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INFLUENCE OF AIR VELOCITY ON EVAPORATIVE COOLING PERFORMANCE OF A NOZZLE-EQUIPPED MIST FAN: A CFD STUDY

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ABSTRACT

Air velocity is a critical operating variable in fan-assisted evaporative cooling because it controls droplet residence time, droplet dispersion and the spatial development of the cooled air field. This study investigates the influence of air velocity on the cooling performance of a nozzle-equipped mist fan using three-dimensional computational fluid dynamics (CFD). A fan-driven mist system was represented using a Lagrangian–Eulerian multiphase formulation, with air as the continuous phase and water droplets as the dispersed phase. The analysis was performed with the optimum nozzle arrangement identified in the wider study, while air velocity was varied at 2.0, 5.96 and 10.0 m/s. Cooling efficiency, average air temperature and relative humidity were evaluated on the Plane_0.9 monitoring plane. The detailed CFD results gave cooling efficiencies of 71%, 59% and 35% at 2.0, 5.96 and 10.0 m/s, respectively. Corresponding average temperatures were 302.3, 303.7 and 306.5 K, while relative humidity was 73%, 68% and 53%. The results show a clear deterioration in evaporative cooling effectiveness as air velocity increased. The reduction is associated with shorter effective droplet residence time and changes in droplet dispersion, which reduce the opportunity for evaporation and spatial interaction between the spray and airflow. The findings establish air velocity as a major control parameter for fan-assisted mist cooling and indicate that high air movement should not be selected solely on the basis of airflow delivery when evaporative cooling is the primary objective.

Keywords: Air Velocity; Evaporative Cooling; Mist Fan; Water Spray; CFD; Droplet Residence Time; Cooling Efficiency

1 INTRODUCTION

Evaporative spray cooling uses the latent heat required for water evaporation to reduce the sensible temperature of an air stream. The process is attractive for applications where conventional mechanical refrigeration is undesirable or where localized cooling is required. In fan-assisted systems, the fan simultaneously transports the droplets and distributes the cooled air, making the interaction between airflow and spray a central part of system performance.

Recent CFD studies have demonstrated that spray cooling is governed by coupled air–droplet transport, evaporation, humidity and spray characteristics. Raoult et al. (2019) showed that evaporative cooling is strongly influenced by droplet characteristics, spray geometry, water flow rate and the thermodynamic state of the air. Their validated CFD framework also demonstrated the importance of resolving spray formation and subsequent dispersion in the carrier airflow. Similarly, Di Giuseppe et al. (2021) reported that airflow conditions strongly affect the cooling capacity and spatial influence of water mist.

Experimental work has also shown that air velocity is directly relevant to the thermal response of spray-cooled environments. Meng et al. (2021), for example, found that the cooling response of a spray-fan environment changed with air velocity and relative humidity, with the strongest incremental benefit occurring at lower air velocities. More recent optimization studies continue to treat airflow velocity as an important operating variable in evaporative cooling systems (Mekonen et al., 2023; Ma et al., 2024).

Although airflow is necessary to transport cooled air away from the spray source, increasing velocity does not necessarily improve evaporative cooling. A higher velocity can shorten the time available for droplets to exchange momentum and heat with the surrounding air. It can also alter the spray coverage and the distribution of water vapor. The present paper therefore isolates air velocity as the principal design variable and examines its effect on a nozzle-equipped mist fan under a common nozzle arrangement.

1.1 Research gap and objective

Much of the recent literature considers air velocity together with several other spray parameters, making it difficult to identify the specific role of airflow in a compact fan-driven mist system. This study addresses that issue by maintaining the selected nozzle arrangement and comparing three air velocities under the same computational framework.

The objective is to quantify the effect of air velocity on spray cooling efficiency, outlet temperature and relative humidity, and to interpret the observed changes in terms of droplet residence time and spray dispersion.

2 LITERATURE REVIEW

Water-spray evaporative cooling has been investigated using both experimental and numerical methods. Raoult et al. (2019) developed a three-dimensional CFD water-spray model and showed that evaporation is particularly sensitive to droplet size distribution, spray geometry, water mass flow and the humidity state of the surrounding air. Their work supports the use of multiphase CFD for examining coupled spray and airflow behaviour.

Yang et al. (2020) experimentally investigated spray evaporative cooling of an air-cooled chiller and found that nozzle positioning, orientation and water-flow control affected system performance. Although the application differs from a mist fan, the study demonstrates that the interaction between spray momentum and airflow is an important system-level design consideration.

Di Giuseppe et al. (2021) developed and validated a numerical model of water-mist cooling and found that wind speed strongly influenced both cooling capacity and the spatial extent of the cooling effect. This result is particularly relevant to fan-driven mist systems, where the airflow field is intentionally generated rather than imposed by ambient wind.

Meng et al. (2021) experimentally evaluated a spray fan in a hot indoor environment and found a measurable relationship between air velocity, relative humidity and thermal conditions. The study reported a stronger cooling response at lower air velocities and a smaller incremental effect at higher velocities, reinforcing the need to distinguish air movement from evaporative cooling effectiveness.

Mekonen et al. (2023) used CFD and experimental validation to investigate an evaporative cooler and found that inlet air velocity significantly affected the cooling performance. Their results further demonstrate the value of CFD for separating the effects of airflow from other geometric and material parameters.

Ma et al. (2024) developed a three-dimensional CFD model for an indirect evaporative cooler with spray and showed that spray parameters interact with the airflow and wetting behaviour of the system. More recently, Wang et al. (2026) reported that spray injection conditions, flow rate, droplet dispersion and spray configuration can substantially change cooling efficiency and temperature uniformity. Collectively, these studies establish that airflow and spray transport must be considered as a coupled system rather than as independent variables.

The present investigation contributes a focused analysis of air velocity in a pedestal mist fan configuration, using a fixed nozzle arrangement and a common computational domain so that the effect of airflow can be isolated.

3 MATERIALS AND METHODS

3.1 Mist-fan system

The experimental system consisted of a 12-V pedestal fan, water storage tank, 12-V pump, mist nozzles, high-pressure hose and tee connection. The fan had a sweep diameter of 250 mm, maximum speed of 2000 rpm, maximum air-volume flow rate of 900 cfm and maximum input power of 75 W. The overall dimensions of the system were 390 × 390 × 590 mm, and the water storage capacity was 4 L. Air temperature, wet-bulb temperature, relative humidity and air-flow-related quantities were measured during the experimental procedure.

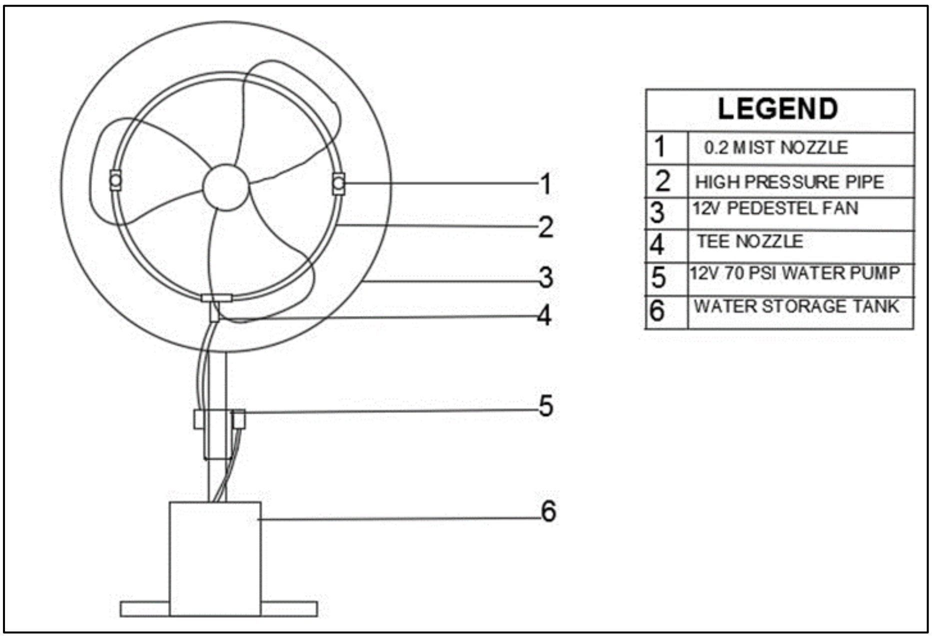

Figure 1: Schematic/photographic representation of the mist-fan system used for the study.

3.2 Computational domain and CFD formulation

The CFD model represented an enclosed rectangular room with dimensions of 7200 × 3600 × 3000 mm. The spray and airflow were solved using a Lagrangian–Eulerian multiphase formulation in which air was treated as the continuous phase and water droplets as the dispersed phase. The model included momentum, energy, mass-transfer and evaporation effects. A hollow-cone spray representation was used, and the droplet population was represented using a Rosin–Rammler distribution.

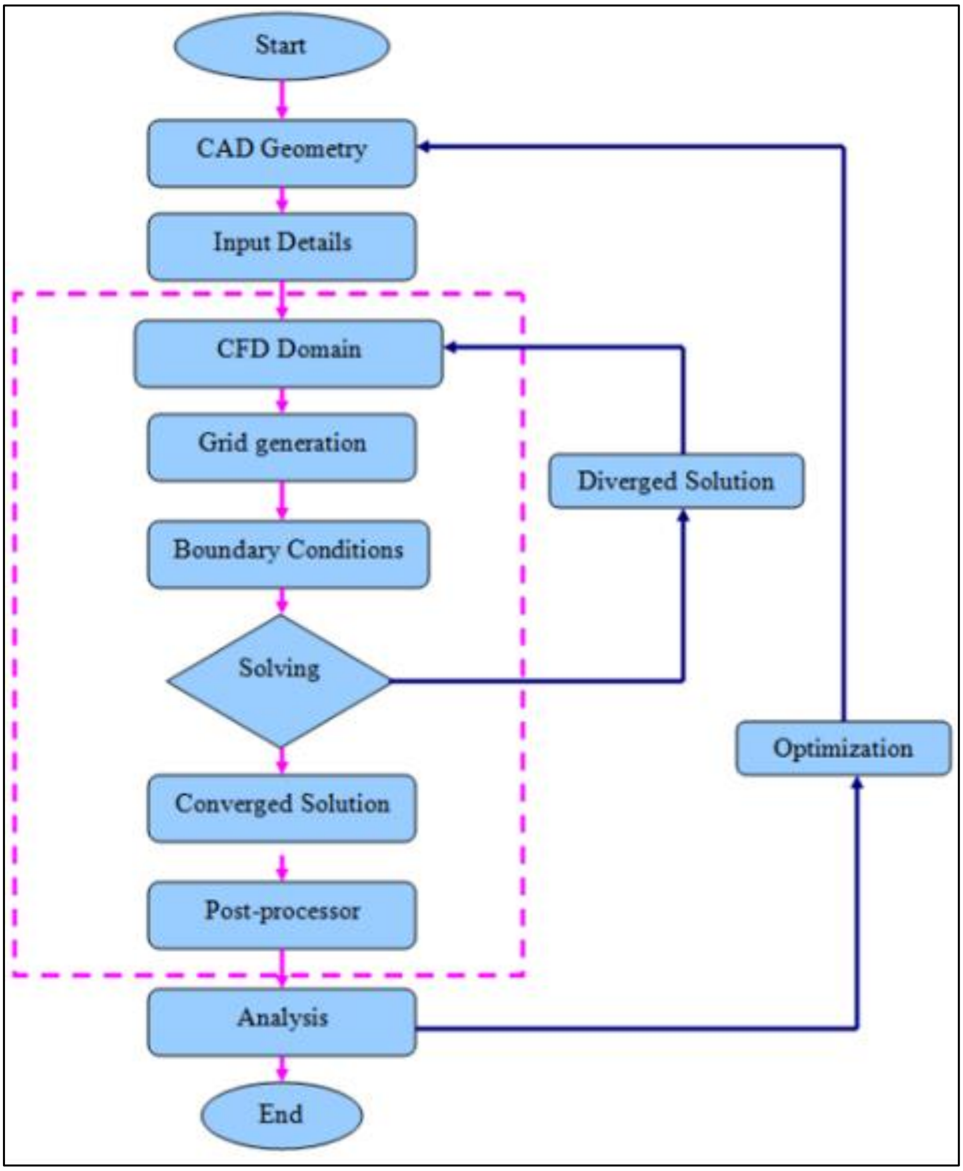

Figure 2: Numerical-modelling workflow used for the CFD analysis.

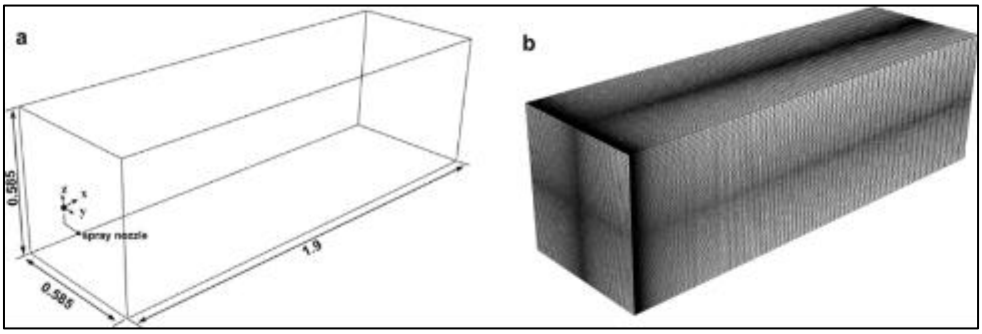

Figure 3: Computational domain and grid representation.

3.3 Grid sensitivity

Three meshes were assessed before the parametric calculations. The meshes contained approximately 24,948, 49,630 and 95,288 cells. Temperature differences between successive meshes were small: 0.09% and 0.04% on the Middle_Plane and 0.47% and 0.65% on Plane_0.9. The selected mesh was therefore considered adequate for the subsequent simulations.

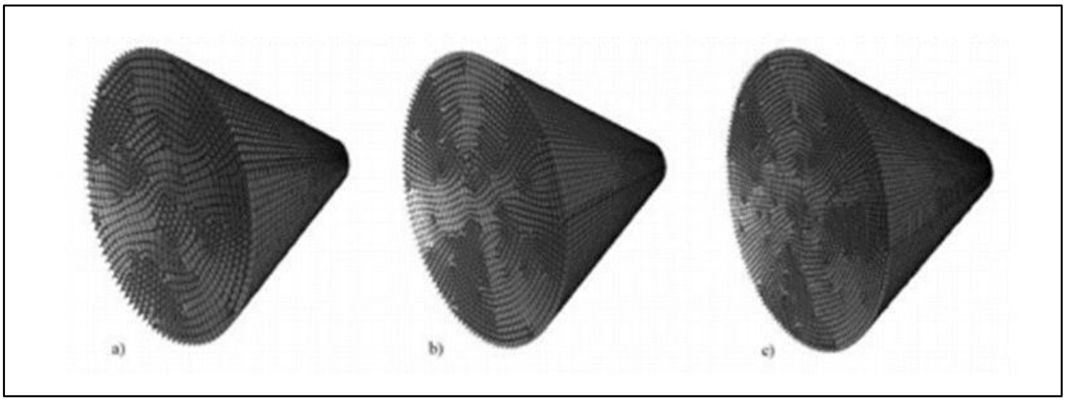

Figure 4: Computational grids used for grid-sensitivity assessment.

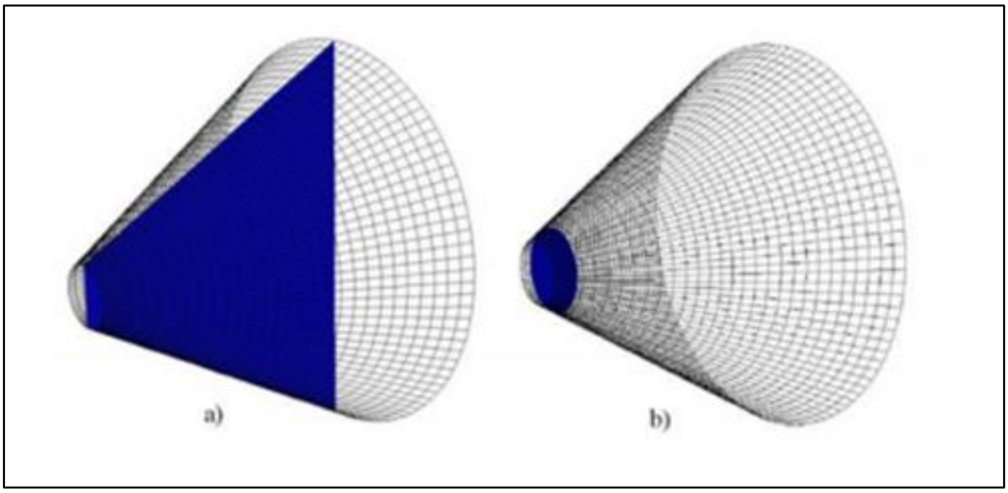

Figure 5: Monitoring planes used for temperature and cooling-efficiency evaluation.

3.4 Air-velocity test cases

The nozzle arrangement identified as the best-performing arrangement in the broader study was retained for the air-velocity analysis. Three air velocities—2.0, 5.96 and 10.0 m/s—were examined. Other spray parameters were held constant so that the influence of air velocity could be evaluated directly.

Table 1: Air-Velocity Analysis Cases and Simulation Parameters

Parameter	**Case 1**	**Case 2**	**Case 3**
Air velocity (m/s)	2.0	5.96	10.0
Nozzle arrangement	4	4	4
Evaluation plane	Plane_0.9	Plane_0.9	Plane_0.9

3.5 Cooling-efficiency metric

Cooling efficiency was evaluated as the ratio of the actual dry-bulb temperature reduction to the maximum possible reduction toward the wet-bulb temperature:

$$\eta_c = [(T_{db,i} - T_{db,o}) / (T_{db,i} - T_{wb})] \times 100$$

where η_c is the cooling efficiency, $T_{db,i}$ is the inlet dry-bulb temperature, $T_{db,o}$ is the outlet dry-bulb temperature and T_{wb} is the wet-bulb temperature. The global efficiency was evaluated from average inlet and outlet air temperatures.

4 RESULTS AND DISCUSSION

4.1 Baseline airflow and temperature field

The baseline CFD field showed strong interaction between the fan-driven airflow and the injected droplets near the spray source. The velocity field was highest around the spray core and decreased with distance downstream. The temperature field also changed progressively along the spray path, indicating that evaporation extracted latent heat from the air. The water-mass-fraction field showed the presence of the dispersed phase and its redistribution downstream.

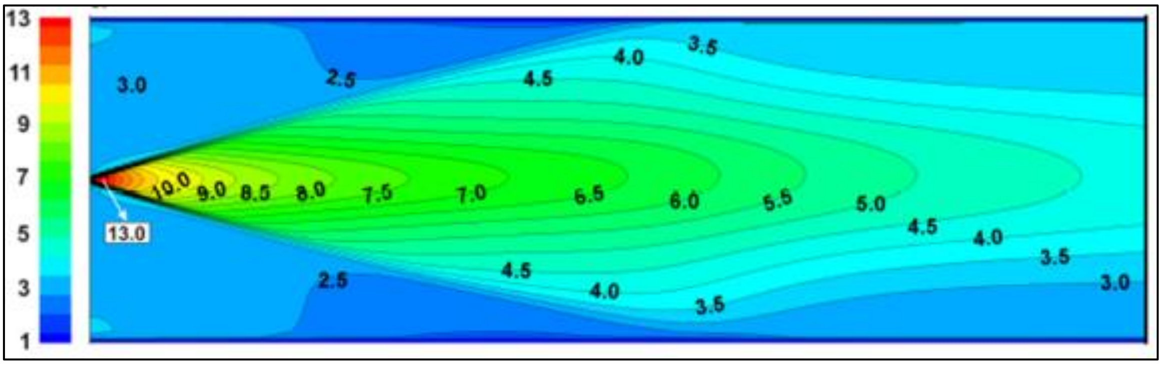

Figure 6: Velocity distribution for the selected nozzle arrangement.

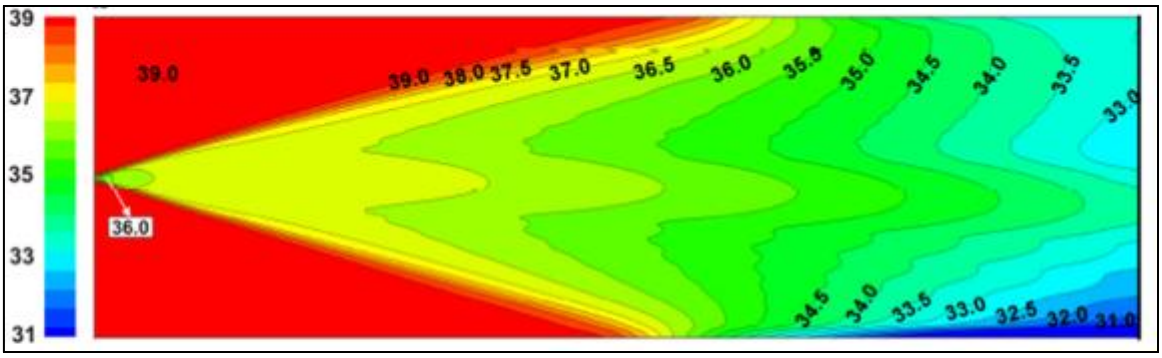

Figure 7: Temperature distribution for the selected nozzle arrangement.

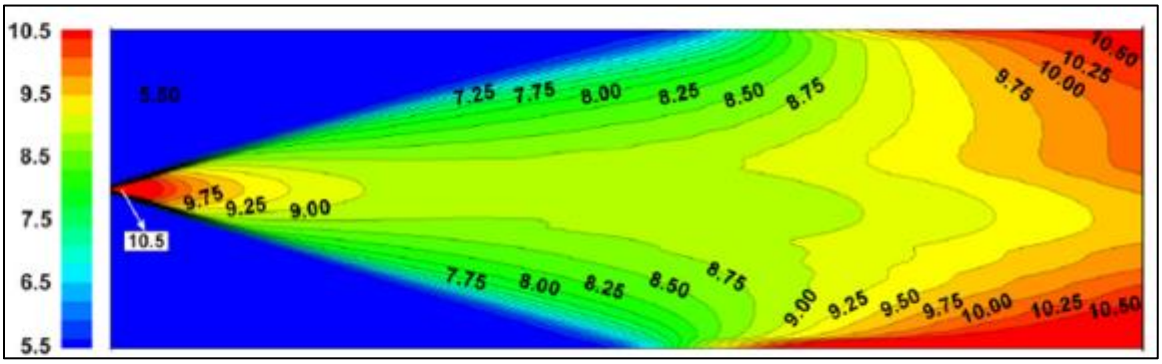

Figure 8: Water-mass-fraction distribution for the selected nozzle arrangement.

4.2 Effect of air velocity on cooling efficiency

The detailed air-velocity results show a monotonic reduction in cooling efficiency as air velocity increases. At 2.0 m/s, the reported cooling efficiency was 71%, decreasing to 59% at 5.96 m/s and 35% at 10.0 m/s. The corresponding average air temperatures were 302.3, 303.7 and 306.5 K, respectively. Relative humidity decreased from 73% to 68% and then to 53%.

Table 2: Effect of Air Velocity on Cooling Efficiency, Average Temperature, and Relative Humidity

Air velocity (m/s)	Cooling efficiency (%)	Average temperature (K)	Relative humidity (%)
2.0	71	302.3	73
5.96	59	303.7	68
10.0	35	306.5	53

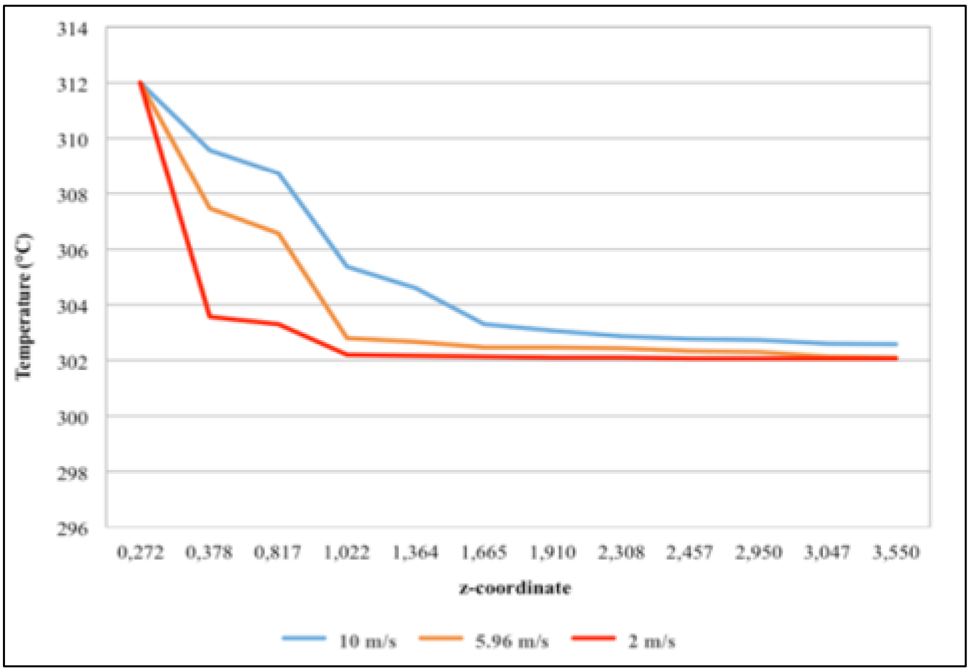

Figure 9: Comparison of average temperature for the different air-velocity cases.

The change from 2.0 to 10.0 m/s represents a 36-percentage-point reduction in the reported cooling efficiency. At the same time, the average temperature increased by 4.2 K. This behaviour indicates that increasing fan-driven airflow does not automatically increase evaporative cooling effectiveness. Instead, the faster airflow changes the time available for droplet–air interaction and modifies the spatial distribution of the spray.

The underlying CFD analysis attributes the velocity effect primarily to changes in droplet transport, dispersion and the time available for air–droplet interaction. Because the source dataset contains an internally inconsistent description of residence time across the three velocity cases, numerical residence-time values are not used as an independent quantitative result here.

4.3 Physical interpretation

At lower air velocity, the spray remains coupled to the surrounding air over a larger effective region, allowing more extensive evaporation before the droplets are transported away from the cooling zone. At higher velocity, the airflow carries the dispersed phase more rapidly and modifies the spray footprint. The reduced humidity reported at 10.0 m/s is consistent with the lower overall cooling efficiency in the simulated plane.

The result is consistent with the broader literature. Raoult et al. (2019) demonstrated that spray evaporation depends on the interaction of droplet transport, spray geometry and the thermodynamic state of the carrier air. Di Giuseppe et al. (2021) found that wind speed strongly affected mist-cooling capacity and influence area, while Meng et al. (2021) reported that the thermal benefit of spray-fan airflow is not linear across the velocity range. Recent CFD optimization work also confirms that airflow and spray parameters must be considered jointly when selecting operating conditions (Mekonen et al., 2023; Ma et al., 2024; Wang et al., 2026).

4.4 Implications for mist-fan design

The results indicate that fan speed should be selected according to the intended cooling objective. If the primary objective is evaporative temperature reduction, a very high air velocity may be counterproductive. A moderate velocity can provide sufficient air movement while preserving the interaction between droplets and air. If the primary objective is distribution of cooled air over a larger occupied zone, a higher velocity may still be useful, but the associated reduction in local evaporative effectiveness should be considered.

5 EXPERIMENTAL VALIDATION

The wider investigation compared CFD predictions with experimental measurements at several distances downstream of the fan. The reported cooling-efficiency values were of similar magnitude at most measurement locations, although the CFD and experimental cases were not operated at identical air velocities. The study also reports an overall CFD–experimental correlation of approximately 96%. Accordingly, the validation is treated here as evidence of general trend agreement rather than as a strict one-to-one validation of each air-velocity case.

Table 3: Comparison of CFD Predictions and Experimental Measurements at Different Downstream Distances

Distance X (mm)	CFD velocity (m/s)	CFD temperature	Experimental velocity (m/s)	Experimental efficiency
500	10.0	37.0	8.0	68%
1000	7.5	39.0	7.15	68.13%
2000	5.5	35.75	4.8	70.40%
2500	2.0	34.25	4.1	71.55%
3000	3.0	33.0	2.8	70.07%

The validation dataset supports the use of the CFD framework for examining the general cooling behaviour along the fan discharge direction. However, because the CFD and experimental velocities differ at the corresponding measurement locations, individual rows should not be interpreted as direct paired tests of the same operating condition.

6 CONCLUSION

- Air velocity has a strong influence on the evaporative cooling performance of the studied mist-fan system.
- Using the detailed CFD results for the selected nozzle arrangement, cooling efficiency decreased from 71% at 2.0 m/s to 59% at 5.96 m/s and 35% at 10.0 m/s.
- Average air temperature increased from 302.3 K at 2.0 m/s to 306.5 K at 10.0 m/s, while the reported relative humidity decreased from 73% to 53%.
- The observed reduction in performance is associated with changes in droplet transport, residence time and spray dispersion as the airflow becomes faster.
- The findings show that maximum fan airflow should not be assumed to produce maximum evaporative cooling. Air velocity must be selected together with nozzle configuration and spray characteristics.
- The CFD framework provides a useful basis for identifying operating conditions before experimental testing, while experimental validation remains necessary for final system design.

Recommendations and Future Work

- Future studies should examine a finer range of air velocities around the observed transition between high and low cooling effectiveness.
- The interaction between fan speed, nozzle arrangement, droplet size and spray cone angle should be optimized simultaneously rather than independently.
- Future experiments should record airflow velocity, temperature and humidity at identical operating points to enable direct one-to-one validation of CFD predictions.
- A larger-scale study should investigate whether the velocity that maximizes local evaporative efficiency also provides the best thermal comfort across the complete occupied zone.
- Water consumption and energy use should be included in future optimization so that cooling performance is assessed together with resource efficiency.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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