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Study The Effect of Water Misting System on The Performance of Outdoor Cooling Numerically

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Abstract

To enhance human thermal comfort and lessening environmental effect, cooling of inlet air with water misting is suggested as a way to improve performance during hot weather. This helps to create sustainable solutions. To find out the impact of various misting system characteristics, a parametric analysis study is carried out including the distance between nozzles (from 5 m to 17 m – three cases) and the number of nozzles (from 3 nozzles to 5 nozzles – three cases), following to the parameter of the distance between nozzles along *x*-axis (from 0.6 m to 1.2 m – four cases). In the current study, a CFD technique was used to study 3D simulations. Discrete Phase Model (DPM) was used for calculating momentum, heat and mass exchange between the water mist and the air. The results showed that, the most successful cases at the following: (1) the distance between nozzles ($\Delta Z = 17$ m), and (2) the number of nozzles (N = 4 nozzles). Which achieves for temperature and relative humidity: (1) 31.56 ℃ & 65.58%, (2) 31.53 ℃ & 65.69% of RH, respectively. Moreover, it’s observed that the best case when the distance between nozzles along *x*-axis (d = 0.8 m) which achieves 31 ℃ and 67% of RH.

Keywords: Climate mitigation, Water Mist, Thermal Comfort, CFD, Discrete Phase Model, Urban Heat Island, Evaporative cooling

1. Introduction

Many studies have been conducted on the effects of temperature on human health, particularly in light of the rising global temperature and the resulting need for efficient cooling systems. Water misting systems have emerged as a viable way to reduce heat stress as a result of this increased attention on innovation, especially in outdoor locations such as corner stores, bus/train stops, and rest areas on the street. Compared to conventional air-conditioning systems, this method saves money, energy, and water. On hot days, for example, misting water in semi-outdoor areas—under umbrellas, for example—may improve people's well-being. It's expected that more people will use these technologies in the future.

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Yoon et al. [1] used the numerical method to study the cooling effect in terms of distribution of the differenent water particles (sizes and heights) and examined the cooling effect of water mist system in the open space. This study utilized the CFD technique to prepare the simulation cases. Mass, momentum, heat, and the Discrete Phase Model (DPM) were resolved. The results presented that, for different particle size distributions, small differernce in the temperature reduction was observed. Also, when using single nozzle and installed at the height (1.5 m from ground) with small daimeters, there is no significant difference of remaining particles. However, with large particles, the remaining particles shown inside the area higher than the other cases. Additionally, a study by Santamouris et al. [2] tested various water-based solutions (evaporative wind towers, pools, ponds, fountains, and water sprinklers) to prevent the Urban Heat Island (UHI) effect and discovered that water spraying was the most successful. The evaporation of water fog, which enables the absorption of thermal energy from the surrounding air and produces an efficient cooling solution, is the basis for the operation of water spray systems. This process influences the convective processes of the fluid in motion and is somewhat comparable to adiabatic humidification. As a result, this technology may be crucial to promoting outdoor thermal comfort and preventing urban overheating and the UHI impact. The technology has drawn a lot of attention over the past 20 years, and according to a recent study by Meng et al. [3], over half of the available studies were published within the last five years. With the primary goal of enhancing thermal comfort, these recent studies concentrated on smaller-scale applications. As Oh et al. [4] and Zhang et al. [5] have shown, typical applications include transportation systems, pedestrian cool spots, and semi-outdoor and temporary spaces. Su et al. [6] investigated the effects of mist spraying system with varying nozzle densities and heights on people's thermal comfort. The study found that, the spraying system reduced the relative humidity and raised mean radiant temperature with increasing the nozzle height. However, the reduction in skin temperature at the forehead and upper arm increased with nozzle number from 4 to 8. Furthermore, as the nozzle height grew from 2.3 to 3.1 m with presence of 8 nozzles, the average skin temperature reduced by 0.72 - 0.53 ºC, respectively.

Most of the research’s looked at outside solutions because evaporative systems can be quite helpful there, even under extreme weather conditions. Narumi et al. [7] constructed water spray systems on an air conditioner's roof, balcony, and outside unit in 2009. The authors employed two different kinds of nozzles: one with fine droplets (40 µm size) and one with huge water droplets (300 µm size). The spray system was shown to save energy consumption by 80% and heat flow by 60%. In a high-temperature and high-humidity area (1.0 m above the floor level of some outdoor locations of the National University of Singapore), Wong and Chong [8] installed a water spray system with a fan in 2010. They discovered that the humidity could be raised by 8.61–10.38% and the air temperature could be lowered by 1.38–1.57 °C. In a high-temperature and high-humidity area (1.0 m above the floor level of some outdoor locations of the National University of Singapore). Huang et al. [9] investigated the influence of a water spray cooling system on outdoor temperature and humidity, taking into account nozzle pressure, droplet sizes, ambient airflow rate, temperature, and humidity levels. The study considers two extreme environmental conditions: (A) high temperature and low humidity, and (B) low temperature and high humidity. The spray mass rate, temperature drop, and humidity are computed in environments A and B using various nozzle pressures (1.5, 2, 3, 5, and 7 MPa). The study found that optimal cooling requires a spray pressure of 3 MPa, a temperature over 30 ºC, and a relative humidity below 70%. Ulpiani et al. [10] presented experimental results and design guidance for an efficient evaporative cooling system. The experiment included a high-pressure pump, a polypropylene filter, and 50 meters of polyamide tubing with 24 nozzles strung in four parallel strings 3 meters above ground. Two setups were examined for six days each: partial load (PL) and full load (FL). Full Load (FL) arrangement had a greater cooling efficiency (20.4%) than Partial Load (PL) (16.7%). FL had a larger temperature reduction, with a maximum drop of 7.4 °C versus 6.4 °C for PL and was more effective on hot days. FL kept temperatures in the target range 37% of the time, compared to 8% for PL.

Farnham et al. [11] reduced the cooling burden of an outdoor space (about 10 m2) that was partially shaded by trees and buildings by using a combination system (fans and sprays). The nozzles could create droplets with an average diameter of 25 μm when they were positioned around the edges of 35 cm fans. The nominal pressure was 6 MPa, and the volume flow rate was 19 L/h. The authors discovered a 1-2 °C temperature reduction with this configuration. Wet skin wetness was deemed acceptable by the residents. Montazeri et al. [12] carried out an experimental investigation to explore the effect of various physical parameters on cooling performance. The experiment was place in an open-circuit wind tunnel, with characteristics such as inlet air temperature, inlet air humidity ratio, inlet air velocity, inlet water temperature, and droplet size distribution. The Results showed that, reducing the average droplet size from 430 to 310 μm enhanced cooling performance by nearly 110%. In addition, increasing the temperature difference between the incoming air and water droplets increased the system's cooling capability by more than 40%. Shakier [13] used the experimental method to assess the effectiveness of a mist cooling system in outdoor places. The study emphasized the importance of water flow rate in improving cooling performance and humidity levels, and it concentrated on evaluating dry bulb temperature (DBT), relative humidity (RH%), and air velocity. The results demonstrated that, increasing water flow rate considerably reduced DBT by up to 9.4 °C while increasing RH% from 21% to 57%. Furthermore, the impact of nozzle elevation modifications (from 2.25 to 2.75 m) revealed minor variations in cooling efficiency, with higher elevations producing less cooling influence. Barrow and Pope [14] demonstrated mathematically how the droplet's temperature and size changes influence its total evaporation duration, with a special emphasis on the droplet's starting size. in this study, they solved the mass, momentum, and energy conservation equations. The results revealed that, with larger initial droplet sizes, both the longevity and the distance traveled before full evaporation rise dramatically. Coccia et al. [15] investigated certain of water spray nozzle parameters such as: (1) the nozzle height from the ground, (2) the existence of an upper shield, and (3) the existence of a side shield. The results indicated that, the nozzle at 2.2 m height with an upper shield and side shielding produced the greatest results. This design allowed them to achieve a -20% temperature reduction while increasing water vapor output by 69%. Balthazar et al. [16] studied the performance of water spray system under various operating situations, including nozzles arrangement in horizontal and vertical positions and varied Reynolds numbers (Re). The results demonstrated that, increasing the Reynolds number from 13,300 to 82,700, reduces the relative humidity (RH) for the 2 × 3 nozzle combinations in a horizontal configuration from 83.5% to 79.7%. Also, increasing the number of nozzles raises the relative humidity in both horizontal and vertical orientations. In addition, the nozzles vertical orientation often produces higher relative humidity than the horizontal arrangement. Bassiouny et al. [17] used an experimental technique to investigate the variation in air temperature when exposed to a downward water spray under various conditions. The different operational circumstances, air inlet temperatures, water spray temperatures, air-water mass ratios, and air inlet velocities. The results revealed that, lowering the air inlet velocity increased the mixing process between the water spray and air, resulting in greater evaporative cooling and overall cooling performance. Huang et al. [18] investigated the efficiency of spray misting system on air cooling using experimental and numerical techniques. The results showed that, high-pressure spray cooling can reduce the air temperatures by 1–2 ºC when the temperatures surpass 30 ºC and relative humidity is below 70%.

From the previous works, remains a lack of reference data regarding the design and the controlling methods of water mist systems, highlighting the need for further research in this area. In the current work, used the model that presented by Yoon et al. [1] to further our research and to study different parameters. Where, these parameters were considered the most influential for creating a water mist system that can have an efficient cooling by reducing temperatures without allowing the RH to increase much. The main goal of the present study, investigate the impacts of changing: (1) the distance between nozzles along *z*-axis, (2) the number of nozzles, and (3) the distance between nozzles along *x*-axis. This will allow for a better experience for users on a scale of thermal sensation and overall comfort.

2. Methodology

In the current study, 3D simulations two phase flow (water / air) were performed using the ANSYS FLUENT software package [19], as illustrated in Fig. 1. The Discrete Phase Model (DPM) was used to calculate the momentum, heat, and mass exchange between the water mist and the air. In addition, the pressure-swirl atomizer model was adjusted for these twenty simulations. The pressure-swirl atomizer concept and DPM have been essentially installed in the Fluent. atomizer concept DPM have been essentially installed in the Fluent. Figure 2 illustrates the computational domain used by Yoon et al. [1].

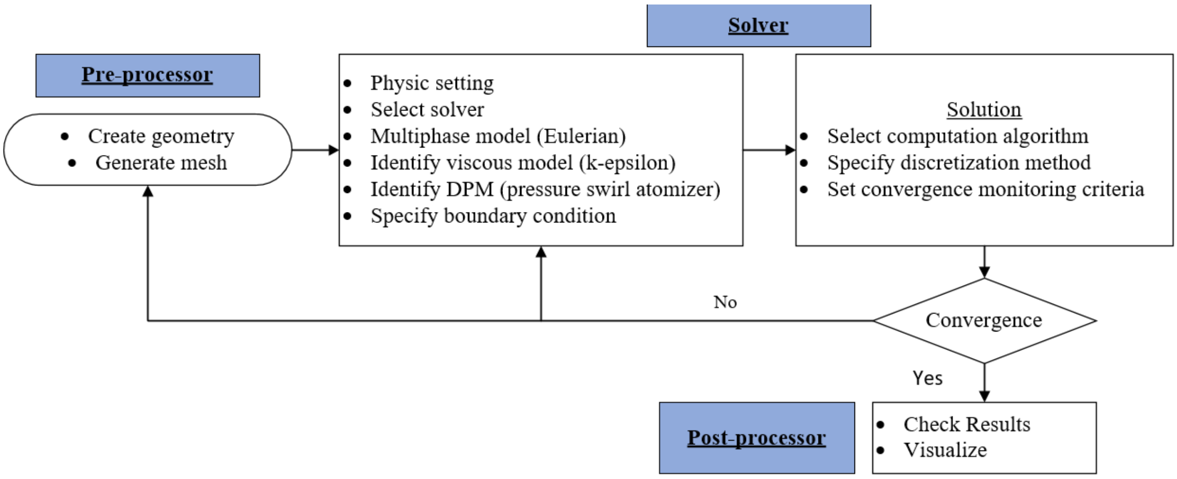


Fig. 1. Computational study procedures

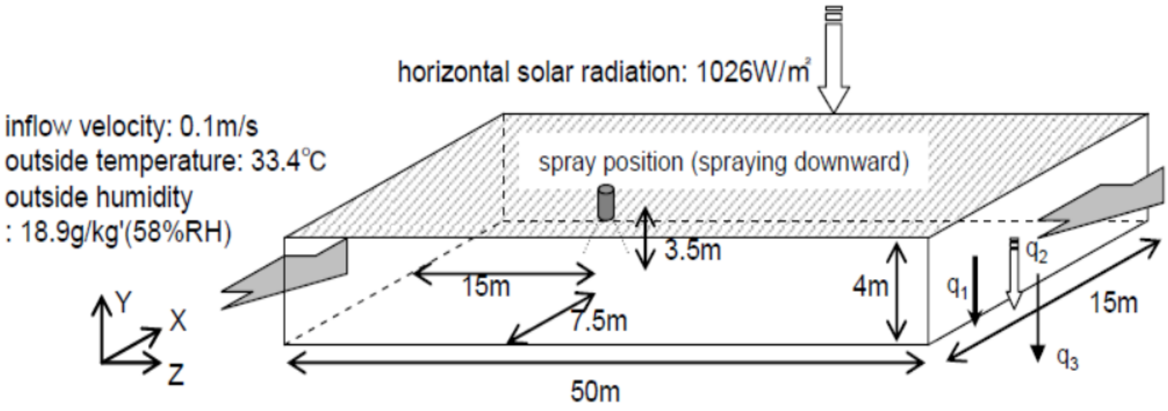


Fig. 2. Details of the computational domain [1]

2.1 Discrete phase model

The discrete phase model (DPM) was used to solve the transport equations for the continuous phase and to simulate a separate second phase inside a Lagrangian framework. Furthermore, as shown in Fig. 3 and the equations published in Yoon et al. [1], DPM facilitates the computation of trajectories for the discrete phase entities as well as the transfer of momentum, heat, and mass to and from them.

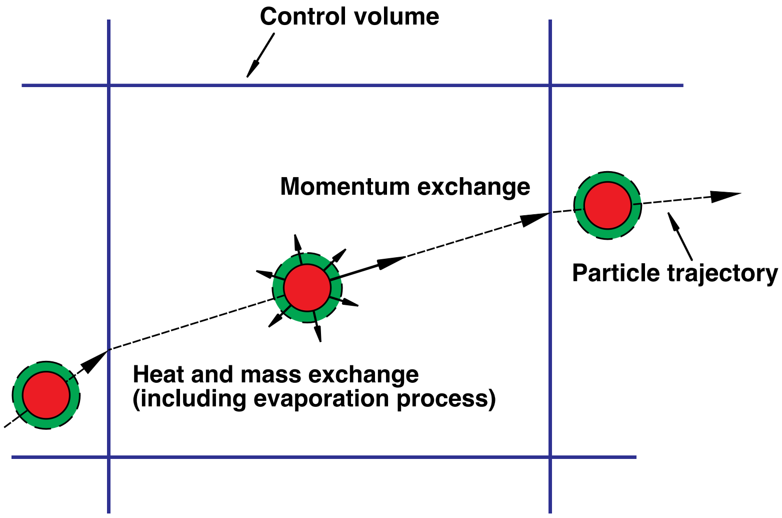


Fig. 3. Diagram of discrete phase model (DPM) [1]

2.2 Atomizer model and meshing details

In the present work, the pressure-swirl atomizer is used. Through swirl ports, which are nozzles, the liquid enters a central swirl chamber at an enhanced speed thanks to this atomizer. The spinning liquid presses up against the walls of the swirl chamber, forming a hollow air core. After that, it separates into droplets and ligaments as an unstable, thinning sheet comes out of the orifice (Schmidt et al. [20]). The droplet size atomizer was calculated and published by Yoon et al. [1].

Furthermore, meshing can be defined as a process of dividing the geometric shape by the number of elements and nodes. The more elements and nodes, the more accurate results, while more time consuming. In the current work unstructured mesh was constructed with 2.61 m maximum face size, 4 m minimum edge length, 24477 numbers of nodes, and 23520 number of cells, which resulting in good mesh quality (0.88 minimum orthogonal quality).

2.3 Mesh Independent Study

In order to guarantee the accuracy of the study's results, an independent mesh study was carried out by varying the number of elements (to above 100,000 no. of elements) until the temperature fluctuation stabilized at a specific point ($x = 7.5$, $y = 3.5$, $z = 15$), as illustrated in Fig. 2. As demonstrated in Fig. 4 for the final five cases, the temperature fluctuation stabilizes as more elements are added, with a maximum inaccuracy of 1.56% as indicated in Table 1.

Table 1. Relation between no. of elements & temperature

No. of elements	Temperature (℃)	Error (%)
16128	32.216	----------
17556	31.509	2.194562
21760	31.278	0.733124
23520	30.788	1.566596
25344	30.82	0.103937
31725	30.9	0.259572
37730	30.8	0.323625

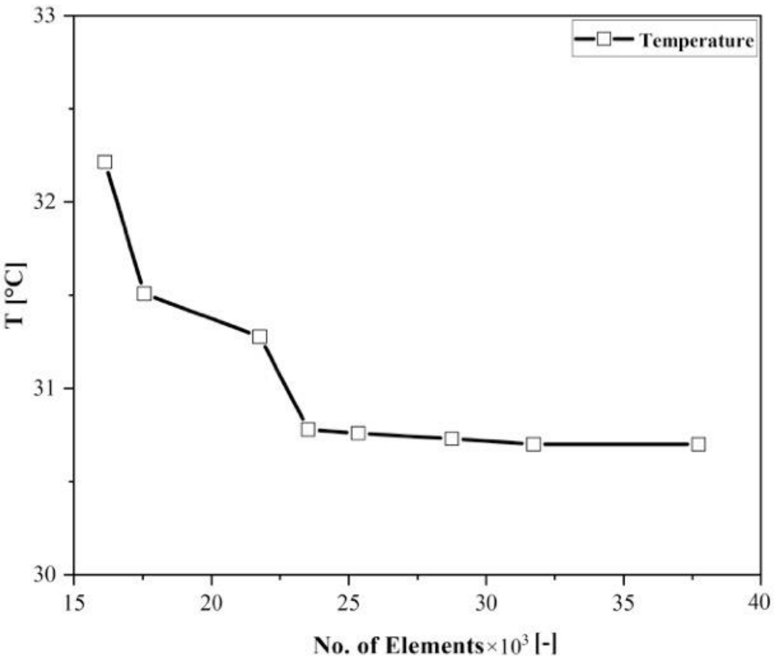


Fig. 4. Relation between No. of elements & temperature

2.4 Model validation

The present model has been validated by comparing the air temperature distribution in model with numerical results estimated by Yoon et al. [1]. As it was discussed in the previous section, Fig. 2 shows the computational domain that utilized by Yoon et al. [1], in addition the boundary conditions were given and presented by Yoon et al. [1]. The spray conditions are illustrated in Table 2.

Table 2. Spraying conditions

Mass Flow Rate	0.83 g/s
Water Temperature	33.4 °C
Injector Orifice Diameter	0.16 mm
Spray Cone Angle	50°
Atomizer Dispersion Angle	6°
Injection Pressure	6 MPa
Sheet Constant	12
Ligament Constant	0.5

Figure 5 shows the comparison between the air temperature distribution of the predicted model and the numerical results obtained by Yoon et al. [1]. It's clear that there's a good agreement between the predicted results and the numerical one with relative error about 1.9 %.

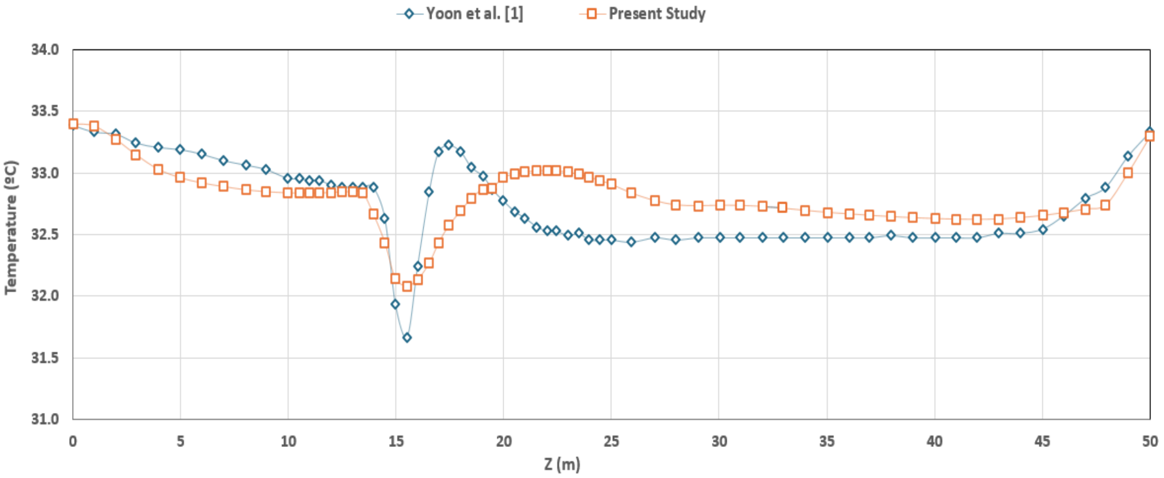


Fig. 5. Validation results

3. Results and discussion

In this section, the effect of different misting operation parameters including distance between nozzles along *z*-axis, number of nozzles, distance between nozzles along *x*-axis are investigated in detail. And the performance of each on temperature & relative humidity distribution for multi-nozzle are presented.

3.1 Effect of changing the distance between nozzles

In the following section, shows the impact of changing the distance between the nozzles on the air temperature and relative humidity. Figure 6 shows the vertical cross-section temperature contours at the spray location (x = 7.5 m) at varying the distance between nozzles (ΔZ) from 5 m to 17 m as listed in Table 3. In addition, the temperature distribution and the RH distribution at (H = 1.5 m) for the spray location of (x = 7.5 m) are presented in Figures 7(a) and 7(b), respectively.

Table 3. Defining the distance between nozzles

Case	Distance between nozzles (Δ**Z**)
1	ΔZ = 5 m
2	ΔZ = 10 m
3	ΔZ = 17 m

Figure 7(a) shows the air temperature distribution for varying ΔZ from 5 m to 17 m. It's clear that, for all cases air temperature has decreased at each spray location due to the cooling effect of each nozzle, and then it gradually increased after each nozzle due to the absence of the nozzle's cooling effect. The minimum simulated room temperature for cases 1, 2 and 3 was 31.91 ℃, 31.78 ℃, and 31.56 ℃, respectively. So, we can see that the lowest minimum room temperature was reached at case 3 when the distance between nozzles was the largest which means that the cooling effect for case 3 is the best. The reason for this phenomenon is that as the nozzle coverage area increase, the clash between the water particles will decrease and so the cooling effect will be better. On the other hand, the highest minimum room temperature was reached at case 1 when the distance between nozzles was the smallest due to the overlap between the water particles.

Figure (7b) shows the air relative humidity distribution for varying ΔZ from 5 m to 17 m. It's noticed that, for all cases air relative humidity has increased at each spray location due to the water effect and then gradually decreased after each nozzle. The maximum simulated air relative humidity for cases 1, 2 and 3 was 64.32%, 64.79%, 65.58%, respectively. So, we can see that the highest maximum RH was reached at case 3 when the distance between nozzles was the largest due to that the nozzle's coverage area was the highest and so the water effect. On the other hand, the lowest maximum RH was reached at case 1 when the distance between the nozzles was the smallest due to the overlap between the water particles which causes a clash for the particles.

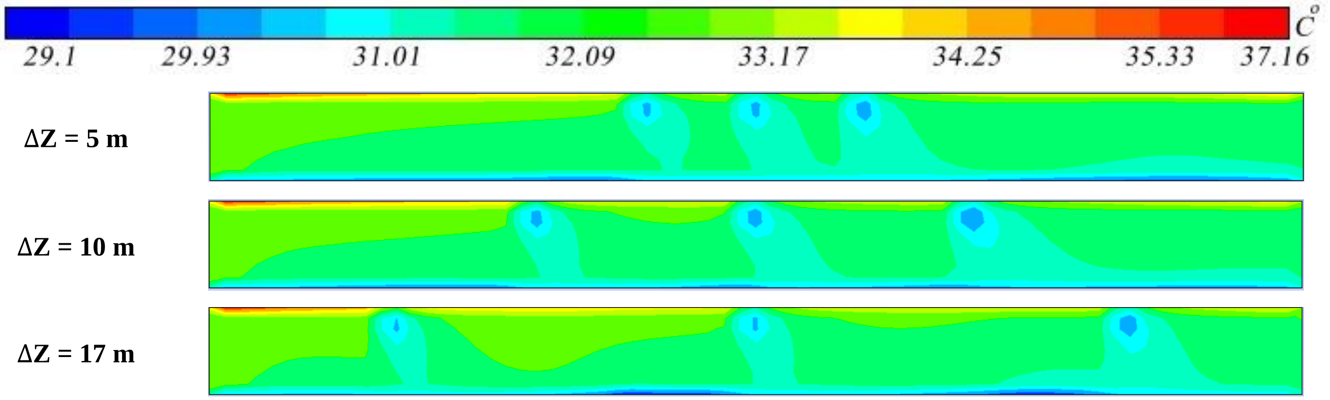
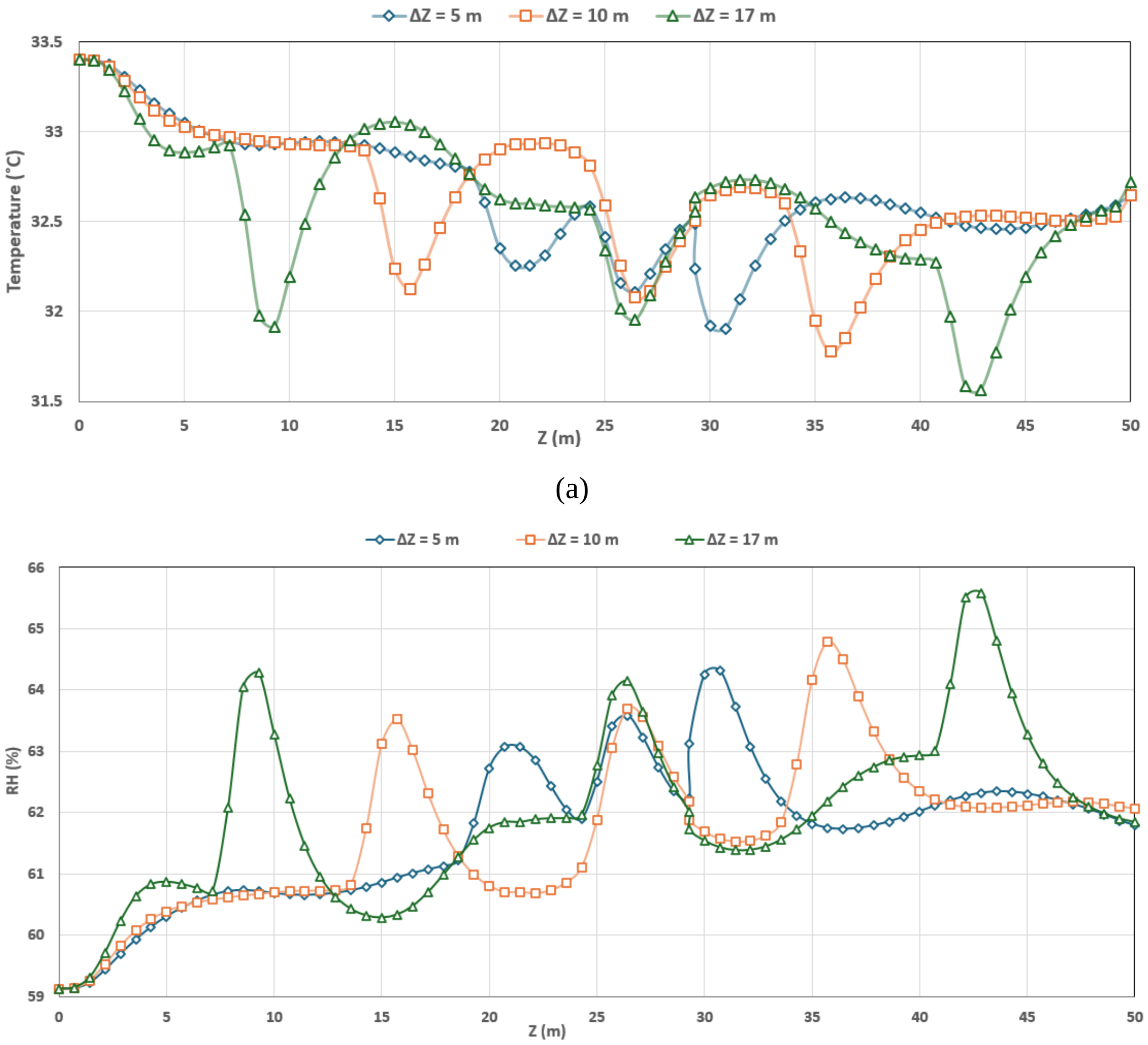


Fig. 6. Air temperature contours at different distance between nozzles (ΔZ) and nozzle location x = 7.5 m



(a)

(b)

Fig. 7. Distribution of (a) air temperature, and (b) relative humidity at different nozzle locations (z) and at line point (y = 1.5 m)

3.2 Effect of changing number of nozzles

This section shows the impact of changing the number of nozzles on the air temperature and relative humidity. Figure 8 shows the vertical cross-section temperature contours at the spray location (x = 7.5 m) at varying the number of nozzles (N) from 3 to 5 nozzles as listed in Table 4. In addition, the temperature distribution and the RH distribution at (H = 1.5 m) for the spray location of (x = 7.5 m) are presented in Figures 9(a) and 9(b), respectively.

Table 4. Defining the number of nozzles

Case	Number of nozzles (N)
1	N = 3
2	N = 4
3	N = 5

Figure 9(a) shows the air temperature distribution for varying N from 3 to 5 nozzles. It's clear that, for all cases air temperature has decreased at each spray location due to the cooling effect of each nozzle, and then it gradually increased after each nozzle due to the absence of the nozzle's cooling effect. The minimum simulated room temperature for cases 1, 2 and 3 was 30.95 ℃, 31.53 ℃, and 30.89 ℃, respectively. We can see that the lowest minimum room temperature was reached at case 3 when the number of nozzles were 5 nozzles but it was reached at the fifth nozzle only. On the other hand, the highest minimum room temperature was reached at case 2 when the number of nozzles were 4 nozzles.

Figure 9(b) shows the air relative humidity distribution for varying N from 3 to 5 nozzles. It's clear that, for all cases air relative humidity has increased at each spray location due to the water effect and then gradually decreased after each nozzle. The maximum simulated air relative humidity for cases 1, 2 and 3 was 67.94%, 65.69%, 68.14%, respectively. So, we can see that the highest maximum RH was reached at case 3 when the number of nozzles were 5 nozzles but it was also reached at the fifth nozzle only. On the other hand, the lowest maximum RH was reached at case 1 when the number of nozzles were 4 nozzles.

For case 1, the cooling effect was high but on the other hand the humidity was also high. For case 2, the cooing effect was moderate allover the 50 m and so for the humidity. For case 3, the cooling effect was moderate until the fourth nozzle and then it increased at the final 5 m because of the fifth nozzle effect. The same was for the humidity.
Finally, we can conclude that the most moderate cooling and humidity effect allover the 50 m was at case 2 when the number of nozzles were 4 nozzles.

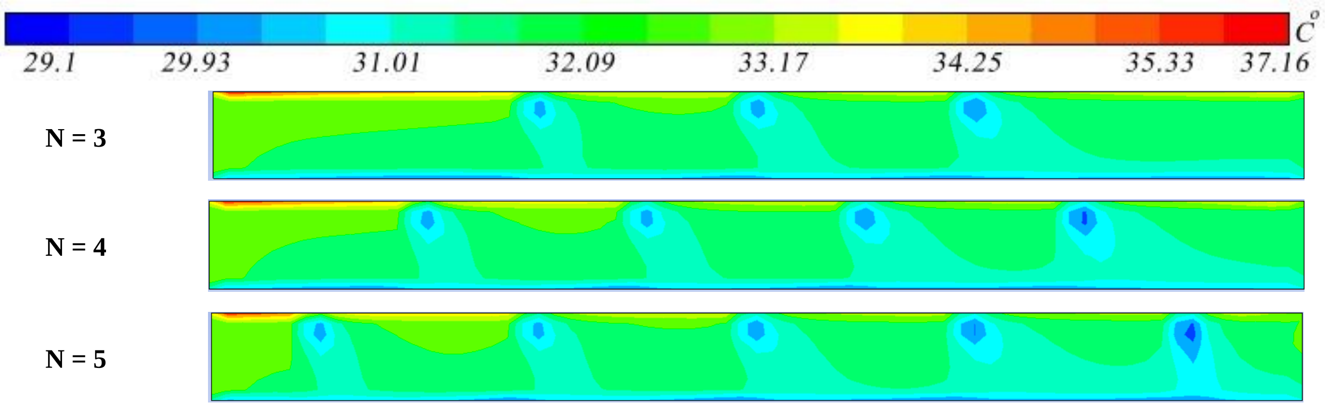
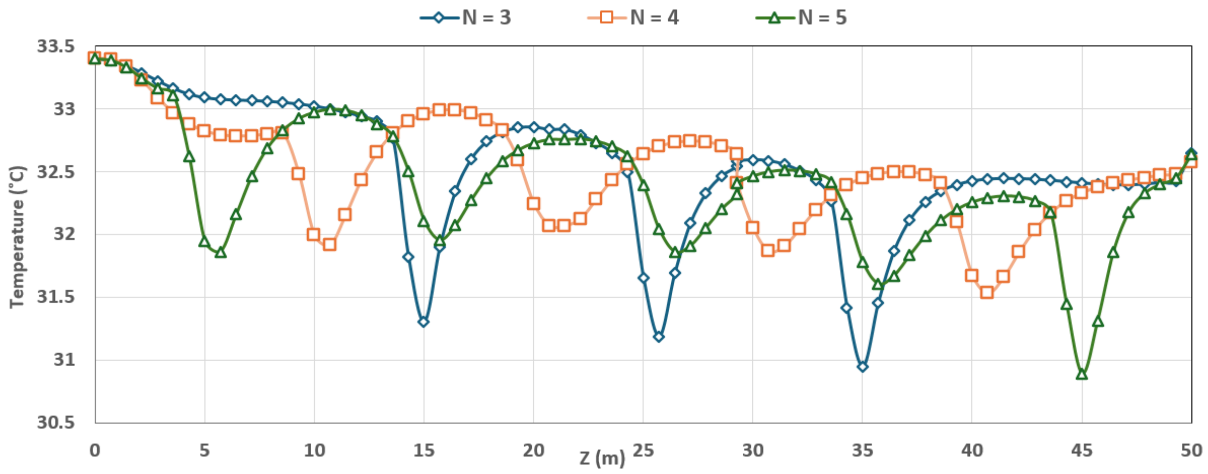
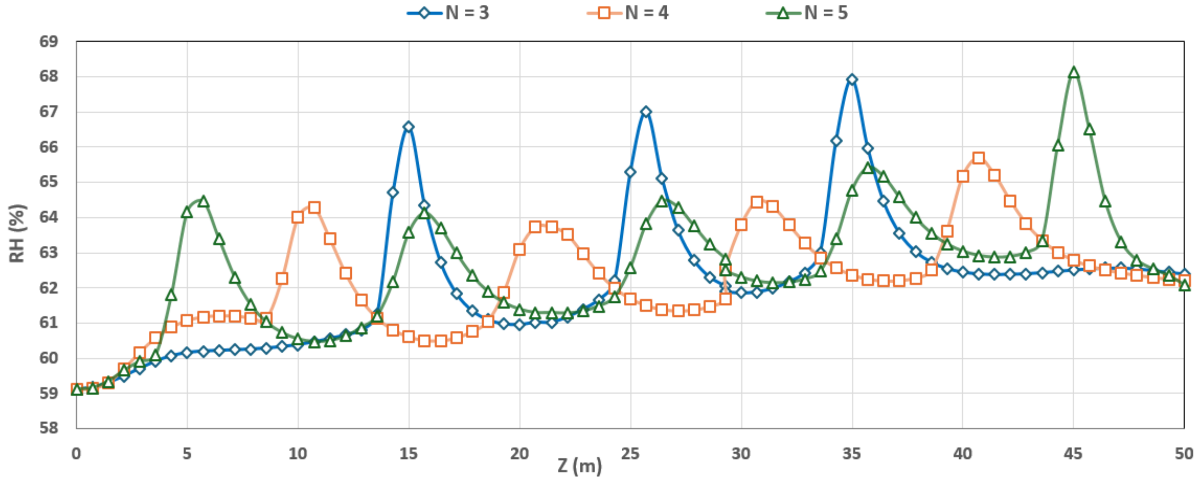


Fig. 8. Air temperature contours at the spray location (x = 7.5 m) and at different number of nozzles (N)



(a)



(b)

Fig. 9. Distribution of (a) air temperature, and (b) relative humidity different number of nozzles (N) and at line point (y = 1.5 m)

3.3 Effect of distance between nozzles along *x*-axis

In the following section, shows the impact of changing the distance between the nozzles along x-axis on air temperature and relative humidity. Figure 10 shows the vertical cross-section temperature contours at the spray location of *x* equals 7.5 m at varying distance between nozzles along x-axis as listed in Table 5. In addition, the temperature distribution and the RH distribution at H equals 1.5 m for the spray location of *x* equals 7.5 m are presented in Figures 11(a) and 11(b).

Table 5. Defining the distance along x-axis in each case

Case	Distance along *x*-axis (d)
1	d = 0.6 m
2	d = 0.8 m
3	d = 1.0 m
4	d = 1.2 m

The distances between nozzles are crucial considerations when initiating a project's design, as they significantly impact water distribution, evaporation, temperature, and humidity, thus affecting maintaining uniform temperature distribution. Additionally, it influences user comfort, as large proximities between nozzle may result in undesirable clothing wetting due to large droplets formation. It should be noted that the outcomes vary from one design to another, as differences in factors such as water pressure, air velocity, or other variables can alter the result.

The measurements of temperature, humidity, and droplet size were taken at the midpoint between the nozzles. In both the first and second cases, the temperatures and humidity levels were quite similar, reaching approximately 31.2 ℃, and 31 ℃, respectively, as shown in Fig. 11(a) with humidity around 67% as shown in Fig. 11(b)in both cases 67.5 %. In the third and fourth case the temperature reach to 32.2 ℃ and 32.1 ℃ with relative humidity 63.3% in both.

It's clear from the measurements that if the distances are reduced, the temperatures decrease, but not in all cases. In the second case, it reached a degree which lower than the first case, and this is due to the idea of collision between the droplets and the lack of good evaporation of the air droplets cause to overlap. In both cases, the difference was small between them, but it is possible that shaking the problem would cause a greater impact on the quality of cooling in other cases.

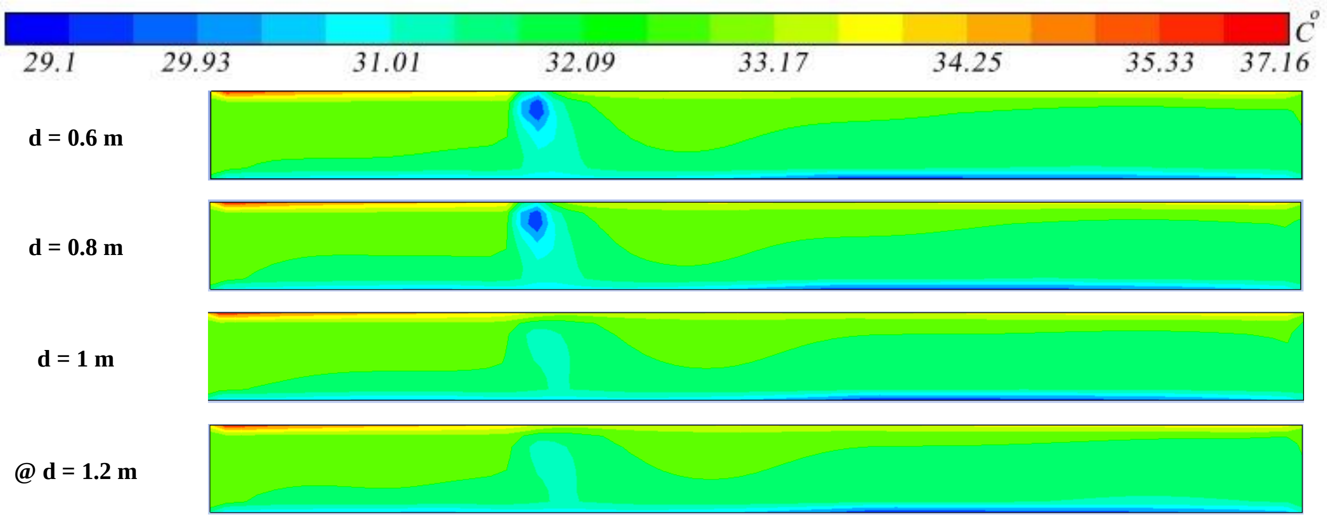
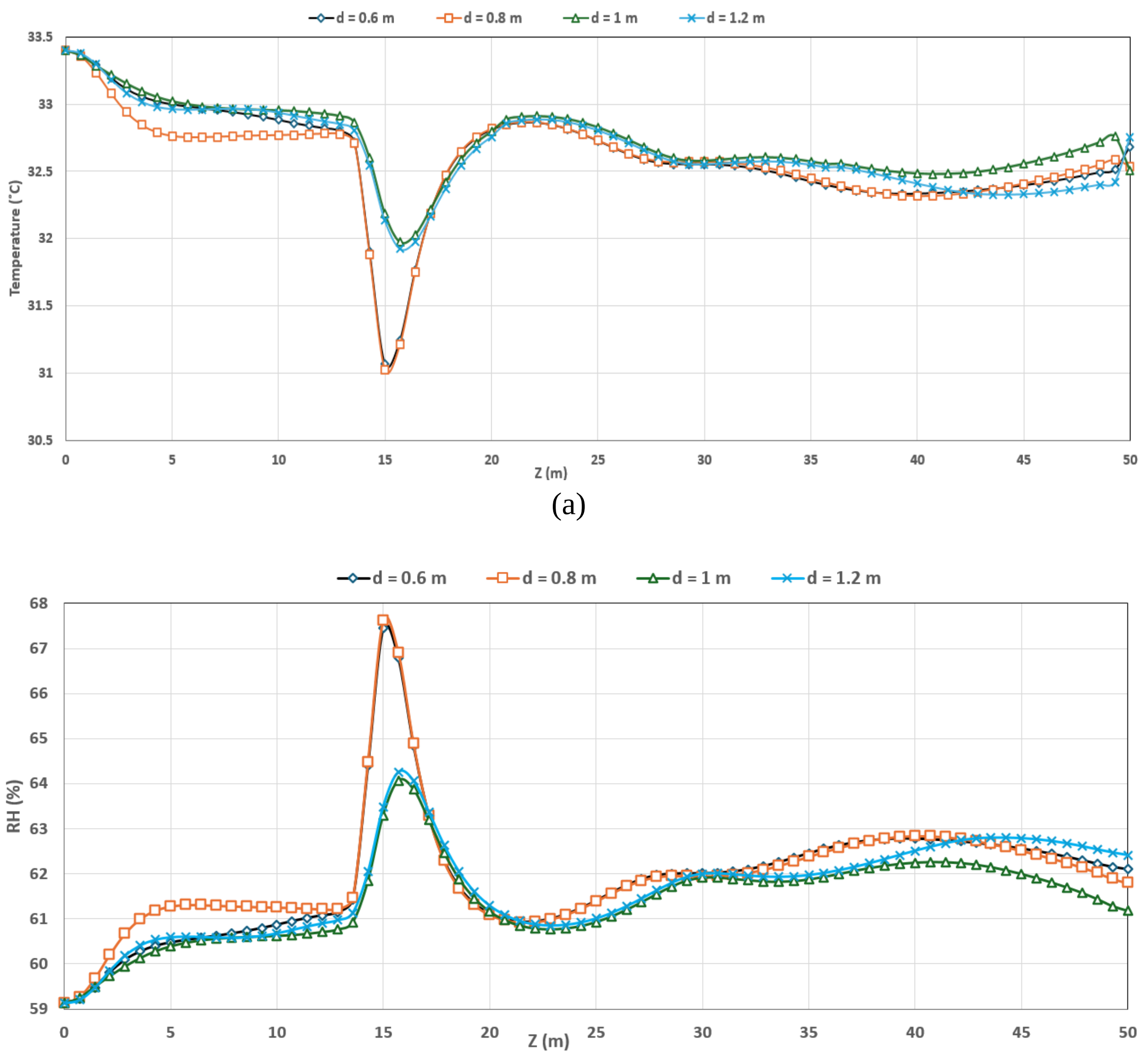


Fig. 10. Air temperature contours at the spray location (x = 7.5 m) and at different nozzle distances (d)



(a)

(b)

Fig. 11. Distribution of (a) air temperature, and (b) relative humidity different nozzle distances (d) and at line point (y = 1.5 m)

4 Conclusions

It is proposed that the air-cooling using water misting will facilitate the development of sustainable solutions by enhancing human thermal comfort. A study employing parametric analysis was carried out to examine the impact of varying misting system parameters, such as changing the distance between nozzles along and changing the number of nozzles.

- By changing the distance between nozzles along *z*-axis (from 5 m to 17 m – three cases), there's a variation in temperatures. The cooling effect increases as the distance between nozzles increases, resulting in a decrease in air temperature and vice versa. And so, the relative humidity increases as the distance between nozzles increases. And the best performance was achieved at the highest distance between nozzles which achieves 31.56 ℃ and 65.58% of RH.

- Building on this foundation, by studying the variation of number of nozzles (from 3 nozzles to 5 nozzles – three cases), the best performance was achieved at a number of nozzles 4 which achieves 31.91 °C and 64.29% of RH.
- Following, in the study of distance between nozzles along *x*-axis (from 0.6 m to 1.2 m – four cases), there's a variation in temperatures. The cooling effect decreases as the distance between nozzles along *x*-axis increases, resulting in an increase in air temperature and vice versa. And so, the relative humidity decreases as the distance between nozzles increases. And the best performance was achieved when the distance between nozzles along *x*-axis 0.8 m which achieves 31 °C and 67% of RH.

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