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Enhancing the Efficiency of Air Conditioning Systems in High-Temperature Climates Through Direct Evaporative Cooling

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Abstract: This study aims to develop energy-efficient and environmentally friendly cooling solutions that are both effective and adaptable to various climates and structural forms. By leveraging computational fluid dynamics (CFD) software ANSYS and simulation software Engineering Equation Solver (EES), an innovative approach was undertaken. The investigation focused on the optimization of external air cooling via adjustable injectors operating at three distinct velocities, across three airflow rates. Concurrently, the adaptability of the cooling flow was enhanced by varying the number of turns in a coil within the heat exchanger's condenser section. This dual-phase method facilitated a comprehensive analysis across 54 scenarios, employing the EES software for the calculation of the coefficient of performance (COP) enhancement metrics. The efficiency of the cooling apparatus was rigorously evaluated by methodically altering the number of cooling tube turns and injection velocities. The apparatus comprised a loop-and-tube heat exchanger with a modifiable structure, where the second phase of the study addressed the thermal impact of air entry velocity and water spray mechanisms, featuring cooling tube adjustments ranging from five to thirteen turns. The initial phase examined the effects of air entry area and water spray techniques through variable injector configurations, with diameters of 15, 24, and 20 cm, and dimensions of 10 cm in height and 25 cm in length, alongside a conduit width of 60 mm. The findings revealed that the thermal dynamics of the heat exchanger and fluid flow are significantly influenced by the apparatus's geometry, particularly the air entry area and water spraying mechanism. Temperature and velocity contours illustrated that the number of loop turns and injections markedly affects system performance. An optimal configuration, consisting of 35 injectors and 13 coil turns, achieved a COP of 4.537 at an inlet velocity of 2.0 m/s, signifying the most effective system design identified within this study.

Keywords: Direct Evaporative Cooling (DEC); High-temperature climates; Energy efficiency; Sustainable cooling solutions; Air conditioning optimization

1 Introduction

DEC systems chill air by evaporating water. These devices force heated air through a damp pad or filter to cool it as water evaporates. DEC systems have various pros and cons and are more energy-efficient and cost-effective than regular air conditioning systems. DEC systems are more energy efficient, sustainable, and improve indoor air quality than standard AC systems [1]. However, building and deploying these systems requires consideration of their limits. In extreme heat, optimizing DEC system design and operation may improve air conditioning systems numerically [2] . Interest in cooling frameworks has continually expanded in warm environments. Most people are aware that traditional air conditioners use a lot of energy, which costs money to run and hurts the environment. Because of these issues, scientists are seeking greener, energy-productive cooling arrangements. DEC is a well-known cost- and energy-productive arrangement. Dizaji et al. [3] utilized Maisotsenko's air conditioning framework (M-cycle). The scientists' clever air-chilling strategy appears to be encouraging. This innovation permits air to be cooled to the dew point, which was already incomprehensible. The researchers tested this method's M-cycle qualities using experimental, statistical, and analytical methodologies. The paper organized and analyzed various methodologies and offered an evolutionary perspective on M-cycle analytical solutions. M-cycle parameters were extensively investigated, and the results were summarized. The report reviewed the M-cycle market and proposed more research. In several simulated climates, Heidarinejad et al. [4] examined the cooling effectiveness of a two-stage indirect/direct evaporative system. Direct and indirect evaporative cooling are used in the system. Two outdoor air simulators tested the system's efficacy. When DEC fails, the new technology can provide comfortable conditions across a vast part of Iran. The system saved over 60% of electricity compared to mechanical vapor compression systems and only 55% of water compared to DEC systems. This energy-efficient and environmentally beneficial technique can bridge DEC with mechanical vapor compression. DEC with cooled water was tested to improve DEC performance in humid situations by Al-Badri et al. [5]. A heat and mass balance model for air and water was used to forecast DEC's efficiency. Their research indicated that DEC's performance was largely affected by the mass flow rate ratio, and freezing the water and reducing it might improve performance even in high-humidity settings. These data suggest DEC could be used in excessively humid climates. Camargo et al. [6] noted that evaporative cooling systems are cheaper than mechanical vapor compression systems for air conditioning. Water and air are used in evaporative cooling, which causes mass and heat transfer processes that evaporate water and lower the air temperature. DEC systems and their mathematical calculations are explained in the study. Experimental data from a direct evaporative cooler is compared to the mathematical model used to calculate the convective heat transfer coefficient. The report suggests that evaporative cooling systems could replace air conditioning at a lower cost.

Dhamneya et al. [7] examined DEC systems' thermodynamic performance with different Aspen fiber topologies. The researchers examined how incoming air temperature, humidity, and mass flow rate affected system performance. All top stream and standard sidelong stream plans had indistinguishable immersion productivity, with the exception of the triangle top stream setup, which had the greatest immersion effectiveness of 97% for Case-I. An evaporative cooling framework with a triangle setup showed a most extreme immersion proficiency of 97%, 88%, 0%, and 89% for Cases I, II, III, and IV, surpassing standard and other top-stream DEC frameworks. Zhao et al. [8] inspected how DEC cools lithium-particle batteries in a battery warm administration framework (BTMS). The review analyzes DEC framework execution for normal air cooling and regular convection cooling in view of relative stickiness and wind stream rate. Individual batteries and a pack of nine cells are tested. According to the findings, the DEC system effectively reduces the maximum temperature and temperature differential of the battery pack. This may make it possible to use Li-ion batteries more frequently in challenging operating conditions. In addition, we construct a DEC tunnel to boost cooling. Chiesa et al. [9] inspected whether uninvolved DEC may work on the Mediterranean inside warm solace. The review assessed DEC practicality in a few settings utilizing three techniques, taking into account directed normal ventilation, inner intensity gains, and warm protection. 60 Mediterranean towns were utilized to mimic a model place of business' warm properties. They looked at a variety of building designs to see how design features affect space cooling. The measurements exhibit that DEC has a significant potential for low-energy cooling, especially in the Eastern Mediterranean and southern Spain, and that significant boundaries that influence cooling requests limit its presentation. This paper additionally proposes imaginative hourly geo-climatic possibility examinations of DEC, showing their reasonableness and giving appraisal apparatuses to originators that assess DEC advancements from the get-go in the plan cycle. Tewari et al. [10] evaluated the summer solace of places of business in the Indian composite environment utilizing DEC frameworks. The specialists adjusted EnergyPlus warm reproduction models utilizing warm checking information from Jaipur places of business during late spring for a very long time, from April to July 2016. They made a L16 symmetrical cluster of control factors and their levels for reenactment runs utilizing the Taguchi plan. DEC might forestall 42% and 52 percent of warm distress hours in summer, as per the CCATCZ and ASHRAE Standard 55-2013 for warm safe places. Two extra structures used for field approval showed a decent understanding ($R2 > 0.90$) between location estimations and assessed indoor temperature values. This demonstrates the way that this philosophy could figure out and further develop the DEC framework for business-warm execution in the Indian composite environment.

Al-Juwayhel et al. [11] tried four evaporative cooling frameworks in Kuwait's warm climate. One-stage DEC, one-stage backhanded evaporative coolers (IEC) coupled to an outer cooling tower, two-stage IEC/DEC, and three-stage IEC/DEC-MVC frameworks were researched. Framework assessments utilized warm viability and energy proficiency proportions (EER). The outcomes showed that IEC/DEC had the most noteworthy EER, trailed by DEC, IEC/DEC-MVC, and IEC. DEC, DEC/IEC, IEC, and IEC/DEC-MVC were the next least effective. The concentrate likewise corresponded to EER, viability, and water-to-air mass stream proportions for every framework. These associations help with the evaporative cooling unit plan and streamlining. Chiesa et al. [12] examined if DEC may diminish Southern European and Mediterranean uneasiness hours. The review worked out cooling degree hours and reenacted climatic inconvenience hours for 20 metropolitan destinations. The review reproduces a pattern (free-running) and DEC case for every area, utilizing an example building. Correlations incorporate night ventilation reenactment. The study helps designers address DEC and night ventilation early by utilizing psychrometric analysis and comfort constraints. Evaporative cooling exploration and use in China were widely analyzed by Xuan et al. [13]. Most distributions are in Mandarin, so a couple of individuals are familiar with the magnificent outcomes. The paper examines immediate, aberrant, and semi-roundabout evaporative cooling thermodynamics and working speculations. After that, it talks about feasibility studies, performance testing, optimization, and a practical and theoretical study of mass and heat transfer analysis. The article examines the reasonableness of evaporative cooling in various districts, the adequacy of various gear, and key contemplations and strategies for upgrading productivity. The report dissects Chinese evaporative cooling hardware and frameworks to a limited extent. Shirmohammadi and Gilani [14] enhanced evaporative cooling frameworks using limited contrasts. Framework proficiency was analyzed according to plate separation, wind current speed, and wettability factor. Utilizing materials with high surface wettability factors, reducing secondary channel air relative humidity, and increasing the secondary-to-primary airflow velocity ratio are all ways to enhance evaporative cooling systems. The review introduced nine cooling techniques, and the co-current DEC and cross-stream backhanded evaporative cooler with f-type had the greatest effectiveness at 73% and 40%, respectively. In order to construct an indirect or DEC system suitable for Iran's diverse climates, the article suggests combining these two technologies. The review's discoveries can be utilized overall to pick evaporative cooling frameworks for various locales. Salins et al. [15] researched Celdek pressing in evaporative cooling under changed conditions. The picture shows how they utilized numerical displaying to anticipate outlet stickiness proportion, dry bulb temperature (DBT), cooling effectiveness, and cooling influence by modifying air speeds, admission DBT, channel relative moistness, and cushion thickness for three Celdek pressing wettability levels. Cushion thickness and material wettability expanded cooling influence, immersion effectiveness, DBT, and dampness proportion, as per studies. DBT, dampness proportion, and cooling productivity diminished with input wind stream rate and RH increments. Celdek 7090, with a thickness of 0.3 m and wettability of 630 $\mathrm{m}^2/\mathrm{m}^3$, performed best with a greatest DBT of 6°C, RH of 55%, immersion effectiveness of 90%, and cooling effect of 7000 Watts.

In regions characterized by high temperatures, such as Turkey and Iraq, the demand for air conditioning systems is paramount to ensuring comfortable indoor environments and maintaining productivity levels. However, conventional air conditioning systems often struggle to cope with the extreme heat, leading to increased energy consumption and strain on electrical grids. In this context, the significance of DEC systems emerges as a promising solution to enhance air conditioning efficiency in high-temperature climates. DEC systems utilize the natural process of water evaporation to cool air, offering several advantages over traditional air conditioning methods, particularly in hot and arid regions like Turkey and Iraq. By introducing water vapor into the air stream, DEC systems can significantly reduce the temperature of the incoming air without the need for excessive energy consumption or environmentally harmful refrigerants. This approach not only provides effective cooling but also offers potential energy savings and environmental benefits, making it a compelling solution for sustainable cooling in these regions. Furthermore, the implementation of DEC systems aligns with the growing emphasis on energy efficiency and sustainability in both Turkey and Iraq. As these countries seek to mitigate the impacts of climate change and reduce their carbon footprints, the adoption of innovative cooling technologies becomes increasingly relevant. By incorporating DEC systems into existing air conditioning infrastructure, businesses, residences, and public facilities can reduce their reliance on conventional cooling methods powered by fossil fuels, thereby contributing to overall energy conservation efforts. Despite the potential advantages of DEC systems, their widespread adoption in Turkey and Iraq faces several challenges, including technical barriers, cost considerations, and cultural acceptance. Therefore, research aimed at optimizing the performance and cost-effectiveness of DEC systems in these specific contexts is crucial for overcoming these barriers and unlocking their full potential. This study seeks to address these challenges by evaluating the feasibility and benefits of integrating DEC technology into air conditioning systems in high-temperature climates, ultimately contributing to the advancement of sustainable cooling solutions in Turkey, Iraq, and similar regions around the world.

This examination demonstrates the way that evaporative cooling arrangements could supplant regular air conditioning frameworks in a reasonable and energy-efficient way. In hot and dry regions, immediate and backhanded evaporative cooling frameworks can decrease building energy utilization, while strong desiccant roundabout cooling can work in sticky environments. The investigations likewise stress the significance of advancing these frameworks' plan and activity boundaries for execution and effectiveness. Evaporative cooling framework input air temperature and moistness, air speed, water stream rate, and framework engineering can influence cooling and energy productivity. Evaporative cooling frameworks have a promising future in naturally well-disposed building planning and upkeep, according to research. A study is expected to amplify these advances' true capacity and work on their exhibition for different structure types and environments. The exploration expressed before shows that the DEC approach lessens central air energy use. The examinations analyzed the effects of front-facing air speed, DBT, and approaching water temperature on cooling execution and tracked down experimental connections. Some examinations likewise analyzed how pre-cooling and post-cooling segments in the DEC framework further develop execution and what wetted media mean for it. DEC might supplant traditional central air frameworks in dry and dry conditions, as per studies. Ebb and flow research explores DEC to further develop cooling viability at high intensity (DEC). DEC frameworks should be measured and intended for the structure and environment. The goal is to reduce energy usage and offer cost-effective, ecologically friendly cooling systems for highly hot conditions. The study's objectives are summarized below:

(1) To construct numerical mode ls to analyze DEC system performance and optimize design parameters for specific applications.

(2) To recommend DEC system design, installation, and operation in real-world applications based on numerical simulations.

(3) To help create ecologically friendly, cost-effective, and energy-efficient cooling systems for extreme heat locations.

2 Methodology

Refrigeration systems need heat exchangers to work better and save energy. Effective cooling is achieved by dissipating heat from one fluid to another without direct contact. This introduction will discuss refrigeration system heat exchanger benefits with references. Adding a heat exchanger to a refrigeration system boosts energy efficiency. Heat exchangers efficiently transmit refrigerant heat to the environment or other system fluids. This technique reduces compressor workload and boosts system efficiency [16]. A heat exchanger reduces the environmental impact of refrigeration systems. Improved energy efficiency and heat transmission in the heat exchanger reduce energy use and greenhouse gas emissions. By reducing energy usage, heat exchangers help achieve sustainability and mitigate climate change [17]. In the system, heat exchangers prevent refrigerant contamination. Because the heat exchanger separates refrigerant from air and other fluids, its purity and integrity are guaranteed. Avoiding cross-contamination maintains refrigeration system reliability [18]. Heat exchangers optimize refrigerant-fluid heat transfer. They provide efficient and fast cooling due to their large heat exchange surface. This improved heat transfer method speeds up refrigeration system cooling, reducing cooling cycle times, and enhancing system performance. Heat exchangers in refrigeration systems improve energy efficiency, environmental impact, refrigerant contamination prevention, heat transfer efficiency, and system design flexibility. Because of these benefits, heat exchangers are crucial to refrigeration systems, improving efficiency and sustainability.

The study aims to test the following hypotheses regarding the performance of DEC systems in high-temperature climates, specifically in regions like Turkey and Iraq:

(1) DEC systems will demonstrate a significant reduction in indoor air temperatures compared to traditional air conditioning methods, thereby providing effective cooling even in extreme heat conditions.

(2) Implementation of DEC systems will result in noticeable energy savings compared to conventional air conditioning systems, attributed to the lower energy consumption associated with evaporative cooling processes.

(3) DEC systems will exhibit favorable environmental impacts, including reduced greenhouse gas emissions and decreased reliance on refrigerants with high Global Warming Potential (GWP), contributing to overall sustainability efforts in the region.

(4) Integration of DEC technology into existing air conditioning infrastructure will be feasible and economically viable, considering factors such as installation costs, maintenance requirements, and long-term operational efficiency.

By testing these hypotheses, the study aims to provide empirical evidence supporting the efficacy and practicality of DEC systems as a sustainable cooling solution in high-temperature climates like Turkey and Iraq, thereby informing decision-making processes for policymakers, businesses, and homeowners seeking to enhance energy efficiency and mitigate the impacts of climate change.

2.1 EES Software

EES is a reliable software program used to solve and evaluate thermodynamics, fluid mechanics, heat transfer, and other engineering problems. EES features a simple interface and a huge library of integrated equations and thermophysical properties for engineers and academics. This introduction will describe the EES package and its capabilities using a reference. The EES package, developed by software developers, solves engineering problems with various capabilities. Equation-solving engines and flexible thermodynamic property databases can accurately model and simulate engineering systems. EES's massive equation and property data collection are major benefits. Energy balance, mass equilibrium, smooth movement, heat movement, and burning cycles are addressed by the framework's conditions. These conditions can be integrated into client-characterized models without tedious calculations or a convoluted framework examination. EES gives an abundance of thermodynamic qualities and formulae. Accordingly, the thermophysical properties of single parts, combinations, gases, fluids, and solids can be determined. Clients can involve precise and dependable property estimations for various materials to work on computations and reenactments. The easy-to-understand EES interface improves establishment and critical thinking. Clients can determine factors, enter information, and produce conditions involving basic punctuation in the calculation sheet, like programming. The program's programmed condition arrangement and continuous outcomes empower iterative enhancement and quick examination. In EES, users can see how input parameters affect system performance with parametric and sensitivity analyses. This attribute further develops framework execution guidance, process assessment, and plan streamlining. Specialists and scientists can utilize the EES bundle to tackle extreme design issues. Because of its situation settling limit, immense thermodynamic property data set, easy-to-understand connection point, and examination highlights, EES gives a solid stage to displaying and dissecting designing frameworks [19].

➤ **Equations of Mass, Energy, and Exergy**

The conservation of mass equation for system:

$$\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{out}} \tag{1}$$

where:

$\sum \dot{m}_{\text{in}}:$ the complete mass stream entering per unit time.
$\sum \dot{m}_{\text{out}}:$ the total mass stream leaving per unit time.

Each component's energy balance follows the system's first law of thermodynamics:

$$\dot{Q} + \dot{W} = \sum \dot{m}_{\text{out}}\, h_{\text{out}} - \sum \dot{m}_{\text{in}}\, h_{\text{in}} \tag{2}$$

where:

$\dot{Q}$: the heat transfer per unit time.
$\dot{W}$: work done by the control volume per unit time.
$h_{\text{in}}:$ specific enthalpy per the mass entering the system.
$h_{\text{out}}:$ specific enthalpy per mass leaving the system.

Since irreversibility produces entropy, it is not conserved in open and closed systems like mass and energy. Open systems have an entropy balance of:

$$\dot{E} = \dot{m}\psi \tag{3}$$

2.2 ANSYS Package

To understand flow, CFD studies are done. Solving a two-transport problem using the $\mathrm{k} - \varepsilon$ model shows the turbulence model's effect. These Cartesian coordinate systems can be solved numerically (x, y, and z). Three-dimensional geometry is created.

To generate, grid, and simulate the system geometry, ANSYS version (19) will be used.

2.2.1 Assumptions

The current study assumes R140A is the running liquid, which can be seen in Table 1, and flow characteristics are:

- Steady flow, three dimensional,
- Newtonian,
- Incompressible, and
- Turbulent.

Table 1. R140A properties [20]

Property	Value
Formula	$\mathrm{CH_2\ F_2(50\%) + CHF_2CF_3(50\%)}$
Molecular weight (Da)	72.6
Melting point $(^\circ\mathrm{C})$	-155
Boiling point $(^\circ\mathrm{C})$	-48.5
Liquid density $(30^\circ\mathrm{C})\,.\mathrm{kg/m^3}$	1040
Vapour pressure at $21.1^\circ\mathrm{C(MPa)}$	1.383
Critical temperature $(^\circ\mathrm{C})$	72.8
Critical pressure, MPa	4.86
Gas heat capacity $(\mathrm{kJ/(kg^\circ C)})$	0.84
Liquid heat capacity @ $1\ \mathrm{atm}, 30^\circ\mathrm{C}, (\mathrm{kJ/(kg^\circ C)})$	1.8

2.2.2 Governing equations

The continuity, momentum, and energy equations dominate.

- Mass Conservation

$$\nabla \cdot (V) = 0 \tag{4}$$

- Momentum

$$\nabla \cdot (\rho \dot{V} \dot{V}) = -\nabla p + \nabla \cdot (\bar{\tau}) \tag{5}$$

The stress tenser $\bar{\tau}$ is given by:

$$\bar{\tau} = \mu \left[\left(\nabla \vec{V} + \nabla \vec{V}^{T} \right) - \frac{2}{3} \nabla \cdot \vec{V} I \right] \tag{6}$$

- Energy

$$\nabla \cdot (\dot{V}(\rho E)) = \nabla \left(k\nabla T - \rho C\dot{V}T'\right) \tag{7}$$

2.2.3 Turbulence model

The $k-\varepsilon$ model is generally utilized in heat move demonstration because of its reasonableness and sensible exactness in many tempestuous streams. In the $k-\varepsilon$ model, two vehicle conditions for violent motor energy (k) and dispersal rate (ε) are tackled, and swirl consistency (μt) is determined as an element of k and ε which settled, and the whirlpool thickness (μ_{t}) is figured as a component of k and ε.

2.2.4 System geometry

Figure 1 shows a coil-and-tube heat exchanger with variable turns. The first element of the simulation process is the air entrance area and the water spraying process with varying numbers of nozzles (15, 24, and 35). The second part is the cooling tube with 5, 9, and 13 turns to determine the thermal influence on heat exchange between fluids. The duct measured 20 cm wide, 10 cm high, and 25 cm long. The duct width and roll diameter were 60 mm.

The rationale behind choosing the number of injectors and coil rotations is to rely on previous research as well as to guess new values to improve performance.

The air inlet temperature range was 25.50 to 50℃ depending on the case, and the gas inlet temperature was 58.40℃.

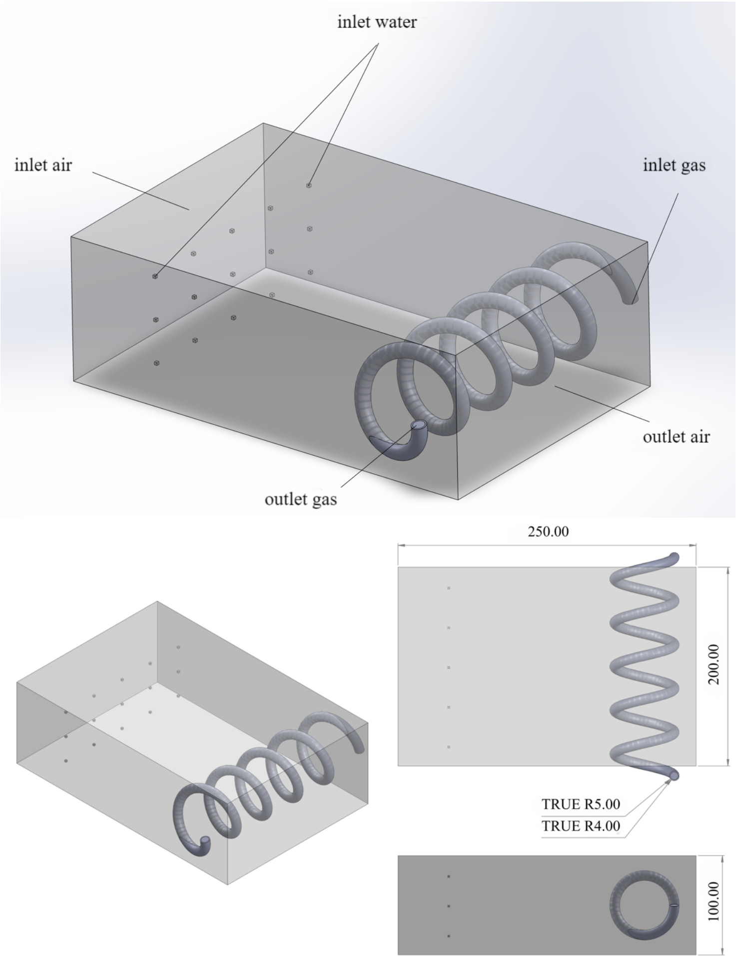

Figure 1. Geometry shape

2.2.5 Mesh generation

This study used a tetrahedron grid because unstructured grids perform well for complex geometries. A mesh for a solid geometry or 3D model can be generated in ANSYS with one phase of input. This study collected (3701221) cells, see Figure 2.

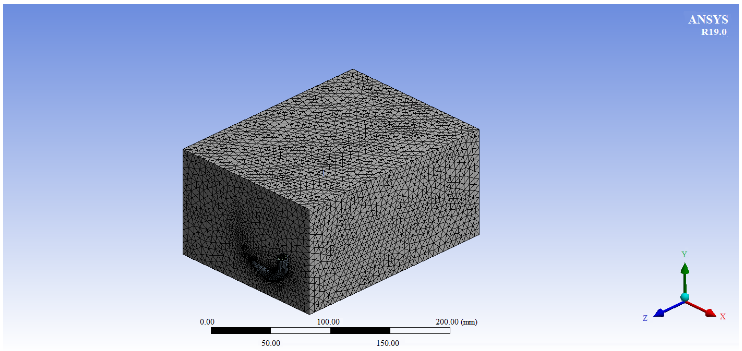

Figure 2. Mesh generated

The simulation method needs complex algorithms to solve domain matrices; therefore, an accurate mesh is needed to solve the equations. Then improve mesh reliability to stabilize the findings. Multiple meshes and reliability are needed due to the number of simulated models. Table 2 shows the element value was 3701221 at a 53.903 m/s average outlet gas temperature.

Table 2. Mesh independence

Case	Element	Node	Average Temperature Gas in Outlet °C
1	2162567	393564	55.734
2	2524690	519076	54.210
3	3025365	623482	53.964
4	3412354	734210	53.909
5	3701221	877558	53.903

2.2.6 Boundary conditions

As a boundary condition, the CFD program used EES pressures and temperatures as shown in Figure 3.

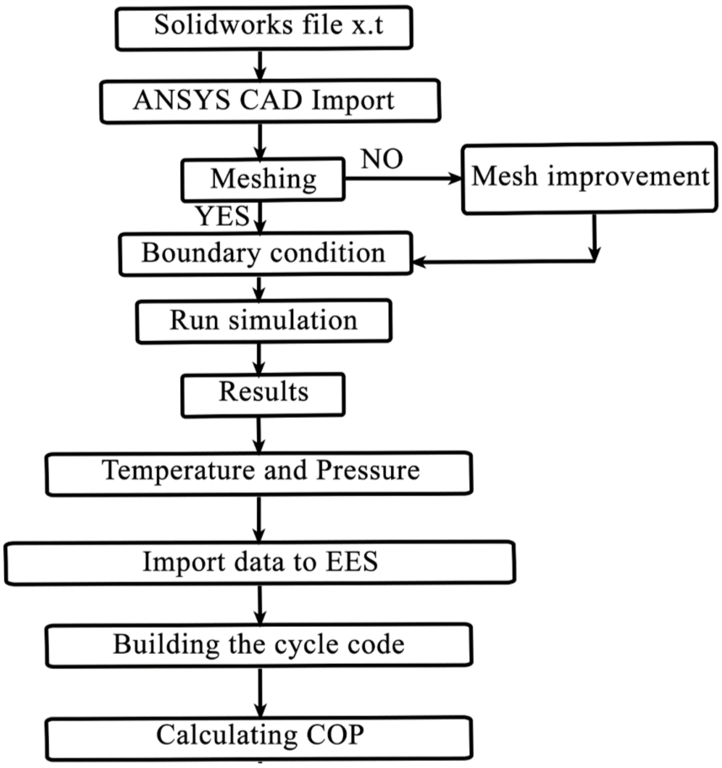

Figure 3. Flow chart

2.2.7 Solution parameters

These are the solution parameters:

(1) Precision Solver Type

Standard precision solver location approaches are single and double. An endlessly accurate computer would eliminate residuals when the answer converges to zero. Before stability, residuals in a real computer "round off" to a small amount (known as "leveling off").

(2) Iteration Count

The highest number of iterations before the solver stops.

(3) Convergence Criteria

In CFD, fluid flow equations are solved until convergence. Iterations stop when the answer does not change beyond the convergence threshold. The most common method for testing solution convergence is error residuals, which are the difference between a variable's value in two successive iterations normalized by the largest absolute residual over the first five iterations. The solution converges when all fluid flow equation residuals fall below 10^{-6}.

3 Results and Discussion

CFD analysis requires understanding the link between system shape and heat transfer efficiency. This study examined how changing a coil and tube heat exchanger's nozzle count and cooling tube turns affects performance. The investigation examined situations with 15, 24, and 35 nozzles with 5, 9, or 13 cooling tube turns and at 0.5, 1, and 2 m/s inlet velocities. An unstructured tetrahedron grid generated by ANSYS helped manage the system's various geometries. Using this technology, patterns in the pressure, temperature, and velocity contours from these alterations were visible, preparing for the outcome's discussion.

3.1 Analysis of Pressure Contours

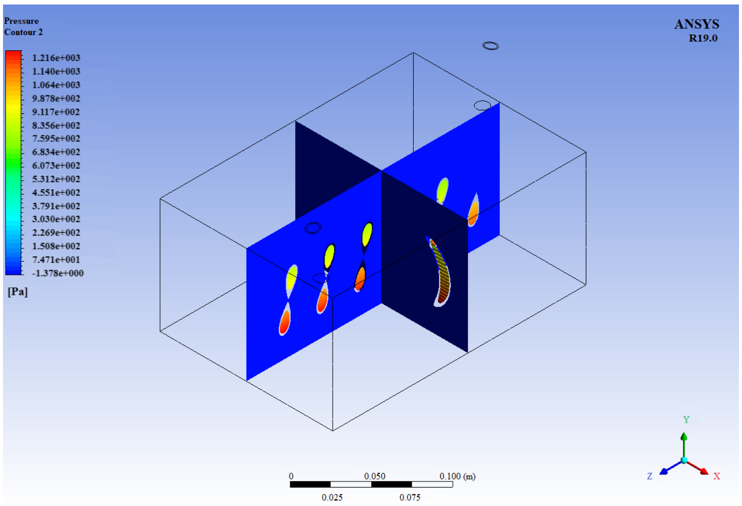

Figure 4. Pressure contours variation for 15 nozzles with air velocity 0.5 m/s

Figures 4 to 12 show the pressure contour analysis of a system with 0.5, 1, and 2 m/s inlet velocities, 15, 24, and 35 nozzles, and 5 cooling tube turns. The ANSYS simulation shows that turns and nozzles affect pressure contours. The most even heat distribution is with 35 nozzles. Turns and nozzles improve temperature distribution and heat exchange efficiency, improving the heat exchanger system's performance. Changing the structure could improve heat exchange. The results are due to the increased heat transfer surface area, tube turns, and nozzles. More turns lengthen fluid exchange pathways, whereas more nozzles increase dispersion. Pressure drops and elaborate patterns may be trade-offs.

The analysis of pressure contours in Figures 4 to 12 provides valuable insights into the performance of a heat exchanger system under varying inlet velocities, nozzle counts, and tube turns. Increasing the inlet velocity from 0.5 m/s to 2 m/s results in changes in pressure contours, suggesting that adjusting the inlet velocity can optimize heat exchange efficiency. The number of nozzles significantly influences pressure distribution, with increasing the number up to 35 leading to more uniform pressure distribution and enhanced heat exchange efficiency. The inclusion of tube turns in the system architecture also impacts pressure contours and heat distribution, improving temperature distribution and heat exchange efficiency.

The findings suggest that adjusting the structure of the heat exchanger system, such as increasing the number of tube turns and nozzles, can lead to improved heat exchange efficiency and temperature distribution. However, it is

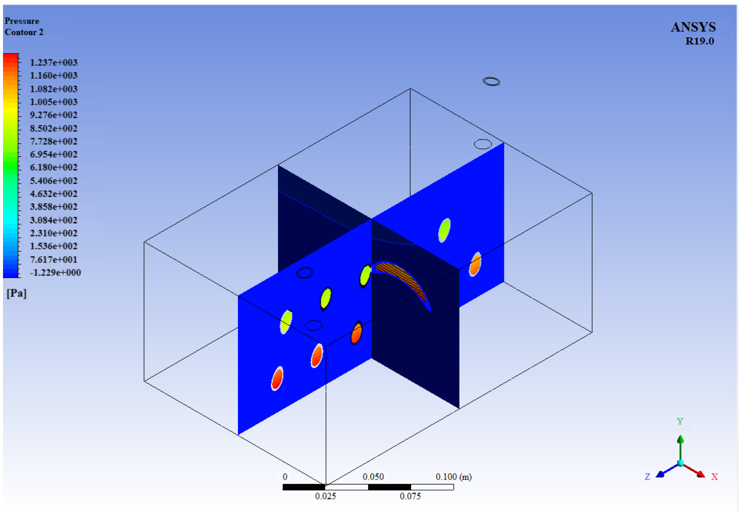

Figure 5. Pressure contours variation for 15 nozzles with air velocity 1.0 m/s

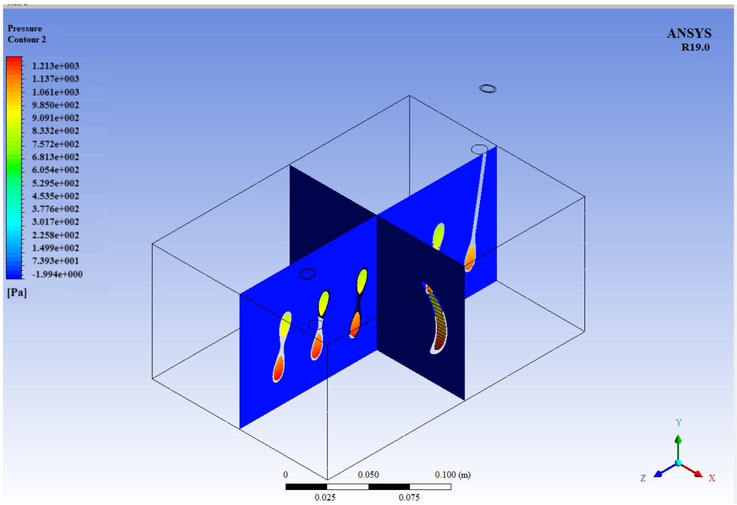

Figure 6. Pressure contours variation for 15 nozzles with air velocity 2.0 m/s

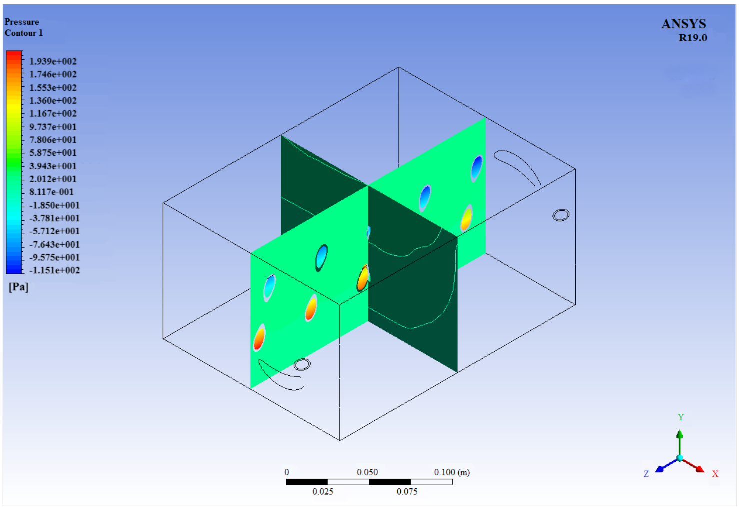

Figure 7. Pressure contours variation for 24 nozzles with air velocity 0.5 m/s

crucial to consider potential trade-offs, such as increased pressure drops and complex flow patterns, when optimizing the system structure.

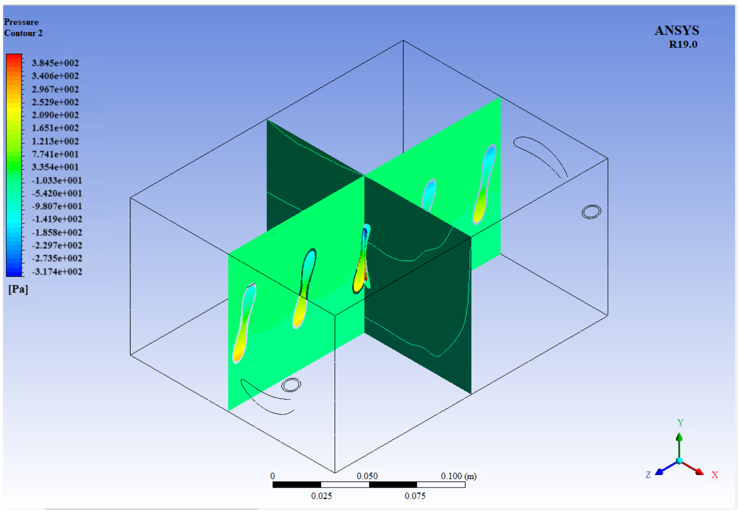

Figure 8. Pressure contours variation for 24 nozzles with air velocity 1.0 m/s

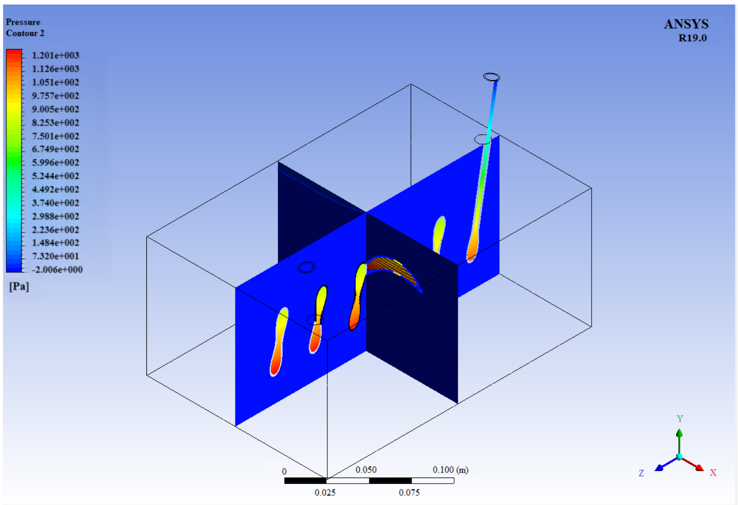

Figure 9. Pressure contours variation for 24 nozzles with air velocity 2.0 m/s

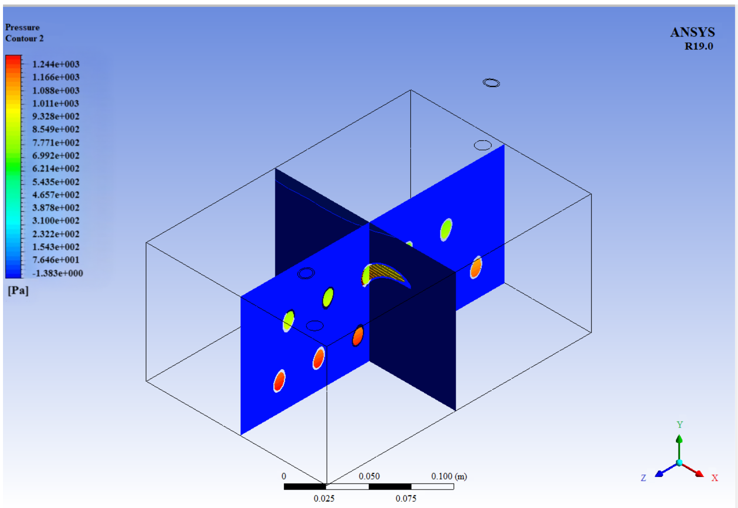

Figure 10. Pressure contours variation for 35 nozzles with air velocity 0.5 m/s

The results emphasize the importance of considering factors such as nozzle count and tube turns in the design of heat exchanger systems, as optimizing these parameters can achieve more uniform temperature distribution, enhance heat exchange efficiency, and improve overall system performance. These insights can inform the design and optimization of heat exchanger systems for various applications, including HVAC systems, industrial processes, and thermal management systems.

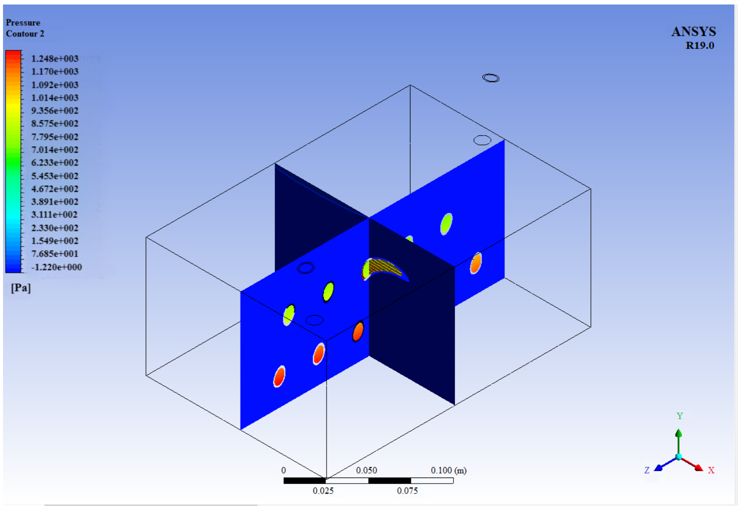

Figure 11. Pressure contours variation for 35 nozzles with air velocity 1.0 m/s

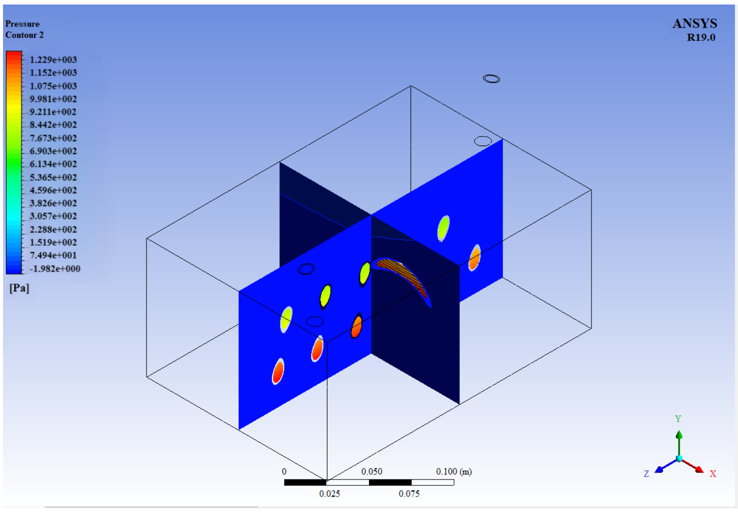

Figure 12. Pressure contours variation for 35 nozzles with air velocity 2.0 m/s

3.2 Temperature with Velocity

Figure 13 shows a growing temperature for three injectors, where the maximum coil turns are 9 at 15 injections and the three coils started at 0.5 m/s with various temperatures. The temperature rises with velocity until it peaks at 1 m/s.

Compared to the other figures, 13 coils reach above 53.5°C at 24 injections, whereas the maximum and lowest coil turns occur at 15 injections.

The analysis of three heat exchanger coils shows a relationship between temperature and velocity. The maximum number of coil turns is 9, and the injections vary between 15 coils. Each coil starts with a 0.5 m/s velocity, exhibiting distinct temperature profiles. As velocity increases, temperature also rises, reaching a peak at 1 m/s. This suggests an optimal velocity for maximum temperature attainment. Beyond this point, further increases may not result in significant temperature gains or diminish returns. This behavior is due to the interaction between fluid flow dynamics and heat transfer mechanisms. Lower velocities cause a lower temperature rise, while higher velocities force fluid to better contact surfaces, enhancing heat transfer and increasing temperature. However, further increases may lead to turbulence or other flow phenomena, limiting temperature gains. Understanding the relationship between velocity and temperature is crucial for optimizing heat exchanger performance and achieving desired temperature levels.

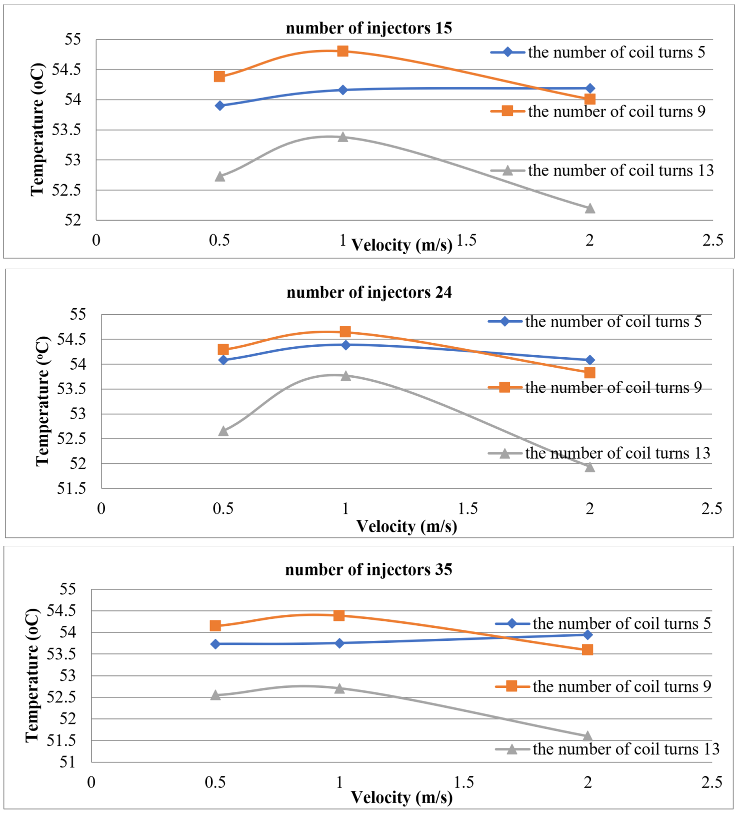

Figure 13. Number of coils turns with temperature

3.3 Influence of Air Velocity

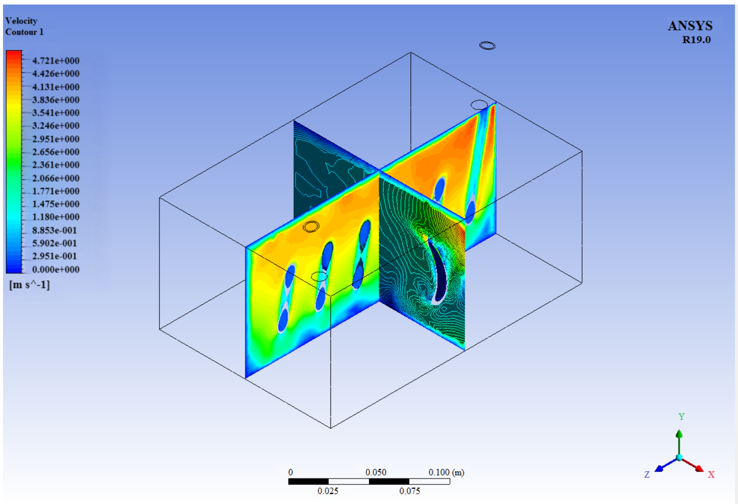

Figure 14. Velocity contours variation for 15 nozzles with air velocity 0.5 m/s

Figures 14 to 22 show how air velocity and nozzle injection affect velocity contours. Simulations showed a consistent system velocity distribution. The extended air residence time in the system allows for appropriate heat exchange with the cooling tubes. Various nozzle configurations affected velocity distribution. The velocity contour trended similarly. Heat exchange was efficient due to the system's continuous, laminar airflow at lower velocities. As air velocity rose and cooling tube interaction time decreased, a more turbulent flow pattern evolved, potentially reducing heat exchange efficiency. The velocity profile was also affected by nozzle quantity. Because air velocity was more evenly distributed with more nozzles, hotspots, and poor heat transmission were less likely. However, fewer nozzles caused air velocity to be less equal, which could limit heat exchange efficiency. These insights help improve system design by enhancing air and water distribution and heat transfer efficiency. The appropriate number of nozzles and air velocity may be determined using these velocity contours, making the system more energy-efficient.

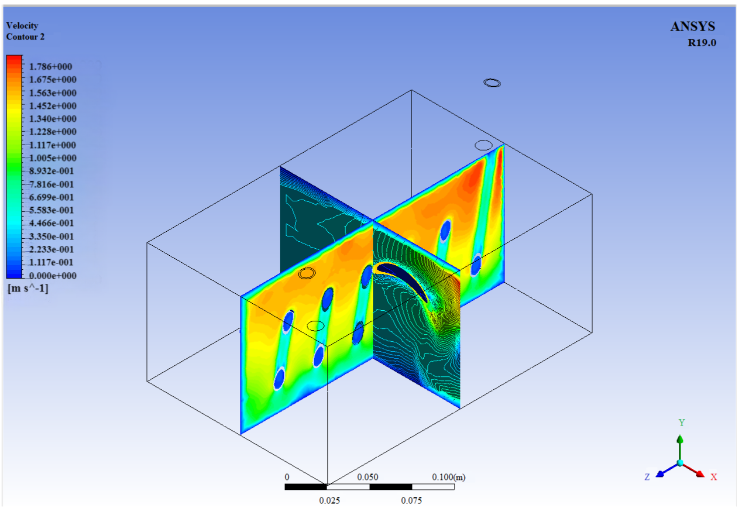

Figure 15. Velocity contours variation for 15 nozzles with air velocity 1 m/s

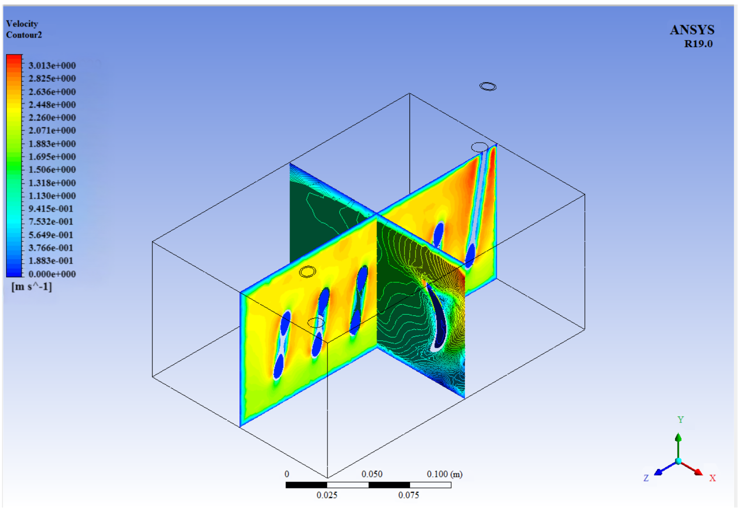

Figure 16. Velocity contours variation for 15 nozzles with air velocity 2 m/s

3.4 COP with Velocity

The performance coefficient is calculated at 15, 24, and 35 injections in the same coil turns. The three turns have larger values than others, as the best injection is 35. The max COP is 4.54 at 13 turns, while 9 turns increase above 4.35. 13 turns differ greatly from 9 and 5 turns, indicating that higher turns cause the coil to revolve faster and enhance COP.

From Figure 23, it can be determined that the maximum COP reaches approximately 4.54 after 13 turns, whereas it increases to over 4.35 after 9 turns. There is a significant difference between 13 and 9 and 5 turns, which indicates that as the number of turns increases, the coil rotates at a high rate, leading to an increase in COP.

4 Environmental Impacts of Implementing DEC Systems

DEC systems offer energy efficiency and reduced greenhouse gas emissions compared to traditional air conditioning methods. However, their widespread implementation may pose environmental challenges, particularly related to water usage.

Water consumption is a significant concern, as DEC systems rely on the evaporation of water to cool air, necessitating a constant supply of water for operation. In regions with scarce water resources or competing demands, increased usage could exacerbate water stress and impact local ecosystems. Therefore, it is crucial to evaluate DEC system water requirements and implement water-saving measures.

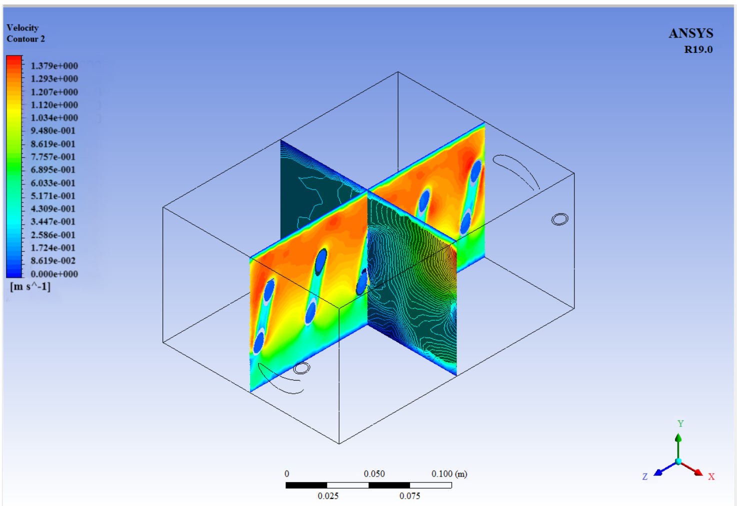

Figure 17. Velocity contours variation for 24 nozzles with air velocity 0.5 m/s

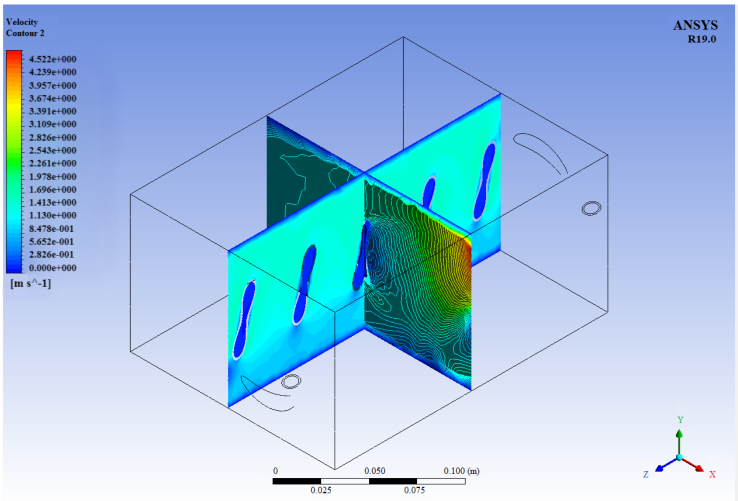

Figure 18. Velocity contours variation for 24 nozzles with air velocity 1 m/s

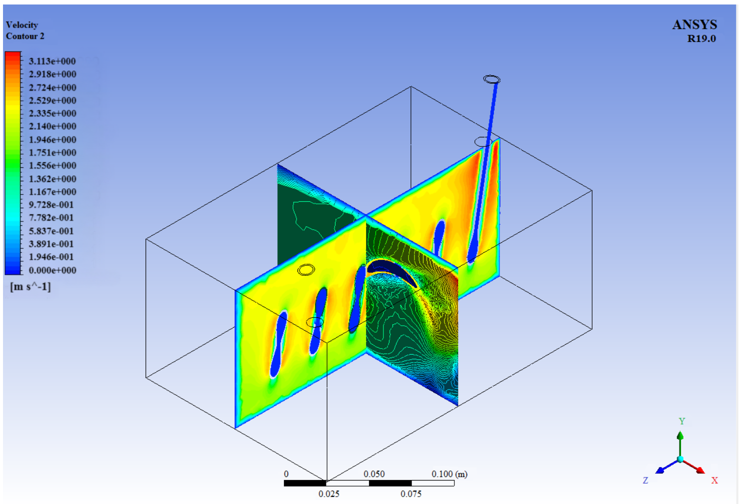

Figure 19. Velocity contours variation for 24 nozzles with air velocity 2 m/s

Water quality and treatment are also important factors in DEC systems. Poor or untreated water can lead to mineral buildup, reducing efficiency, and increasing maintenance requirements. Proper water treatment and management practices, including filtration, chemical treatment, and responsible wastewater disposal, are crucial to mitigating adverse environmental impacts.

The energy-water nexus is particularly relevant in DEC systems, as DEC technology can reduce energy consumption but indirectly increase water demand for evaporative cooling. Balancing these competing demands and optimizing resource utilization is essential for sustainable outcomes.

Climate change resilience is another challenge, as potential shifts in precipitation patterns may increase drought frequency and intensity in some regions. Designing DEC systems with resilience to climate change, such as by incorporating water-saving features, diversifying water sources, and exploring alternative cooling technologies, can enhance their long-term sustainability and adaptability in a changing climate.

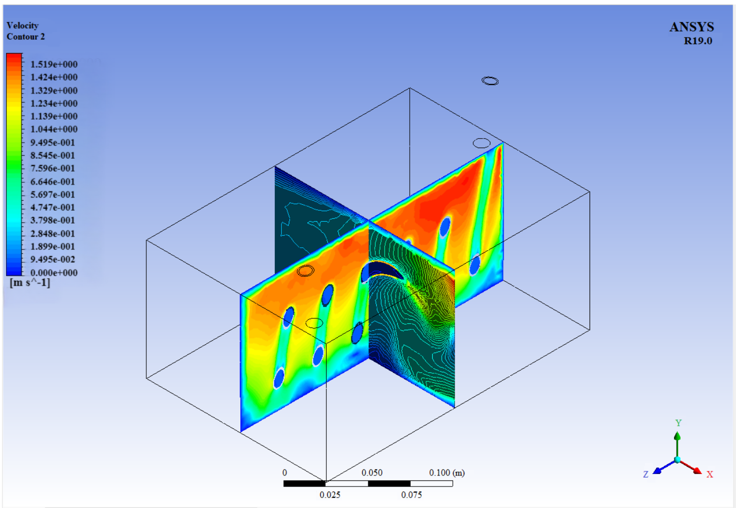

Figure 20. Velocity contours variation for 35 nozzles with air velocity 0.5 m/s

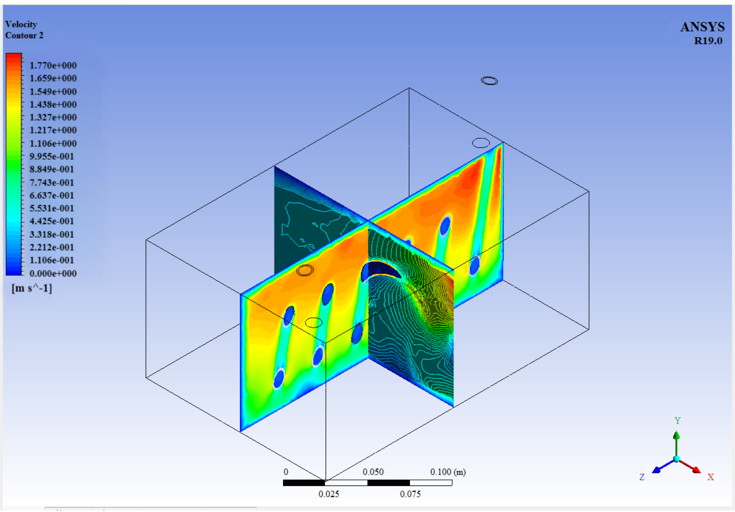

Figure 21. Velocity contours variation for 35 nozzles with air velocity 1 m/s

5 Economic Aspects of DEC Systems

DEC systems are a promising alternative to traditional air conditioning systems, offering significant energy savings and cost reductions. However, their economic viability is also crucial. Initial capital costs, such as equipment purchase, installation, and commissioning, are a primary economic factor influencing the adoption of DEC systems. A comprehensive cost analysis can provide insights into the relative affordability and payback period of DEC investments.

Operational and maintenance costs, such as electricity consumption, water usage, periodic maintenance, filter replacement, and repairs, are also essential. Estimating the lifecycle costs over their operational lifespan can help evaluate their long-term affordability and financial sustainability. Energy modeling and simulations can quantify

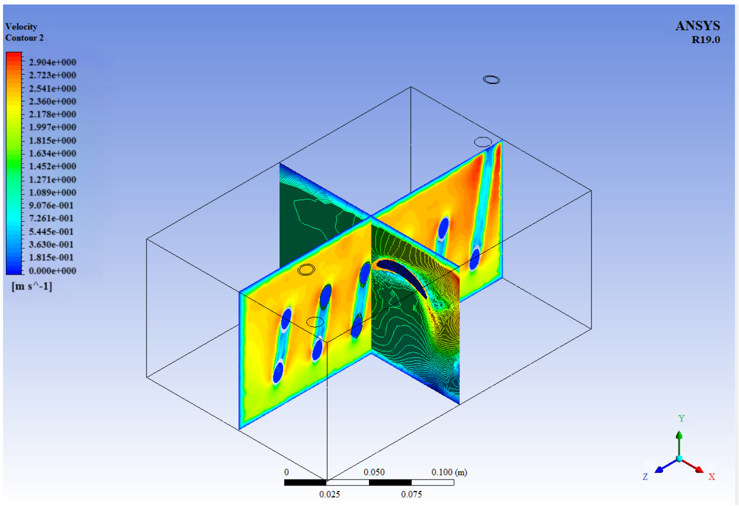

Figure 22. Velocity contours variation for 35 nozzles with air velocity 2 m/s

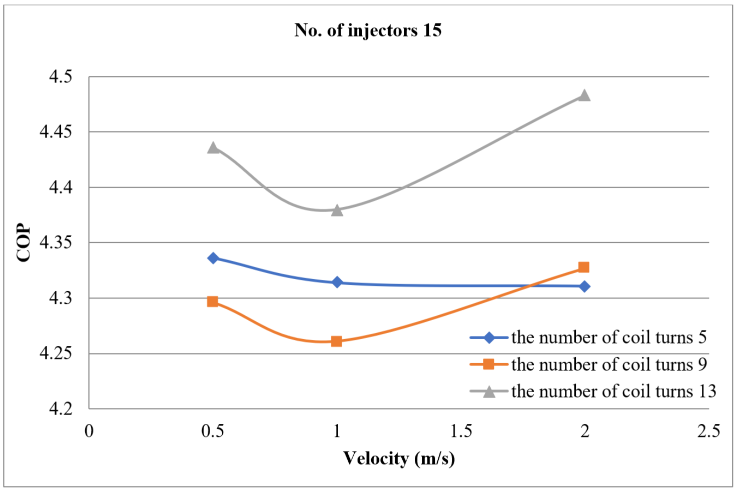

Figure 23. Number of coils turns with COP

these savings and corresponding cost reductions, while utility incentives or rebates can enhance the economic attractiveness of DEC investments.

A comprehensive cost-benefit analysis helps stakeholders evaluate the economic feasibility of DEC systems by comparing total costs with anticipated benefits, such as energy savings, reduced environmental impacts, and improved occupant comfort. Factors such as discount rates and project timelines can be considered to assess the overall economic viability of investing in DEC technology.

The return on investment (ROI) and payback period for DEC systems provide valuable financial metrics to assess the profitability and financial feasibility of investments. Shorter payback periods and higher ROI values indicate greater economic attractiveness and the potential for widespread adoption of DEC technology. By addressing these economic aspects and conducting rigorous cost-benefit analyses, stakeholders can gain a more comprehensive understanding of the feasibility and financial implications of implementing DEC systems in various applications and contexts.

6 Scalability Considerations for Improved DEC Systems

The scalability of DEC systems, particularly in high-temperature climates like Turkey and Iraq, is a critical factor to consider. This involves upgrading infrastructure to support increased water supply, distribution networks, and cooling equipment, as well as updating building codes and regulations to accommodate the installation of DEC systems in commercial, industrial, and residential buildings on a larger scale.

Water availability and sourcing are also significant challenges in scaling up DEC systems, especially in regions with limited water resources or competing demands. To mitigate these issues, water conservation measures, efficient water management practices, and alternative water sourcing strategies are essential.

Energy and environmental impacts of scaling up DEC systems include increased electricity consumption for water pumping and distribution, potential impacts on water quality, ecosystem health, and carbon emissions. Comprehensive lifecycle assessments and environmental impact analyses can help identify mitigation measures and optimize the sustainability of large-scale DEC deployments.

Economic feasibility and cost considerations depend on factors such as upfront capital costs, operational expenses, energy savings, and potential revenue streams. Cost-benefit analyses and financial modeling at scale can help assess the overall economic feasibility of large-scale DEC deployment and identify opportunities for cost optimization, financing mechanisms, and ROI strategies.

Technological innovation and integration play a crucial role in facilitating scalability and overcoming technical barriers to large-scale implementation. Innovations such as modular design, advanced controls, and smart sensors can enhance the performance, reliability, and flexibility of DEC systems, making them more adaptable to diverse applications and building types.

Stakeholder engagement and policy support are also essential for achieving scalability. Establishing supportive policies, incentives, and regulatory frameworks can encourage investment in DEC technology, streamline permitting processes, and facilitate knowledge sharing and capacity-building initiatives. Engaging with end-users, building owners, and facility managers can drive demand and accelerate market adoption.

7 Validation with Other Work

Polydisperse evaporating spray is hard to examine due to many physical reasons. Many CFD models have been used to study water spray systems' cooling efficacy, but few have examined their effects on heat exchangers. A unique and simple way to recreate polydisperse-evaporating sprays over complex 3D geometries is of great interest for industrial applications. This research creates the CFD numerical tool to study water spray's effects on heat exchangers and present a CFD water spray model. The spray model has two stages: spray creation and airflow dispersion. Between droplet injection and air velocity, the spray formation stage occurs. The droplet trajectory analysis gives this position and spray dimension, and the droplet size decrease equation gives the liquid water evaporated. The second stage of the 3D CFD program Code Saturne has boundary conditions in this initial portion. This CFD code solves spray Navier-Stokes equations using the k-e turbulence model. The three transient variables are the liquid potential temperature, L, the total water-specific humidity, qw, which is conservative for evaporation, and the droplet number, Nc. A source-term approach is utilized to add droplet evaporation to the NC calculation. The lognormal law was used to represent and track droplet spectra.

A good agreement exists between Raoult et al.'s Figure 24 and our Figure 25 [21].

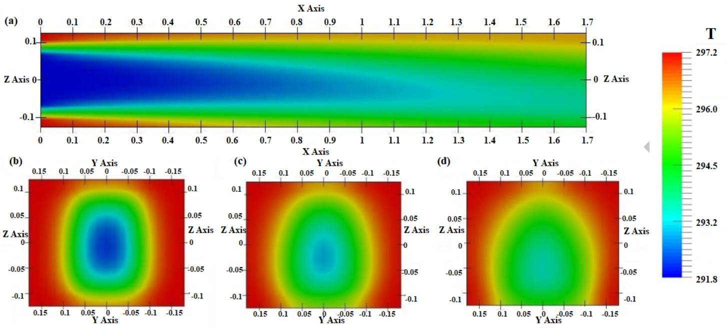

Figure 24. Air temperature field at y=0 m, x=0.5 m, x=1 m and x=1.5 m (Raoult et al.'s work) [21]

8 Conclusions and Recommendations

As this study on system geometry and coil-and-tube heat exchanger performance discusses, numerous significant observations and insights need summarizing. Analysis of complex geometrical arrangements using ANSYS' strong simulation capabilities was the research's main idea. The study simulated the complicated effects of coil turns and nozzles on system performance by carefully altering these factors. These geometrical features affect heat exchanger thermal dynamics and fluid flow, as shown by unique pressure and velocity contours. Therefore, system geometry, particularly the air entrance area and water spraying mechanism, is critical to heat exchange. This study has fundamental implications for heat exchanger layout and optimization. The results show that strategic geometrical parameter changes can improve the overall performance and efficiency of the system.

The conclusion includes these major points:

(1) System geometry, mainly air entrance and water spraying, influences heat exchanger thermal dynamics and fluid flow.

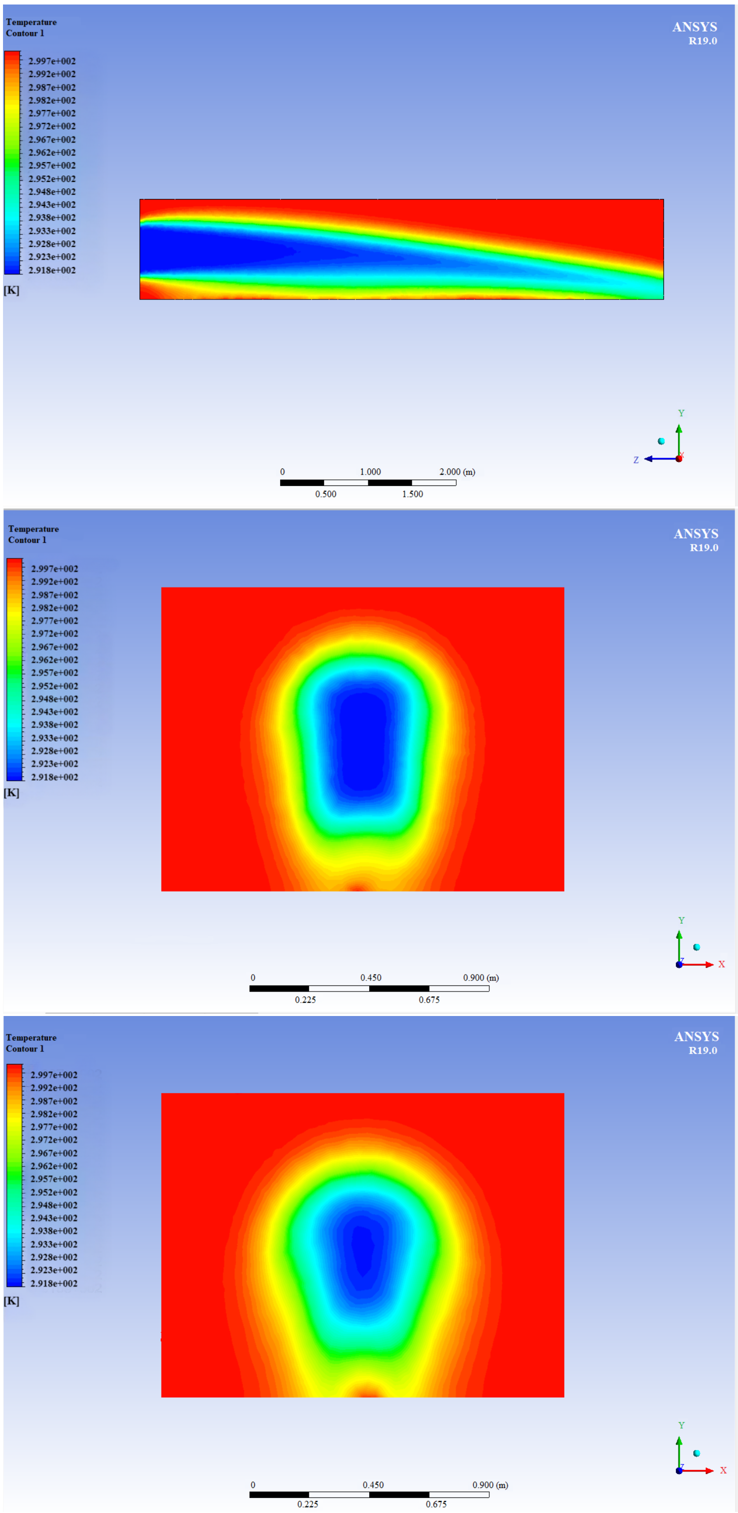

Figure 25. Air temperature field at y=0 m, x=0.5 m, x=1 m and x=1.5 m (our work)

(2) The number of coil turns and nozzles can significantly affect system performance, as seen via the pressure and velocity curves.

(3) The observer utilized ANSYS's powerful simulation abilities to address complex geometrical configurations and provide widespread insights.

(4) The high-quality configuration for the device has 35 injectors, thirteen coil turns, and a COP of 4.537 at 2.0 inlet velocity.

(5) The highest device COP is 4.537 at 35 injectors and thirteen coil turns.

The particular ANSYS simulation we have looked at indicates several methods to better recognize how gadget geometry impacts heat exchanger performance. These hints expand the findings' use and might resource future research.

(1) Research should enhance the coil turn and nozzle count parameters, making the tool extra effective.
(2) Expand the study to examine how fluids affect system performance.
(3) An analysis should be done on how duct size affects system heat exchange.
(4) Future studies should examine how geometrical differences affect transient system performance.
(5) Variations in pressure and geometrical changes may be worth studying.
(6) Simulation gives reliable insights, but real-world testing and validation are necessary for experimental application.

Several prior studies have investigated the effectiveness of DEC systems in various climatic conditions and building types. Our findings align with those of studies conducted in similar hot and arid regions, which have consistently demonstrated the ability of DEC systems to provide significant cooling while consuming less energy compared to traditional air conditioning methods [22, 23]. Furthermore, our observations regarding the environmental benefits of DEC systems, including reduced greenhouse gas emissions and lower reliance on high-GWP refrigerants, corroborate findings from previous research [24, 25]. However, it is important to note that the performance of DEC systems can vary depending on factors such as climate, building design, and system configuration, highlighting the need for region-specific assessments and optimization strategies.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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