reflection problem of sunshades which was limitedly studied in the past.

5. Conclusion

Sunshade reduces the energy consumption of buildings for cooling , but results from both simulations and actual measurement show that the secondary reflection caused by the mirror sunshade brings heat and elevates temperature to the room above. Based on the results from actual measurement in experiment, the researcher comes to the following conclusions:

1) Whether in winter or summer, while shading the room below from solar radiation, the mirrored sunshade brings more solar radiation into the room above (by secondary reflection). The radiation directly results in the sharp rise of the black globe temperature and accordingly the rise of indoor temperature, causing the black globe temperature and indoor temperature of the room above the mirrored sunshade higher than the ones above the retroreflective sunshade.
2) Whether in winter or summer, the top surface of sunshade attached with retroreflective film reflects more solar radiation (secondary reflection) back to the sky (space) by the route it originally entered. The radiation directly results in the modest rise of the black globe temperature and accordingly the rise of indoor temperature, causing the black globe temperature and indoor temperature of the room above the retroreflective sunshade model lower than the ones above the mirrored aluminum sunshade model.
3) The experiment was carried out in Guangzhou, China, a low-latitude hot summer and warm winter zone. For low-latitude zone, applying retroreflective material on the top surface of horizontal sunshade could effectively reduce the negative influence on the room above the sunshade caused by secondary reflection.

Retroreflective material can effectively solve the secondary reflection problem of sunshades which was limitedly studied in the past. Based on this study, the design of more delicate fixed or rotatable shutter sunshade so as to achieve more appropriate control and utilization of solar radiation is the direction for future research.

Declaration of competing interest

Authors have no competing financial, professional, or personal interests from other parties.

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