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CFD-Based Optimization of Nozzle Arrangement for Enhanced Evaporative Cooling Performance of a Mist Fan

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Abstract- The research investigated the cooling efficiency of a mist fan by redesigning its nozzle arrangement and determining the effects of nozzle arrangement on cooling performance, with emphasis on temperature distribution, velocity distribution and water-mass-fraction distribution. Five different nozzle arrangements were comparatively analyzed to determine the arrangement with the highest efficiency. A three-dimensional computational fluid dynamics (CFD) model based on a Lagrangian–Eulerian approach was used to simulate the interaction between the air and dispersed water droplets. The computational domain represented an enclosed room geometry measuring 7200 mm × 3600 mm × 3000 mm. A grid-sensitivity analysis was performed using three grids, and the reported temperature differences between successive grids were small. The five nozzle arrangements were compared at an air velocity of 5.96 m/s. The reported cooling efficiencies for arrangements 1, 2, 3, 4 and 5 were 66%, 67%, 68%, 70% and 63%, respectively, while the corresponding average temperatures were 304.2, 303.7, 303.6, 303.4 and 303.8 K. Nozzle arrangement 4 produced the highest reported cooling efficiency and the lowest average temperature. The temperature contours also indicated a more uniform distribution for arrangement 4. The further compared the CFD predictions with experimental measurements and reported strong agreement between the two approaches.

Keywords— computational fluid dynamics; nozzle size; cooling efficiency; nozzle arrangement

I. INTRODUCTION

Misting systems operate by forcing water through a small nozzle to produce fine droplets. The droplets evaporate and use heat from the surrounding air during the phase-change process, thereby reducing air temperature. Misting systems are used in applications including cooling of produce, greenhouses, livestock environments and outdoor spaces.

Misting fans combine the evaporative effect of water mist with the convective effect of moving air. The fan circulates the mist over a wider area, allowing the water droplets to interact with the surrounding warm air. The describes low-, mid- and high-pressure misting systems and notes that high-pressure systems use pumps producing about 1000 psi or more to generate very small droplets.

For evaporative cooling by mist spray systems, the identifies full-scale measurements, wind-tunnel measurements and numerical simulation using computational fluid dynamics as possible methods of assessing performance. Full-scale and wind-tunnel measurements provide experimental information but are generally limited to a finite number of measurement locations. CFD provides whole-flow-field information on relevant parameters throughout the computational domain.

The performance of a mist cooling system is influenced by several parameters, including continuous-phase velocity, temperature, relative humidity, droplet-size distribution, droplet velocity and temperature, replenishment rate and number of nozzles. The source study therefore focused on the influence of nozzle number and arrangement and used CFD to examine the resulting velocity, temperature and water-mass-fraction distributions.
The objective of this work was to develop and validate a CFD model for predicting the air velocity and temperature distributions for a nozzle-equipped mist fan and, within that investigation, to determine the nozzle arrangement providing the most effective cooling.

1. Research objective
The aim of the research was to develop CFD analysis of the cooling effect of a mist fan. The objectives relevant to this article were the development of a mist fan, determination of factors affecting cooling efficiency, determination of the optimal nozzle arrangement for effective cooling, CFD analysis of air velocity and temperature distribution, and experimental validation.

II. LITERATURE REVIEW

The literature indicates that nozzle design, injection direction, spray coverage, droplet characteristics, and airflow are important determinants of evaporative cooling performance. However, the comparative effect of alternative nozzle arrangements on the cooling field of a mist fan requires further examination. The present study therefore compares five nozzle arrangements under a common reference operating condition using CFD and experimental validation.

Ma, Shi, and Yang (2024) further developed a three-dimensional CFD model incorporating actual surface wettability and the movement of spray droplets. Their analysis showed that nozzle spacing, droplet diameter and flow rate influenced water-film coverage, and optimization of nozzle parameters improved wet-bulb efficiency and coefficient of performance. This provides further evidence that nozzle geometry and spatial arrangement should be optimized together rather than considered independently.

Ma, Shi, and Yang (2022) specifically investigated water-spray distribution and nozzle-arrangement optimization in an indirect evaporative cooler. Their numerical model evaluated single- and multi-nozzle arrangements using spray uniformity and coverage ratio. The optimized arrangement improved water distribution and produced greater cooling and dehumidification performance than the original arrangement, confirming that nozzle layout can be a decisive design parameter.

Di Giuseppe et al. (2021) developed and experimentally validated a numerical model for water-mist cooling in urban environments. Their results showed that wind speed strongly affected both cooling capacity and the spatial influence of mist, while water flow rate and injection height could be adjusted to regulate cooling performance. These findings demonstrate the sensitivity of mist cooling to airflow and spray-distribution conditions.

Yang et al. (2020) experimentally investigated a spray evaporative cooling system applied to an air-cooled chiller. Their system incorporated a gas–liquid two-phase swirl nozzle, and the study found that appropriate control of water flow and reasonable positioning and orientation of the nozzles could further improve system performance. The findings reinforce the importance of nozzle positioning and spray direction in practical evaporative-cooling systems.

Sun et al. (2020) experimentally investigated water spraying from the perspectives of nozzle type and spray strategy. Five commonly used spray nozzles were evaluated using coverage ratio, uniformity coefficient and water volume in the distribution region. The results showed that nozzle selection strongly affected water-distribution uniformity and coverage, demonstrating the importance of spray distribution in evaporative-cooling performance.

Raoult et al. (2019) developed and experimentally evaluated a three-dimensional CFD model for evaporating water sprays. Their study considered spray formation and dispersion in airflow and investigated the effects of relative humidity, spray angle, water mass flow rate and droplet-size distribution. The authors reported that smaller droplets and broader droplet-size distributions enhanced evaporation, while the spray surface size relative to the target surface affected cooling performance.

III. MATERIALS AND METHODS

1. Mist-fan system

The developed mist-fan system consisted of a 12 V pedestal standing fan, water collecting tank, 12 V water pump, misting nozzles, high-pressure hose and tee nozzle. The describes the fan as the component producing the air flow, the collecting tank as the water reservoir, the pump as the device moving the water, and the nozzle as the device controlling the characteristics of the exiting fluid flow.

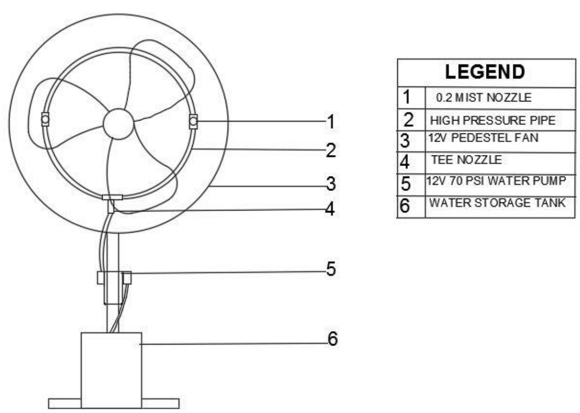

Figure 1. Mist fan setup reproduced from the.

The developed misting system used an axial fan with a sweep diameter of 250 mm and a maximum speed of 2000 rpm. The maximum reported air volume flow rate was 900 cfm with a maximum input power of 75 W. The overall dimensions were 390 mm × 390 mm × 590 mm and the water storage capacity was 4 litres.

The nozzle section of the report states that the nozzle had a nominal diameter of 0.2 mm and that the hose was 0.4 mm in diameter. The nozzle data reported a pressure of 2.0 bar and a water volume flow rate of 2.0 litres/min for the referenced condition; the calculated condition in the report was 2.17 litres/min at 2.35 bar.

Table 1. Output data for nozzles from the.

Mass-flow entry (kg/s)	Volume-flow entry (litres/min)	Reported Q (litres/min)	P (bar)
0.217	0.0362	2.17	2.35

2. CFD methodology

The detailed investigation during the design phase was performed through numerical simulation. The flow characteristics were analyzed using a three-dimensional approach to the governing fluid-flow equations. The states that the commercial CFD code ANSYS/Fluent was used and that a Lagrangian–Eulerian approach was implemented to simulate multiphase flows in sprays and atomizers.

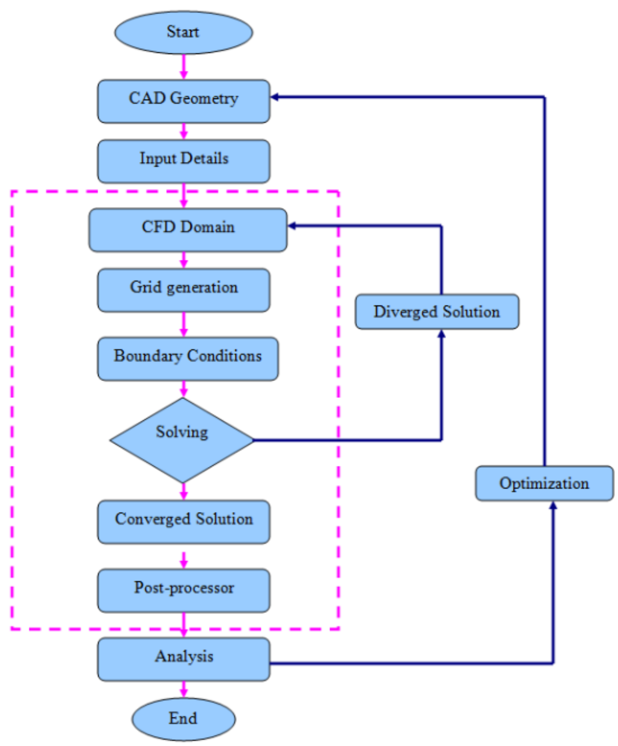

Figure 2. Flowchart of numerical modeling reproduced from the.

3. Computational geometry and grid

The computational domain was developed to investigate the air velocity and temperature distribution of the air/mist cooling system using an enclosed room geometry. The cross-section of the domain was rectangular, with dimensions of 7200 mm × 3600 mm × 3000 mm. The geometry was selected to examine the air velocity and temperature distribution at different distances from the fan in a room-like section.

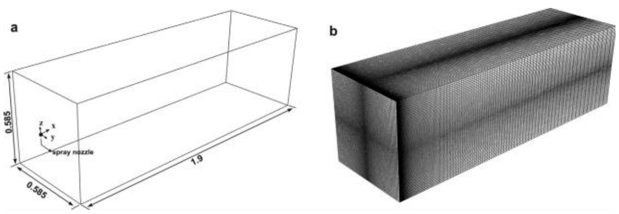

Figure 3. Computational domain and computational grid reproduced from the.

4. Grid-sensitivity analysis

A grid-sensitivity analysis was performed using three grids designated M1, M2 and M3. The gives approximately 24,948, 49,630 and 95,288 cells for M1, M2 and M3, respectively. Mesh independence was assessed from temperature profiles at the Middle_Plane and Plane_0.9.

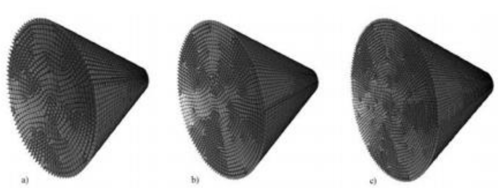

Figure 4. Computational grids used for grid-sensitivity analysis, reproduced from the.

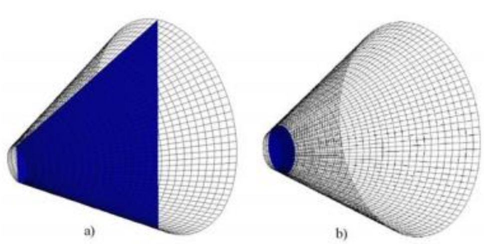

Figure 5. Planes used for grid-sensitivity analysis, reproduced from the.

Table 2. Mesh-independence values of temperature.

Plane	M1–M2	M2–M3
Middle_Plane	0.09%	0.04%
Plane_0.9	0.47%	0.65%

The states that the results showed negligible dependence on grid resolution and that grid M1 was therefore used for further analysis.

5. Nozzle arrangements

The study investigated five different nozzle arrangements because the number and arrangement of nozzles were identified as factors affecting the cooling effect of a mist-spraying system.

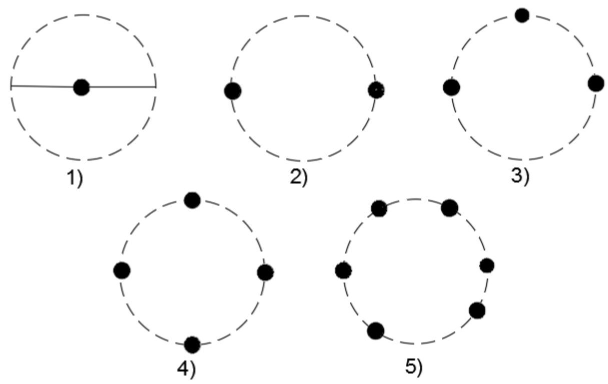

Figure 6. Five different nozzle arrangements reproduced from the.

6. Spray and droplet representation

The water droplets were injected into the computational domain from a nozzle positioned in the middle of the inlet plane and oriented horizontally in the downstream direction. The states that the hollow-cone spray model available in ANSYS/Fluent was used. The nozzle coefficient was taken as approximately 0.9 based on the cited work of Sureshkumar et al.

The droplet-size distribution was represented using the Rosin–Rammler model. The model describes the relationship between droplet diameter and the mass fraction of droplets having diameters greater than a specified diameter.

7. Continuous and discrete phases

The continuous phase consisted of air, while the mist was treated as a discrete phase because the mass fraction of the mist was small. The continuous-phase equations included conservation of mass, momentum, energy and species. A source term representing mass transfer from the dispersed phase to the continuous phase due to droplet evaporation was included in the continuity equation.

The discrete phase model was used to calculate droplet trajectories and heat and mass transfer between the droplets and the surrounding air. Initial droplet position, velocity, size and temperature were used to initiate trajectory and heat/mass-transfer calculations.

8. Reference operating condition

The five nozzle arrangements were compared at an air velocity of 5.96 m/s. The psychrometric calculation in the gives an inlet air temperature of 39.0°C, inlet relative humidity of 40.0%, inlet specific humidity of 0.0176 kgw/kga, outlet temperature of 29.07°C, outlet relative humidity of 85.0%, outlet specific humidity of 0.0217 kgw/kga, an air volume-flow entry of 44.113, an air mass-flow entry of 52.94 and six nozzles for the reported calculation.

Table 3. Psychrometric calculation reported in the attached study.

Va (m/s)	Ta,i (°C)	Ψa,i (%)	Xa,i	Ta,o (°C)	Ψa,o (%)	Xa,o	Qa	ma	No.
5.96	39.0	40.0	0.0176	29.07	85.0	0.0217	44.113	52.94	6

9. Cooling-efficiency evaluation

Spray cooling efficiency was used as the performance indicator. The defines it as the ratio of the actual air-temperature drop to the maximum possible temperature drop relative to the wet-bulb temperature.

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

where $T_{db,i}$ and $T_{db,o}$ are the inlet and outlet dry-bulb temperatures and T_{wb} is the wet-bulb temperature. The global cooling efficiency was evaluated using average temperatures at the inlet and outlet/evaluation plane.

IV. RESULTS AND DISCUSSION

1. Flow, temperature and water-mass-fraction distributions

The CFD results showed strong interaction between the air flow and injected water droplets. The liquid-water concentration was relatively large near the nozzle, where momentum exchange between the droplets and the air was more pronounced. Close to the nozzle, velocity, temperature and mass-fraction distributions were relatively symmetric. Farther downstream, decreasing droplet momentum made gravity more pronounced, producing a downward movement of the droplets and an asymmetric distribution.

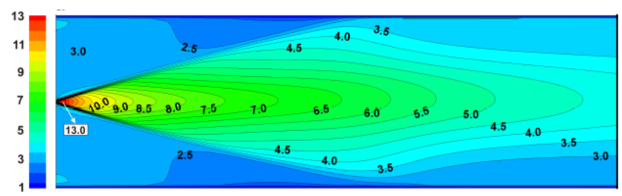

Figure 7. Velocity distribution for nozzle arrangement 4 reproduced from the.

For nozzle arrangement 4, the reported velocity distribution showed a velocity of approximately 13 m/s at the tip of the nozzle and a reduction toward approximately 3 m/s with increasing distance. The report attributes the reduction in mist velocity to distance and interaction with the air.

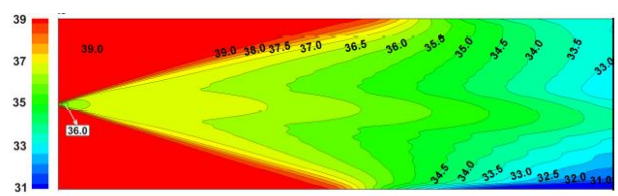

Figure 8. Temperature distribution for nozzle arrangement 4 reproduced from the.

The temperature distribution for nozzle arrangement 4 was simulated using an ambient temperature of 39°C. The states that the mist became cooler along the distance from the nozzle and that the temperature reduced along the spray path, indicating increased cooling as the droplets were transported away from the nozzle.

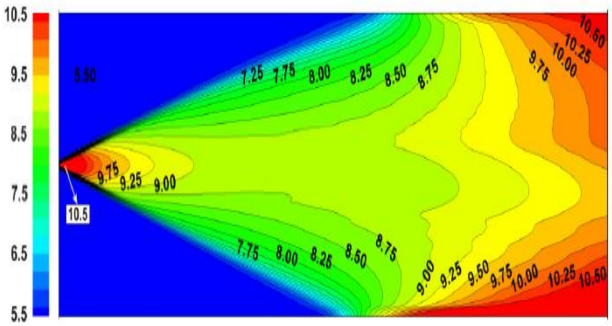

Figure 9. Water-mass-fraction distribution for nozzle arrangement 4 reproduced from the.

The water-mass-fraction distribution illustrates the interaction between water and air from the fan. The states that the water–air mixture changes along the spray distance, with the water concentration highest near the nozzle and the flow becoming more streamlined as the air velocity changes along the domain.

2. Effect of nozzle arrangement on cooling efficiency

The five nozzle arrangements were compared at an air velocity of 5.96 m/s. The gives the cooling efficiency, average air temperature and relative humidity in Plane_0.9 for each arrangement.

Table 4. Cooling efficiency, average air temperature and relative humidity for the five nozzle arrangements.

Nozzle arrangement	ηc	T (K)	Ψ
1	66%	304.2	74%
2	67%	303.7	78%
3	68%	303.6	88%
4	70%	303.4	90%
5	63%	303.8	88%

Arrangement 4 produced the highest reported cooling efficiency, 70%, and the lowest reported average temperature, 303.4 K. Arrangement 5 produced the lowest cooling efficiency, 63%. The identifies arrangement 4 as the optimal configuration because it allowed better distribution of the water flow and consequently more efficient evaporation.

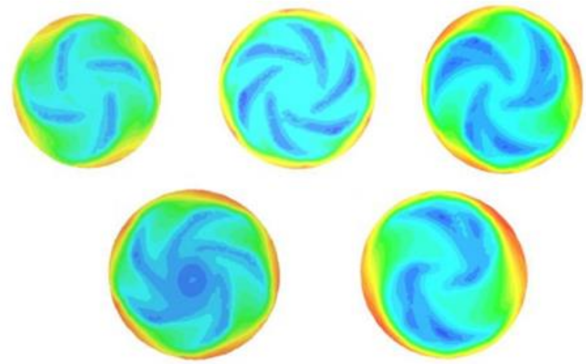

Figure 10. Temperature contours for the five nozzle arrangements at Plane_0.9 reproduced from the.

The temperature contours show differences in the spatial distribution of cooling among the five arrangements. The states that arrangement 4 had a more uniform temperature distribution than arrangement 1.

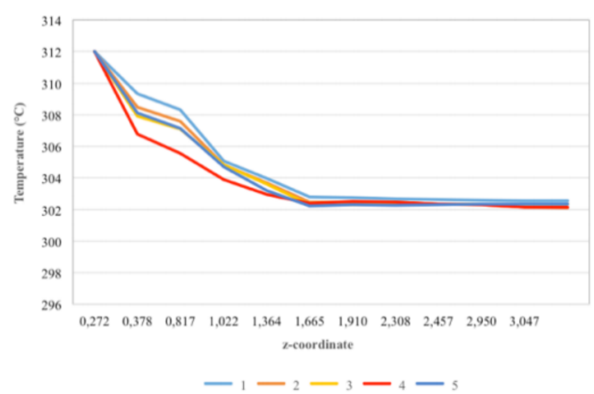

Figure 11. Comparison of average temperatures in the Middle_Plane for the five nozzle arrangements reproduced from the.

The comparison of average temperature along the Middle_Plane supports the cooling-efficiency results. The identifies arrangement 4 as having the best performance because of its quicker temperature drop compared with the other arrangements. It also identifies arrangement 5 as the poorest-performing configuration and relates its performance to the distribution of water mass flow among five nozzles.

3. Identification of the optimum nozzle arrangement

Based on the cooling-efficiency values, average temperatures and temperature contours reported in the study, nozzle arrangement 4 was identified as the optimum configuration among the five investigated arrangements. Its reported cooling efficiency was 70%, compared with 66%, 67%, 68% and 63% for arrangements 1, 2, 3 and 5, respectively. Its average temperature of 303.4 K was also the lowest among the five arrangements.

The result indicates that the number of nozzles alone does not determine cooling performance. The specifically notes that arrangement 5, in which the water mass flow was distributed among five nozzles, did not produce the best performance. The distribution of the water flow and the resulting evaporating area were therefore important to the observed performance.

4. Experimental validation

The source study compared the CFD analysis with experimental measurements at distances of 500, 1000, 2000, 2500 and 3000 mm from the fan. The report states that the CFD analysis was accurate when compared with the experimental data and that high cooling efficiency was achieved at approximately 2.5 m from the fan.

Table 5. Comparison of CFD analysis and experimental values as reported in the attached file.

Point	CFD X/mm	CFD Air	CFD Temp.	CFD efficiency	Exp. X/mm	Exp. Air	Exp. Temp.	Exp. efficiency
1	500	10.0	37.0	40%	500	8.0	32	68%
2	1000	7.5	39.0	67%	1000	7.15	29	68.13%
3	2000	5.5	35.75	68%	2000	4.8	25.32	70.40%
4	2500	2.0	34.25	71%	2500	4.1	25.10	71.55%
5	3000	3.0	33.0	67%	3000	2.8	24	70.07%

The validation table is reproduced exactly in substance from the. The report's abstract states that the experimental and CFD results showed 96% correlation.

V. CONCLUSIONS

The study investigated the effect of nozzle arrangement on the cooling performance of a mist fan using CFD and experimental measurements. Five nozzle configurations were evaluated using cooling efficiency, average temperature and flow-field distributions as performance indicators.

Nozzle arrangement 4 was identified in the as the best configuration among the five arrangements investigated. At the reported comparison condition of 5.96 m/s air velocity, arrangement 4 produced a cooling efficiency of 70% and an average temperature of 303.4 K. The corresponding efficiencies for arrangements 1, 2, 3 and 5 were 66%, 67%, 68% and 63%, respectively.

The CFD contours showed that nozzle arrangement 4 provided a more uniform temperature distribution and better water-flow distribution. The results also showed that simply increasing the number of nozzles does not necessarily improve cooling performance, as demonstrated by the lower performance of arrangement 5.

The CFD model provided whole-flow-field information on velocity, temperature and water-mass-fraction distributions, while experimental measurements provided validation of the predicted cooling behaviour. The states that the CFD and experimental results showed 96% correlation.

Recommendation

Based on the simulation and experiments reported in the study, nozzle arrangement 4 should be adopted in the design of mist fans to enable quality air distribution and quick humidification. The also recommends optimizing the relationship between liquid-mixture particle sizes and nozzle size to prevent nozzle clogging and carrying out a mechanistic model to determine the relationships among blade length, nozzle configuration, air velocity and cooling temperature for large-scale product design.

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