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Mist Spraying as an Outdoor Cooling Spot in Hot-Humid Areas: Effect of Ambient Environment and Impact on Short-Term Thermal Perception

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Abstract: Mist spraying is an active cooling technology used to alleviate heat stress during hot summers. However, there is limited experimental research on the relationship between ambient thermal parameters and spray cooling efficiency, as well as the transient and short-term thermal perceptions of local residents. In this study, an intermittent mist spraying system was set up, and environmental measurements, coupled with questionnaire surveys, were conducted under typical high temperature and still air conditions. The aim was to investigate the relationship among environmental factors, spray cooling effects, and dynamic improvements in human thermal perception. The results showed that higher ambient temperatures resulted in a more significant cooling effect, with a maximum value of 5.68 °C. Upon entering the spraying area, people experienced a large perceptual change, with the mean thermal sensation and thermal comfort change covering 73% and 62% of the total change ranges, respectively. This study indicated that the mist spray system can be activated if the ambient temperature exceeds 32.5 °C, helping local residents maintain a physiological state close to slightly hot and neutral comfort. These findings suggest that mist spraying can be applied in environmental design as an outdoor cooling spot to mitigate urban overheating, providing valuable insights for the application of mist spray systems in actual outdoor settings in hot-humid areas.

Keywords: periodic mist spraying; urban cooling spot; outdoor microclimate; environmental impact factor; short-term thermal perception

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Citation: Wang, P.; Lu, S.; Wu, X.; Tian, J.; Li, N. Mist Spraying as an Outdoor Cooling Spot in Hot-Humid Areas: Effect of Ambient Environment and Impact on Short-Term Thermal Perception. *Buildings* **2024**, *14*, 336. https://doi.org/10.3390/buildings14020336

Academic Editor: Benedetto Nastasi

Received: 13 December 2023
Revised: 21 January 2024
Accepted: 22 January 2024
Published: 25 January 2024

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1. Introduction

Urbanization has rapidly transformed urban structures and landscapes, resulting in a significant increase in carbon emissions [1]. Urban heat island and extreme heat have been occurring more frequently in cities across the world [2], increasing the discomfort of people and leading to a rise in the rate of heat-related mortality [3]. In hot and humid regions, high summer temperatures often fail to ensure pedestrian safety and comfort, impacting residents' daily mobility [4]. The inadequate urban pedestrian environment hinders city sustainability [5]. Therefore, integrating heat stress mitigation measures into urban outdoor design is crucial [6]. Establishing small and dispersed cool spots may mitigate urban overheating, reduce heatstroke risk, and enhance outdoor livability for people's travel and activities [7].

Most passive measures, like retro-reflective materials and vegetation, have limited controllability [8]. In contrast, mist spray systems, an active cooling technology based on evaporative cooling principles [9], offer flexibility and dynamic controls, effectively reducing heat stress [10]. Santamouris compared thermal environment improvement methods in hundreds of projects worldwide and found that spray-based evaporative cooling showed excellent cooling effects [11]. Mist spray systems have been installed in bus waiting areas, semi-outdoor public spaces in shopping malls, and significant event venues (such as the World Expo) in some cities. The installation and concealment of hydropower equipment in these locations, including the host control equipment, water filters, high-pressure water pipes, and fixed nozzle installations, provide important conditions for the application of mist spray systems and their cooling effects on the environment. During hot summers, creating scattered cool spots in open or semi-open spaces, such as station waiting areas, squares, and green belts where pergolas or pavilions can attract people to gather or briefly stop, can alleviate pedestrians' thermal discomfort through environmental design combined with spraying [12]. This can be effective even after just a few minutes, providing relief from the heat and enhancing the overall comfort of public spaces.

In recent years, the spray cooling system has gained attention in the built environment [12]. Ulpiani [13,14] and Giuseppe [15] conducted experiments in an Italian park and found that the spraying reduced air temperature by 8 °C and increased relative humidity by 7%. Sureshkumar [16] carried out experiments in India, where the temperature drop was up to 5.2 °C. Yamada [17] and Oh [18] executed experiments at the Aichi Expo and at a station in Japan. The results showed that air temperature could be reduced by 3 °C while relative humidity increased by over 23%. Huang [19] conducted mist spraying experiments at the Shanghai Expo, reducing air temperature by 5–7 °C with an ambient temperature and humidity of around 35 °C and 45%. Zhang [20] found that the mist spraying resulted in an average and maximum temperature reduction of 2.7 °C and 4.7 °C, respectively, as well as an average and maximum humidity increase of 9.4% and 15.5% at a bus stop waiting area built in the experiment in China. In these studies, the temperature reduction range was mostly within 1.0 °C to 9.0 °C, with a maximum of 15 °C [21], and the overall increase in relative humidity was within 5.3% to 29.3%, mostly related to the local climate [12].

Mist spray also affects the thermal perception of the human body. Farnham [22] conducted experiments and found that subjects' thermal sensation decreased from "Hot" (+2.7) to "Slightly cool" (−1.41) due to the outdoor mist. The research of Ulpiani [13] showed that 83% of the subjects felt uncomfortably hot outside the spraying area between 12:00 and 14:00, and the percentage dropped to 4% as they entered the mist. Zhang [20] suggested that participants' thermal sensation decreased from "between Hot and Slightly hot" (+1.44) to "near to Neutral" (+0.33), and thermal comfort increased from "almost Slightly uncomfortable" (−1.13) to "near to Slightly comfortable" (+0.76) as a result of spraying experiments. Desert [21] demonstrated that subjects experienced a reduction of 2~3 in thermal sensation in hot and humid extreme regions. Wong [23] found that the spraying could effectively achieve thermal neutrality by reducing air temperatures in Singapore. The effect of increased humidity caused by mist spraying on thermal perception has not been consistently observed in related studies. Wong [23] and Desert [21] suggested that severe discomfort was increased due to higher moisture levels of the skin, while Ulpiani [13], Farnham [22], and Vanos [24] believed that the moisture created by the spray was pleasing to the subjects. Indeed, the benefits of mist spray for enhancing physiological comfort could vary for people in different regions and climates [25]. Residents may have become accustomed to the prevailing weather conditions in their locality [26], including those living in hot-humid areas [27], especially when they are outdoors and semi-outdoors [28]. This may affect their assessment of the effect of mist spraying. Therefore, when evaluating the thermal perception and acceptability of the local population, it is essential to conduct targeted spraying experimental research in specific regions.

Most existing studies have focused on the thermal adaptation of participants to the spraying environment. Desert [21] compared subjects' thermal perception before entering the spray area and after spending 2–10 min in the mist. Participants in Ulpiani's experiments [13] stayed in the spraying area for 5–7 min before conducting the assessment. Zhang [20] had subjects remain in the mist for 10 min and complete a questionnaire evaluation every 3 min. In Wong's experiment [23], subjects completed a questionnaire at half-hour intervals after being exposed to the mist for at least 30 min. However, few studies have paid attention to the change in thermal perception at the moment of entering the mist spray. When people move into different environments, the human body is sensitive to sudden changes in local temperature, and thermal perception may undergo significant instantaneous changes [29], which may form a person's initial impression of the new environment and likely last for some time. It is necessary to study the changes in transient and short-term thermal perception when people enter the spraying area in the summer because people are more sensitive to cold stimulation [30].

The cooling efficiency of the spraying is partly determined by the setup of the mist spray equipment, including water pressure [12,13], droplet size [31,32], and the height of nozzles [13,15,33], among others. Sureshkumar [16] and Wang [10] revealed that higher pressure with smaller nozzles could produce more cooling. Yamada [34] proved that larger droplets remained in a lower position when spraying. When coming into contact with pedestrians, water spray may cause a strong sensation of wetness. Additionally, water spraying requires a larger amount of water usage. In contrast, the dispersed and smaller droplets of mist spray almost evaporate immediately after being injected, which is not only effective for cooling but also avoids unpleasant dampness for pedestrians [9]. Related studies suggested that the optimal water pressure range of high-pressure spraying was around 2 MPa–7 MPa [14,15,19], and the design value of spray volume was around 20 mL/min–50 mL/min [35,36]. Although most of these results were obtained under ideal conditions [12], they have a certain value for improving the operation performance of the spraying and can provide a useful reference for the construction of a typical mist spray system.

In addition to the setup of the mist spray equipment, outdoor thermal parameters also influence the cooling efficiency of the spraying [12]. Rising temperatures caused by solar radiation can accelerate mist evaporation [18]. Ulpiani [37] found that the intensity of solar radiation was negatively correlated with the drop in temperature during the spray experiment. He also reported that 80% of subjects felt pleasant warmth in the mist and concluded that mist spray was well suited to highly irradiated regions [13]. Meng [12] suggested that appropriate shading treatments combined with spraying could have a better cooling effect when the solar radiation intensity was too high. Wind can speed up water evaporation and lower air temperature more effectively [22,23], making mist-spray well-suited to suitable airflow conditions [13]. At the same time, wind will also make mist droplets run away from the target location, and non-directional wind could reduce the cooling efficiency of the spray system [31,38]. Giuseppe's numerical simulation analysis showed that the cooling capacity increased in calm air [15]. Ulpiani also concluded that the spray cooling effect was more apparent and easily measurable in still air conditions [9].

Several studies have shown that temperature and humidity are the primary outdoor thermal parameters affecting the effectiveness of spray cooling, with researchers demonstrating this through mathematical models [31] and numerical simulations [32]. For instance, Huang [31] used a developed mathematical model to calculate two extreme environmental conditions: one with a temperature of 38 °C and a relative humidity of 40%, and the other with a temperature of 30 °C and a relative humidity of 70%. The results indicated that higher temperatures and lower humidity resulted in higher cooling efficiency compared to lower temperatures and higher humidity. However, the mathematical model and numerical simulation are based on assumed ideal droplet evaporation conditions and a steady environment, which differ from actual outdoor spraying situations [12]. On the other hand, experimental testing is relatively commonly used and generally acknowledged as a more accurate method. Xie [39] constructed a small-scale experimental platform in a confined space and found that the higher the ambient temperature, the more significant the cooling efficiency. In an area with extremely high radiation and humidity, Desert established a three-dimensional spray experimental platform and found that mist cooling was more effective at higher ambient temperatures [21]. Huang's mist-spray testing experiments at the Shanghai World Expo also confirmed that the hotter and drier the weather, the higher the cooling reduction [19]. Nonetheless, these experimental studies have only yielded qualitative conclusions based on the comparison of a limited number of operating conditions. Due to uncontrolled environmental changes, there is a significant lack of experimental research that considers environmental factors as variables to quantitatively study the relationship between ambient thermal parameters and spray cooling efficiency.

In most experimental studies, the spray system operates continuously [20,23], which may potentially damage the equipment's lifespan, increase water consumption, and lead to excessive accumulation of water vapor in the air. A few studies have utilized spraying on/off modes, with timing variables ranging from several seconds to several minutes [9]. For instance, Ishii's experiment employed a pattern of the spray running for 2 min followed by a 3 min pause [38]. However, a short spray duration may not provide sufficient cooling of the micro-environment, and when combined with a survey, it may offer too few opportunities for individuals to enter the misted area for evaluation.

Therefore, in order to investigate the relationship between environmental factors, spray cooling effects, and improvements in human thermal perception, this study adopted intermittent spraying. The test experiment and questionnaire survey were conducted simultaneously. The dynamic effects of periodic spraying on the local thermal environment under typical high temperatures and still air conditions were analyzed. Each spraying operation period was considered a working condition for studying how the ambient thermal environment affects the efficacy of misting. Furthermore, this study compared the instantaneous thermal perception changes when people entered the mist under different ambient thermal environmental conditions and explored the dynamic changes in thermal perception of local people in hot-humid areas during their short-term stay in the spray. The findings are applicable to similar urban environments where conditions permit the installation of mist spray equipment and are expected to provide control strategies and application guidance for the efficient implementation of mist spraying as an outdoor cooling spot.

2. Materials and Methods

2.1. The Experimental Site

The experiment took place in the University Innovation Zone in Dongguan City, Guangdong Province, China. The area is surrounded by a mix of residential buildings, research centers, and office buildings. The test site was situated on the periphery of a grassy area adjacent to a pedestrian walkway, with no buildings within 25 m of the site (see Figure 1).

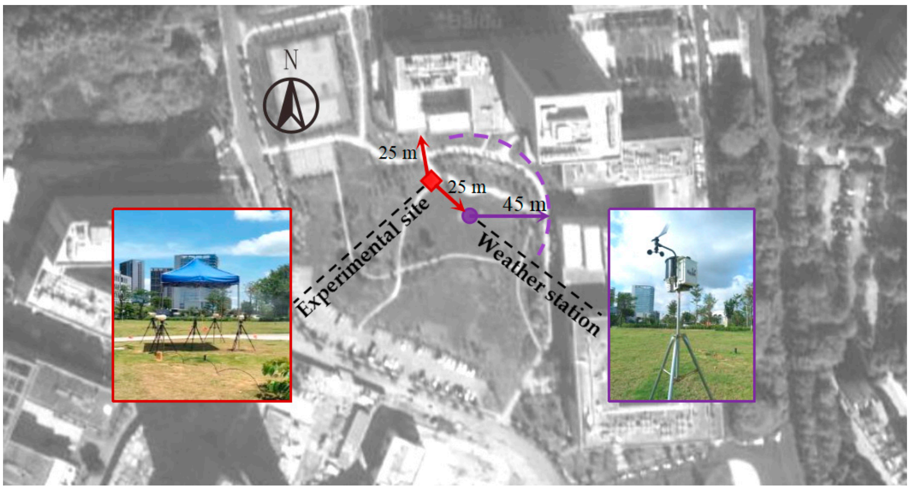


Figure 1. Schematic map of the experimental site.

During the local hot summer, outdoor activities can be extremely uncomfortable due to the lack of wind during the daytime. The experiment was conducted to align with typical weather conditions, taking place from 13:00 to 16:00 on 27 June, 8:30 to 16:00 on June 28, and 8:30 to 13:00 on 29 June. According to data from the weather station, the experiment occurred under conditions of maximum solar radiation of 967 kW/m^2, with the highest ambient temperature reaching 36.9 °C and relative humidity ranging from 48.4% to 74.5%. The average wind speed was 0.18 m/s, reflecting the typical summer heat climate in Dongguan City.

2.2. The Mist Spray System

A small square shed measuring approximately 2.2 m on each side was constructed at the experimental site with an internal height of about 2.3 m, similar in size to typical pergolas or pavilions, and was designed to replicate a semi-open, shaded outdoor space. The internal support structure of the shed top was equipped with the nozzles of the mist spray system. Experiments, including environmental measurements and questionnaire surveys, were conducted in and around this shed.

A total of 9 nozzles were arranged in a matrix in the central area of the shed top, approximately 0.35 m apart and positioned 2.35 m–2.45 m above the ground, directing the mist downwards. Each nozzle had an effective humidification diameter of about 1 m, ensuring that the spraying wet area was centered at the experimental site. The chosen nozzle height was consistent with previous research conducted by Desert [21] and Zheng [40].

Figure 2 illustrates the schematic diagram of the mist spray system. Filtered water entered the system through the inlet pipe and was pressurized to 6 Mpa. After the start-up and debugging of the host machine, the pressurized water flowed through the high-pressure outlet pipe. Subsequently, mist was ejected from high-pressure nozzles with a discharge diameter of approximately 0.15 mm. The experimental period was set to 30 min in on-off mode, with the mist system operating continuously for the first 25 min of each period and then stopping for the remaining 5 min. The three-day experiment comprised a total of 30 experimental periods.

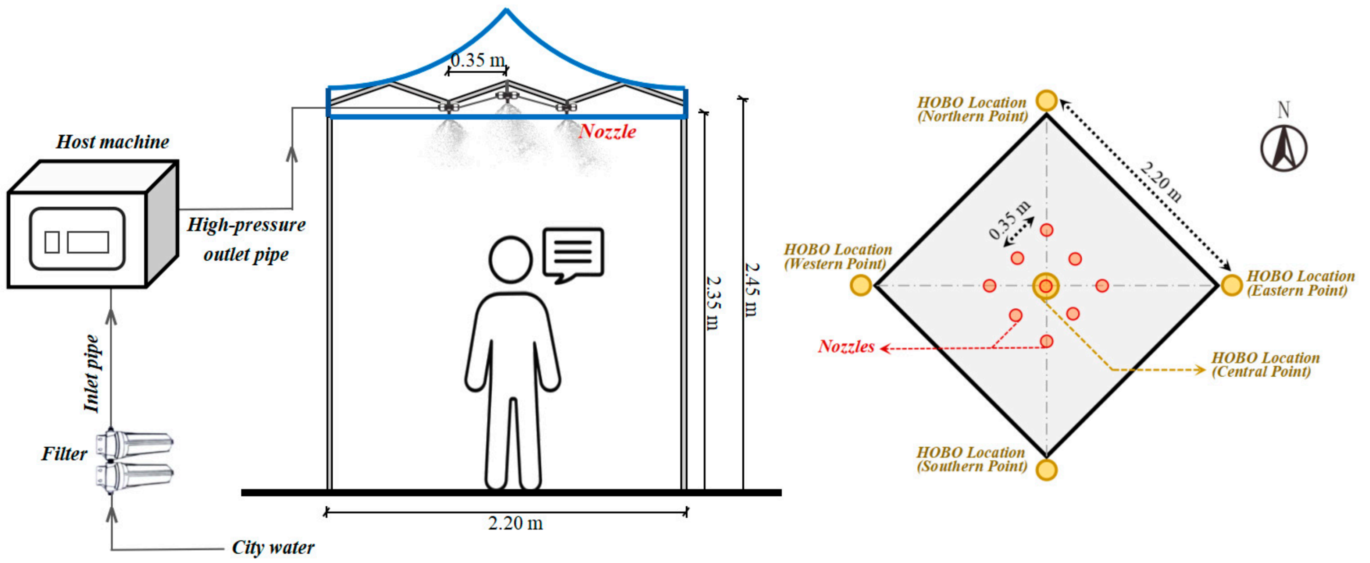


Figure 2. Schematic illustration of the mist spray system.

2.3. Environmental Measurement

The main instruments used for environmental measurements are listed in Table 1. The environmental experiment utilized the HOBO logger to measure air temperature and relative humidity, recording data at 30 s intervals. The instrument's probe was mounted on a tripod at a height of 1.1 m above the ground. Additionally, a radiation box with three blades providing shelter was placed outside the HOBO instrument (see Figure 3).

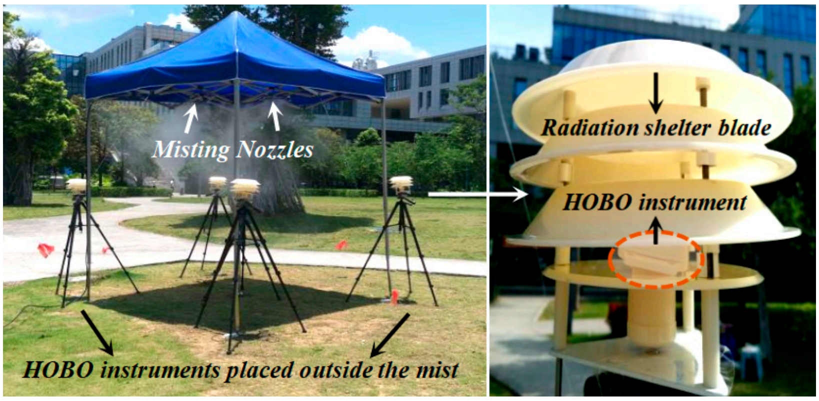


Figure 3. Hobo instruments and the radiation shelter blades.

Two groups of HOBO instruments were used in the experiment. The first group was placed in the center of the misting area to measure changes in temperature and humidity within the mist. The second group was positioned outside the misting area, beyond the four pillars of the shed, to measure ambient temperature and humidity changes surrounding the mist. Due to the low wind conditions during the experiment, the mist droplets did not drift sideways, ensuring that the second set of HOBO instruments would not be affected by the spray. This allowed for the simultaneous collection of environmental data inside and outside the misting area and the dynamic monitoring of the cooling and humidifying effects of the mist.

A weather station (Watch Dog, WD for short) was also included in this study, recording solar radiation, air temperature, relative humidity, and wind speed data at 10 min intervals. It was located in an open area 25 m away from the misting area, with no obstruction from buildings within a 45 m radius. The longer minimum time interval and lower accuracy of the WD data make it unsuitable for comparison with the HOBO data collected in the spray area. The WD data were used as a reference to verify whether the data collected by HOBO outside the mist accurately reflected the outdoor thermal environment without misting in the experiment.

Table 1. Measuring range and accuracy of Instruments used in the experiment.

Instrument	Environment Factor	Range	Accuracy
Temperature and humidity data logger (HOBO MX2301) Manufacturer: Onset, USA	Air temperature	−40~70 °C	±0.2 °C
	Relative humidity	0~100%	±2.5%
Weather station (WatchDog 2000) Manufacturer: SPECTRUM, USA	Solar radiation	0~1500 W/m^2	±5%
	Air temperature	−32~100 °C	±0.5 °C
	Relative humidity	10~100%	±3%
	Air speed	0.1~322 km/h	±5%

2.4. Questionnaire Survey

Dozens of participants were invited to the experimental site, and selected based on the following criteria: healthy adults who could understand the test rules, had proportional body shapes, had resided in the local city for more than 1 year, and had adapted to the local climate. An effort was made to ensure a similar number of men and women were selected as subjects.

During the hot summer daytime, people generally avoid staying outdoors for extended periods unless necessary, with the most common exception being waiting for transportation or taking a brief rest in pergolas and pavilions when feeling fatigued from walking. Zhang [20] noted that people typically wait at transportation sites for about 5 min or more. As a result, this study standardized the time for participants to stay in the mist at 5 min. The simulation replicated pedestrians entering the cool spot from an open space and staying briefly in the misting area.

Each participant was given a questionnaire form with three parts: (1) Personal information, including gender, age, and height; (2) Thermal perception survey before participants entered the mist area (see Figure 4); and (3) Thermal perception survey after participants entered the mist area (see Figure 5).

2. Please fill in the following questions before you step in the mist area.

Current date and time: ______________________

- ***How do you feel at this moment?***

Cold (−3)	Cool (−2)	Slightly cool (−1)	Neutral (0)	Slightly hot (1)	Hot (2)	Very hot (3)
□	□	□	□	□	□	□

- ***Do you feel comfortable or not at this moment?***

Very uncomfortable (−3)	Uncomfortable (−2)	Slightly uncomfortable (−1)	Neutral (0)	Slightly comfortable (1)	Comfortable (2)	Very comfortable (3)
□	□	□	□	□	□	□

- ***Do you think the current environment indicators need to be changed?***

	Substantially decrease (−2)	Slightly decrease (−1)	Unchanged (0)	Slightly increase (1)	Substantially increase (2)
Temperature:	□	□	□	□	□
Humidity:	□	□	□	□	□

Figure 4. Thermal perception survey before participants entered the mist area.

3. Please fill in the following questions when you step in the mist area, and fill in the same questions every one minute.

Current time: ______________________

- ***How do you feel at this moment?***

	Cold (−3)	Cool (−2)	Slightly cool (−1)	Neutral (0)	Slightly hot (1)	Hot (2)	Very hot (3)
Just step in:	□	□	□	□	□	□	□
After 1 min:	□	□	□	□	□	□	□
After 2 mins:	□	□	□	□	□	□	□
After 3 mins:	□	□	□	□	□	□	□
After 4 mins:	□	□	□	□	□	□	□
After 5 mins:	□	□	□	□	□	□	□

- ***Do you feel comfortable or not at this moment?***

	Very uncomfortable (−3)	Uncomfortable (−2)	Slightly uncomfortable (−1)	Neutral (0)	Slightly comfortable (1)	Comfortable (2)	Very comfortable (3)
Just step in:	□	□	□	□	□	□	□
After 1 min:	□	□	□	□	□	□	□
After 2 mins:	□	□	□	□	□	□	□
After 3 mins:	□	□	□	□	□	□	□
After 4 mins:	□	□	□	□	□	□	□
After 5 mins:	□	□	□	□	□	□	□

- ***Do you think the current environment indicators need to be changed?***

		Substantially decrease (−2)	Slightly decrease (−1)	Unchanged (0)	Slightly increase (1)	Substantially increase (2)
Just step in:	*Temperature*:	□	□	□	□	□
	Humidity:	□	□	□	□	□
After 1 min:	*Temperature*:	□	□	□	□	□
	Humidity:	□	□	□	□	□
After 2 mins:	*Temperature*:	□	□	□	□	□
	Humidity:	□	□	□	□	□
After 3 mins:	*Temperature*:	□	□	□	□	□
	Humidity:	□	□	□	□	□
After 4 mins:	*Temperature*:	□	□	□	□	□
	Humidity:	□	□	□	□	□
After 5 mins:	*Temperature*:	□	□	□	□	□
	Humidity:	□	□	□	□	□

Figure 5. Thermal perception survey after participants entered the mist area.

Thermal perception aspects included thermal sensation, thermal comfort, and preferences for temperature and humidity. Thermal sensation evaluation adopted 7-point scales from Very hot (3) to cold (–3), based on the 7-point standardized scale by ASHRAE and used in existing studies by Zhang [20]. Thermal comfort also employed 7-point scales from Very comfortable (3) to Very uncomfortable (–3). In addition, the 5-point scale from Substantially increase (2) to Substantially decrease (–2) was used to rate the preferences for temperature and humidity.

After providing their personal information, participants completed their initial assessment outside the spraying area. They then entered the mist, stood under the nozzles, and immediately performed a second assessment to obtain instantaneous thermal perception data. Subsequently, they conducted an assessment every minute until they left. Assessments were completed within the first 25 min of each experimental period; that is, the mist spraying kept running continuously for each participant during the questionnaire assessment. Each participant completed seven assessments within a 6 min timeframe, both outside and inside the mist, to monitor dynamic changes in their thermal perception.

3. Results

3.1. Experimental Results and Analysis

The measurement results from the weather station were compared with the mean results from the second group of HOBO instruments. As shown in Figure 6, the maximum differences in temperature and humidity were found to be 0.53 °C and 6.46%, respectively, while the average differences were 0.53% and 3.21%, respectively. The measurement results from the HOBO instruments showed consistency with the weather stations, indicating minimal impact from the mist. Therefore, they can be considered representative of the ambient temperature and humidity outside the mist spray area for comparison purposes.

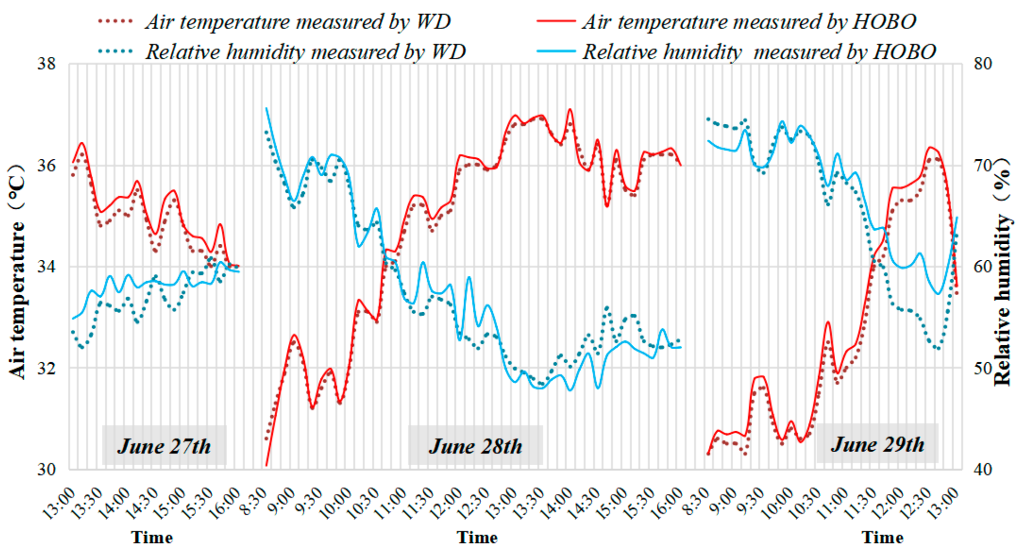
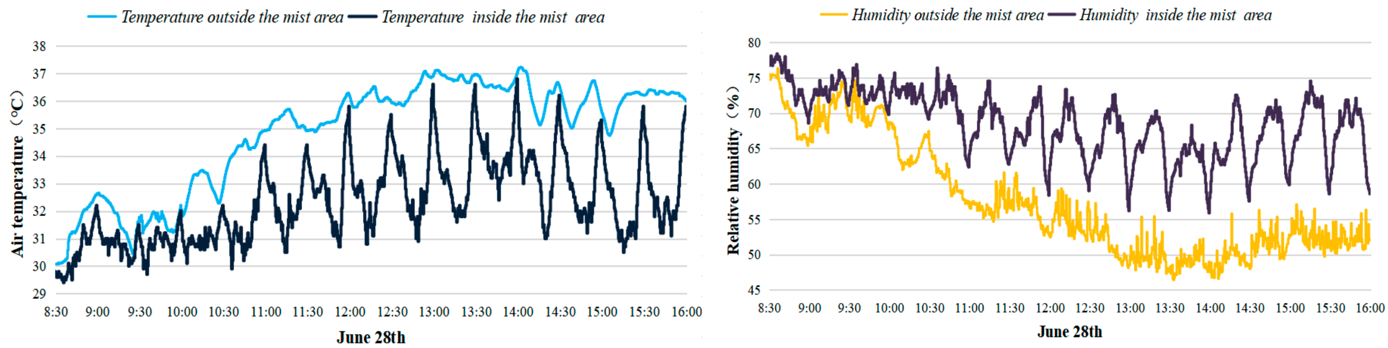


Figure 6. Comparison of the temperature and humidity between the WD and the second group of HOBO outside the mist area.

Figure 7 compares the temperature and humidity inside and outside the spraying area. The variations are essentially the same, with a decrease in air temperature and an increase in relative humidity. Additionally, the periodic changes in temperature and humidity align with the time periods of the mist spray system. At the start of each period, the air temperature drops and the relative humidity rises. When the system stops running after 25 min of each period, the air temperature increases and the relative humidity decreases, approaching the values observed outside the spray area at the end of the period. Throughout the experiment, the spraying reduces the air temperature by approximately

0.12 °C to 5.68 °C, with an average decrease of 2.42 °C. Moreover, the relative humidity in the mist area increases by around 0.04% to 22.21%, with an average humidification of 9.02%.



(**a**) (**b**)

Figure 7. Comparison of the temperature and humidity inside and outside the mist area during the experiment: (**a**) Air temperature on 28th June; (**b**) Relative humidity on 28th June.

Figures 8 and 9 illustrate the average cooling and humidifying effects during each spraying period. The data indicates that the average temperature difference gradually increases throughout the day. Prior to 10:00, the average temperature difference was 0.83 °C. From 10:00 to 11:00, it rises to 1.83 °C, and after 11:00, it further increases to 3.02 °C. Similarly, the average humidity difference follows a comparable pattern. Before 10:00, the average humidity difference is 3.44%, increasing to 7.84% from 10:00 to 12:00, and eventually reaching 11.71% after 12:00. The decision to activate the mist spray system early during the cooler morning hours, despite achieving some degree of cooling, raises questions about its necessity. The cost-effectiveness and energy efficiency of running the spraying should be considered. A more strategic approach may involve activating the system later in the morning when the ambient temperature is higher. Based on these results, it can be inferred that the mist spraying system demonstrates optimal cooling performance after 10:00 during the daytime in summer.

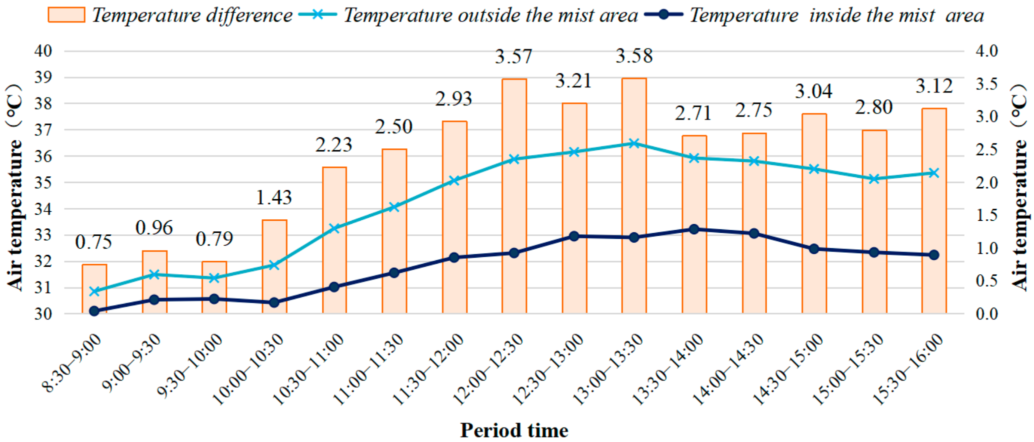


Figure 8. Comparison of the average air temperature for each period of time.

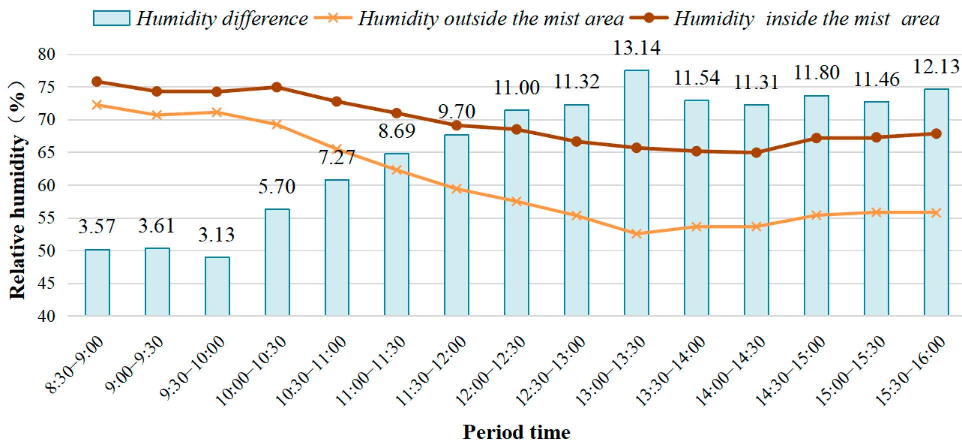


Figure 9. Comparison of the average relative humidity for each period of time.

To better illustrate the relationship between ambient thermal parameters and spray cooling efficiency, the average cooling and humidification levels under each working condition were used for comparison, considering the fluctuations in temperature and humidity during the spraying process. Each spraying operation period is considered a working condition for conducting a quantitative analysis of the relationship between ambient temperature and humidity and the magnitude of cooling and humidification, as shown in Figure 10. The x-axis represents the average ambient air temperature and the average relative humidity for each spraying period, while the y-axis represents the average decrease in air temperature and the average increase in relative humidity in the mist area within the corresponding period of spraying. The significance (p-value) is reported using a t-test, as are the graphs below in this article. The model is statistically significant, with a correlation r^2 greater than 0.9. The analysis demonstrates that as the ambient temperature increases, the cooling and humidifying effects of the mist spray become more pronounced. For every 1 °C increase in ambient air temperature beyond 31 °C, the average air temperature reduction caused by spraying increases by approximately 0.5 °C. At an ambient temperature of around 31.28 °C, the mist spray can achieve an air temperature reduction of about 1.0 °C. Meanwhile, at an ambient temperature of about 35.48 °C, the mist spray can lower the average air temperature by approximately 3.0 °C.

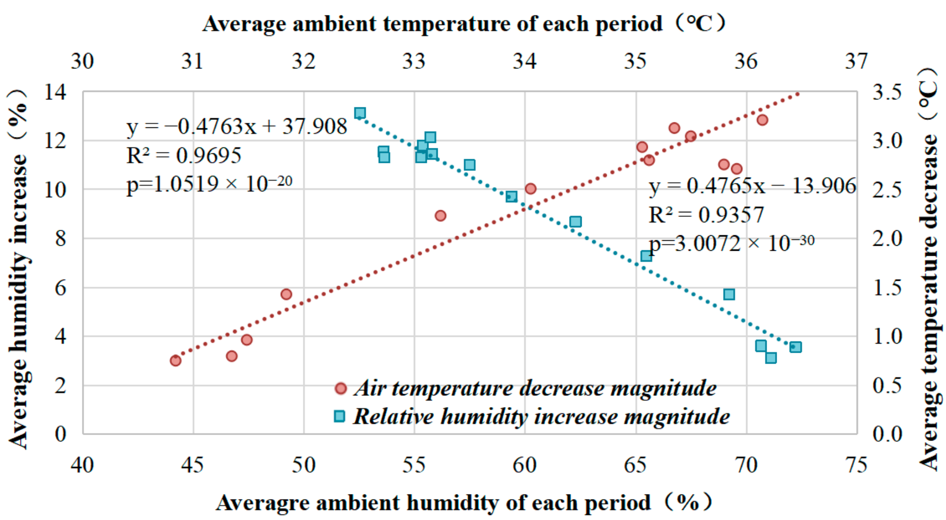


Figure 10. Relationship between ambient temperature and humidity and magnitude of cooling and humidification during spraying periods.

The spraying periods are sequentially numbered from 1 to 30 to facilitate the comparison and analysis of the dynamic changes in cooling and humidification. Periods 1–6, 7–21, and 22–30 correspond to 6 experimental periods from 13:00 to 16:00 on 27 June, 15 experimental periods from 8:30 to 16:00 on 28 June, and 9 experimental periods from 8:30 to 13:00 on 29 June, respectively. Figure 11 illustrates the variation in the temperature difference magnitude for different periods during the operation of the spray system. The graph depicts a continuous increase in the temperature difference within the first 2 min of each period. Subsequently, some curves start to fluctuate between 2 and 4 min due to the influence of the external environment and the mist spraying. The curves are categorized based on the initial ambient temperature of each period. The most rapid cooling rate is observed in the first 4 min of Period 18, which has the highest initial ambient temperature of 37.09 °C. Periods 7 and 22, with the lowest initial ambient temperatures of 30.07 °C and 30.32 °C, respectively, exhibit the most stable curves. It can be inferred that the magnitude of the temperature difference is correlated with the ambient temperature, influencing the rate at which the temperature difference increases. When the ambient temperature is below 32 °C, there is a minimal temperature difference between inside and outside the mist area, resulting in relatively flat curves. Conversely, when the ambient temperature exceeds 32 °C, the temperature difference becomes obvious, with the temperature magnitude increasing by approximately 0.5 °C to 1.0 °C per minute in the first 2 min.

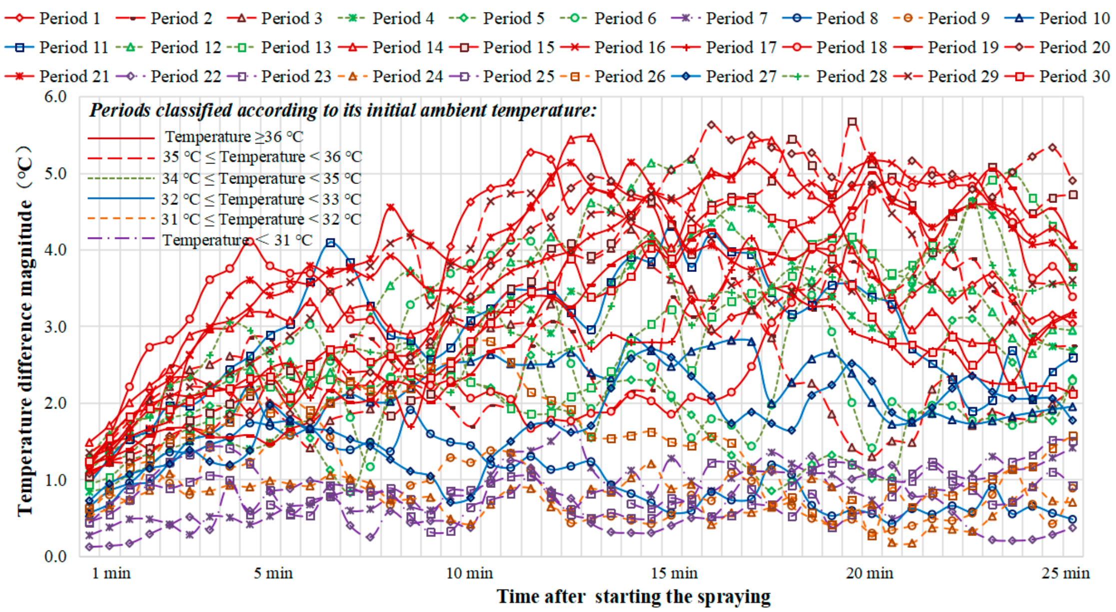


Figure 11. Variation in the magnitude of temperature difference during the operation of the spray.

3.2. Results and Analysis of the Questionnaire Survey

The number of participants willing to take part in the experiment was limited since the test was conducted during the COVID-19 pandemic. A total of 59 questionnaires were distributed, out of which 2 were invalidated due to incompleteness. Ultimately, 57 participants (29 males and 28 females) were involved in the experiment, with 86% aged between 19 and 29 (8 individuals aged under 20, 41 individuals aged 20–29, 5 individuals aged 30–39, and 3 individuals aged over 40) entering the mist area randomly. The average height was 167.5 cm (173.7 cm for men and 162.2 cm for women). None of the subjects were considered overweight or underweight. Throughout the experiment, participants completed questionnaires during 93% of the spraying periods, indicating that they entered the mist area under various ambient temperature and humidity conditions, as shown in Figure 12.

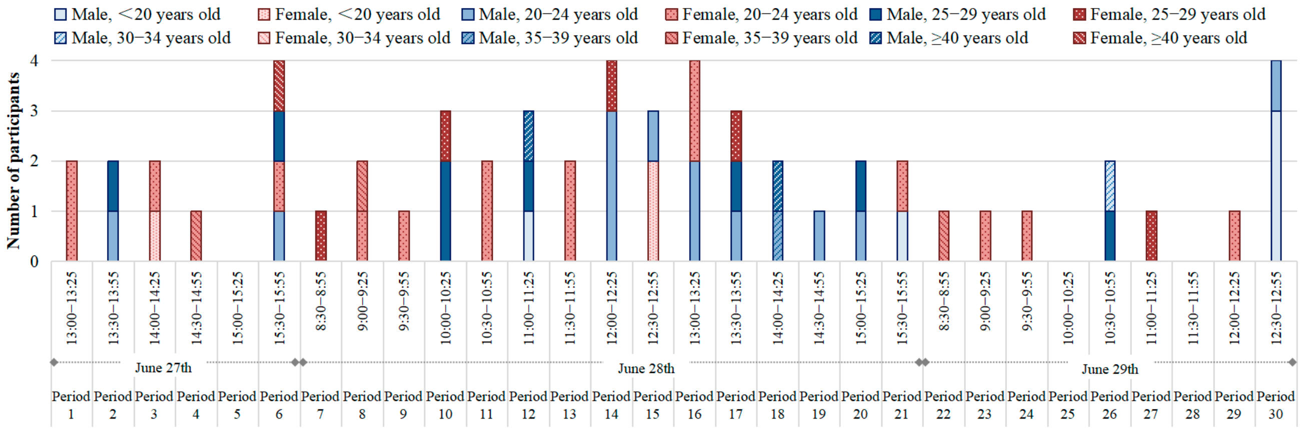


Figure 12. Distribution of participants of different genders and ages in each period.

Figure 13c–f presents statistical results of participants' thermal perception ratings at various times during the questionnaire survey, while Figure 13a,b display the air temperature and relative humidity of the environment where the participants were located at those moments.

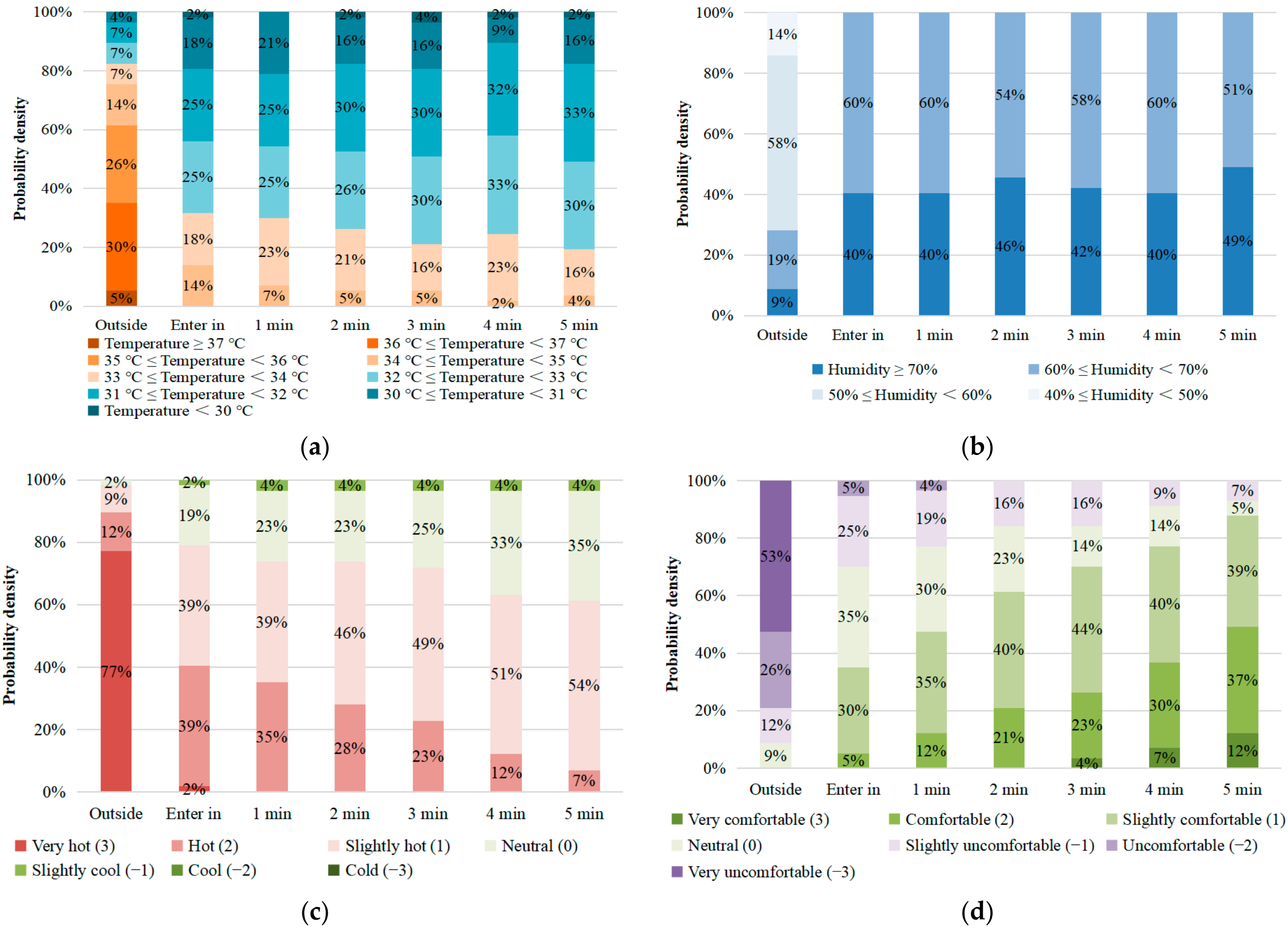


Figure 13. *Cont.*

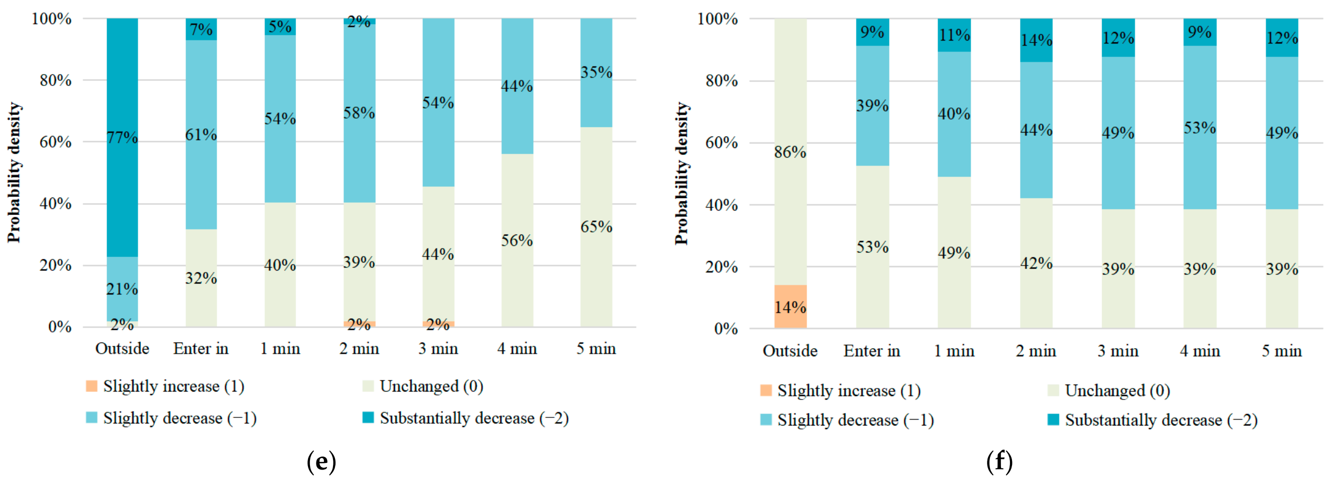


Figure 13. Questionnaire results and experimental results at different moments outside and inside the mist spray area: (**a**) Air temperature; (**b**) Relative humidity; (**c**) Thermal sensation; (**d**) Thermal comfort; (**e**) Temperature preference; (**f**) Humidity preference.

Prior to entering the misting area, 75% of the subjects were exposed to ambient temperatures above 34 °C, with 61% experiencing temperatures above 35 °C, 35% encountering temperatures surpassing 36 °C, and 5% even facing temperatures exceeding 37 °C. In terms of humidity levels, 58% of the participants were in an environment with humidity ranging from 50% to 60%. Meanwhile, 14% experienced humidity levels below 50%, while only 9% were exposed to humidity levels above 70%. Before entering the mist, 89% of the participants rated their thermal sensation as above 2 (Hot), with 77% reporting 3 (Very hot), resulting in an average rating of 2.65. In terms of thermal comfort, 79% of the subjects selected −2 (uncomfortable), with 53% choosing −3 (Very uncomfortable). The average rating result was −2.23. A total of 98% of the participants believed that the air temperature should be reduced. 86% of the participants were adaptive to the ambient humidity, while 14% were looking forward to a slight increase in humidity.

Upon entering the misting area, 50% of the subjects experienced temperatures ranging from 31 °C to 33 °C, while 32% were exposed to temperatures above 33 °C, and only 14% experienced temperatures exceeding 34 °C. Over the subsequent 5 min period, the number of subjects exposed to temperatures between 31 °C and 33 °C increased to nearly 65%, while the proportion of those exposed to temperatures above 34 °C decreased to less than 5%. Additionally, all participants were subjected to relative humidity of more than 60%, and within the following 5 min, the percentage of participants experiencing humidity levels above 70% rose to 49%.

The average temperature and humidity dynamics experienced by all the subjects during the test were statistically analyzed, as shown in Figure 14. Before and after entering the misting area, the temperature and humidity differences were as high as 2.7 °C and 10.22%, respectively. In the following five minutes, the average temperature and humidity of the spraying environment experienced by the subjects changed slightly, with maximum change values of 0.29 °C and 0.91%.

The thermal perceptions of the subjects underwent significant changes upon entering the misting area. Initially, only 2% of the participants reported feeling Very hot (rating 3), while 39% selected Slightly hot (rating 1), resulting in an average thermal sensation rating of 1.19. However, within the subsequent 5 min, the percentage of participants rating their thermal sensation as 0 and 1 increased to 35% and 54%, respectively, leading to a decrease in the average thermal sensation rating to 0.65. Notably, no participants reported feeling Very hot (rating 3) after 1 min in the mist. In terms of thermal comfort, 30% of the participants reported feeling Slightly uncomfortable (rating below −1), 35% felt Neutral (rating 0), and 35% felt Slightly comfortable (rating above 1) upon entering the misting area, resulting in an average rating of 0.05. Over the next 5 min, the percentage of participants rating 0 and −1 decreased to 5% and 7%, respectively, with no participants reporting Uncomfortable (rating −2) after 2 min in the mist. As the participants continued to stay in the mist, the percentage of participants reporting feeling Comfortable (rating 2) gradually increased, reaching 37% towards the end, and the average rating for thermal comfort eventually reached 1.42.

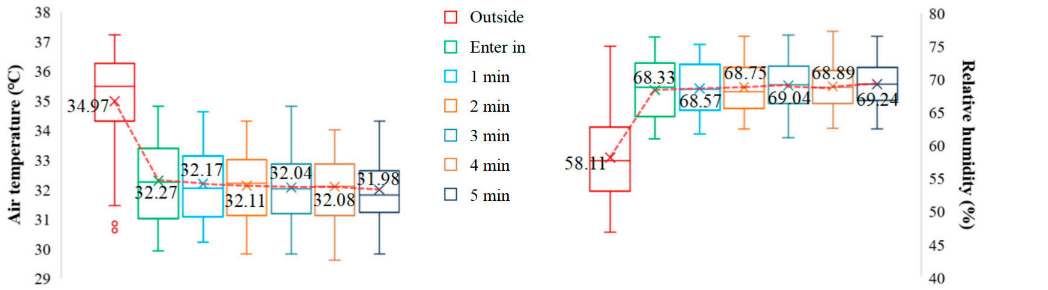


Figure 14. The average temperature and humidity dynamics to which all the subjects were exposed during the test.

The average thermal perception dynamics of all the subjects during their entire evaluation test are displayed in Figure 15. It is evident that there was a larger range of change in thermal comfort (−2.23 to 1.42) compared to thermal sensation (2.65 to 0.65), indicating that mist spraying provided a greater improvement in thermal comfort than in thermal sensation.

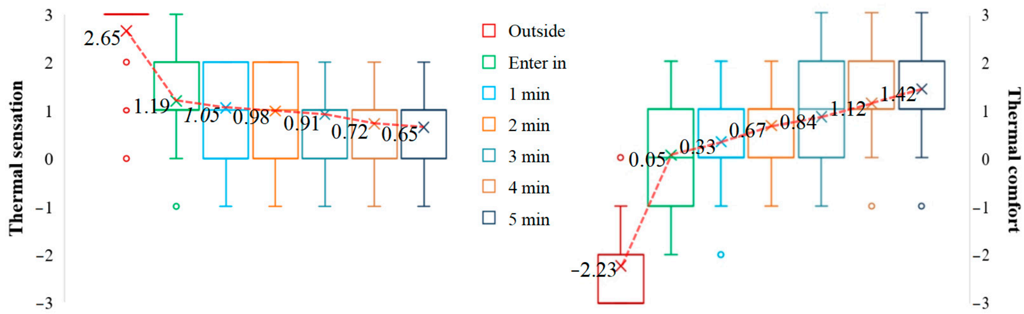


Figure 15. The average thermal perception dynamics of all the subjects during the test.

Upon entering the mist area, 68% of the participants believed that the air temperature should be reduced, while 32% preferred it to remain constant. However, the desire to lower the air temperature steadily decreased over the next 5 min, despite the temperature change not being obvious. Although 61% of participants felt Slightly hot or Hot, only 35% believed that the air temperature should be slightly decreased. Conversely, the percentage of participants who believed that the temperature could remain constant increased to 65% after staying in the mist for 5 min, indicating that they were gradually adapting to the temperature in the mist environment. Regarding humidity preference, most participants were comfortable with the ambient humidity outside the misting area. When entering the spraying, the percentage of participants who felt the humidity should remain unchanged dropped to 53%. Over the next 5 min, the percentage of participants who desired a slight decrease in humidity increased to 49%. Participants were able to feel the humid environment. As they spent more time in the mist, their demand for reduced humidity increased. However, participants tend to have a high tolerance for high humidity. By the 5 min mark, 61% of participants were requesting lower humidity, and only 7% felt Slightly uncomfortable.

The relationship between thermal perception evaluation results and ambient temperatures was analyzed before participants entered the mist area. As shown in Figure 16, a correlation is observed between them prior to participants entering the mist area. When the ambient temperature exceeded 31.3 °C, most participants reported feeling Slightly hot. When it exceeded 32.6 °C, most participants reported feeling Hot. The temperature reflecting thermal sensation neutrality was found to be 30.3 °C. Additionally, when the ambient temperature exceeded 32.4 °C and 34.4 °C, most participants reported feeling Slightly uncomfortable and uncomfortable, respectively. The temperature reflecting comfortable neutrality was 30.6 °C.

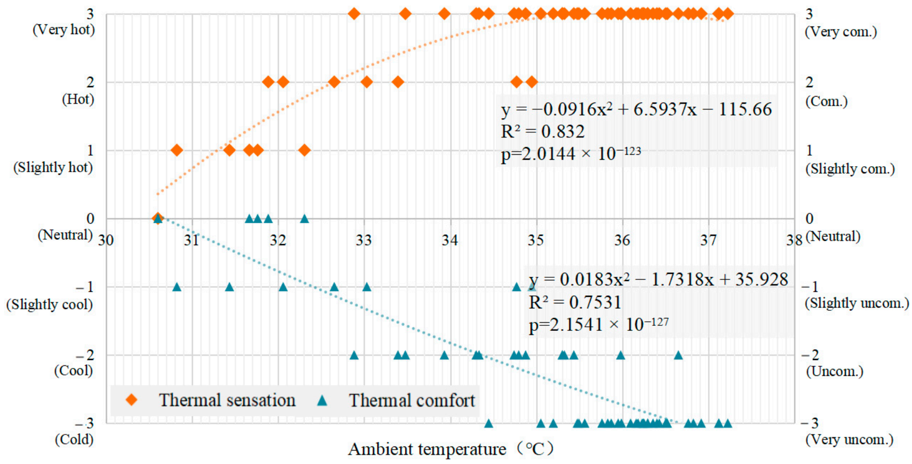


Figure 16. The relationship between evaluation result and ambient temperature outside the mist.

The total change in thermal sensation and thermal comfort during the entire evaluation process, both outside and inside the spray area, was −2 and +3.65, respectively. When the subjects first entered the spray area, the mean thermal sensation changed from 2.65 (between Very hot and Hot) to 1.19 (approaching Slightly hot), covering 73% of the total change range of thermal sensation. Upon entering the spray area, their mean thermal comfort changed from −2.23 (approaching Uncomfortable) to 0.05 (Neutral), which accounted for more than 62% of the total change range. The remaining small part of the change in thermal perception occurred as the participants gradually adapted to the mist area. These dramatic, instantaneous changes are related to the immediate temperature difference between inside and outside the mist area, as shown in Figure 17. The analysis demonstrates that as the instantaneous temperature difference increases, the magnitude of variation in thermal perception becomes more pronounced, and the increase in thermal comfort outweighs the decrease in thermal sensation. For every 1 °C increase in temperature difference, the thermal sensation decreases by 0.53, while thermal comfort increases by 0.64. The thermal sensation rating decreases for 95% of participants (54 subjects), while all individuals report feeling more comfortable. Despite the air temperature inside the mist remaining relatively high after cooling in some cases, participants still felt more comfortable.

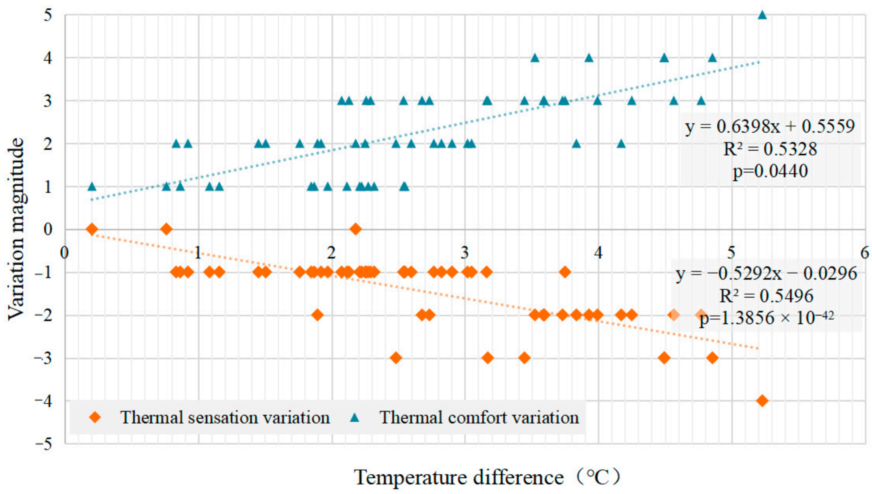


Figure 17. The relationship between the magnitude of variation in thermal perception and the instantaneous temperature difference.

After spending time in the mist area, the subjects' thermal sensation and thermal comfort continued to change, accounting for the remaining 27% and 38%, respectively, compared to the small changes in the mean temperature and humidity of the environment. As these subjects gradually acclimated to the spraying environment, the relationship between the objective micro-environment and thermal perception seemed to weaken. Furthermore, the impact of temperature on thermal perception was examined based on the duration that participants spent in the mist. Figure 18 illustrates the analysis findings for participants who stayed in the mist for 1 min, while Figure 19 shows the results for those who stayed for 5 min. The correlation gradually decreases as participants spend more time in the spraying area, indicating that the impact of temperature on thermal perception diminishes over time. These findings suggest that individuals may adapt to the misty and cool environment over time, leading to a reduced sensitivity to temperature changes as well as a diminished reliance on environmental temperature for thermal perception.

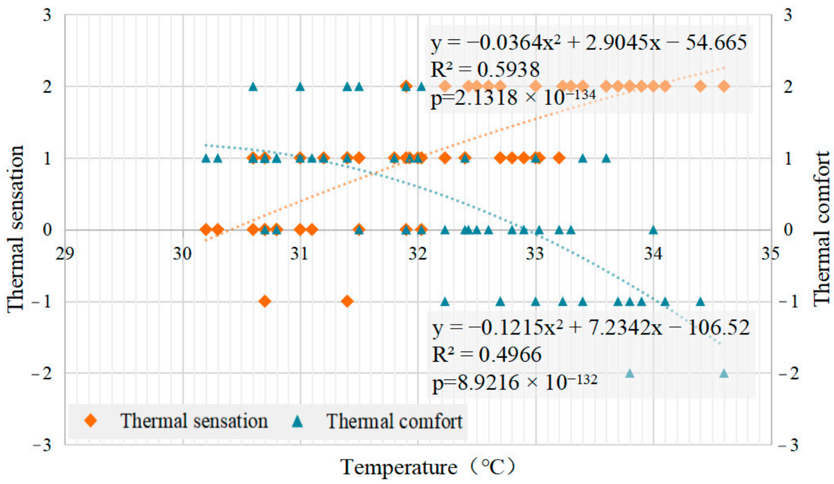


Figure 18. The relationship between thermal perception evaluation result and the temperature when the subjects stayed in the mist for 1 min.

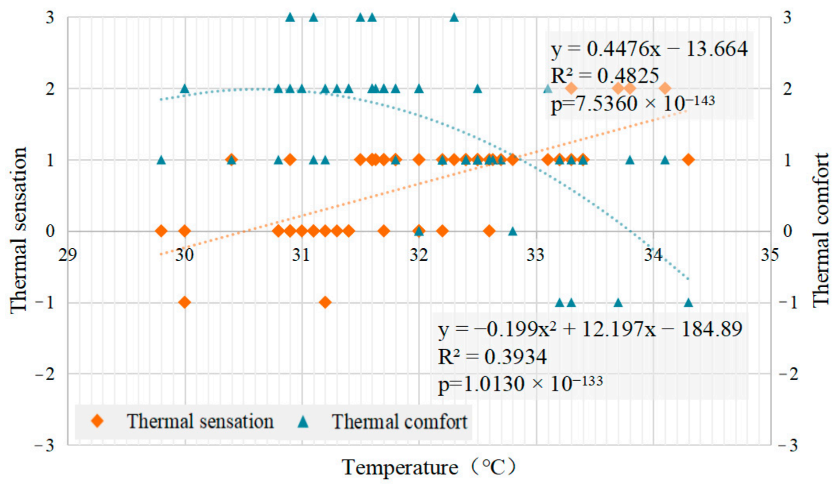


Figure 19. The relationship between thermal perception evaluation result and the temperature when the subjects stayed in the mist for 5 min.

4. Discussions

4.1. Cooling Efficiency of the Mist Spray System

In this study, the running period of the spraying resulted in a changing period of low temperature and high humidity in the mist, with the maximum and average temperature difference being 5.68 °C and 2.42 °C, respectively. This cooling effect aligns with previous literature [16,19,20], indicating that the mist spray system used in the experiment, which simulated an outdoor semi-open shaded space, has relatively high cooling efficiency. This is consistent with Meng's suggestions that combining appropriate shading treatments with spraying could have a better cooling effect [12]. Some studies have suggested that increased humidity from mist spraying may exceed the human body's tolerance limit, impacting subjective perception [41], but in our study, participants were able to perceive the humid environment, and this sensation did not diminish over time. However, the presence of moisture in the air and a relative humidity of up to 75% in the mist area did not compromise the effectiveness of the mist spray. It can be assumed that moderately high humidity does not necessarily prevent the perception of comfort. Individuals living in hot-humid climates generally have a higher tolerance for humidity and provide positive feedback when evaluating their thermal comfort, which aligns with findings from other studies in the literature [13,22,24].

From 12:00 to 14:00, when solar radiation is strong and the background temperature is high, the temperature difference is the largest in this study. The experimental results show that ambient temperature affects the magnitude of spray cooling and the rate of temperature difference. This conclusion is similar to Meng's view, who claimed that original temperature and humidity affect spray cooling [12]. Since the amount of spray is assumed to be constant and completely evaporates, the amount of cooling and humidification should not change as the ambient temperature changes. However, in the experiment, some of the mist might be attached to the subjects' hair, skin, or surrounding objects, such as the surface of the radiation box and the ground surface, without evaporating. In other words, the amount of spray is not equal to the amount of evaporation. Due to the changing participants and environment, the actual amount of mist evaporation was changed, which may be the reason why the amount of cooling and humidification varied with the ambient air temperature in this study.

4.2. Criteria for Activation of the Spraying

In this study, it was observed that the cooling range of the spray before 10:00 was limited, suggesting that the spray after 10:00 could achieve a better cooling effect, potentially leading to greater overall effectiveness and resource conservation. This finding aligns with Huang's recommendation to apply spray cooling technology during 10:00–16:00 in the summer [19]. However, it is important to note that the conclusion of the latter is based on specific temperature and humidity criteria (temperature $\geq$ 30 °C and humidity $\leq$ 70%) for time screening. Since temperature and humidity are relatively easy to obtain as environmental factors, they are often used as indicators to determine whether to start spraying. The automatic control condition used by Ishii in the experiment applied at the station in Japan was that the temperature was greater than 28 °C and the relative humidity was less than 70% [38]. Yamada suggested that mist spray is suitable when the temperature is above 30 °C and the humidity is below 70%, based on a numerical simulation analysis of three working conditions [34]. Huang reached the same conclusion from the analysis of two working conditions [31]. Several studies have used the neutral temperature as the criterion for activating the mist spray. According to Wong's regression model of the observed thermal sensation and the temperature recorded for the semi-outdoor experiment conducted in Singapore, it is suggested that mist spray should be turned on when the neutral temperature is above 29.2 °C [23]. The experimental results from this study suggest a neutral temperature of 30.3 °C, and further analysis is needed to determine the optimal timing for activating the spray system, taking into account both the environmental conditions and the desired cooling outcomes.

It is widely believed that temperatures above 30 °C are favorable for spray application. Figure 16 in this study shows that at an ambient temperature of 30 °C, the average thermal sensation rating is −0.29, and the average thermal comfort rating is 0.44. This indicates that local residents, accustomed to hot weather, can tolerate such outdoor thermal conditions. Although the mist can lower the temperature by approximately 0.40 °C (inferred from Figure 10), its necessity appears to be relatively low. By combining the results of Figures 10, 16 and 17, it could be concluded that when the ambient temperature reaches around 32.5 °C, the average level of thermal sensation is 1.88 (approaching Hot), and the average level of thermal comfort is −1.03 (around Slightly uncomfortable). Utilizing the mist spray at this point can lower the temperature by 1.58 °C. After participants enter the mist area, the average level of thermal sensation decreases to 1.02 (Slightly hot), while the average level of thermal comfort increases to 0.54 (between Neutral and Slightly comfortable). At an ambient temperature of 34 °C, the average level of thermal sensation is 2.64, while the average level of thermal comfort is −1.80. When participants enter the mist, which provides a cooling effect of 2.30 °C, the average level of thermal sensation decreases to 1.39, and the average level of thermal comfort increases to 0.23. Although most of the participants still feel slightly hot, they do not feel uncomfortable. This indicates that the mist system is effective. Spraying could help local residents maintain a physiological state close to slightly hot and neutral comfort.

4.3. Impact on Short-Term Thermal Perception

When participants spend a short time (5 min) in the mist, the change in thermal sensation and thermal comfort compared to being outside the spray is 2 and 3.65, respectively. This is consistent with the findings of Desert [21] in hot and humid extreme areas. The majority of this change occurs upon entering the mist, accounting for over 73% (thermal sensation) and 62% (thermal comfort) of the total change range. The sudden change in thermal perception was influenced by the temperature difference in the environment before and after the subjects were exposed. The longer the time spent in the mist, the more the subjects will gradually adapt to the environment, making their preference for temperature in misty areas more apparent. When comparing humidity preference with thermal comfort evaluation, we can see that participants tend to have a high tolerance for high humidity.

On the other hand, the correlation between the thermal perception assessment and the actual temperature in the spraying area is not very strong. Desert believed that the change in thermal comfort after cooling was not only caused by the change in the physical environment [21] but also by psychological factors [22], such as thermal expectation [42]. In other words, the subjects' anticipation of the cooling spot may enhance their perception of thermal delight [43], thus amplifying the impact of their subjective perception. This may be one of the reasons why the subjects in this study can feel comfortable in the mist even when the thermal sensation has not reached a neutral level.

4.4. Potential Application in the Actual Scenes

The practical application of this study is to implement spray cooling technology in outdoor environments during hot and humid summers with minimal wind. The selection of the experimental space and the setup of the spray equipment were based on common urban public settings and relevant studies. Therefore, the conclusions of this study can also be extended to comparable partially sheltered public settings (e.g., traffic waiting areas, pergolas, and pavilions), where conditions allow for the installation of typical mist spray hydro-power equipment. The mist spray system is capable of utilizing and filtering urban water sources, and the equipment can be installed underground, on walls, or in other structures to accommodate the host control equipment and high-pressure water pipes, with overhead structures for the installation of a specific number of nozzles. This study focused on the cooling efficiency of a mist-spray system in a simulated outdoor semi-open shaded space, considering its environmental influencing factors and short-term impact on the thermal perception of the crowd.

Based on this study's findings, it is recommended to activate the mist spray in outdoor spaces when the ambient temperature exceeds 32.5 °C in the summer. To achieve this, it is advisable to place the ambient temperature probe near public settings. Initiating the spray too early, such as before 10 a.m., or for extended periods is not conducive to a water-saving and energy-efficient spray mode. Given that the primary purpose of the spray is to enhance human thermal comfort, individuals experience a noticeable improvement in thermal perception upon entering the spraying area. Therefore, it is worth considering integrating a human body sensing device with the spray control system. The spray should not be activated when no one is around, and short bursts of spraying should only be triggered when human presence is detected approaching in high ambient temperatures. The initial minutes of spraying rapidly cool the environment, so the spraying duration should not be too short, lasting at least 2 min. By networking and controlling the mist spray system, temperature sensor, and body recognition device, an operation mode may be designed to efficiently create cool spots while conserving water and reducing energy consumption. The findings aim to offer control guidance for the application of mist spraying in outdoor environment design to enhance the micro-environment for citizens and improve thermal comfort levels.

4.5. Limitations and Future Research Directions

Due to the additional power consumption and challenges in controlling wind speed while operating mist-spray equipment, this study did not incorporate a fan into the test setup, in line with some published studies conducted in calm or breeze conditions [44]. This decision aimed to minimize variables (such as wind speed, wind direction, wind temperature, and so on) and investigate the quantitative relationship between spraying efficiency and initial temperature and humidity under typical weather conditions with minimal wind. Future studies on spray cooling will consider wind as a new variable. Some literature suggests that combining a fan with mist spraying can further reduce local temperatures [23,35]. Therefore, wind will be considered a new variable for future studies on spray cooling.

In order to fully explore the potential of spray cooling, future research should extend this study to multiple days in hot-humid areas. Increasing the number of subjects will enhance the credibility of the research conclusions, and participants' age, height, and weight can be more diverse. Conducting more detailed participant classification studies is expected to aid in the development of targeted and efficient spray control strategies for real-life public scenarios involving diverse audiences.

Furthermore, a crucial future research direction involves the comprehensive exploration of the practical application of spray system facilities in urban settings. Different urban scenarios may have varying requirements for technical parameters such as the number of nozzles and water consumption. This may include addressing issues such as integrating and filtering urban water sources in various urban settings, as well as strategically and flexibly planning the spray equipment and devices, seamlessly integrating them with municipal and landscape facilities, without compromising the cityscape or disrupting public activities. Additionally, it involves enhancing the intelligence of the spraying equipment, ambient temperature sensors, human body recognition devices, and other auxiliary devices, and future integration of them with the urban Internet of Things for more efficient control and operation of the mist spray system.

5. Conclusions

This paper studied the effects of periodic mist spraying on the outdoor thermal environment and the short-term thermal perception of local residents. The main conclusions are enumerated as follows:

(1) The intermittent on-off mist spray system caused periodic changes in the local environment. The spraying could reduce the air temperature by an average of 2.42 °C, with a maximum cooling value of 5.68 °C. The relative humidity was increased by an average of 9.02%, with a maximum humidification value of 22.21%. When comparing different time periods, it was observed that the temperature reduction was less than 1 °C before 10:00. The spraying system demonstrated its optimal cooling performance after 10:00 during the daytime in the summer.

(2) The quantitative analysis of each experimental period showed that higher ambient temperatures resulted in a more significant cooling and humidification effect. With every 1 °C increase in ambient temperature beyond 31 °C, the average temperature reduction caused by spraying increased by approximately 0.5 °C. Qualitative analysis also revealed that elevated ambient temperatures might lead to a faster increase in the rate of temperature difference between inside and outside the mist area after the beginning of each experimental period.
(3) With the exception of a few subjects who performed thermal perception assessments at low ambient temperatures, 95% of participants reported a decrease in thermal sensation, and all individuals reported feeling more comfortable. There was a larger range of change in thermal comfort (−2.23 to 1.42) compared to thermal sensation (2.65 to 0.65).
(4) Upon entering the spray area, the mean thermal sensation and thermal comfort change covered 73% and 62% of the total change ranges, respectively. These dramatic, instantaneous changes are related to the immediate temperature difference between inside and outside the mist. For every 1 °C increase in temperature difference upon entering the spray area, the thermal sensation decreased by 0.53, while thermal comfort increased by 0.64.
(5) During the 5 min stay in the mist, the subjects' preference for reducing the air temperature weakened, although the change in temperature and humidity was not obvious. However, their preference for reducing humidity strengthened. Their tolerance for high humidity causes them to still find the mist more comfortable. The impact of temperature on thermal perception diminishes as participants spend more time in the spraying area.
(6) The neutral temperature reflecting thermal sensation outside the mist is 30.3 °C. When the ambient temperature exceeds 32.5 °C, the average thermal sensation level approaches Hot, with the average thermal comfort level approaching Slightly uncomfortable. This information can serve as a reference for establishing criteria for activating spraying in hot-humid areas. Using the mist spray system at this point can reduce the temperature by 1.58 °C. The mist could help local residents maintain a physiological state close to slightly hot and neutral comfort.

In conclusion, the mist spray is expected to improve the outdoor thermal environment more efficiently and provide people with a more comfortable experience. Further research will be conducted to facilitate the application, control, and adjustment of the mist spray system in actual outdoor scenes.

Author Contributions: Conceptualization, P.W.; methodology, P.W., S.L. and N.L.; formal analysis, X.W. and J.T.; investigation, P.W.; resources, P.W., S.L. and N.L.; data curation, P.W.; writing—original draft preparation, P.W.; writing—review and editing, P.W., X.W. and J.T.; visualization, P.W.; supervision, P.W.; project administration, P.W.; funding acquisition, P.W., X.W. and J.T. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Basic and Applied Basic Research Foundation of Guangdong Province (No. 2020A1515111115); the National Natural Science Foundation of China (No. 52178275); and the Humanities and Social Science Research Program of the Ministry of Education (No. 22YJAZH112).

Data Availability Statement: The data presented in this study are openly available in Mendeley Data at https://doi.org/10.17632/dc4y7v47ff.1.

Acknowledgments: Thanks to the property management department of the University Innovation Zone for providing the site, water, and electricity support for this experiment.

Conflicts of Interest: The authors declare no conflicts of interest.

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