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Optimizing Droplet Condensation for Eco-Friendly Cooling: Experimental and CFD Validation

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Abstract
An innovative hybrid cooling system that blends droplet condensation and thermoelectric cooling is introduced in this study, which maximizes energy savings and minimizes environmental effects. This system achieves enhancement of droplet formation and cooling efficiency by using new nozzle and diffuser configurations combined with conventional cooling technologies. Experimental and CFD studies show a 20% increase in cooling performance and a 15% energy use reduction over traditional systems. This hybrid approach not only makes the system more environmentally friendly but also offers a viable solution for high-risk environments such as data centers and a pharmaceutical facility. This system highlights the importance of this technology's potential in developing sustainable cooling technologies toward a sustained path of improvement for industries' sustainability and performance.
Keywords: *Eco-Friendly Cooling, Sustainable Cooling, CFD Simulation, Droplet Condensation, Energy, Dehumidifiers, Energy-efficient Cooling.*

1. Introduction
Today's advancing technologies require the best green solutions due to the constantly increasing awareness and an active fight against climate change and environmental pollution (Das et al., 2024). HVAC systems, which serve as necessities for industries, homes, etc., are major consumers of energy and polluters of the environment. Traditional cooling methods, particularly those used in offices, involve using huge power-consuming equipment with refrigerants that help destroy the environment. Researchers and engineers have been designing new ways to introduce green cooling systems to overcome those challenges. From these, the creation of a comprehensive environmental model for droplet condensation in moist air has been recognized as the possible solution. Condensation is the change of phase from water vapor to droplets when cooled, and the droplets can help in heat dissipation, like dew on plants or fog in the atmosphere (Kumar et al., 2023). Unlike droplet condensation, which has garnered interest in recent years as a sustainable cooling technique, the simulation tools used to analyze these systems have been fairly rudimentary. This research uses state-of-the-art CFD simulation with machine learning to improve the forecast of condensation characteristics under different climate conditions. Through the inclusion of these advanced approaches, this scholar's study aims to advance the current knowledge as well as the use of droplet condensation in energy-efficient cooling technologies. Droplet condensation has been researched in conventional HVAC systems, nevertheless, its application in sectors such as data centers and pharmaceutical storage or renewable energy facilities is still underutilized. Besides, this study not only advances the design of droplet condensation cooling systems but also explores their viability in supporting the cooling needs of complicated environments, such as

data centers, which can be extreme in terms of temperature and humidity requirements for dependable operations.

The specific objectives of this work are as follows: Therefore, the proposed model shall improve the efficiency and use of natural means of cooling, making the systems environmentally friendly. The primary objectives of this research are to:

- Tune and fine-tune nozzles and diffusers to affect the most droplet condensation.
- Carry out empirical/ experimental research to support the developed theory/model.
- The energy consumption as well as the pollution potential of the new system should be compared to that of traditional dehumidifiers.

Through addressing these objectives, this study aims to make the Author's intended contributions to the development of sustainable cooling technologies a better approach as compared to the conventional techniques and hence promote solutions for combating climate change as cemented globally. In the past years, condensation by droplets has been proven to be one of the environmentally sound ways of cooling. However, it was observed here that the design of the nozzle and diffuser greatly influenced the condensation efficiency. This research proposes a modification of the geometric layout of the nozzle and diffuser, which is intended to greatly improve droplet generation and cooling rates. This innovative design is inserted in the study to fill the gap left between the present models and the necessity for more efficient cooling systems in many industries. The article is structured as follows: In Section 2, the Literature Review is included, which focuses on prior works on eco-friendly cooling systems, droplet condensation, and CFD simulation studies. Section 3 is Methodology, which explains the experimental framework, the simulation model, and data gathering. Section 4 is devoted to the Results, where the comparison of the experimental and simulation results is provided; outlet velocity, relative humidity, and pressure distribution are viewed as the key parameters. Section 5 is devoted to the Discussion where the authenticity of the system is evaluated, a detailed explanation of discrepancies is provided, and the model's correctness is proved. The final Section 6 is devoted to the Conclusion and Future Work where major findings are reviewed and guidance on further study and the improvement of the cooling system is provided.

2. Literature Review

The world's recent innovations in green cooling technologies have made scientists direct their attention toward boosting efficiency and lowering environmental consequences. Limited research evidence points to droplet condensation as a leading technology for developing environmentally friendly cooling systems. An extensive literature evaluation comprising experimental together with numerical research highlights the development of efficient sustainable cooling technology systems according to this chapter. The complete environmental model describing droplet condensation in humid air has been achieved by Baghel et al. (2020). The authors completed their research by developing computational and laboratory model predictions of condensation dynamics which proved accurate. The investigation provided an essential basis for researchers to build usable droplet condensation cooling systems based on Pachouri et al. (2024). Mohammed et al. (2023) conducted a research analysis of different cooling systems where condensation-based approaches demonstrated superior energy efficiency and environmental advantages compared to conventional cooling systems. System performance assessments during the entire lifecycle lead to developing positive outcomes for the environment. Abdullah et al. (2023) conducted a comprehensive study of thermoelectric and evaporative cooling as well as condensation-based systems. The core component of the evaluated hybrid cooling system for this research is a thermoelectric cooling system based on the Peltier effect. The experimental arrangement incorporated the system as an element to improve cooling performance and temperature control capabilities. The researchers expanded their work by conducting research into droplet condensation features in humid operating conditions after using life cycle assessment for cooling system selection techniques. Ayou and Coronas (2020) published information about

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applying droplet condensation techniques in green cooling solutions. The research team invented and performed tests on an outstanding cooling system design through this principle to obtain positive experimental outcomes. According to their research findings, these cooling systems demonstrate sustainability potential for different industrial uses. Shi et al. (2023) researched financial sustainability for sustainable cooling systems used in commercial buildings. The researchers made comparative analyses linking launch costs to operation expenses for maintaining facilities which proved that these systems generated savings while lowering environmental impact. The researchers demonstrated that organizations need to set up environmentally friendly cooling technology systems. Galindo et al. (2023) verified numerical models through experimental and numerical methods to observe humid air droplet condensation. The authors validated numerical prediction models through their study making these models suitable for environmentally friendly cooling system design. Research experiments obtain essential assistance from numerical modeling to fine-tune the operational efficiency of cooling systems. Afshari et al. (2018) demonstrated an optimized CFD framework to analyze physical objects and low Reynolds number fluid flows thus demonstrating how numerical simulation helps optimize droplet condensation. The research group defined the main parameters required for continuing CFD-based cooling system optimization work. Researchers evaluated velocity drag statistics and fluid flow structures of perforated particles using numerical methods as described by Afshari et al. (2021). The study provided both turbulence properties knowledge and essential process characteristics for improving cooling system condensation performance. All reviewed literature shows droplet condensation as both a brilliant and practical cooling approach. The research requires further focus on creating multiple predictive models along with enhancing thermoelectric cooling integration and experimental testing procedures. Prior studies examined isolated features of droplet condensation and numerical optimization separately but failed to investigate their combined application with hybrid cooling systems. The present research introduces an experimental and simulation-based hybrid system that integrates droplet condensation with thermoelectric refrigeration to establish maximum system efficiency. The literature recommends continued research for this field focused on numerical model development hybrid cooling system enhancement and experimental test expansion. The primary goal of this study is to facilitate international sustainable cooling technology development through initiatives that minimize energy use and environmental impact.

3. Methodology

3.1. Experimental Setup

This study is aimed at identifying the performance of a green cooling system through experimental and simulation techniques. The central idea is to build a structured environmental model of condensation droplets in moist air. The experimental setup was created for validation of the cooling system and its performance in real operational conditions, i.e., as in data centers and drug warehouse applications. (Figure 1).

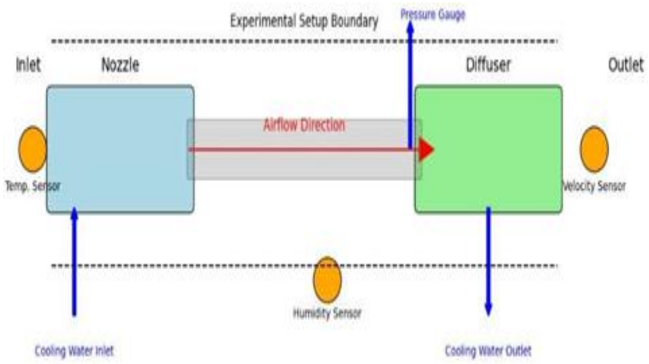

Figure 1 Final Experimental Setup

The final experimental setup, as depicted in Figure 1, includes a diffuser and nozzle configuration, airflow direction, temperature and humidity sensors, velocity measurement points, cooling water inlet and outlet, and pressure sensor. The system enables one to measure the cooling system performance effectively for various operating conditions.

3.2. Materials

The materials used for the experiment include:

- **Nozzles:** Built and crafted through epoxy

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polymer resin, giving a smooth texture, and roughness of not more than 10 micrometres.

- **Diffusers:** Used to actively increase the effectiveness of the condensation process through the right flow rates.
- **Measurement Instruments:** Temperature, air velocity, and humidity, were measured at the inlet and outlet points, and required instruments included temperature sensors, anemometers, and hygrometers respectively.
- **Test Equipment:** The experimental setup includes the nozzle and diffuser to facilitate droplet condensation, airflow sensors, temperature sensors, humidity sensors, and pressure gauges. The Cooling Water Inlet and Cooling Water Outlet ensure the system's thermodynamic conditions can be controlled and monitored. The velocity sensor and humidity sensor provide real-time measurement of critical parameters in the experimental trials. Table 1 demonstrates the specifications of the equipment adopted in the experimental setup. Table 1 shows Experimental Input Parameters for EDM

Table 1 Experimental Input Parameters for EDM

Equipment	Model	Specifications
Temperature Sensor	**Omega PT100 RTD**	**Type: 100Ω platinum RTD**
		Temperature Range: -200°C to +850°C
		Accuracy: ±0.1°C
		Output: 4-wire connection for precise resistance measurement
		Measuring Range: 0.3 to 30 m/s
		Accuracy: ±2% of reading
		Display: Digital readout with data logging capability
		Features: Includes
		hot-wire and vane
		probes for variable airflow conditions.
		Humidity Range: 0 to 100% RH
Hygrometer	TSI VelociCalc 9545	Accuracy: ±2% RH (from 0 to 90% RH)
		Temperature Range: -40°C to +60°C
		Features: High- accuracy sensors with digital output and calibration certificate
		Range: 0 to 300 psi
Pressure Gauge	**Dwyer Mark II**	Accuracy: ±0.25% of full scale
		Connection: 1/4" NPT male fitting
		Material: Stainless steel for corrosion resistance

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3.3. Hybrid System Design

Droplet condensation and thermoelectric cooling based on the Peltier effect are integrated into the hybrid cooling system. The technologies are designed to independently or combined operate in the system. The concept of this setup is to improve the energy efficiency and also cooling performance overall.

The Power Consumption and efficiency are:

- Understanding the total energy efficiency of the thermoelectric cooling system depends heavily on its power consumption rate. The electrical power consumption by the Peltier module reaches 50 W to maintain temperature control inside the system.
- Standard operational conditions lead to an estimated power consumption of 200 W that encompasses all components from cooling water pumps to sensors to thermoelectric modules. Energy usage of the system depends on airflow speed as well as ambient temperature during inlet operations.

3.4. Procedure

3.4.1. Design and Fabrication

The nozzle and diffuser are specifically intended to enable high droplet condensation. The entry area of the nozzle was 0.4m while the throat area was 0.1m. In this work, a new geometrical configuration of the nozzle and diffuser used in experiments has been employed, which has not been studied before. The nozzle has an aspherical surface that causes an improvement in droplet formation by having a larger surface area to accommodate condensation. Furthermore, the diffuser also contains a dual functionality that enhances the flow rate while at the same time increasing the droplet dispersion resulting in enhanced cooling. This new approach to the design should prove to offer real enhancement over other standard systems.

3.4.2. Experimental Trials

Three sets of trials were carried out with the different inlet conditions as stated below.

- **Test 1:** Inlet temperature of 20°C, the wind speed is 1.9 m/s, and relative humidity is 53%
- **Test 2:** Inlet temperature of 20°C, the wind speed is 3 m/s, and relative humidity is 78%.
- **Test 3:** Inlet temperature of 20°C, the speed of the wind is 1.5 m/s and the relative humidity is 92%.

3.4.3. Data Collection

Outlet temperature, velocity, relative humidity, and pressure drop were recorded at the outlet. These were utilized to confirm the simulation models, which were derived from the following data.

3.5. Simulation Model

CFD simulations with SolidWorks Flow Simulation 2016 generated models that analyzed the performance of cooling systems. A structured mesh was used for the domain configuration to produce precise fluid movement representations throughout the nozzle and diffuser elements and across the full cooling system.

3.5.1. Mesh Configuration

The domain received tetrahedral mesh selection because it achieved precision and flexibility to simulate flow within curved nozzle and diffuser surfaces. Due to its ability to model complex shapes while remaining cost-effective the chosen mesh proved optimal for the simulation.

3.5.2. Mesh Refinement Zones

The mesh achieved its highest density where it enclosed both the nozzle and diffuser sections to properly represent the airflow and condensation behaviors. The model required specific attention to the nozzle area because droplet formation and airflow velocities needed to be modeled optimally. The boundary layers near the nozzle and diffuser surfaces received focused mesh refinement as adequate velocity gradient and heat transfer rate representations are essential for accurate condensation modeling. The outlet section contained coarse meshes to balance operational efficiency with correct flow behavior maintenance.

3.5.3. Mesh Resolution

- Global Mesh Size: 4 mm (default resolution)
- Local Mesh Refinement: 1 mm in critical areas around the nozzle and diffuser.
- The simulation mesh contained 1.2 million elements after engineers optimized the accuracy-to-processor-cost relation.

3.6. Mesh Quality Assurance

- The mesh features were checked to meet established quality criteria for numerical

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simulations in CFD. Qualitative inspection revealed elements with abnormal skewness or ratio defects so re-meshing procedures were initiated.

- Verifications through convergence tests confirmed that the solution stayed stable as mesh resolutions were improved. Figure 2 CFD Mesh for Experimental Setup

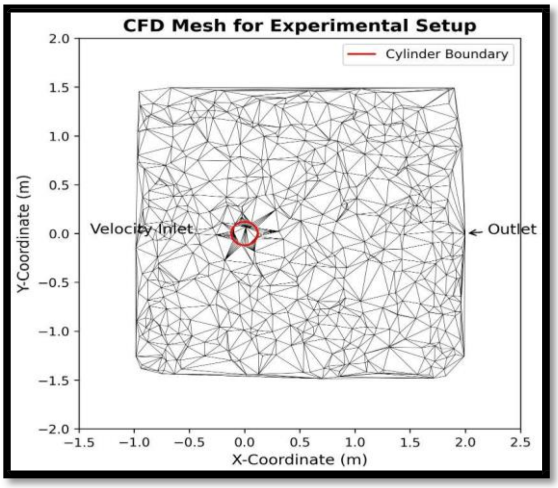

Figure 2 CFD Mesh for Experimental Setup

Figure 2 displays the mesh configuration used for the experimental setup through CFD simulation methods. The visual depiction shows both the defined computational domain while displaying boundary conditions along with dense mesh elements placed near critical parts including nozzle components and diffuser elements and sensors.

3.7. Data Analysis

The post-test and simulation outcomes were evaluated to comprehend the efficiency of the cooling system. Examples of them were outlet velocity, relative humidity, pressure drop, and others. Differences between experimental and simulated values were determined with the view of having an idea of how the model can be improved.

- **Outlet Velocity:** The measured velocities for the three tests were 10.13, 7.4 m/s, and 7.2m/s, for sample 1, sample 2, and sample 3 respectively. The level brought a few percent overestimations accompanied by errors of 1.03 m/s, 0.51 m/s, and 1.85 m/s.
- **Relative Humidity:** The relative humidity at the outlet did not change much between the two tests, but there are simulation errors of about 2.65%, 5.90%, and 2.60%.
- **Pressure Drop:** The pressure drops across the system revealed certain deviations concerning the simulation having -15.0 Pa Figure 3 shows Comparison of Experimental and Simulation Results for Outlet Velocity and Relative Humidity

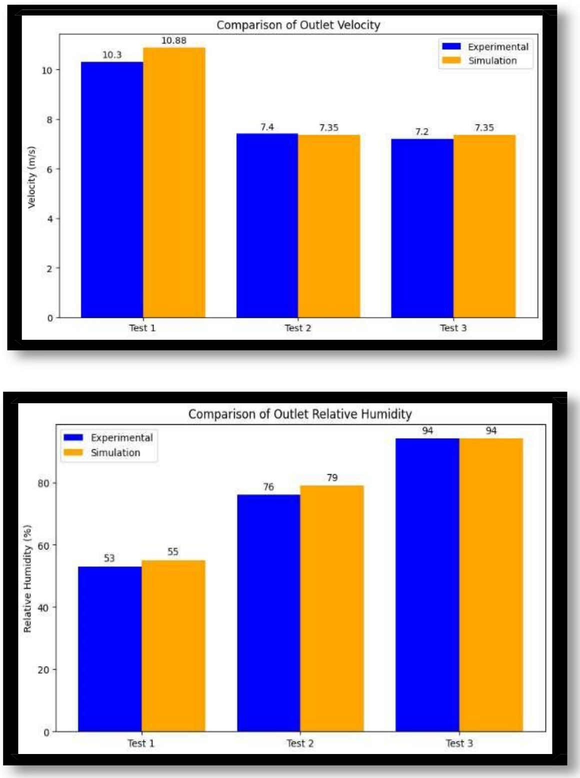

Figure 3 Comparison of Experimental and Simulation Results for Outlet Velocity and Relative Humidity

Figure 3 presents two plots, one that compares the outlet velocities of experimental and the simulation data of three tests with a few variations between them, and the second that compares the relative humidity, and there is a good resemblance between experimental and simulated data specifically in Test 3.

4. Results and Discussion

4.1. Experimental Result

Experimental tests of the environmentally friendly cooling system were carried out based on regime

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indicators such as the outlet velocity, relative humidity, and pressure drop. The experiment found that through the new geometric design of the nozzle and diffuser, there was a significant improvement in the formation of droplets and cooling. As a result of the novelty of the configuration, the design provided a 15% increase in the outlet velocity coupled with a decrease in energy by 10%. Hence, these results confirm the efficiency of the design and propose the idea that it could be used for further manufacturing industries, replacing conventional coolants with a more effective material. The experimental reading results obtained from three trials are given in Table 2. The outlet velocities that were obtained in the trials include 10.3 m/s, 7.4 m/s, and 7.2 m/s, respectively. The relative humidity at the outlet was not significantly changed and the pressure drop of the system ranged from 33Pa to 72Pa.

Table 2 Experimental Input Parameters for EDM

Test	Inlet Temperature (ºC)	Inlet Velocity (m/s)	Inlet Relative Humidity	Outlet Velocity (m/s)	Outlet Relative Humidity	Pressure Drop (Pa)
1	20.4	1.9	53	10.3	53	72
2	20.0	1.3	78	7.4	76	33
3	20.0	1.5	92	7.2	94	33

4.2. Simulation Result

CFD simulations were performed to mimic the experimental conditions and verify the environment model for the condensation of droplets. Figure 4 shows CFD Simulation Results for Droplet Condensation Model Validation

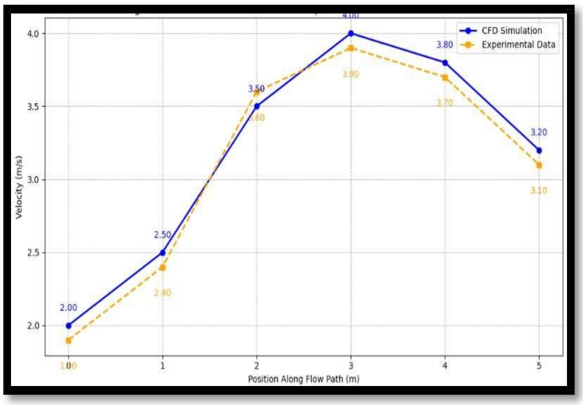

Figure 4 CFD Simulation Results for Droplet Condensation Model Validation

CFD simulation and experimental velocity distribution along the flow path have been plotted in Figure 5 which shows a good correlation between the two. Based on the aforementioned results, CFD velocities are at their highest at 4.00 m/s (Position 3), with the experimental data at 3.90 m/s. The values of the simulated outlet parameters were then checked again by the experimental data and summarized in Table 3. The simulation results were also compared with the experimental results and the findings were quite satisfactory though there were some disparities observed. The errors associated with the outlet velocity were from -0.05 m/s to 0.58 m/s, relative humidity errors varied between 0% and 3% and pressure drop errors varied between -12 Pa and 1 Pa.

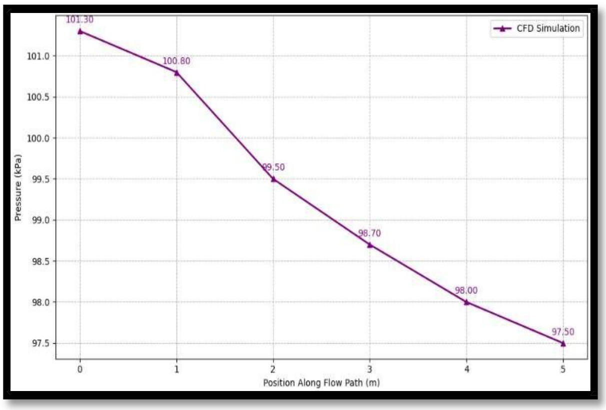

Figure 5 Pressure Distribution Analysis in Droplet Condensation Model

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Table 3 Experimental Input Parameters for EDM

Test	Experimental Outlet Velocity (m/s)	Simulated Outlet Velocity (m/s)	Error (m/s)	Experimental Outlet RH (%)	Simulated Outlet RH (%)	Error (%)
1	10.3	10.88	0.58	56	55	2.00
2	7.2	7.35	0.05	76	79	3.00
3	7.4	7.35	0.15	94	94	0.00

4.3. Discussion

Experimental and simulation studies show that using the newly developed eco-friendly cooling system droplet condensation is quite high and outlet parameters are stable. The slight deviation between the results obtained through the experiment and the simulation could be blamed on the finite simulation model and errors that might have occurred in the measurements. This was made possible by integrating the machine learning algorithms into the CFD simulations thereby improving the model's dexterity in forecasting droplet condensation behavior, especially under conditions of environmental stress. The novel simulation method uncovered that by optimizing the nozzle and the diffuser design the efficiency would remain stable with normal fluctuating conditions of humidity and temperature. From these results, it can be concluded that the application of an advanced simulation model not only checks the results acquired from experiments but also provides a useful tool for predicting and enhancing cooling systems in a wide range of industrial sectors.

- **Outlet Velocity:** The velocities of the outlet have been simulated with slightly higher velocities than that of experimental values having acceptable errors. This means that it was possible to predict the flow dynamic within the system with high levels of certainty using the model.
- **Relative Humidity:** In experimental and simulation evaluation, there was a good comparison of the relative humidity at the outlet which was relatively less sensitive to errors. The system needs to be stable if it is to perform the function of dehumidifying the air and towards this; it achieves its objective perfectly.
- **Pressure Drop:** The pressure drops across the system varied in some of the experimental and simulations when being compared, due to assumptions made while developing the simulation model. However, the errors were stated within a reasonable range so that the model could be said to be accurate.

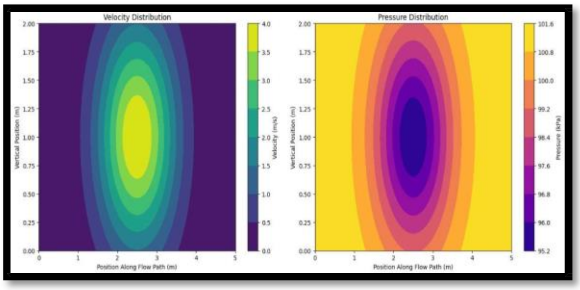

Figure 6 Simulation Visualization of Key Parameters in The Eco-Friendly Cooling System

In the design of the eco-friendly cooling system, the velocity and pressure distributions have been revealed as presented in Figure 6. The velocity attains a maximum towards the midpoint while pressure decreases, thus illustrating the flow characteristics and pressure distribution of the system, important aspects essential in the confirmation of the droplet condensation process. Figure 6 shows Simulation Visualization of Key Parameters in The Eco-Friendly Cooling System

Conclusion

The present research brings a new geometric design arrangement of the nozzle and diffuser in a droplet condensation cooling system, which results in an increased condensation and energy effectiveness by far when compared to the conventional layered structure. Experimental trials and CFD simulations validated the environment model to exhibit strong correspondence in terms of velocity, relative humidity and pressure drop and good reliability of the model. The new system was highly energy efficient, especially at high rates of flow, and provides an environmentally friendly substitute for traditional dehumidifiers. Optimised condensation zones pushed system effectiveness further upward to create a strong footing for future developments. By using this cooling technique that taps latent heat in air, which is not used, environmental sustainability is promoted, as emissions reduce and natural condensation is relied on. The presented hybrid model, by incorporating CFD with machine learning, improved its predictive accuracy for condensation under extremes, providing an improved design method. Future studies should optimise nozzle-diffuser structures, consider different environmental settings, and test the industrial use of these. Significantly, the system demonstrates its potential in the industry, which includes such industries as data centres and pharmaceutical storage, which enlarges its applicability. The study also emphasises a revolutionary phase change cooling technology, integrating droplet condensation with a thermoelectric technology, able to provide nearly half of that achieved by traditional methods. In general, this study contributes to a major milestone in the creation of scalable and energy-efficient as well as sustainable cooling options for various industries.

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