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# Improvement of thermal environment in the outdoor atrium by employing the spray system

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**Outdoor atriums have recently been applied with increasing frequency for natural illumination, but they produce a harsh thermal environment easily in summer. Moreover, overheating of the outdoor atrium necessitates air-conditioning to moderate indoor thermal comfort. Simultaneously, the substantial heat emissions from air-conditioning outdoor units worsen the outdoor thermal environment, creating a vicious cycle. Traditional passive evaporative methods involving water and greenery, while capable of regulating the thermal environment, suffer from low evaporative efficiency and pose significant challenges. To improve thermal environment in outdoor atriums, the spray system was employed due to its high cooling efficiency, especially in open or semi-open spaces. In this study, a comparative experiment was conducted to evaluate the effectiveness of using a spray system for evaporative cooling in open outdoor spaces. Furthermore, employing high-efficiency evaporative cooling through spraying to disrupt the vicious cycle of indoor and outdoor thermal environments. The dual goals include regulating indoor and outdoor thermal conditions while also mitigating the local heat island effect. Temperature and humidity distribution within the atrium and adjacent hallways were monitored, along with the impact on air-conditioning operation consumption in neighboring offices. Results showed that the spray system significantly improved the thermal environment in the outdoor atrium, reducing the average and peak air temperatures by 0.94–2.83 °C and 2.92–5.21 °C, respectively. It also resulted in a drop in the average temperature by 0.56–1.62 °C and the peak temperature by 2.31–3.25 °C in adjacent hallways. This effectively eased the issue of overheating in these areas while raising the comfort level in adjacent office spaces. The predicted mean vote decreased from 1.46 to 0.87, indicating a significant improvement in thermal environment in neighboring offices. Furthermore, the daily energy consumption was reduced by 10.6–12.4% in neighboring offices. This study provided the valuable guidance for improving thermal environments within outdoor atrium.**

**Keywords** Thermal environment, Spray system, Outdoor atrium, Energy consumption, Office building

Energy and environment are two major challenges faced by mankind[1,2]. With the urbanization process, large individual buildings are increasingly prevalent[3]. In these buildings, atriums are widely employed as a common feature to enhance the lighting environment and natural ventilation[4]. As spaces for exchanging climate between indoor and outdoor environments, atriums create unique thermal environments that regulate indoor climates[5]. In high outdoor atriums, thermal stratification is significantly exacerbated by natural convection[6]. Furthermore, numerous air-conditioning units are installed on exterior walls near outdoor atriums. Consequently, driven by both air-conditioning heat dissipation and natural convection, the thermal environment in outdoor atriums tends to be poor, particularly in higher Sect[7].

Regarding the thermal environment in atrium spaces, Holford and Hunt[8] conducted a study on the impact of atrium geometry on natural ventilation. They developed a theoretical model to predict the steady stack-driven displacement flow and thermal stratification in the building. Aldawoud[9] carried out a comprehensive investigation into the thermal performance of various atrium shapes and geometries in buildings, aiming to evaluate their influence on total energy consumption and identify optimal designs for energy-efficient atria. Wang et al.[10] examined temperature distribution profiles in atriums with different section aspect ratios to optimize annual energy consumption. Ge et al.[11] analyzed the effect of non-enclosed atriums on the surrounding thermal environment in shopping malls, revealing that glass ceilings exacerbated thermal stratification by 50%, while air infiltration from upper openings resulted in heat gain ranging from 94-213w/m$^2$. Shaeri et al.[12] explored

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how 12 different ceiling shapes influenced internal thermal comfort in Bushehr city, Iran, finding a significant correlation between predicted percentage of dissatisfied individuals and thermal environmental parameters.

Lu et al.[13] investigated the thermal performance of atria in cold climates and emphasized the need for roof ventilation to prevent overheating, even in severe cold conditions. They also stressed the importance of strict regulations on air infiltration rates in atria due to significant heat loss through infiltration. Moosavi et al.[14] examined passive cooling strategies for controlling atrium overheating in an office building located in Malaysia and found that implementing cross ventilation and appropriate inlet openings could improve indoor thermal conditions by reducing temperature and humidity levels.

The thermal and daylight performance of atriums and courtyards in hot climates were compared by Asfour[15]. It was concluded that both types have equivalent cooling and lighting loads. Buildings with a 30% window-wall ratio, equipped with shading devices, are the optimal choice between the two options. The effects of wind direction and openings on atrium ventilation were defined in a study conducted by Horran and Finn[16]. The analysis revealed that perpendicular winds to the openings result in the highest ventilation, while winds blowing at an angle of 135° have the least impact on ventilation. Consequently, reducing the area of openings would lead to a decrease in ventilation rates by 23% and 11%. Xu et al.[17] investigated the thermal characteristics of the atrium space in a teaching building during winter. Their findings revealed a vertical temperature gradient of 0.49 °C/m and an indoor air temperature range of 8.22 °C. Liu et al.[18] examined the impact of buoyancy-driven ventilation on buildings with atria, highlighting that optimizing the position and size of stack openings can enhance thermal comfort levels.

Based the above studies, the outdoor atrium's thermal phenomena, particularly thermal stratification, significantly influence both surrounding rooms' thermal environment and air-conditioning energy consumption. Therefore, it is imperative to improve the thermal environment of outdoor atrium to achieve favorable levels of thermal comfort. The spray system offers several advantages, making it a viable choice for enhancing the thermal environment in outdoor atriums due to its efficient evaporative cooling capabilities (Outdoor temperature reduction of 3.5 °C-8.2 °C[19–21], methods and impacts, as well as high cost-effectiveness (spraying system in taxi waiting area costs only $16.43 per day)[22,23].

Zhang et al.[24] further reported that women and overweight individuals exhibited higher thermal sensitivity to the spray environment compared to men and underweight individuals. Meng et al.[25] demonstrated that the suitable flow rate is 30 ml/min in Qingdao city. In a study conducted by Oh et al.[26], a spray experiment was carried out in the city square, revealing that the thermal sensation rating transitioned from warm to neutral upon exposure. Furthermore, there was an observed decrease of 0.53 °C in mean skin temperature after spending 10 min within the spray environment. Chan et al.[27] improved thermal comfort prediction by incorporating additional predictor variables into artificial neural network models, resulting in a significant performance enhancement. Abdullah et al.[28] enhanced the indoor thermal environment within an atrium with a transparent envelope by implementing blinds and an evaporative spray. Yang et al.[29] installed a misting system in an atrium with a glass ceiling to mitigate thermal conditions, effectively reducing surface temperature by 5-5.6 °C. The above studies proved that spraying cooling has a significant effect on human thermal comfort[24,26,27], and verified the feasibility of spray evaporative cooling in Qingdao area[25]. Furthermore, the combination of spray evaporative cooling and building atrium can effectively change the indoor and outdoor thermal environment[28,29]. There is a possibility that integrating the spray system with an open building atrium can enhance both indoor and outdoor thermal environments, thereby improving overall comfort levels.

Therefore, it is proved that the spray system had the high cooling efficiency, especially in open or semi-open spaces, where the traditional air-conditioning system cannot operate efficiently.

The efficient cooling of the spray system in open or semi-open spaces becomes a potential method to address the thermal problems within the atrium, but there is the clear gap on the application of the spray system in outdoor atrium. Therefore, it is necessary to substantiate its efficiencies on the thermal environment improvement with the atrium.

To achieve this purpose, an experiment was conducted to compare the thermal environment in the atrium before and after implementing the spray system. The air temperature and relative humidity were mainly monitored in the atrium. The thermal environment improvement in the atrium can impact the thermal environment in adjacent hallways and neighboring offices, so indoor thermal conditions and air-conditioning energy consumption in adjacent hallways and neighboring offices also assessed. This study aims to evaluate how incorporating a mist spray system positively impacts improving the thermal environment within the atrium. Additionally, high-efficiency evaporative cooling is used to break the vicious cycle of indoor and outdoor thermal environments. The dual objective is to regulate the indoor and outdoor thermal conditions while mitigating the local heat island effect.

# Methodology
## Description of experimental platform
The experimental site was in the atrium of a five-story educational building in Qingdao city, China (120°37′N and 36°10′E). Figure 1a shows a photo of the experimental atrium and building model, while Fig. 1b,c,d give the three-level floor plan, East-west building section and North-south building section. The experimental building is about 17.8 m tall and covers an area of around 12,706.73 $m^2$. It serves multiple purposes, including education, office work, and conducting experiments. The atrium measures 12.7 m (Length) × 15.28 m (Width) × 17.80 m (Height), with an opening roof connected directly to the outdoor environment. Spray nozzles were installed on the atrium roof at a height of 17.8 m. In this study, twelve spray locations were used at the top of the atrium as shown in Fig. 2, with each location spaced approximately four meters apart from adjacent ones. The spray system consists of a pump, nozzles, water pipes and fittings, and a control device; municipal tap water is used directly. Table 1 presents equipment parameters for the spray system. It was confirmed that all experiments in

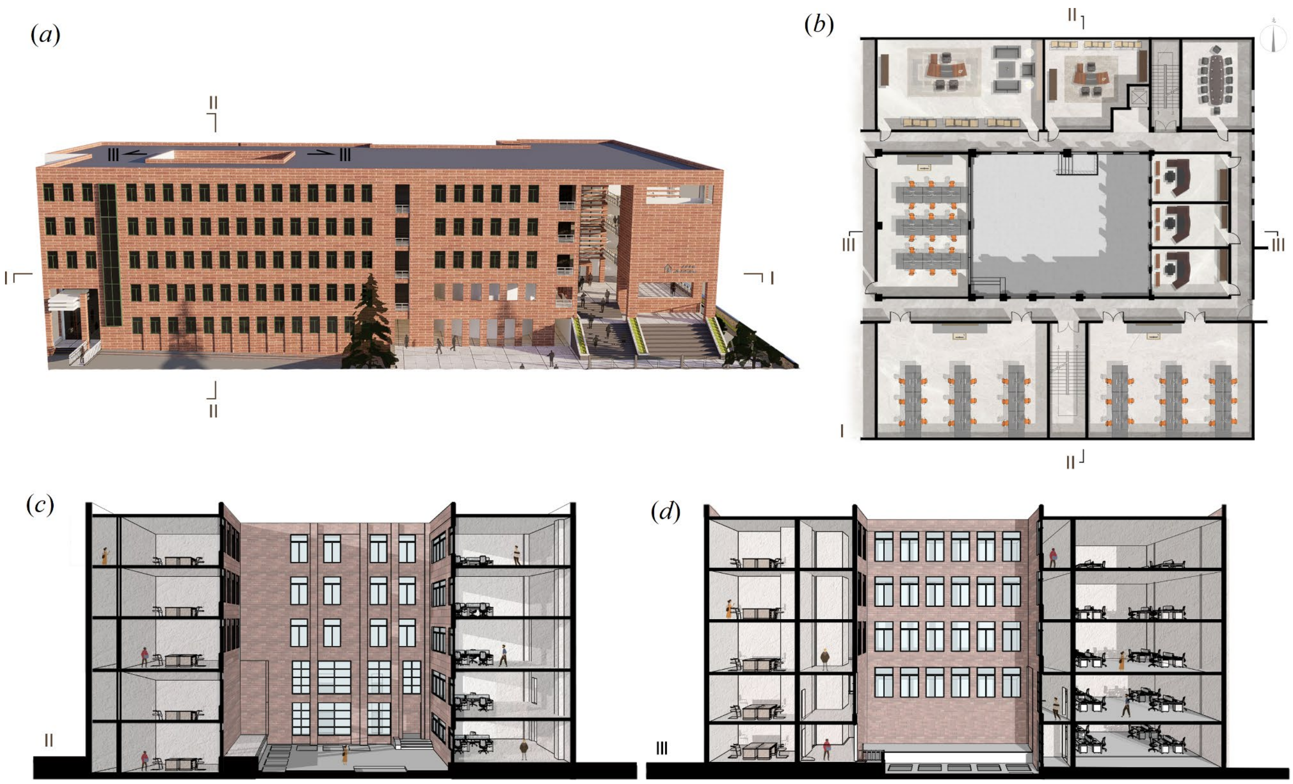


**Fig. 1**. The schematic diagram of (**a**) building model, (**b**) Three-level floor plan, (**c**) East-west building section and (**d**) North-south building section. (Drawn by SketchUp Pro 2021 (21.0.339-64bit)[30]).


**Fig. 2**. The schematic diagram of the measurement location in the atrium & the adjust hallway and the monitored offices on the third floor. (Drawn by SketchUp Pro 2021 (21.0.339-64bit)[30]).

| Component | Type | Specifications |
|---|---|---|
| Nozzle | N-3010 | Pressure: 6 MPa |
| | | Flow rate: 1.8 L/h |
| | | Droplet particle size: 0.3 mm |
| Spray pump | PC-2801 | Pressure: 6 MPa |
| | | Flow rate: 18 L/h |
| | | Power: 120 W |

**Table 1**. The equipment parameters of the spray system.

| Component | Type | Variable | Measuring range | Accuracy |
|---|---|---|---|---|
| Thermal comfort meter | JT-IAQ-50 | Air temperature | -20 ~ + 125 °C | ± 0.2 °C |
| | | Relative humidity | 0 ~ 100% | ± 3% |
| | | Wind speed | 0.05 ~ 5 m/s | ± 2% |
| | | Globe temperature | -20 ~ + 85 °C | ± 0.2 °C |
| Toprie data measuring instrument | TP1000 | Air temperature | -20 ~ + 70 °C | ± 0.2 °C |
| | | Relative humid | 0 ~ 100% | ± 3% |
| Solar radiometer | JTR05 | Solar radiance | 0 ~ 2000 $W/m^2$ | ± 2% |
| The electric meter | SPM-10 A | Electric power | 0 ~ 4500 W | 0.01 W |

**Table 2**. Meteorological parameter measuring range and accuracy of the instrument.

this study were performed in accordance with the relevant guidelines and regulations. The building selected for this experiment complies with the Chinese civil building design code, and the thermal conductivity of the wall of the composite insulation material of the building is 0.45 W/(m·K), and the thermal resistance of the wall is 2.1 $m^2$·K/W. The thermal conductivity of the single-layer glass is 1.1 W/(m·K), and the transmittance coefficient is 0.6, and the ratio of the building's windows to the walls is about 32.6%.

## Description of measurement location

The thermal environment in the atrium has the certain influence on the adjacent indoor environment, and as shown in Fig. 1b, there are the hallways and offices close to the atrium. Therefore, the thermal environment in the atrium, hallways and offices were monitored. Figure 2 also illustrates the schematic diagram of measurement locations in both the atrium and adjacent hallways as well as monitored offices on the third floor. To measure thermal environment distribution within these areas, five hygrometers (T&RH-A-1 ~ T&RH-A-5) were placed at level heights of 1.5 m, 4.8 m, 8.l m, 11.4 m and 14.7 m and five hygrometers (T&RH-C-1 ~ T&RH-C-5) were in the hallways under the same heights, which is 1.5 m above floors[31]. At the midpoint of each floor of the building, 1.5 m above the ground level, near the windows, becomes a critical point for heat exchange between indoor and outdoor air. This location is also near indoor hallway, which are usually pedestrianized areas. A position at 1.5 m, 4.8 m, 8.l m, 11.4 m and 14.7 m height (Building floor height 3.3 m) can represent the average height at which people breathe and more accurately reflect the effect of cooling on the human body[25]. Moreover, indoor thermal environment (PMV-1) is measured by a thermal comfort meter in a neighboring office under the natural condition at a height of 1.1 m above the floor, which is the appropriate measurement height for a human body in a seated office situation. The air-conditioning power consumption (PC-1) in another neighboring office is also tested by an electric meter. A solar radiometer was in the building roof to monitor the horizontal solar radiation intensity. Table 2 showed the equipment test parameters.

The study duration encompassed a total of 19 days, with all instrument data recorded at 10-minute intervals. Specific measurement points and data acquisition details are outlined as follows:

- Thermal comfort meter instruments were utilized in offices adjacent to the outdoor atrium to measure temperature, relative humidity, wind speed, and globe temperature. One room per floor was selected, resulting in 5 measurement points with a total of 20 datasets.
- Toprie Data measuring instruments were employed in hallways and atrium spaces to measure temperature and relative humidity, resulting in 10 measurement points with 20 datasets.
- The electric meter was used to measure power consumption of the air-conditioning, with one measurement point per floor, resulting in 5 measurement points and 5 datasets.
- Outdoor meteorological parameters were recorded using Toprie Data measuring instruments and a Solar radiometer to measure outdoor temperature, relative humidity, and solar radiation. This involved 1 measurement point with 3 datasets.

Therefore, the study encompassed a total of 21 measurement points, yielding 48 datasets. Daily data recording amounted to 6,912 entries, resulting in a total of 131,328 recorded data points throughout the experimental period.

## Uncertainty analysis

Due to the uncertainties of the individual measuring instruments, errors in the experimental results are inevitable. The absolute error of air temperature measurement is 0.20 °C, which leads to the uncertainty of 2.70%, while the absolute errors are 0.51%, 2.00%, 2.00%, and 3.00% for the electric meter, relative humidity, Solar radiance, and wind speed according to Table 2, respectively. Combining with the accuracy parameters, the total uncertainty of the experimental system was calculated as from the following equation[32].

$$\varepsilon = \sqrt{\left(\frac{\partial f}{\partial x_1}U_1\right)^2 + \left(\frac{\partial f}{\partial x_2}U_2\right)^2 + \cdots + \left(\frac{\partial f}{\partial x_n}U_n\right)^2} \tag{1}$$

where $U_I$ is synthetic standard uncertainty for each instrument. The variables in Eq. (1) are the synthetic standard uncertainties for temperature, relative humidity, electric meter, solar radiation, and wind speed, respectively, and the value of this variable is calculated from the absolute error of each instrument.

Moreover, the space was devoid of high-intensity illumination and shaded by blinds during typical diurnal periods to mitigate the impact of the mean radiant temperature. Meanwhile, the discrepancy between the mean radiant temperature and the desired temperature was quantified in all test rooms prior to the experiment, with a mean difference of less than 0.5 °C. Accordingly, the mean radiant temperature was not assessed on a separate basis.

## Results

The experiment was carried out between Aug. 4. and Aug. 21, 2022, with the spray system being activated from Aug. 14 to Aug. 22. Figure 3 illustrates the variations in outdoor air temperature, relative humidity, and solar radiation during the experimental period. Notably, comparable climate conditions were detected between Aug.

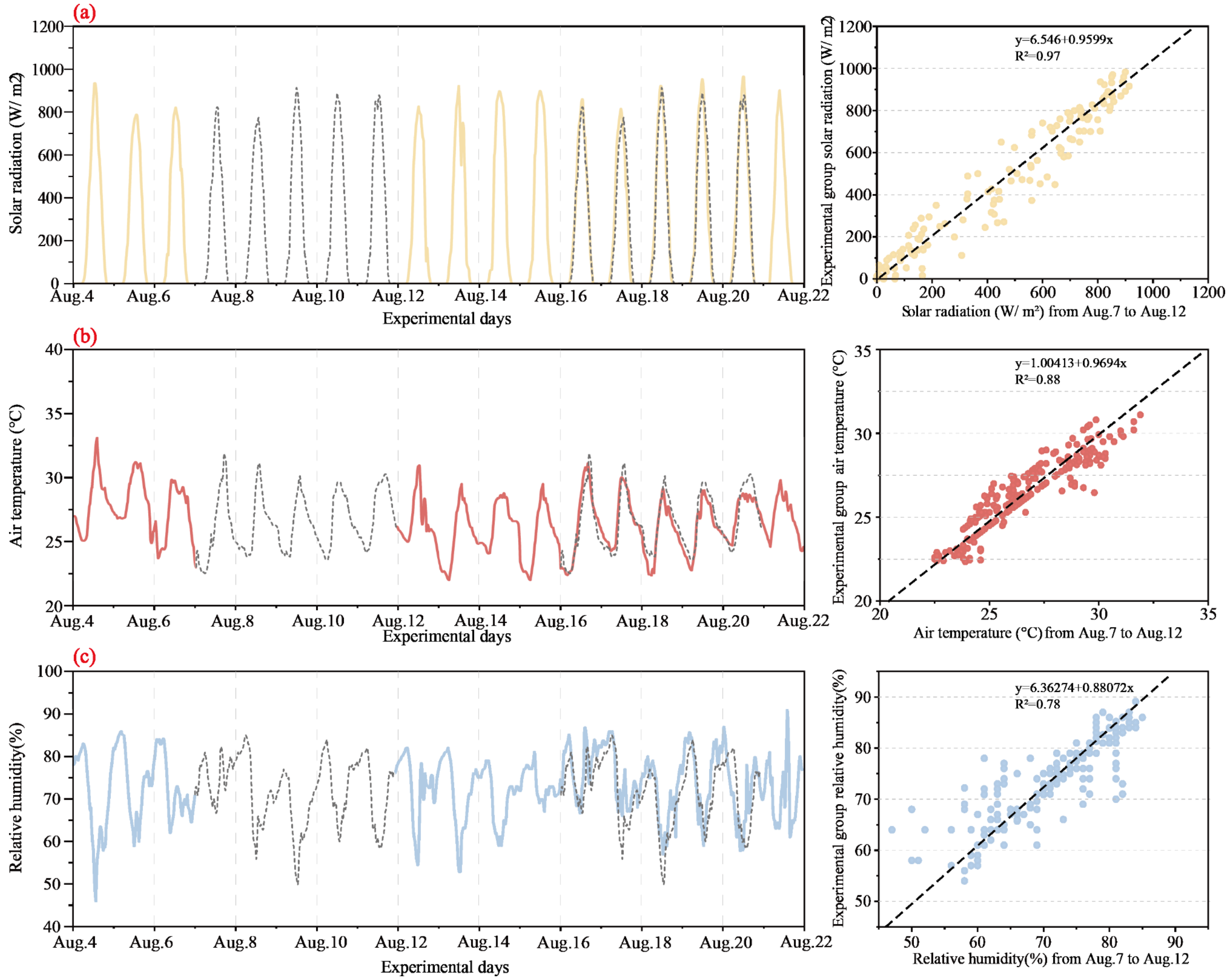


**Fig. 3**. Variation of (**a**) outdoor air temperature, (**b**) relative humidity, and (**c**) solar radiation during the experimental period.

7–11 and Aug. 16–20. Consequently, the data from Aug. 7 to 11 served as a baseline to evaluate the spray system's cooling efficiency during its operation from Aug. 14 to 22. Furthermore, based on fitting the data from Aug. 7–11 and Aug. 16–20, the $R^2$ values for solar radiation, air temperature and relative humidity were 0.97, 0.88 and 0.78, respectively. This indicates that the selected outdoor meteorological parameters are similar and can be used for this experiment.

Throughout these times, the outdoor air temperature fluctuated between 22.5 °C and 31.9 °C, with an average of 26.5 °C. The relative humidity also varied from 54 to 85%, with an average of 71.8%. The peak solar radiation was as high as 914.1 W/m$^2$. The outdoor meteorological parameters are in accordance with the summer meteorological parameters of Qingdao area (high humidity area). Additionally, the spray system was operational from 8:00 AM to 6:00 PM. Taking into account the spray system's impact on the entire day, the comparison of experimental data was conducted over the full duration. Since the experimental period coincided with the summer vacation in Chinese universities, any human interference was minimal and could be disregarded.

## Air temperature and relative humidity in the outdoor atrium

The spray system was situated at the roof of the studied building. Figure 4a displays the comparison of air temperatures across each layer following spray application. It's evident that the installation of the spray system substantially cooled the outdoor air temperatures, particularly in the third, fourth, and fifth layers, where temperatures decreased by 2.03 °C to 2.75 °C. The most significant drop in peak air temperature was observed in the fourth layer, with a reduction as high as 5.21 °C, while the average decrease in peak temperatures was approximately 3.70 °C. This reduction helped mitigate excessive heat in the outdoor atrium's thermal environment. Additionally, a notable thermal stratification used to occur due to natural convection and heat dissipation from the air-conditioning outdoor unit, but the spray system effectively reduced this stratification from 0.37 °C/m to 0.28 °C/m.

Figure 4b shows the temperature difference distribution within the outdoor atrium area: ranging primarily between 1 and 3 °C for the two lower floors and 2–4 °C for the three upper floors, owing to the spray system's placement atop the fifth floor. The proportions with a temperature difference of 5–6 °C could respectively reach up to 1.28%, 2.97%, and 1.23% in the third, fourth, and fifth layers. Compared with the cooling effect of plant transpiration in the outdoor atrium, the spray system can turn water into smaller and easier to evaporate small droplets, accelerating the heat exchange between droplets and air, and then a rapid cooling effect occurs. Furthermore, due to the air convection between the upper and lower levels of the outdoor atrium, the cooling effect of the spray system on the fourth and fifth floors can be transferred to the first and second floors, realizing the cooling effect on the whole outdoor atrium.

The relative humidities in each layer of the outdoor atrium were compared before and after spraying in Fig. 5a. Prior to the spray system, the relative humidity decreased with altitude due to the thermal stratification and plant transpiration on the ground. After implementing the spray system, there was a significant increase in relative humidity, particularly in the fourth and fifth layers, with average increases of 22.30% and 22.91%, respectively. The addition of the spray system improved uniformity of relative humidities vertically.

Figure 5b also illustrates the distribution of relative humidity differences within the outdoor atrium. The humidity difference mainly ranged from 0 to 5% on two bottom floors, 5-15% on the third floor, and 15-30% on

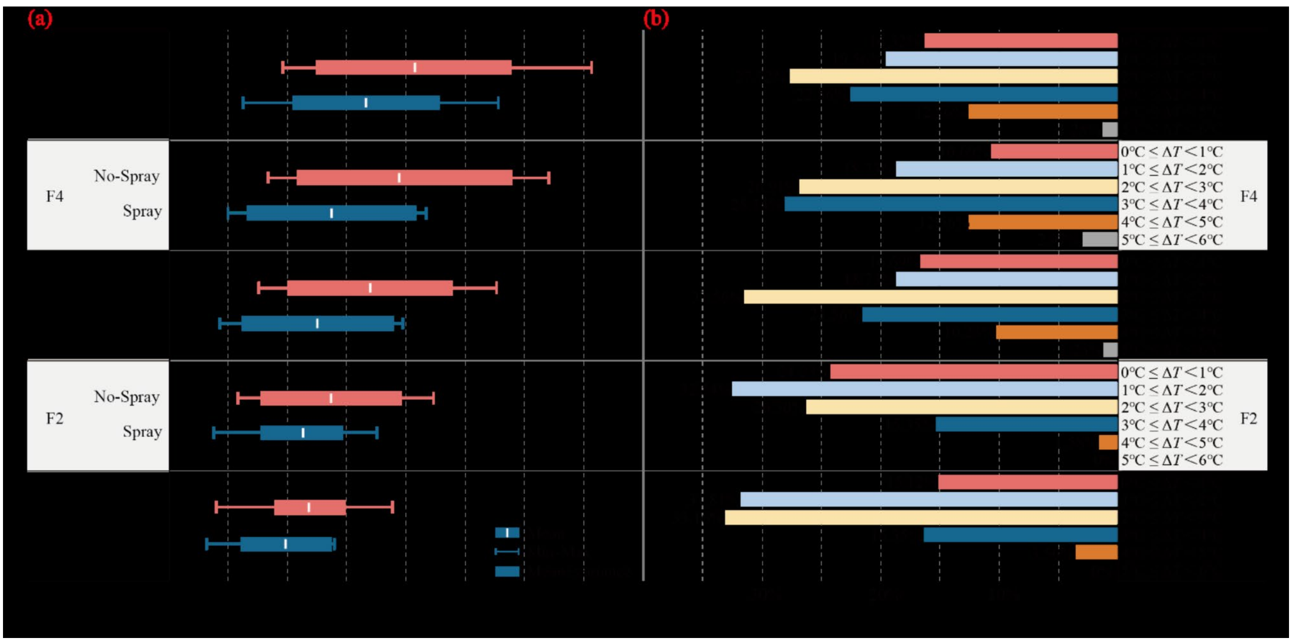


**Fig. 4**. Comparison of (**a**) air temperature and (**b**) its distribution of temperature difference in the outdoor atrium.

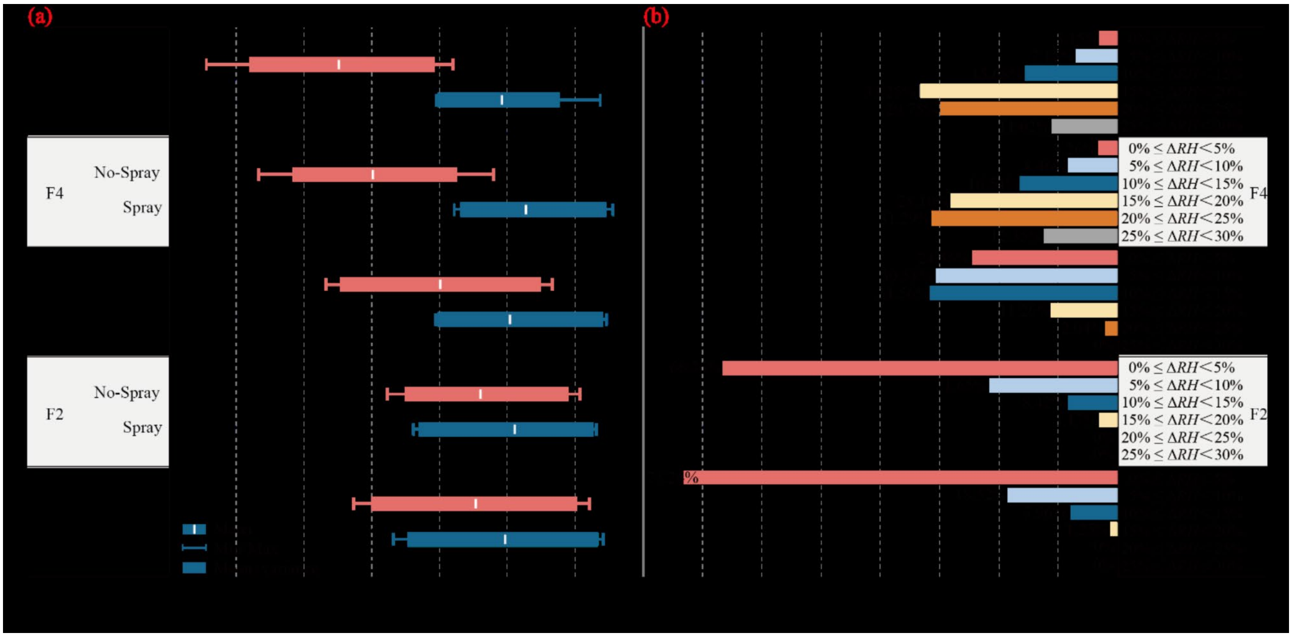


**Fig. 5**. Comparison of (**a**) relative humidity and (**b**) its distribution of humidity difference in the outdoor atrium.

two top floors. This phenomenon is attributed to the location of the spraying system on the fifth floor. Compared to the increase in relative humidity due to plant transpiration, there are two components to the increase in relative humidity after spraying. These include the increase in absolute humidity in the air due to the evaporation of droplets from heat absorption to water vapor, and the increase in relative humidity due to the decrease in the vapor saturation pressure of the air as a result of the decrease in temperature. Furthermore, due to the high concentration of water vapor in the air of the fourth and fifth floors will be diffused with the low concentration of water vapor in the first and second floors, resulting in an increase in the relative humidity of the first and second floors as well.

## The air temperature and relative humidity in the hallway near the outdoor atrium

The adjacent space benefits greatly from the presence of an outdoor atrium, which plays a crucial role in moderating the thermal environment. The hallway serves as a direct link to this atrium, facilitating a seamless exchange of air.

The air temperatures in each layer of the hallway were compared before and after the spraying, as shown in Fig. 6a. It is evident that the addition of the spraying system significantly reduced the air temperature in the hallway, particularly in the third, fourth, and fifth layers. The values in these three layers decreased by 1.20–1.62 °C, which was lower than those observed in the outer atrium. On average, the peak air temperature was reduced by 2.87 °C. Additionally, there was a noticeable thermal stratification with thermal stratification strengths of 0.25 °C/m and 0.16 °C/m before and after spraying respectively. Compared to the first and second floors, the third to fifth floors are directly affected by the spray system, which leads to a direct heat exchange between the indoor and outdoor air and a significant drop in air temperature. In addition, the air temperature varies with height, resulting in a large temperature difference between the upper floors and the lower floors.

The temperature difference in the hallway was lower than that in the outdoor atrium, as shown in Fig. 6b. The distribution of temperature difference mainly focused on 0–1 °C in the bottom floors and 1–3 °C in the top floors. This phenomenon is attributed to the spraying system on the fifth floor, which resulted in a temperature difference of up to 5–6 °C percentages of 1.28%, 2.97%, and 1.23% for the third, fourth, and fifth layers respectively.

The relative humidities in each layer of the hallway were compared before and after spraying in Fig. 7a. It is evident that the spray system significantly increased the relative humidities in each layer, particularly on the three top floors, with average increases of 10.31%, 14.00%, and 13.31% on the third, fourth, and fifth floors respectively. Figure 7b also illustrates the distribution of relative humidity differences in the hallway, showing a focus on ranges of 0-5% on two bottom floors, 5-15% on the third floor, and 10-20% on two top floors. Compared to the lower floors, the high concentration of water vapor in the upper floors is easily diffused with the low concentration of water vapor indoors, resulting in high relative humidity in the upper floors. Additionally, the rapid diffusion of water vapor in the air results in a lower relative humidity at the first floor of the outdoor atrium, which also results in a lower indoor exposure.

## The air temperature and relative humidity in offices near the outdoor atrium

The outdoor atrium also affected the thermal environment in the nearby offices. An office on the third floor (shown in Fig. 2) was selected, and its doors and windows were closed.

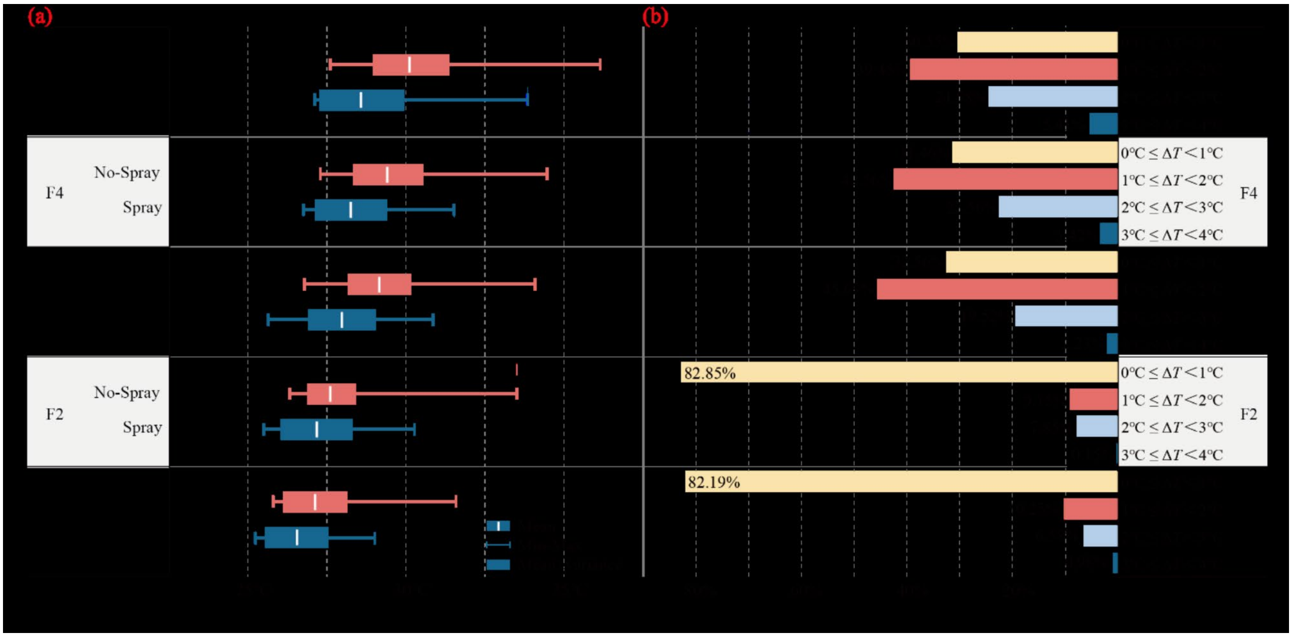


**Fig. 6**. Comparison of (**a**) air temperature and (**b**) its distribution of temperature difference in the hallway.

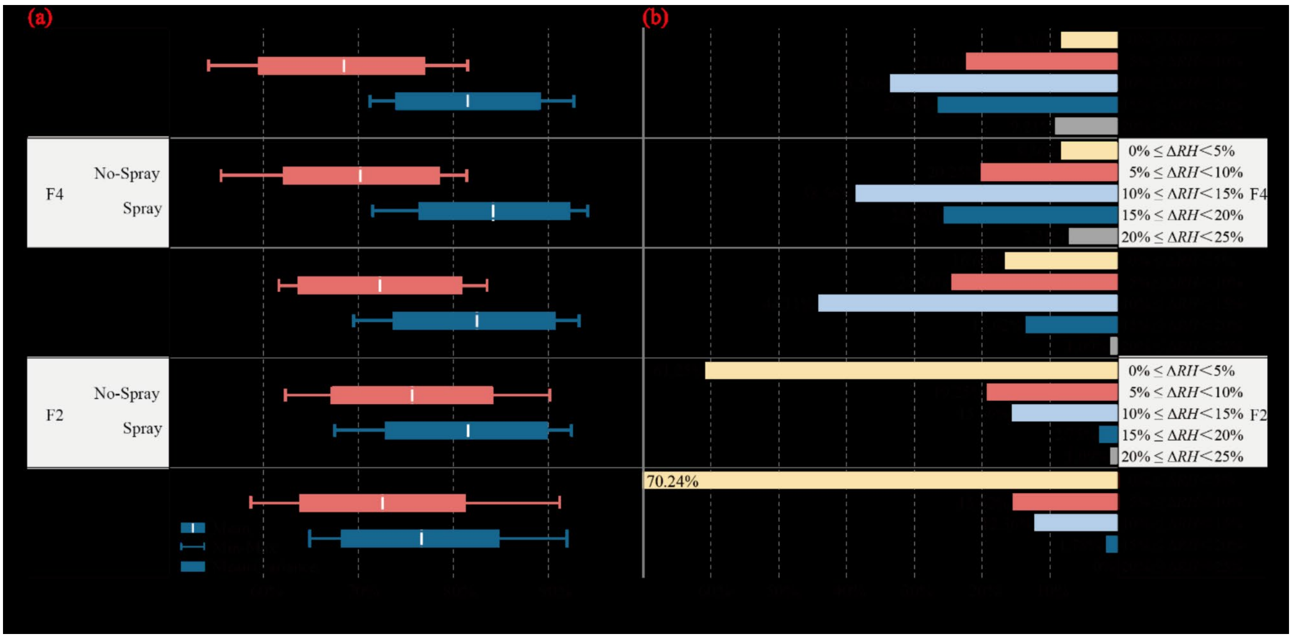


**Fig. 7**. Comparison of (**a**) relative humidity and (**b**) its distribution of relative humidity difference in the hallway.

Figure 8 compares air temperature, relative humidity, and the predicted mean vote (PMV) in offices before and after implementing the spraying system. PMV was gained by the thermal comfort meter (JT-IAQ-50)[33]. Preliminary research indicates that during the summer months, individuals primarily engage in sedentary activities within office environments, such as desk work and document handling. These activities are typically conducted while wearing clothing items such as trousers, shirts, lightweight pants, socks, and shoes. Accordingly, the baseline metabolic rate for individuals engaged in this occupational activity is established at 1.2, with a heat dissipation rate of 60 W/m$^2$ for the specified activity level and a clothing thermal resistance of 0.6. The Fanger's PMV-PPD model[34] was employed to calculate the PMV during the study period using a formula based on environmental parameters, set metabolic values, heat dissipation rates, and clothing thermal resistance.

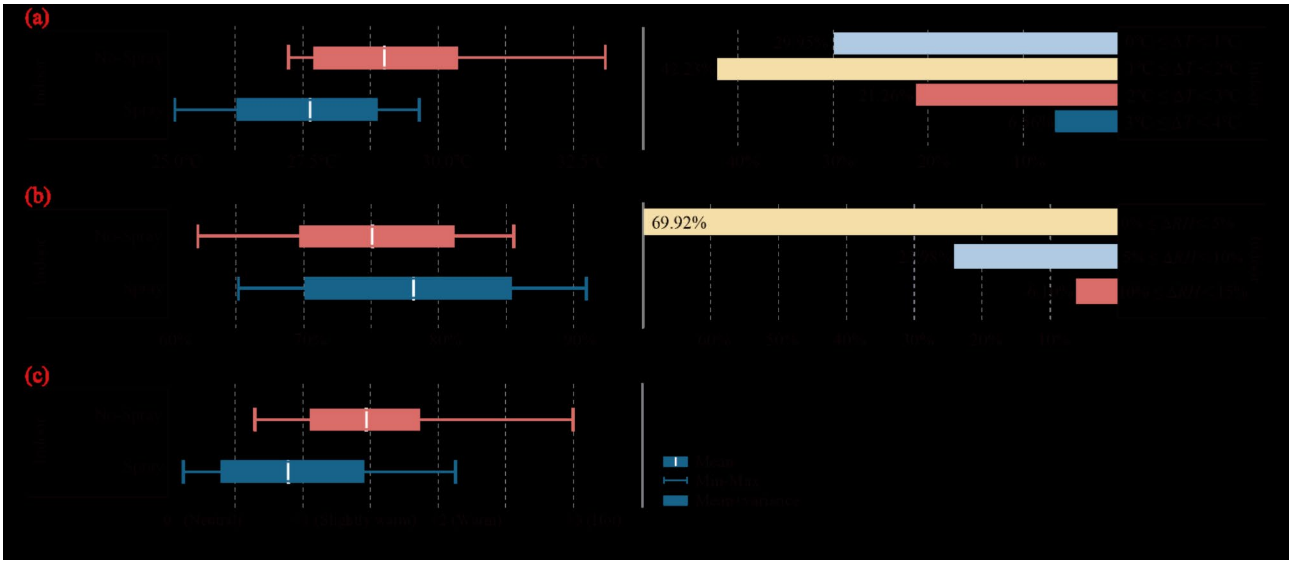


**Fig. 8**. Comparison of (**a**) air temperature, (**b**) relative humidity and (**c**) predicted mean vote in offices.

As shown in Fig. 8, indoor air temperatures decreased by an average of 1.41 °C and a peak of 3.45 °C, with a main temperature difference of 1–2 °C. The average and peak values of relative humidity decreased by 2.69% and 5.41%, respectively, with a main humidity difference less than 5%. Correspondingly, due to the spray system, the predicted mean vote reduced from 1.46 to 0.87, indicating significant improvement in the indoor thermal environment due to the enhanced thermal conditions created by the spraying system in the outdoor atrium. Calculations based on Fanger's PMV-PPD model[35] show that the PPD was reduced by 21% from 58%, which indicates that the use of misting systems in outdoor atriums effectively improves the indoor thermal environment. Furthermore, existing research indicates that droplets also exert a certain impact on solar radiation, resulting in a slight reduction in indoor solar radiation and an additional enhancement in bodily thermal comfort[36].

## The energy consumption of air-conditioning in offices near the outdoor atrium

The influence of the spraying system on air-conditioning energy consumption in offices was evaluated by selecting an office surrounding the outdoor atrium (In Fig. 2) with a set air temperature of 25 °C and closed doors and windows. In the studied offices, there are the air conditioners with the operating power of 1000w. Figure 9 compares air-conditioning energy consumption in five days before and after the spraying system installation, showing a noticeable reduction in energy usage due to the spray system's ability to lower ambient temperature within the outdoor atrium. This facilitates heat dissipation from the air-conditioning outdoor unit under lower ambient temperatures, resulting in a daily energy consumption reduction of 10.6-12.4%. Due to the reduction of air temperature at both the inlet and outlet al.ong with the evaporating droplets, it reinforced the heat dissipation of the air-conditioning condenser. This enabled more refrigerant to complete condensation within the same timeframe, thereby lowering the power consumption during compressor operation[37]. With enhanced heat rejection from the condenser achieved through evaporative spray cooling of air streams at multiple points, the compressor could obtain heat more efficiently and rapidly to relieve its working load under high ambient conditions[38]. These findings highlight that not only does the spray system improve thermal conditions within the outdoor atrium, but it also effectively reduces air-conditioning energy usage in surrounding office spaces.

This study merely conducted energy consumption measurements and feasibility validation in one room per floor of the building, without considering all rooms adjacent to outdoor atrium within the building. The above conclusions demonstrate a significant reduction in localized energy consumption due to the spraying system. Future research will comprehensively assess the energy consumption of all air conditioning systems and spraying systems within the building to ascertain the impact of spraying systems on the building's energy consumption.

# Discussion

Compared to the study of the cooling of the artium by means of a spray system (maximum cooling of 2.06 °C)[39], the difference in the cooling effect of the interior could be due to the area of the openable of the window, which in the present study could be up to 3 °C due to the evaporative cooling of the liquid droplets. This difference leads to air convection and heat exchange between the indoor and outdoor air, which in turn affects the cooling effect. Moreover, wind speed and wind angle can have a significant effect on the cooling effect and mitigate thermal stratification to some extent[40].

The composite spray system in the outdoor unit reduces the energy consumption of air conditioning by 13.9-37.3% compared to the existing studies[7], and the maximum energy saving in this study is 13%. The direct combination of the spray equipment with the air-conditioning outdoor unit can reduce the energy consumption by 37.3% by allowing the cooled air and droplets to exchange heat directly with the condenser. However, since the droplets first cool the air in the outdoor atrium, the cooled air improves the efficiency of the condenser,

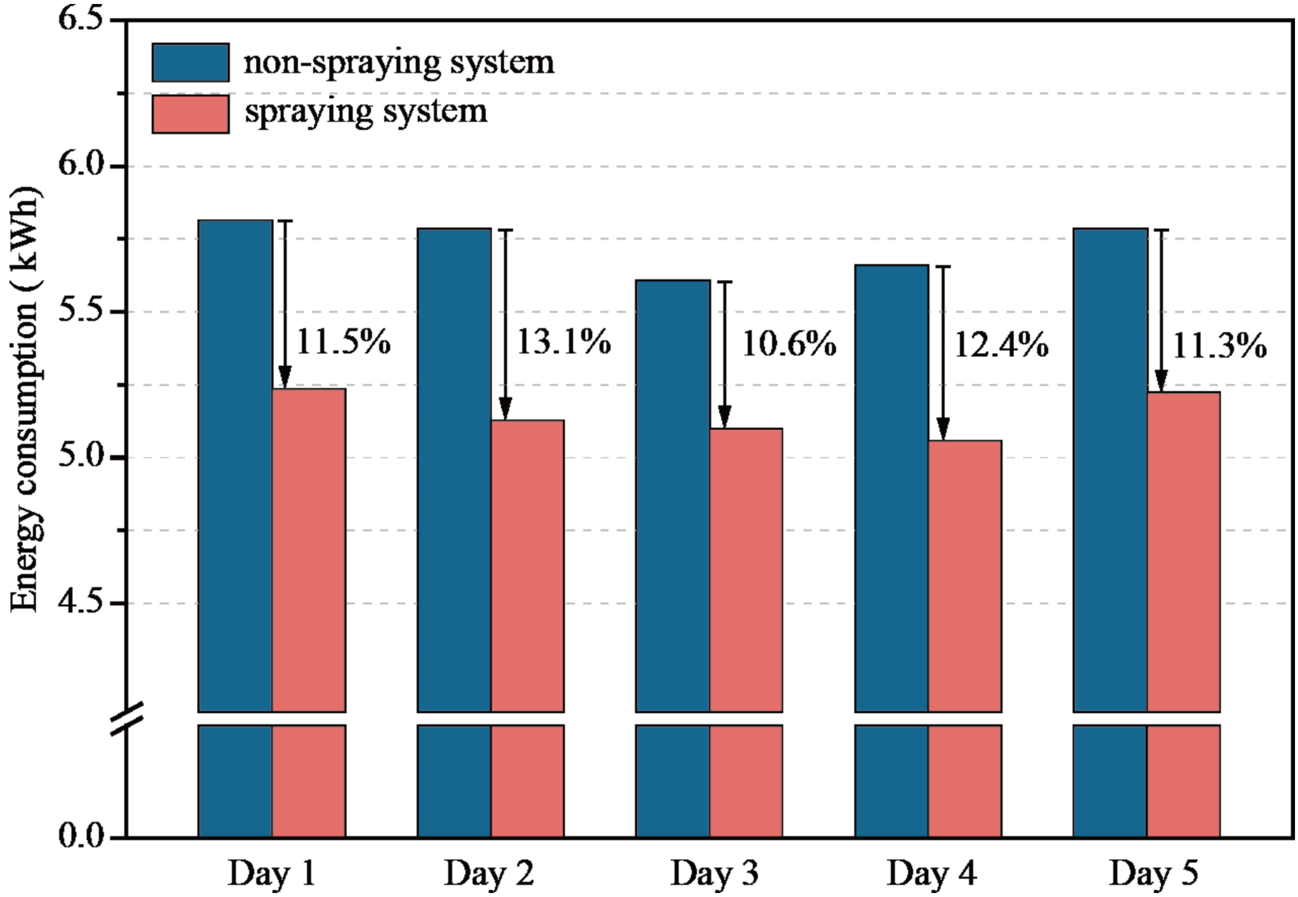


**Fig. 9**. Comparison of air-conditioning energy consumption in offices near the open Atrium.

which in turn reduces the energy consumption generated by the compressor. The effect of this process on the condenser of the air-conditioning outdoor unit is indirect, and therefore the energy saving efficiency will be lower than that of the existing studies. Therefore, in subsequent studies of outdoor atriums, the energy-saving effect can be enhanced by adding baffles to capture air[41].

Furthermore, similar to the findings of other researchers, the significant improvement of the PMV reduction from 1.46 to 0.87 indicates the improvement of the thermal comfort of the room by the external fogging device. The shading effect of the droplet mist layer can reduce the solar radiation transmittance by 9.0–12.3% compared to the cooling effect of the air conditioning system, which effectively improves the indoor thermal environment[42].

This method uses a spray system to mitigate the thermal environment of outdoor atriums. It has a high cooling efficiency, significantly reduces the local air temperature, significantly reduces the energy consumption of air-conditioning systems, has a low construction investment and a long service life. The method can be widely applied in summer to spaces such as building atriums and enclosed courtyards. In these places, a local heat island effect is formed due to poor air convection and heavy heat dissipation from the outdoor air-conditioning, which affects indoor and outdoor thermal comfort.

## Conclusions

In this study, the spray system was utilized to enhance the thermal environment in the outdoor atrium and its surrounding spaces. To assess the positive impact of the spray system, air temperature and relative humidity were tested within the atrium and adjacent areas, while also evaluating indoor thermal conditions and air-conditioning energy consumption in neighboring offices. The key findings are as follows:

(1) The spray system effectively enhances the thermal environment in the outdoor atrium by reducing average air temperature by 0.94–2.83 °C and peak air temperature by 2.92–5.21 °C, thereby mitigating thermal stratification from 0.37 °C/m to 0.28 °C/m. Additionally, it increases relative humidity by an average of 12.89%.
(2) The spray system implemented in the outdoor atrium positively contributes to improving the thermal environment in hallways as well, with an average reduction of 0.56–1.62 °C in air temperature and a decrease of approximately 2.31–3.25 °C in peak temperatures, effectively alleviating overheating issues while maintaining comfort levels intact. Furthermore, there is an average increase of relative humidity by 9.82%.
(2) In the office adjacent to the outdoor atrium, indoor air temperature was reduced by an average of 1.41 °C with the peak value decreased by 3.45 °C, while relative humidity increased by an average of 2.69% and

5.41% respectively. The predicted mean vote reduced from 1.46 to 0.87, indicating a significant improvement in the indoor thermal environment. The daily energy consumption was lowered by 10.6-12.4%.The experiments have demonstrated the potential of the spray system in improving the thermal environment in outdoor atrium and its adjacent offices. However, there are the certain limitations, due to the local climate condition and the special spray system. The variation in climate condition must potentially affect the results and the spray system may had the promotion potential. Further research under a wider range of climate and equipment conditions would be required to generalize the results.

## Data availability

All data generated or analysed during this study are included in this published article.

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## Author contributions

Conceptualization, N.D., J.Y.S., F.P., and X.M.; methodology, N.D. and X.M.; formal analysis, J.Y.S. and X.M.; investigation, N.D., J.Y.S., F.P., and X.M.; data curation, N.D. and X.M.; writing—original draft preparation, N.D.; writing—review and editing, N.D. and X.M.; supervision, X.M.; project administration, N.D., and X.M.;

## Declarations

## Competing interests

The authors declare no competing interests.

## Additional information

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