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Performance Analysis of a Helical Tube Heat Exchanger Using Experimental and Simulation Methods

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Abstract

Heat exchangers are essential in various industrial applications, facilitating heat transfer between different mediums. Among these, helical tube heat exchangers are widely used due to their superior heat transfer efficiency and compact design. This study evaluates the performance of a helical tube heat exchanger comprising a copper tube with a 10 mm diameter and six helical turns. Hot water flows through the tube, while cold water circulates within the shell. Water is employed as the working fluid. A comparative analysis between experimental data sourced from literature and simulation results is conducted to validate performance outcomes. The simulation is performed using ANSYS software to model heat transfer characteristics and flow behavior. The results demonstrate key performance indicators and provide insights into optimizing heat exchanger designs for improved thermal efficiency. This work contributes to a deeper understanding of helical tube heat exchanger performance through a combination of experimental and numerical approaches.

Keywords: Helical tube heat exchanger, Heat transfer performance, ANSYS simulation, Comparative analysis, Thermal efficiency, Copper tube

1. Introduction

Heat exchangers are essential devices for transferring heat between fluids in various industrial applications, providing better energy efficiency and process control. Among the many types of heat exchangers, helical tube heat exchangers are notable for their compact design, improved heat transfer characteristics, and minimal space requirements. These heat exchangers feature one or more helically wound coils arranged in a circular configuration, with fluid flowing through headers. The helical design induces a swirling motion within the fluid, maintaining fully turbulent flow at lower velocities compared to straight-tube exchangers, which enhances heat transfer efficiency [1].

Helical tube heat exchangers offer numerous advantages over conventional designs, such as reduced fouling, lower wall resistance, and superior handling of thermal expansion and shock. Their increased surface area provides higher thermal efficiency in a smaller reactor volume. Key design parameters influencing their performance include the number of loops, coil pitch, coil orientation, and mass flow rate [2]. These heat exchangers are widely used in industries including power generation, space heating, nuclear reactors, and refrigeration systems.

Several researchers have analyzed the performance of helical heat exchangers. Bharathi [3] demonstrated the benefits of spiral heat exchangers with a helical angle of 30° over traditional parallel-flow designs. Khorshidi [4] used Gambit and Fluent software to simulate heat transfer, and explore the governing equations of thermal exchange. Kumar and Gupta [5] studied flow parameters such as pressure drop and temperature variations under different mass flow rates and coil diameters. Behara and Satapathy [6] applied ANSYS 13.0 to analyze counterflow effects, revealing improvements in heat transfer rates and Nusselt number distributions. These studies underline the importance of optimized designs for further enhancing performance.

In the present study, a helical tube heat exchanger is analyzed using both experimental data sourced from literature and numerical simulations performed in ANSYS software. The results aim to offer insights into improving heat exchanger efficiency and design optimization.

2. Methodology

2.1 Experimental Procedure

The experimental study focused on analyzing the performance of a helical tube heat exchanger. The heat exchanger was selected considering critical design parameters such as heat transfer rate, size, weight, and operating conditions. The heat transfer rate determines the amount of heat transferred per unit of time and is vital to achieve the desired temperature change at specified mass flow rates. A compact and lightweight heat exchanger is preferable for industrial applications, especially in the automotive and aerospace sectors, where space and weight constraints are significant. Additionally, design pressure and temperature influence material selection and wall thickness, with higher pressures necessitating thicker walls to withstand stress. For safety and performance, the high-pressure fluid was placed on the tube side [7].

The experimental setup consisted of a helical tube heat exchanger with six turns of copper tubing, each having a 10 mm diameter. Hot water flowed through the tube while cold water circulated within the shell. Temperature sensors and flow meters were installed to monitor inlet and outlet temperatures and flow rates for both fluids. Data was collected by recording the temperatures and adjusting the mass flow rates to evaluate performance. The heat transfer rate, Q, was determined using the equation:

$$Q=m\times Cp\times \Delta T \qquad (1)$$

where m is the mass flow rate, Cp is the specific heat capacity of water, and ΔT represents the temperature difference between inlet and outlet points. The experimental values provided a basis for validating the simulation results [8].

2.2 Simulation Procedure

The simulation of the helical tube heat exchanger was performed using ANSYS software. The process involved several stages:

- **Geometric Modeling**

A 3D model of the heat exchanger was developed using ANSYS Design Modeler. The geometry replicated the experimental setup, including tube diameter, coil turns, and shell configuration.

- **Meshing**

Tetrahedral elements were used for meshing the computational domain. A finer mesh was applied near the tube walls to capture boundary layer effects, improving the accuracy of temperature and velocity predictions [9].

- **Setup**

  - Material properties for copper (tube) and water (fluid) were defined.

  - Boundary conditions: Hot water inlet temperature and mass flow rate were set for the tube side, while the cold-water inlet was specified for the shell side. Pressure outlets were applied at the exits.

- **Solution**

The energy equation and turbulence models were solved iteratively using the Fluent solver. Convergence criteria were checked for velocity, pressure, and temperature residuals to ensure solution accuracy [10 -11].

- **Post-Processing**

Results, including temperature contours, velocity fields, and heat transfer rates, were analyzed. The simulation results were compared to experimental data to assess the accuracy and reliability of the computational model.

2.2.1 Geometrical Modeling

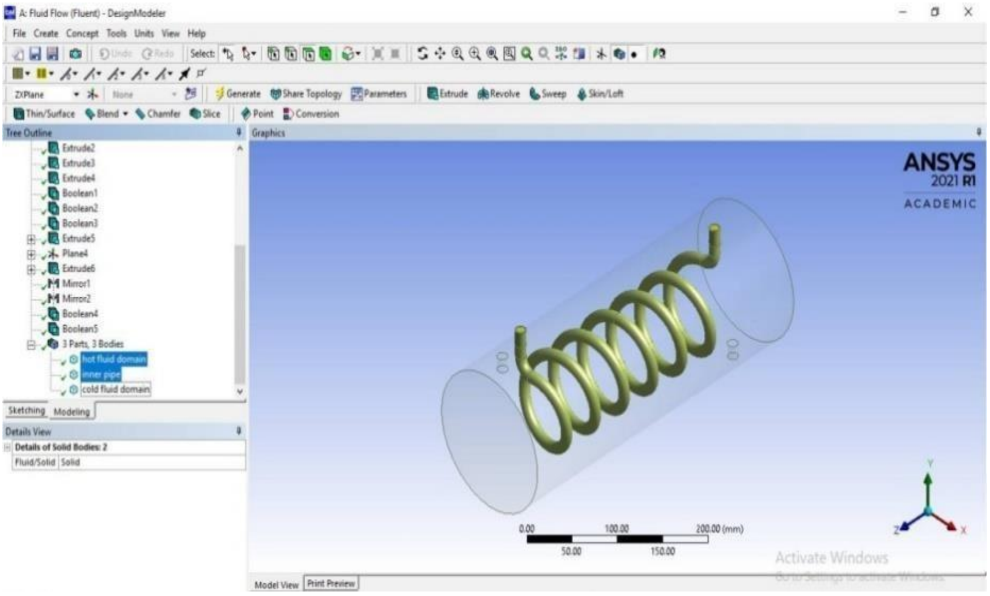
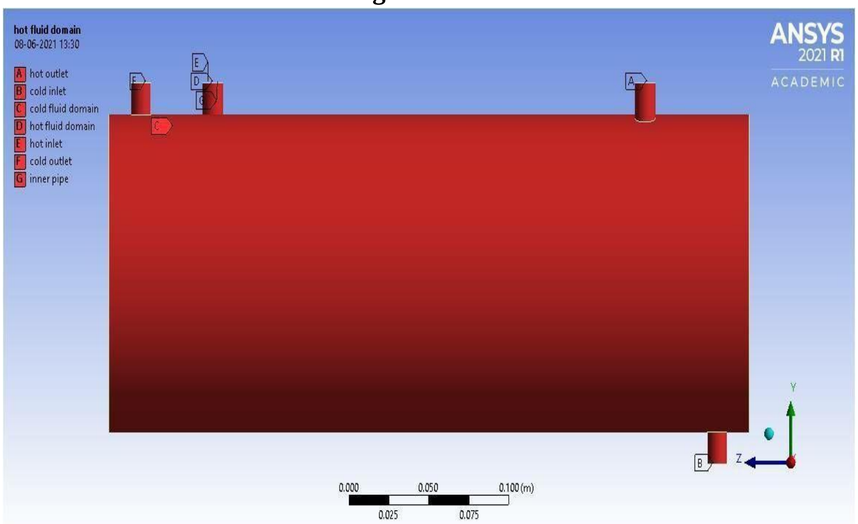


Figure: 1 3D Geometric model of shell and helical tube.

In this research, the geometry for the fluid flow simulation was constructed using ANSYS Workbench, which provided an integrated environment for model development, meshing, and analysis [12]. The process began by selecting the fluid flow module within Workbench, thereby configuring the simulation workflow from the outset. Double-clicking the Geometry cell launched ANSYS Design Modeler, where a series of systematic operations were performed to create the model. Initially, precise two-dimensional sketches were generated on predefined work planes; these sketches-constrained with appropriate dimensions and relationships- formed the fundamental profiles for the design [13]. The next step involved a sweeping operation, in which the 2D profiles were extruded along specified paths to create three-dimensional solids that accurately represent the physical fluid domain [14]. Finally, a merging operation was executed to combine individual bodies and eliminate overlapping surfaces, ensuring a cohesive, error-free geometry. This comprehensive geometric modeling approach not only facilitated the generation of a high-quality mesh but also established a robust foundation for subsequent fluid flow analysis.

2.2.2 Meshing

Figure: 2 Mesh Generation



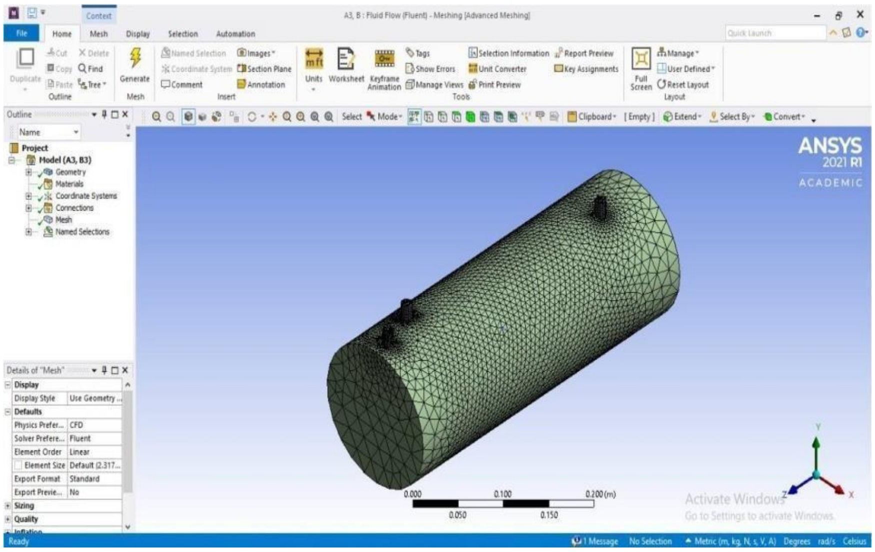


Figure: 3 Naming of inlet and outlet

Creating an effective mesh is a critical step in the simulation process as it partitions the computational domain into a discrete number of elements, within which the governing equations are numerically solved. The mesh configuration significantly influences the accuracy, convergence, and computational speed of the solution [12]. Initially, a free meshing strategy is applied to generate a relatively coarser mesh comprising both tetrahedral and hexahedral cells, with triangular and quadrilateral faces forming the boundaries. This preliminary mesh provides a general discretization of the domain; however, its resolution may be insufficient for capturing intricate variations in regions with steep gradients. To address this, edge sizing is later employed to create a fine mesh, particularly along edges and in regions where high pressure and temperature gradients occur. This refinement ensures that the numerical solution accurately captures localized phenomena, thereby enhancing both the convergence behavior and the fidelity of the obtained results [15-16]. Furthermore, overall mesh quality-including element shape, skewness, and aspect ratio is essential, as poor mesh quality can adversely affect both convergence and the reliability of the simulation outcomes.

2.2.3 CFD Analysis of Shell and Helical Tube Heat Exchanger

Table 1: Design parameters and dimensions of heat exchanger components

Type of Heat Exchanger	Design Parameter	Dimensions (mm)
Shell	Outer diameter of shell (d)	150
	Thickness (t)	1.2
	Length of shell (L)	400
Helical Tube	Diameter of inner tube (di)	10
	Diameter of outer tube (do)	12.7
	Number of turns on the tube (N)	6
	Pitch of helical tube (P)	45

	Outside diameter of coil (D)	100

Table 2: Flow Parameters for Heat Exchanger

Flow Parameter	Value	Unit
Inlet temperature of hot fluid (Thi)	358	K
Inlet temperature of cold fluid (Tci)	298	K
Outlet temperature of hot fluid (Tho)	328	K
Outlet temperature of cold fluid (Tco)	315	K
Specific heat of hot and cold fluid (water) (Cw)	4200	J/kg·K
Mass flow rate of hot fluid (mh)	0.0169	kg/s
Mass flow rate of cold fluid (mc)	0.019	kg/s

2.2.4 Shell and Helical Tube Experimental Calculation

Below is the text formatted in a style suitable for inclusion in a Microsoft Word document as a research paper section. You can copy and paste this text directly into your MS Word file and adjust the formatting (font, spacing, heading styles) as needed.

3. Results and Discussion

In this research, the thermal performance of the heat exchanger was evaluated through the determination of several key parameters, including the heat transfer rates, the logarithmic mean temperature difference (LMTD), the overall heat transfer coefficient, and the exchanger effectiveness. The hot fluid enters the heat exchanger at an inlet temperature (Thi) of 358 K and leaves at an outlet temperature (Tho) of 328 K, while the cold fluid enters at 298 K (Tci) and exits at 315 K (Tco).

The heat transfer rate for the hot water stream is calculated using the relation:

$$Q_h = m_h \times C_w \times \left(T_{\{hi\}} - T_{\{ho\}}\right) \tag{1}$$

where the mass flow rate of the hot fluid $m_h = 0.0169 \frac{kg}{s}$ and the specific heat capacity of water $C_w = 4200 \frac{J}{kg \cdot K}$ Substituting the values:

$$Q_h = 0.0169 \times 4200 \times (358 - 328) = 2129.4\, W \tag{2}$$

Similarly, the heat transfer rate for the cold-water stream is determined by

$$Q_c = m_c \times C_w \times \left(T_{\{co\}} - T_{\{ci\}}\right) \tag{3}$$

with the mass flow rate of the cold fluid mc= $0.019 \frac{kg}{s}$

$Q_c = 0.019 \times 4200 \times (315 - 298) = 1356.6\, W$

To quantify the driving force for heat transfer, the logarithmic mean temperature difference (LMTD) was computed as follows:

$$\Delta T = \frac{\{(T_{\{hi\}} - T_{\{co\}}) - (T_{\{ci\}} - T_{\{ho\}})\}}{ln\frac{\{T_{\{hi\}} - T_{\{co\}}\}}{\{T_{\{hi\}} - T_{\{co\}}\}}} = 36.11K \quad (4)$$

The overall heat transfer coefficient (U) was then determined using the equation:

$$U = \frac{Q_h}{A_s \times \Delta T} \quad (5)$$

where the effective heat transfer surface area As is estimated from the geometry (for example, ($A_s = \pi \times 0.14744\,\text{m} \times 0.27\,\text{m}$). This calculation yielded an overall heat transfer coefficient of approximately:

$$U = 469.38\,\frac{w}{\text{m}^2 K}$$

Furthermore, the effectiveness (ε)of the heat exchanger was evaluated. The heat capacity rates for the cold and hot streams are determined as:

$$C_c = m_c \times C_w = 0.019 \times 4200 = 79.8\frac{w}{k} \quad (6)$$

$$C_h = m_h \times C_w = 0.0169 \times 4200 = 70.98\,\frac{w}{k}$$

$Since(C_c > C_h), the\ effectiveness\ is\ computed\ by$:

$$\varepsilon = \frac{T_{hi} - T_{ho}}{T_{hi} - T_{ci}} = \frac{358 - 328}{358 - 298} = \frac{30}{60} = 0.5 \quad (7)$$

These results indicate that the hot stream releases approximately 2129.4 W of energy, while the cold stream absorbs 1356.6 W. The computed LMTD and overall heat transfer coefficient further confirm the efficiency of the thermal design, and an effectiveness of 0.5 suggests that there is potential for further optimization of the heat exchanger design.

In order to investigate the influence of inlet temperature variations on the thermal performance of a shell and helical tube heat exchanger, a series of simulations were conducted using ANSYS 2021 R1. For this study, all design parameters including geometry, fluid properties, and especially the mass flow rate were maintained constant to ensure that any performance differences could be solely attributed to changes in the inlet temperatures. Specifically, the inlet temperatures on both the shell side and the tube side were varied in increments of 10°C. This parametric variation allowed for a systematic analysis of the exchanger's response, focusing on key performance indicators such as the overall heat transfer coefficient, temperature distributions, and thermal efficiency. The use of ANSYS 2021 R1, with its advanced meshing techniques and robust numerical solvers, ensured high-fidelity simulation results and reliable convergence. The outcomes of this investigation provide critical insights into how small variations in inlet temperature can affect the heat transfer performance, thereby offering guidance for the design optimization and operational control of heat exchangers in practical applications [14].

Table: 3 Software results for constant mass flow rate

Parameters	Trial 1 Hot fluid inlet = 65°C Cold fluid inlet =15°C	Trial 2 Hot fluid inlet = 75°C Cold fluid inlet = 20°C	Trial 3 Hot fluid inlet = 85°C Cold fluid inlet =25°C

Mass flow rate of hot fluid (m_a)	0.0169 Kg/s		
Mass flow rate of cold fluid (m_c)	0.019 Kg/s		
Inlet temperature of hot fluid (T_{hi})	338 K	348 K	358 K
Inlet temperature of cold fluid (T_{ci})	288K	293 K	298 K
outlet temperature of hot fluid (T_{ho})	310.91 K	318.19 K	325.46 K
outlet temperature of cold fluid (T_{co})	308.65 K	315.70 K	322.75 K
Temp difference of hot fluid (ΔT_h)	27.09 K	29.81 K	32.54 K
Temp difference of cold fluid (ΔT_c)	20.65 K	22.7 K	24.75 K
LMTD (ΔT)	25.98 K	28.58 K	31.18 K
Heat transfer rate (Q_h)	1933.15 W	2126.46 W	2319.78 W
Overall Heat transfer co-efficient	592.18 W/m^2 K	592.18 W/m^2 K	592.17 W/m^2 K
Effectiveness of heat exchanger	0.5418	0.5420	0.5447

the thermal performance of a shell and helical tube heat exchanger was systematically evaluated under constant inlet fluid temperature conditions while varying the mass flow rates of both the shell and tube sides. Using ANSYS 2021 R1, simulations were conducted with identical design parameters across all cases to isolate the effect of mass flow rate on the exchanger's performance. By keeping the inlet temperatures constant, any observed changes in heat transfer characteristics—such as the overall heat transfer coefficient, heat transfer rate, and exchanger effectiveness—could be directly attributed to variations in the mass flow rates. This approach allowed for a detailed analysis of how increased or decreased fluid velocities influence the thermal boundary layer development and overall energy transfer efficiency, providing critical insights into the optimization of operating conditions for improved heat exchanger performance in industrial applications.

Table: 4 Software results for constant inlet temperature of hot and cold fluid

Parameters	Trial 1	Trial 2	Trial 3
Inlet temperature of hot fluid (Thi)	353 K (80ºC)		
Inlet temperature of cold fluid (Tci)	293 K (20ºC)		
Mass flow rate of hot fluid (ma)	0.0275	0.0291	0.0326
Mass flow rate of cold fluid (mc)	0.1239	0.1771	0.2173

Inlet pressure in shell side	1000 Pa	2000 Pa	3000 Pa
Inlet pressure in tube side	600 Pa	800 Pa	1000 Pa
outlet temperature of hot fluid (Tho)	317.73 K	317.70 K	317.67 K
outlet temperature of cold fluid (Tco)	315.22 K	316.48 K	317.75 K
Temp difference of hot fluid (ΔTh)	35.42 K	35.45 K	35.47 K
Temp difference of cold fluid (ΔTc)	22.07 K	23.48 K	24.60 K
LMTD (ΔT)	30.74 K	30.20 K	29.62 K
Heat transfer rate (Qh)	4101.07 W	4340.26 W	4870.74 W
Overall Heat transfer co-efficient	1061.91 W/m^2 K	1166 W/m^2 K	1308.57 W/m^2 K
Effectiveness of heat exchanger	0.5903	0.5908	0.5913

4. RESULTS AND DISCUSSION

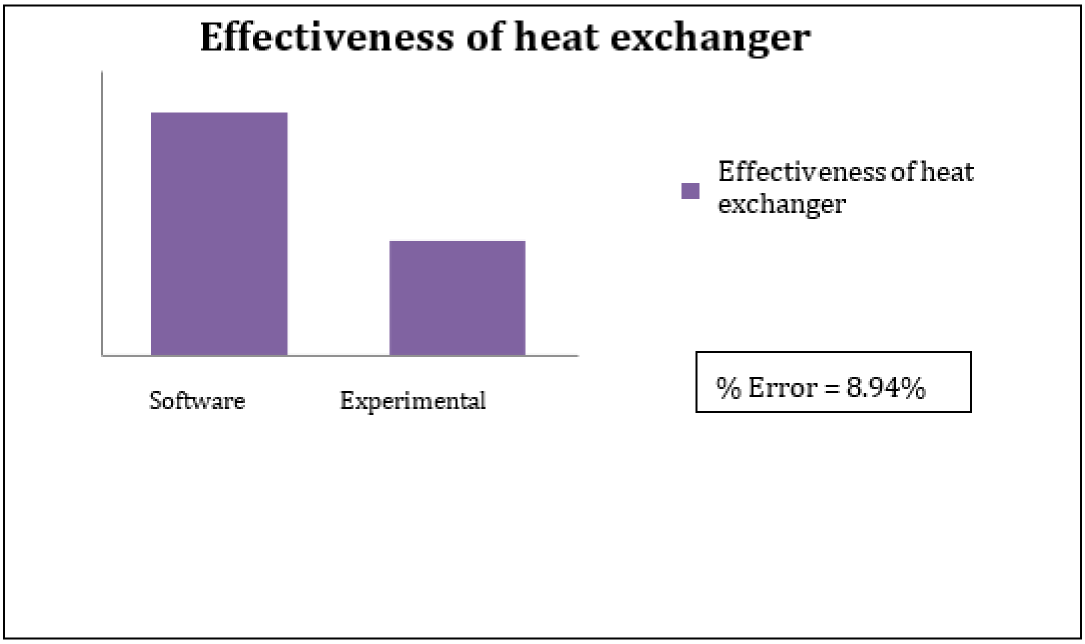
4.1 Comparing Experimental Results V/S Software Results

Table 5: Comparison of software and experimental results

SL. No	Parameters	Software Results	Experimental results	Difference
1	Outlet temperature of hot fluid (T_{ho})	325.46 K	328 K	2.54 K
2	Outlet temperature of cold fluid (T_{co})	322.75 K	315 K	7.75 K
3	LMTD	31.18 K	36.11 K	4.93 K
4	Heat transfer rate of hot water	2319.78 W	2129.4 W	190.38
5	Heat transfer rate of cold water	1963.60 W	1356.6 W	W 607 W
6	Heat transfers co-efficient	592.179 W /m^2 K	469.38 W/m^2 K	122.79 W/m^2 K
7	Effectiveness of heat exchanger	0.5447	0.50	0.0447

The effectiveness difference between experimental and software results was 8.94%, which is within an acceptable range of simulation accuracy.

Influence of Inlet Temperature and Mass Flow Rate, Constant mass flow rate, varying temperature: When inlet temperatures were increased by 10°C increments, effectiveness values from ANSYS simulations ranged between 0.5418 to 0.5447, indicating a moderate improvement in heat transfer efficiency. Constant inlet temperature, varying mass flow rate:
By varying mass flow rates while keeping inlet temperatures fixed, effectiveness values increased from 0.5903 to 0.5913, demonstrating that higher flow rates improve thermal performance.



5. CONCLUSION

This study evaluated the performance of a helical tube heat exchanger using both experimental measurements and numerical simulations. The key findings include:

- The heat exchanger demonstrated an effectiveness of **0.50** in experiments and **0.5447** in simulations, with a **8.94% error margin** between the two methods.
- The **overall heat transfer coefficient** was found to be **469.38 W/m²K** experimentally and **592.17 W/m²K** via simulation, with minor discrepancies attributed to computational assumptions.
- Increasing the **temperature difference** between hot and cold fluids improved effectiveness.
- Raising **mass flow rates** led to higher heat exchanger effectiveness, confirming the influence of velocity on thermal performance.

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