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Numerical Investigation and Optimization of Heat transfer and Exergy Loss in Geometrically Modified Tube Heat Exchangers Using Nanofluids

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ABSTRACT

This study numerically investigates the thermal and energy performance of double helical and conical coil heat exchangers using CFD simulations under turbulent flow conditions. The analysis focuses on optimizing key design parameters—coil geometry, coil pitch (16 mm and 20 mm), and hot and cold flow rates (1.5 to 6 LPM)—while evaluating the impact of different working fluids: water, 0.4% CuO, 0.4% Al_2O_3, and 0.4% Fe_2O_3 nanofluids. The Taguchi method (L_{16} orthogonal array) was employed to identify optimal parameter combinations for maximizing heat transfer and minimizing exergy loss across 16 simulation cases. Simulation results revealed that Nusselt number increases with both cold rates, particularly for Al_2O_3 nanofluid, which demonstrated the highest heat transfer performance. In contrast, exergy loss increases with increasing cold flow rate, while water exhibits the lowest and most stable exergy loss across flow conditions. Additionally, increasing coil pitch was found to reduce the heat transfer coefficient, especially in helical configurations. The Taguchi analysis identified that: The optimum combination for maximum heat transfer is a conical coil with 16 mm pitch, 0.4% Al_2O_3 nanofluid, cold flow rate 6 LPM, and hot flow rate 1.5 LPM. The optimum condition for minimizing exergy loss is a conical coil with 16 mm pitch, water, and both cold and hot flow rates at 1.5 LPM. This study provides a comprehensive framework for enhancing the design of compact coil heat exchangers for energy-efficient applications.

Keywords: Turbulent Flow, Helical, Conical, Energy Loss

1. Introduction

Heat exchangers are essential components in an extensive range of industrial and engineering systems, facilitating efficient energy transfer between two fluids at different temperatures. From power generation and refrigeration to automotive and chemical processing industries, heat exchanger performance and design have a significant impact on energy efficiency, system reliability, and operating cost. [1-2]

Alimoradi et al. [3] numerically studied heat transfer coefficients in helically coiled tube and shell heat exchangers. The most important geometrical and operational parameters were considered, including coil size, temperatures, velocities, and fluid properties. They concluded that Overall heat transfer is enhanced by bigger coil diameters, but shell-side Nusselt numbers are considerably lowered by bigger shell dimensions. Celik et al. [4] optimized the performance of a concentric pipe heat exchange using experimental methods, Taguchi design, and grey relational analysis. The parameters Reynolds number, tape width, pitch, and thickness were considered. Heat transmission was found to be greatly influenced by Reynolds number and tape width, and friction factor by thickness, based on the results. Majid Etghani et al. [5] used the Taguchi approach and numerical simulations to study heat transfer and exergy loss optimization in shell and helically coiled tube heat exchangers. The important variables that have a strong effect on heat transmission and energy performance are pitch coil, tube diameter, and flow rates. They concluded that smaller coil pitches improve exergy efficiency, while larger tube diameters improve heat transfer. Zeinali et al [6] reported an energy, exergy, and economic analysis of spiral coil heat exchangers, focusing particularly on the influence of geometric parameters. They demonstrated that irreversibility is largely accountable to thermal transfer. They also established that the efficiency of the coils decreased by 4% with the rise in coil pitch, and the efficiency of the coils decreased by 19% for larger radii.

Kashani et al. [7] applies numerical simulations (ANSYS Fluent) and experimental experiments to achieve highest heat transfer in a helically coiled pipe with water–Fe_3O_4 nanofluid. Taguchi method is employed to examine three control factors on four levels (mass flow rate, coil curvature ratio, and fluid type). The optimum conditions for highest efficiency (η) were: Mass flow rate of 6.98 g/s,1% nanofluid by volume, Coil curvature ratio of 0.048. Tang et al. [8] investigated the influence of various parameters of vortex generators location, attack angle, and height—on heat transfer (Nusselt number) and flow friction for a fin-and-tube heat exchanger. By using a Taguchi-designed set of 16 model variations, it was determined that reducing the location and attack angle of the generator and increasing its

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height considerably enhances heat transfer but at increased pressure drop. The study properly identifies optimal geometries.

This research aims to make a numerical investigation of double conical and double helical coil heat exchanger performance by analyzing the effects of different kinds of nanofluids with the same volume concentration and geometrical parameters. The goal is to identify the optimum geometrical configurations and nanofluids by Taguchi method that can result in improved heat transfer and energy efficiency, and improve the performance of the coiled heat exchanger.

2. GOVERNING EQUATIONS AND BOUNDARY CONDITIONS

The numerical simulations have been carried out under steady-state conditions using a pressure-based solver. The working fluid is treated as incompressible with constant thermophysical properties. The flow has been assumed to be turbulent, three-dimensional, and steady in nature. To account for turbulence effects, the realizable k–ε model with enhanced wall treatment has been adopted, as it is well suited for predicting swirling and recirculating flows in coiled heat exchanger geometries. The governing equations of mass conservation (continuity), momentum, and energy, as applied to the helical tube, are expressed as follows

$$\frac{\partial p}{\partial t} + \frac{\partial pU_1}{\partial x_1} + \frac{\partial pU_2}{\partial x_2} + \frac{\partial pU_3}{\partial x_3} = 0 \ldots \ldots (1)$$

$$\mathrm{p}\left(u\frac{\partial U}{\partial x} + v\frac{\partial V}{\partial x}\right) = -\mathrm{p}g - \frac{\partial p}{\partial x} + \mu\frac{\partial^2 y}{\partial x^2} \ldots \ldots (2)$$

$$\mathrm{p}C_p\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = k\frac{\partial^2 T}{\partial y^2} \ldots \ldots (3)$$

Total exergy loss of hot and cold fluid [9]:

$$E = E_h + E_c \ldots \ldots (4)$$

And

$$\dot{E}_{x,loss} = T_{environmet}[\dot{m}_h C_{ph} \ln(T_{h,out}/T_{h,in}) + \dot{m}_c C_{pc} \ln(T_{C,out}/T_{c,in})] \ldots \ldots (5)$$

Nusselt number, $N_u\,(nf) = \frac{h_i * d_i}{K_c} \ldots \ldots$ (6)

In this study, water and water nanofluids with a volume concentration of 0.4% have been employed as the working fluids. The inner coil has been operated with mass flow rates ranging from 1.5 LPM to 6 LPM, while the initial inlet temperature of the inner tube has been maintained at 305 K. The same water or nanofluid has flowed through both the inner and outer coils to ensure uniformity of working fluid conditions. Correspondingly, the outer coil has been subjected to the same mass flow rate range of 1.5 LPM to 6 LPM, with an initial inlet temperature of 337 K. The flow velocity within both the inner and outer tubes has been varied between 0.93 m/s and 2.72 am/s to capture a wide range of hydrodynamic conditions. These boundary conditions have been adopted to investigate the influence of nanofluid flow and thermal parameters on the heat transfer and exergy performance of the tube-in-tube heat exchanger.

3. NUMERICAL MODELLING

In this study, four different coil geometries were designed using ANSYS 2022 R1 Design Modeler to evaluate the thermal–hydraulic and exergy performances of tube-in-tube heat exchangers. Two of the models were double helical coils, while the other two were double conical coils, allowing a comparative analysis between geometric configurations. For all models, the inner tube was designed with an inside diameter of 5.85 mm and an outside diameter of 6.35 mm, whereas the outer tube was designed with an inside diameter of 12 mm and an outside diameter of 12.7 mm. The first helical model was constructed with a 16 mm pitch, consisting of 15 turns, a mean coil diameter of 100 mm, and a total coil length of 240 mm. The second helical model was created with the same number of turns but a 20 mm pitch, resulting in an increased total length of 300 mm.

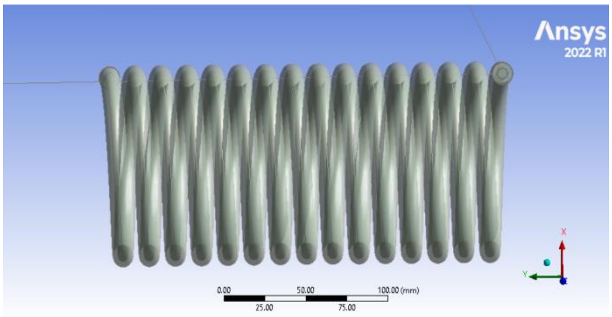

Fig. 1: Double helical geometry in Design Modeler (16mm pitch)

For the conical designs, the larger coil diameter was set to 150 mm, whereas the smaller coil diameter was set to 50 mm, resulting in a gradual conical taper along the flow direction. These four geometrical configurations were employed as the basis for the numerical simulations, which were conducted to investigate the influence of coil geometry on heat transfer and exergy performance.

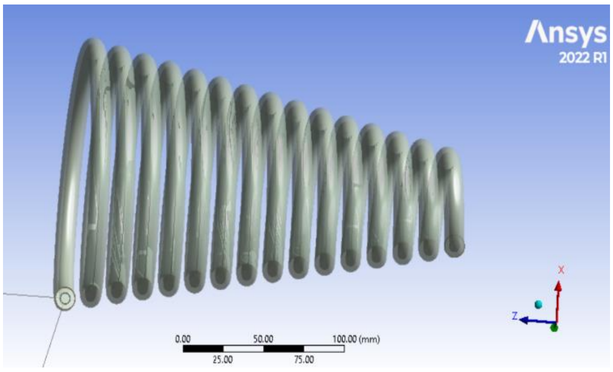

Fig. 2: Double conical geometry in Design Modeler (16mm pitch)

3.1 Taguchi method

In my thesis, applying the S/N ratio helps identify the best combination of coil shape, nanofluid type, and flow rates that result in minimum exergy loss and maximum heat transfer efficiency. When the goal is to minimize a response variable, such as exergy loss, the "smaller-the-better" S/N ratio is used. Conversely, to maximize responses like Nusselt number or heat transfer coefficient, the "larger-the-better" formula is appropriate. These formulations were originally proposed by Genichi Taguchi and are widely adopted in robust design analysis (Taguchi, 1987; Ross, 1996). [10,11]

Smaller-the-Better S/N Ratio (for minimizing responses like exergy loss):

$$SN_s = -10Log\left(\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right)$$

Larger-the-Better S/N Ratio (for maximizing responses like Nusselt number):

$$SN_L = -10Log(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2})$$

Table 1: The levels and factors

code	Control Factors	Level 1	Level 2	Level 3	Level 4
A	Pitch coil	16mm (Helical)	20mm (helical)	16mm (Conical)	20mm (Conical)
B	Water or nanofluids	H_2O	0.4%CuO	0.4%Al_2O_3	0.4%Fe_2O_3
C	Cold flow rate	1.5 LPM	3 LPM	4.5LPM	6 LPM
D	Hot flow rate	1.5LPM	3 LPM	4.5LPM	6 LPM

Table 2: L16 orthogonal arrays

Simulations Runs	Coil and pitch	fluids	Cold flow rate	Hot flow rate
1	1	1	2	3
2	1	2	3	1
3	1	3	1	4
4	1	4	4	2
5	2	1	1	2
6	2	2	2	4
7	2	3	4	3
8	2	4	3	1
9	3	1	4	1
10	3	2	1	3
11	3	3	3	2
12	3	4	2	4
13	4	1	3	4
14	4	2	4	2
15	4	3	2	1
16	4	4	1	3

In this study, a total of 16 simulations were performed, and the Taguchi method was applied to identify the optimal set of parameters, thereby reducing the total number of required simulations from 256 to 16.

4. RESULTS AND DISCUSSION

In this study, heat transfer and exergy loss in modified double helical and double conical tube heat exchangers were investigated using water and nanofluids as working fluids. The design and operating parameters, including geometry, flow rates, and fluid type, were optimized through the Taguchi method. Furthermore, the significant parameters influencing heat transfer and exergy loss were identified and analyzed to determine their relative importance.

4.1 Nusselt Number vs. Cold Flow Rate for Different Coil Configurations

This graph compares how the Nusselt number (Nu) varies with increasing cold flow rate across four coil configurations: helical 16 mm, helical 20 mm, conical 16 mm, and conical 20 mm. Higher flow improves convective heat transmission in all geometries, as seen by the Nu values' steady increase with flow rate. Conical 16 mm is one of them; it constantly exhibits competitive Nu values, frequently surpassing or equal the helical forms. This implies that compact conical shapes improve surface renewal and secondary flow, which raises thermal performance. Differences become more noticeable at high flow rates, with conical 16 mm frequently reaching the maximum performance zone. At most sites, helical coils follow somewhat behind conical coils by 16 mm, but they still function well. This demonstrates the significant thermal benefit of conical coils with a lower heat pitch.

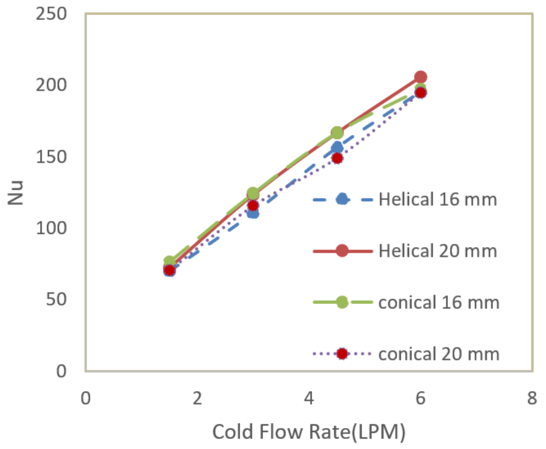

Fig. 3: Nusselt number vs. cold flow rate for different coil configurations

4.2 Nusselt Number vs. Cold Flow Rate for Different Nanofluids

This figure displays the impact of various working fluids on the Nusselt number as cold flow rate increases. All fluids show a rising trend in Nu, but nanofluids clearly outperform water, confirming their improved heat transfer potential. Among nanofluids, 0.4% Al_2O_3 consistently achieves higher Nu values, closely followed by Fe_2O_3 and CuO. Water shows the lowest Nu across the range, reinforcing its lower thermal conductivity. Al_2O_3 performs best across all flow rates, indicating its superior ability to enhance convective heat transfer. This makes it an effective nanofluid for applications that prioritize thermal performance. Therefore, based on this graph, 0.4% Al_2O_3 nanofluid is the best performer for maximizing heat transfer in coil heat exchangers.

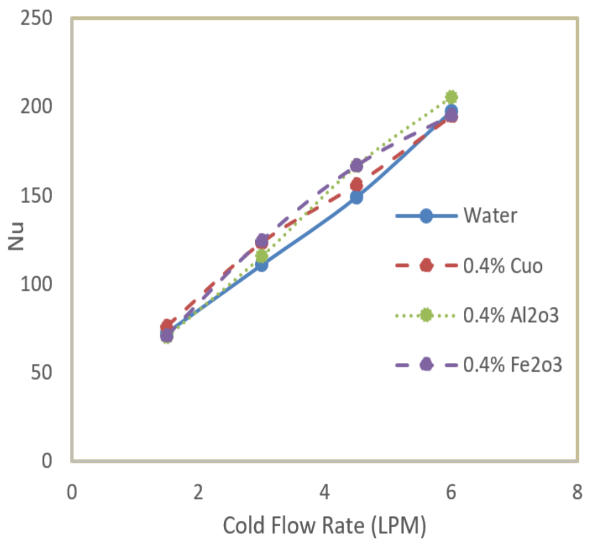

Fig. 4: Nusselt number vs. cold flow rate for different nanofluids

4.3 Exergy Loss vs. Coil Pitch for Cold Fluid in Helical and Conical Coils

Variation of exergy loss at coil pitch and cold flow rates are shown in fig. 5. This Figure compares exergy loss for different cold fluid flow rates in helical (h) and conical (c) coils at two coil pitches: 16 mm and 20 mm. It shows that exergy loss is generally lower at 16 mm pitch for both coil types. Notably, conical coils (e.g., 3c) show the lowest exergy loss at 16 mm, suggesting superior thermodynamic efficiency.

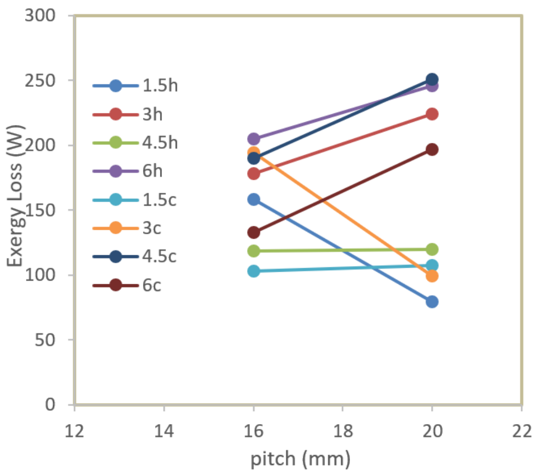

Fig. 5: Exergy loss vs. coil pitch for cold fluid in helical and conical Coils

In contrast, helical coils are less sensitive to pitch changes, with flatter trends like 1.5h and 4.5h. At 1.5 LPM, the conical coil (1.5c) consistently performs better than the helical coil (1.5h), indicating that the conical 16 mm configuration is effective even at low flow rates. These trends imply that tighter, conical coil designs help reduce irreversibility due to enhanced secondary flow and heat transfer.

4.4 Exergy Loss vs. Cold Flow Rate for Different Fluids

This graph shows how exergy loss varies with cold fluid flow rate for different working fluids: water, 0.4% CuO, 0.4% Al_2O_3, and 0.4% Fe_2O_3 nanofluids.

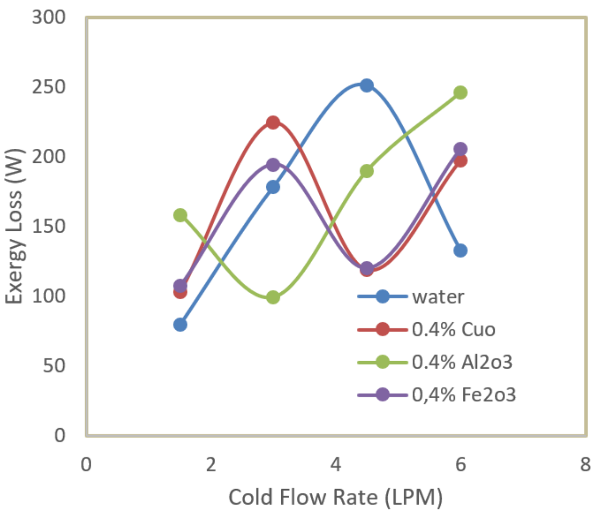

Fig. 6: Exergy loss vs. cold flow rate for different fluids

While nanofluids like Al_2O_3 and Fe_2O_3 reach lower exergy loss at specific flow rates, they also exhibit more variation. Water maintains a relatively low and stable profile, especially at lower flow rates (1.5–3 LPM), which makes it a thermodynamically steady and reliable fluid. Al_2O_3 offers a local minimum around 3–4.5 LPM, indicating high efficiency in a narrow range. However, water's consistent performance across all flow rates makes it suitable where uniformity and stability are critical. Thus, water can be preferred for balanced energy performance, even if some nanofluids show peaks of better efficiency.

4.5 Exergy Loss by Fluid Type and Coil

Fig.7, illustrates the exergy loss (in watts) for four fluids water, 0.4% CuO, 0.4% Al_2O_3, and 0.4% Fe_2O_3 across helical and conical coil geometries.

Water consistently achieves the lowest exergy loss, while Al_2O_3 nanofluid incurs the highest losses due to its elevated viscosity and thermal irreversibilities. Helical and conical 16mm coils exhibit the smallest exergy losses for all fluids, whereas conical 20mm coils perform the worst, particularly with nanofluids. The trend confirms that nanofluids, despite improving heat transfer (as seen in Graph 1), degrade thermodynamic efficiency by increasing pumping power and friction losses. Fe_2O_3 offers a middle ground, balancing moderate exergy loss with improved heat transfer compared to water.

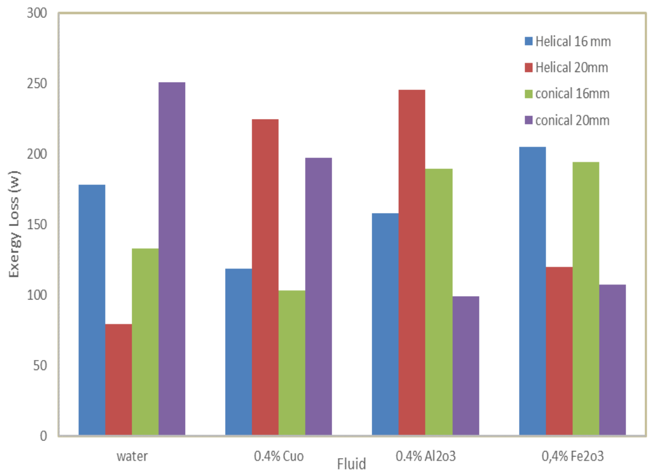

Fig. 7: Exergy loss by fluid type and coil geometry

4.6 Validation of Numerical model

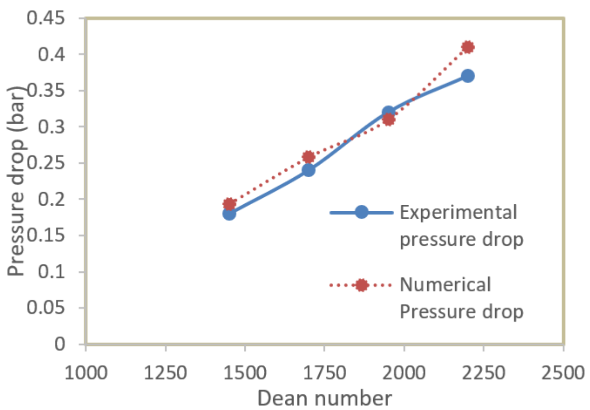

Fig. 8: Validation of numerical model (M. Chandrasekar,2018) [12]

For validation, a helical tube with a 20 mm pitch was used to compare experimental and numerical pressure drop values against the Dean number. (M. Chandrasekar,2018) [12] In Fig. 8, The results showed that both the experimental and numerical pressure drop values were in close agreement, confirming the reliability of the numerical model.

As the Dean number increased, the pressure drops also rose in both cases, demonstrating consistent trends between the two approaches. This correlation indicates that the numerical simulations accurately capture the flow dynamics in helical geometries.

4.7 Analysis of SN ratio

For heat transfer and energy loss, Tables 3 and 4 present the SN ratio based on 16 simulation runs. The current study uses the larger-the-better and smaller-the-better equations for the rate of heat transfer and energy loss, respectively. The highest SN ratio indicates better quality of the parameter.

Table 3: Means of SN ratio for Nusselt number

Level (coil and pitch, fluid, cold, hot flow rate)	Pitch	Fluid	Cold flow rate	Hot flow rate
1(h16,1.5,1.5, H_2O)	42.6375	41.8725	38.7075	43.8725
2(h20,3,3, CuO)	42.19	42.2925	41.47	43.3175
3(c16,4.5,4.5, Al_2O_3)	42.775	42.735	44.06	40.1975
4(c20,6,6, Fe_2O_3)	41.875	42.28	45.6925	41.7925
Delta	0.9	0.8625	6.985	3.68
Rank	3	4	1	2

Table 4: Means of SN ratio for exergy loss

Level (coil and pitch, fluid, cold, hot flow rate)	Pitch	Fluid	Cold flow rate	Hot flow rate
1(h16,1.5, 1.5, H_2O)	-44.185	-43.37	-40.7075	-41.3675
2(h20,3,3, CuO)	-43,59	-43.665	-44.4375	-43.9225
3(c16,4.5, 4.5, Al_2O_3)	-43.5175	-44.3225	-44.1575	-43.425
4(c20,6,6, Fe_2O_3)	-43.6025	-43.545	-43.385	-46.19
Delta	0.6675	0.9525	3.73	4.8225
Rank	4	3	2	1

Based on the table 1 and 2. It is clear that the highest SN ratio for each level of parameters demonstrates the highest optimum level. The optimum levels for heat transfer coefficient are conical pitch 16 mm, 0.4% Al_2O_3 nanofluid, cold flow rate 6 LPM and hot flow rate 1.5LPM. Furthermore, the optimum levels for Exergy loss are conical pitch 16 mm, water, cold and hot flow rate 1.5LPM. As the Tables 4.7 and 4.8 show, the most significant design parameters are indicated by Delta. The more Delta indicates more significance parameter. In this case, hot flow rate and cold flow rate are the most significant parameters in double helical and conical coil heat exchangers.

4.8 Confirmation test

The confirmation test, a critical step in Taguchi's methodology, was conducted to validate the experimental conclusions derived from the simulation runs. For the Nusselt number, the predicted signal-to-noise (SN) ratio under the optimal levels (A_3, B_3, C_4, D_1) was calculated using the additive model:

$\eta_{pred}=A_3+B_3+C_4+D_1-3\eta=46.495dB$

$Nu_{pred}=10^{46,495/20}=211.28$

Where η represents the overall mean SN ratio, and A_3, B_3. C_4, D_1 denote the means SN ratios for each factor at their optimal levels. Similarly, for exergy loss (optimal levels: A_3, B_1, C_1, D_1), the predicted SN ratio was computed as:

$\eta_{pred}=A_3+B_3+C_4+D_1-3\eta=-38.1628$

$Ex_{pred}=10^{-38.1628/20}=80.8W$

Subsequent simulation runs under these conditions yielded actual values of 207.09(Nusselt number) and 74.1W (exergy loss), demonstrating excellent agreement with the predictions. The discrepancies of less than 2.023% for the Nusselt number and 9.04% for exergy loss confirm the robustness of the Taguchi-optimized parameters and the reliability of the additive model in predicting the performance of the helical tube heat exchanger.

5. CONCLUSION

This study was conducted to optimize and analyze the thermal and flow characteristics of double helical and conical coil tube heat exchangers under turbulent conditions using nanofluids. CFD simulations were performed with variations in coil geometry (helical/conical), pitch (16 mm and 20 mm), cold/hot flow rates, and four working fluids—water, 0.4% CuO, 0.4% Al_2O_3, and 0.4% Fe_2O_3.

The analysis shows that the Nusselt number increases with higher cold flow rates, highlighting improved convective heat transfer. Among the fluids, 0.4% Al_2O_3 nanofluid exhibited the highest Nusselt numbers, indicating the best heat transfer performance. However, water provided the lowest exergy loss, especially at lower flow rates, showing higher thermodynamic efficiency and stability.

Regarding coil geometry and pitch, conical coils with a 16 mm pitch consistently achieved better performance in both heat transfer and exergy efficiency compared to their 20 mm counterparts. Helical coils showed more balanced results across all operating ranges but were slightly behind conical coils at lower pitches in efficiency.

Optimization using the Taguchi method revealed that:

- The optimal configuration for heat transfer includes a conical coil with 16 mm pitch, 0.4% Al_2O_3 nanofluid, cold flow rate of 6 LPM, and hot flow rate of 1.5 LPM.
- The optimal setup for minimizing exergy loss includes a conical coil with 16 mm pitch, water as the fluid, and both hot and cold flow rates at 1.5 LPM.
- Among all parameters, cold flow rate and hot flow rate were identified as the most influential factors, affecting both heat transfer and exergy performance significantly.

The confirmation test results strongly support the reliability of the simulation and the Taguchi-optimized parameters, with minimal deviation from predicted values. Overall, this study offers a robust methodology for enhancing heat exchanger performance while balancing thermal and energy efficiency considerations.

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