Experimental and Numerical Heat Transfer Analysis of Shell and Tube Heat Exchanger by Using Helical Finned Tubes

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Abstract. This paper primarily aims to improve the heat transfer coefficient of the shell and tube heat exchanger by incorporating the helical finned tubes. Both experimental analysis and computational fluid dynamics (CFD) simulations were carried out to evaluate the thermal efficiency of heat exchangers with regular tubes and helical finned tubes. The findings have shown that helical finned tubes enhance thermal efficiency by amplifying the surface area for heat exchange, encouraging fluid turbulence, and improving the temperature gradients between the fluids. Experimental data is validated with the CFD model and confirmed that higher outlet temperatures for the cold fluid side and lower outlet temperatures for the hot fluid side in the helical finned tube configuration, prove its superior heat transfer capability. The mean absolute error (MAE) between the experimental and CFD results was minimal, confirming the reliability of the CFD models. Additionally, a system efficiency comparison has shown that the helical finned tube exchanger achieved greater efficiency than the regular tube exchanger, emphasizing the practical benefits of using helical finned tubes in industrial applications where enhanced heat transfer is important.

Keywords: Computational fluid dynamics (CFD), helical finned tubes, heat transfer efficiency, shell and tube heat exchanger (STHE), thermal efficiency, mean absolute error (MAE).

1. Introduction

As displayed in Figure 1, heat exchangers are critical parts of several mechanical/chemical processes. The principle behind their design is exchanging heat between two fluids for other purposes [1]. Sample uses for them include electricity generation, processing chemicals, HVAC setup, and refrigeration units. The main uses of heat exchangers are to improve energy consumption, maintain efficiency, and reduce costs related to electricity consumption [2]. Of these many designs, shell, and tube heat exchangers are quite common; their flexibility, effectiveness, and strength in handling high-pressure, high-temperature fluids make them quite useful [3]. The STHES are made up of a shell with a suite of tubes inside, where a single fluid passes via the inner part of the tubes and the other passes outside the tubes, thus allowing heat transfer between them without being in contact [4]. Recently, the trends of the studies have been focused more on enhancing thermal efficiency in STHEs by increasing surface area and improving heat transfer rates [5]. However, conventional STHEs with regular tubes have had limitations up to a certain degree due to their relatively low surface area, which caused limitations in heat transfer capacity [6]. Thus, this weakness has often led to higher energy consumption and a loss of overall efficiency. One of the possible ways of overcoming such shortcomings is using finned tubes as part of the STHE structural components [7]. The simplest but quite effective modification of basic STHEs is provided by finned tubes. This means fins increase the thermal transmission surface area, increasing thermal gradients between fluids. These fins increase turbulence and, as a result, the convective heat transmission coefficient of the fluid, which in turn enhances the effectiveness of the system. It finds a large application in the field where area constraints arise along with effective dissipation. The usual examples are automobile radiators, air conditioning, and compact industrial cooling systems [8]. The advantages of using finned tubes now are specific in certain applications in STHEs when one of the fluids is to be used with much lower heat transfer coefficients than the other, for example, air against liquid [9]. It is very handy in such applications where high heat transfer rates are required inside a tight space. However, fin design optimization and appreciation of its impact on the performance of STHEs are achievable only through empirical studies and with a hybrid approach, supported by computational modeling [10]. While there are theoretical benefits, there remains a dearth of empirical validation and computational modeling of the performance of finned tubes. Most STHEs found in common applications exhibit inefficiencies greater than those currently estimated, leading to further operation costs and environmental impacts [8]. Finned tubes hold the potential to overcome this inefficiency, though with uncertain effectiveness for varying conditions. It is also remarked that, though CFD has developed as a reliable equipment for modeling fluid stream and thermal transmission, experimental validation is still needed to make the simulations of finned-tube performance reliable.

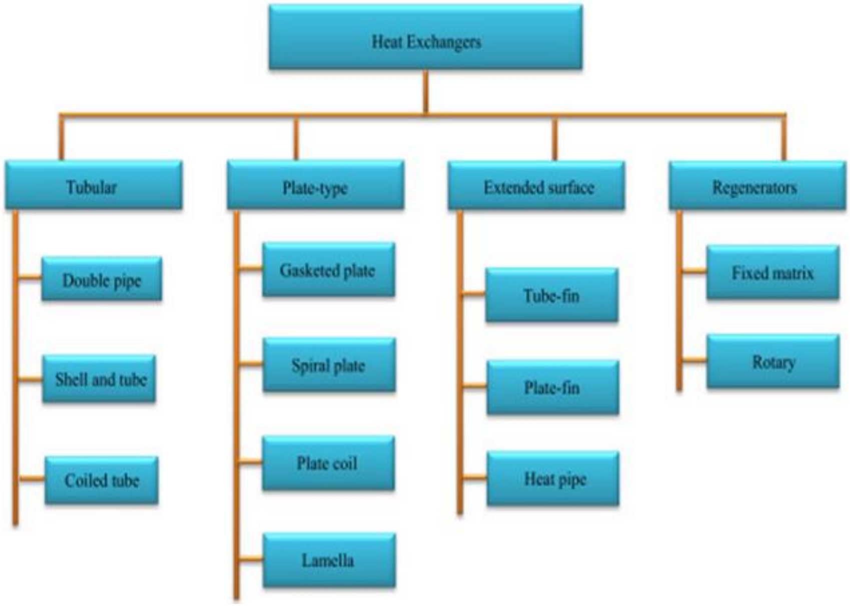

Figure 1. Heat Exchanger

The overall aim of the present paper is to validate analytically and numerically the effectiveness of the helical finned tubes on the efficiency of heat transfer in STHEs. The specific objectives include:

1. A comparison between the heat transmission performance of STHEs with helical finned and regular tubes operating under identical conditions.
2. CFD simulations for heat transfer dynamics in STHEs with helical finned tubes.
3. Validating CFD results by comparing simulated data with experimental findings and assessing model accuracy.
4. System Energy efficiency analysis of impacts caused by helical finned tube design.

The following sections of the paper include the methodology which describes the experimental setup and CFD simulation processes. Further, the obtained results are presented. The discussion section analyses these results, while the conclusion gives insights into the pragmatic applications of helical finned tube designs for heat exchanger technology.

2. Methodology

This research has experimental testing and CFD simulations for validation and examining the enhancement of thermal transmission efficiency in STHEs using helical finned tubes. The said approach is structured in multiple phases, which are organized as an experimental setup, CFD simulations, and validation.

2.1 Experiment Inlet Parameters and CFD Boundary Conditions

Tables 1 and 2 show the inlet parameters and material components used in the STHEs experiments which are also used in boundary conditions and geometry for the CFD simulations.

Table 1. Inlet Parameters Used in The Experiment & Boundary Conditions for CFD.

Cases	Fluid (Tubes& Shell)	Mass Flow Rate (Tubes& Shell)	T Cold (Tube)	T Hot (Shell)
Regular Tubes	Water	0.266 kg/s	25° C	50° C
Helical Finned Tubes	Water	0.266 kg/s	25° C	50° C

Table 2. Materials of Heat Exchanger Components

Component	Material	Material Code
Shell	Carbon Steel	ASTM A306
Tubes	Copper	ASTM B88
Helical Fins	Copper	ASTM B88
Baffles	Carbon Steel	ASTM A306
Tube Sheet	Carbon Steel	ASTM A306
Shell Caps	Carbon Steel	ASTM A306
Shell	Carbon Steel	ASTM A306

2.2 Experimental Setup

The experimental part, as shown in Figure 2, entailed designing a shell and tube thermal exchanger with two configurations, one having helical finned tubes while the other had plain tubes and served as the control. This design allowed a direct comparison of the heat transfer characteristics between these two setups under similar operating conditions. The reason for choosing the helical finned tubes is that they can provide more heat transfer surface area, which will necessarily improve the thermal performance. Tube materials were chosen for optimal thermal conductivity.

Figure 2. Experimental Setup

2.3 Measurement and Instrumentation

The experimental setup includes all the necessary measurement devices for recording parameters such as temperature, pressure, and flow rates. Thermocouples have been placed at the required positions along the tubes to record the inlet and outlet hotness of both the shell and tubing sides. Pressure sensors were also provided to measure pressure drops, and flow meters measured the fluid flow rate. These measurements were indispensable to discovering the rate of thermal transmission and to compare the helical finned and normal tube configurations.

2.4 Measurement and Instrumentation

The tests were operated under laboratory states, in a steady state throughout the entire test. The STHEs were operated at counterflow rates adopting the experiment parameters shown in Table 1. Data for both configurations were recorded once the steady state had been reached. Multiple trials were used to enhance the data reliability. The heat transfer rate for each configuration was computed by obtaining the temp variance between the inlet and outlet streams flowing through both the shell and tube sides.

2.5 CFD Modelling

The CFD simulations, in conjunction with ANSYS Fluent software, provide a high-resolution representation of liquid dynamics and thermal transfer characteristics within the thermal exchanger. As shown in Figure 3, the starting point was geometrical modeling of STHE with helical finned tubes and without fins. This digital replication enabled a precise definition of fluid flow paths and thermal boundaries but is critical for accurate simulation results.

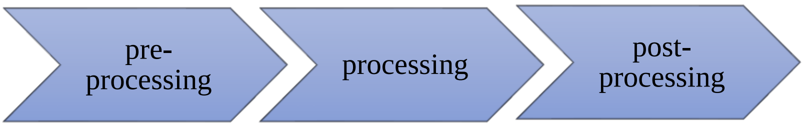

Figure 3. CFD Simulation Workflow

Preprocessing: Geometric models of both cases were created and imported into the CFD environment. The geometries were then meshed, creating computational zones.

Meshing: Mesh Quality was checked by performing a mesh grid independence study. The study aims to ensure the accuracy and quality of meshing structures. Table 3 shows the mesh properties and Figures 4& 5 show the mesh configuration for both STHE cases.

Table 3. Mesh Properties

Cases	Cell Size	Cell Count	Max Aspect Ratio	Min Quality
Regular Tubes	0.0005m	960594	19.219	0.2027
Helical Finned Tubes	0.0005m	2164019	14.964	0.2078

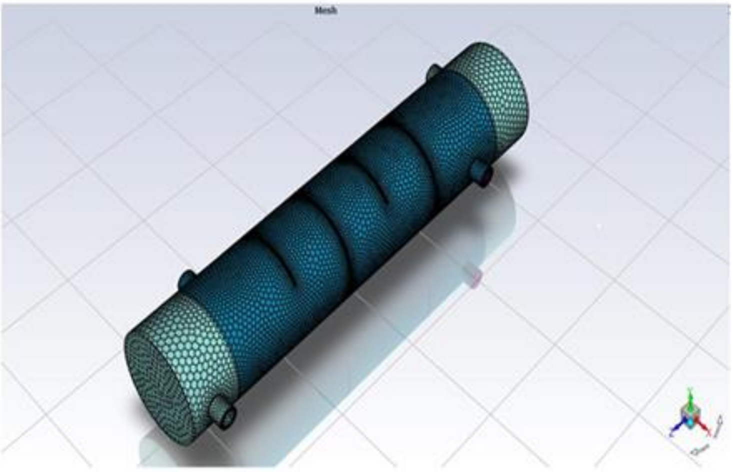

Figure 4. Mesh Structure Regular Tube

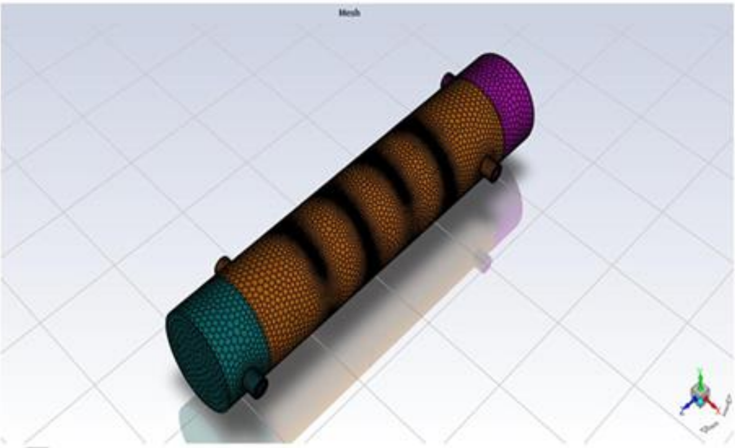

Figure 5. Mesh Structure Regular Tube

Solver Setup: The boundary conditions were set to most closely simulate the experimental conditions by using the same inputs for temperature and flow rates used in laboratory tests. In the present water and air flow simulation, the k-ε turbulence model was chosen, as this turbulence model has become quite well known and vastly applied for the simulation of turbulent stream and heat transmission in CFD analysis.

Governing Equations: The continuity, the momentum, and the energy equations for the turbulent flow are written as follows:

$$\partial u/\partial x+\partial v/\partial y+\partial w/\partial z = 0 \tag{1}$$

$$\rho\ (u\ \partial u/\partial x+ v\ \partial u/\partial y+ w\ \partial u/\partial z) = - \partial p/\partial x+ [\ (\mu+ \mu_t)\ (\partial^2 u/\partial x^2 +\partial^2 u/\partial y^2 +\partial^2 u/\partial z^2)] \tag{2}$$

$$\rho\ (u\ \partial v/\partial x+ v\ \partial v/\partial y+ w\ \partial v/\partial z) = - \partial p/\partial y+ [\ (\mu+ \mu_t)\ (\partial^2 v/\partial x^2 +\partial^2 v/\partial y^2 +\partial^2 v/\partial z^2)] \tag{3}$$

$$\rho\ (u\ \partial w/\partial x+ v\ \partial w/\partial y+ w\ \partial w/\partial z) = - \partial p/\partial z+ \rho g+ [\ (\mu+ \mu_t)\ (\partial^2 w/\partial x^2 +\partial^2 w/\partial y^2 +\partial^2 w/\partial z^2)] \tag{4}$$

$$\rho Cp\ (u\ \partial T/\partial x+ v\ \partial T/\partial y+ w\partial T/\partial z) = (\lambda+ \lambda_t)\ (\partial^2 T/\partial x^2 +\partial^2 T/\partial y^2 + \partial^2 T/\partial z^2) \tag{5}$$

Hence, p is the pressure. T is the temperature. ρ is the density. u, v, w are the velocities in the x, y, and z directions. G is the gravity acceleration. λt and μt are the turbulent conductivity and viscosity respectively, which are calculated in the turbulent models.

Solution and Convergence: The solver iterated over the flow equations, and variables were adjusted until the convergence criteria were satisfied. Convergence was considered achieved when the residuals dropped to a level where further iterations would show no significant divergence of the results.

3. Results and Discussion

As a preliminary insight into relative effectiveness, the thermal exchanger temp distribution between the inlets and outlets of hot/cold liquids is measured.

3.1 Experimental Results

From the experimental results summarized in Table 4, the outlet temperature in the cold liquid (tube side) for the helical finned tube configuration is higher (28.5°C compared to 27°C), while the outlet temp in the hot flowing (shell side) is lower (43°C compared to 44°C). This temperature shift indicates that helical finned tubes improve the efficiency of STHEs by enhancing the thermal exchange between the hot and cold fluids.

Table 4. Experimental Inlet and Outlet Temperatures

Cases	T in (Cold)	T out (Cold)	T in (Hot)	T out (Hot)
Regular Tubes	25°C	27°C	50°C	44°C
Helical Finned Tubes	25°C	28.5°C	50°C	43°C

The higher outlet temperature of the cold fluid and the lower outlet temperature of the hot fluid in the helical finned tube case mean that the fins enhanced the efficiency of STHEs by expanding the effective thermal exchange space. This added surface area encourages greater thermal contact between fluids and improves the overall rate of heat transfer.

3.2 CFD Results

The CFD simulations provide a computational verification of the experimental data by comparing simulated and measured outlet temperatures. Table 5 summarises these values for each tube configuration.

Table 5. CFD Inlet and Outlet Temperatures

Cases	T in (Cold)	T out (Cold)	T in (Hot)	T out (Hot)
Regular Tubes	25°C	28.17°C	50°C	46.83°C
Helical Finned Tubes	25°C	28.93°C	50°C	46.12°C

The CFD model of the regular tubes managed to predict an outlet temperature of 28.17°C on the cold side and 46.83°C on the hot side, both slightly higher than the experimental values at 27°C and 44°C, respectively. Likewise, for the helical finned tubes, CFD predictions showed 28.93°C on the cold side and 46.12°C on the hot side just a little higher than experimentally measured at 28.5°C and 43°C. The minor discrepancy between the CFD and experimental results could be related to idealized conditions in the simulations, which do not allow possible heat losses in the experimental setup or measurement inaccuracies. While that may be true, this CFD is very close to the experimental results, which means the model represents the thermal behaviour for both configurations.

3.3 Temperature Distribution and Contour Analysis

Temperature contour plots, shown in Figures 6 and 7, represent the hotness distribution in the heat exchanger. In the helical finned tube configuration, the temperature gradient along the tube is smoother indicating better heat transfer efficiency since the fins spread the heat more evenly.

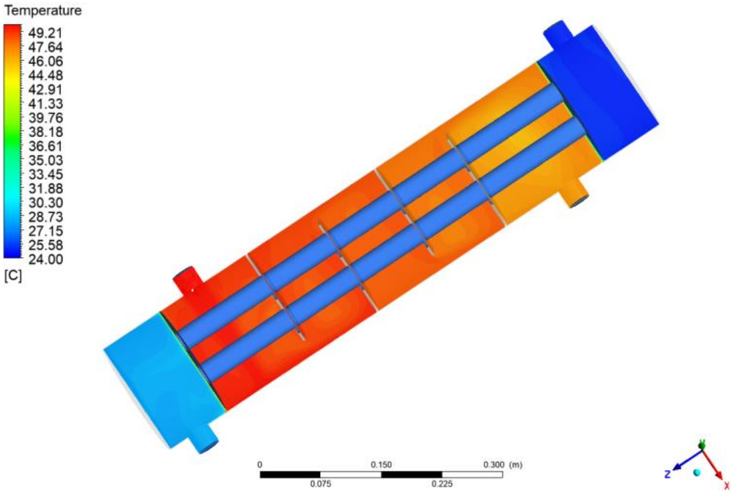

Figure 6. Temperature Contour Regular Tubes

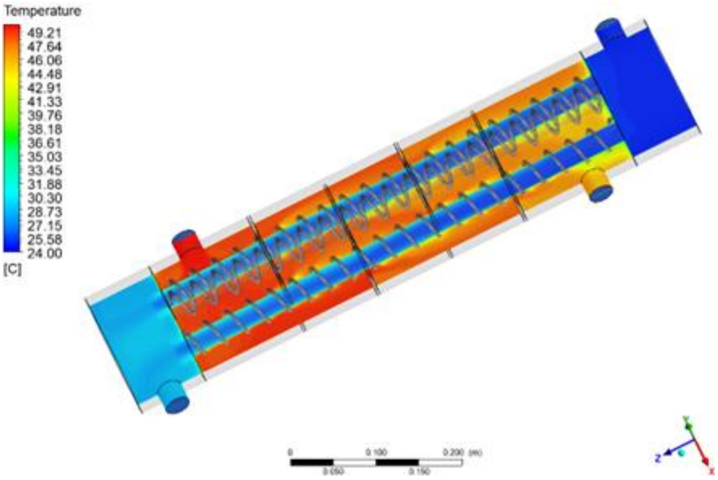

Figure 7. Temperature Contour Helical Finned Tubes

3.4 Velocity Distribution and Streamline Analysis

The velocity streamlines indicate the fluid flow pattern in the heat exchanger, as can be realized in Figures 8 and 9.

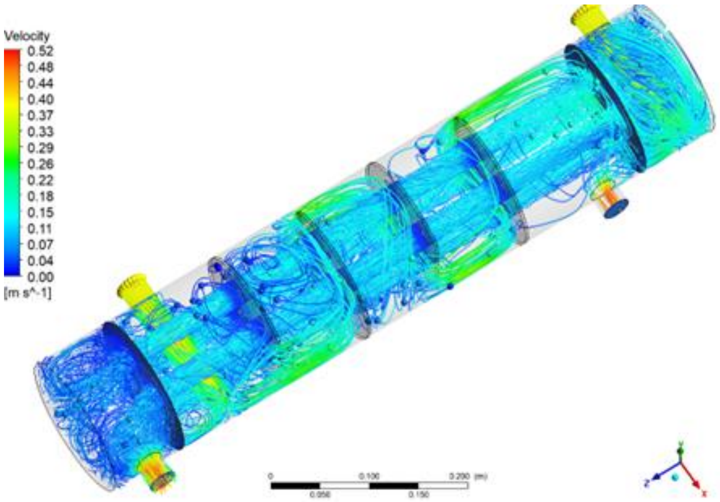

Figure 8. Velocity Streamline Regular Tubes

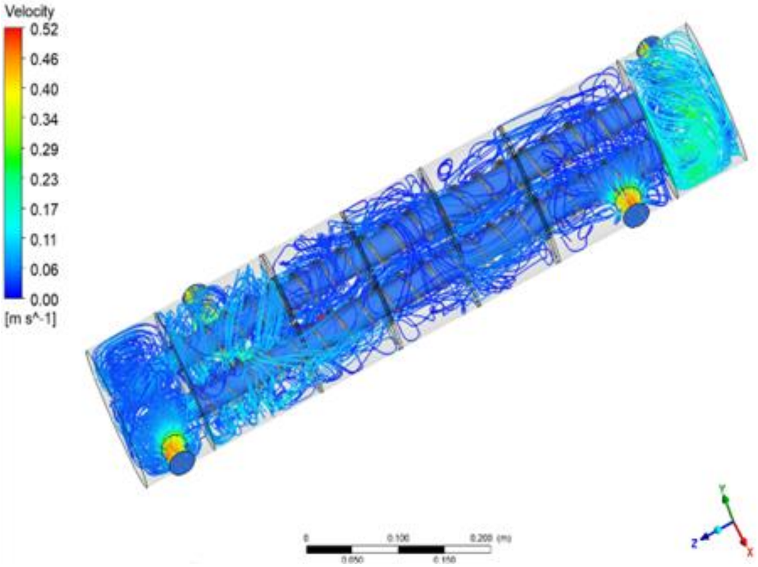

Figure 9. Velocity Streamline Helical Finned Tubes

In the case of the helical finned tube setup, flow around the fins is more turbulent, and there are higher velocities as the fluid about a fin surface moves quickly. Such turbulence would interrupt the partition layer and boost convective thermal transfer. The helical finned configuration t would have a better mixing of fluids, a higher heat transfer coefficient, and, consequently, better thermal efficiency. For the regular tubes, there is more uniformity in velocity distribution because the turbulence is less, resulting in less heat transfer efficiency.

3.5 Heat Transfer Rate & Efficiency Comparison

The experimental heat transfer rates are figured out from the equation:

$$\dot{Q} = \dot{m} * \dot{c}p * \Delta T \qquad (6)$$

$\dot{Q} = \dot{m} * cp \overset{\cdot}{*} (\dot{T}_{in} - T_{out})$ (7)

Where:
Q is the heat transmission rate (W),
$m^{\cdot}$ is the mass flowing rate (kg/s),
cp is the specific hotness of the flowing (J/kg·K),
Tin and Tout are the inlet and outlet temps (°C).

The thermal efficiency of STHE can be defined as the ratio of the actual heat transfer rate for the tube side to the maximum possible heat transfer rate.

The thermal efficiency (η) is calculated as:

$$\eta = \frac{Q_{act}}{Q_{max}} \times 100\% \quad (8)$$

$$Q_{max} = \dot{m} * cp * \left(T_{in,hot} - T_{in,cold}\right) \quad (9)$$

Where:
Q_{act} is the actual heat transfer rate,
Q_{max} is the maximum possible heat transfer rate.

Table 6. Thermal Efficiency Comparison

Cases	Q_{max}	Exp Q_{act}	CFD Q_{act}	Exp η	CFD η
Regular Tubes	27810 W	2225 W	3543W	8%	12.7%
Helical Finned Tubes		3893 W	4378 W	14%	15.7%

As shown in Table 6, the efficiency of the STHEs was calculated for both cases of experimental and CFD results. The results showed that the helical finned tube had a higher efficiency than the regular tube, further supporting the use of finned tubes in industrial applications where enhanced heat transfer is required.

3.6 Mean Absolute Error (MAE) Analysis

To back up the precision of the CFD model, the MAE is calculated grounded on the differences in CFD and experimental outlet temperatures. Table 7 summarizes the MAE values for the two configurations of the tubes.

Table 7. Mean Absolute Error Calculations

Cases	Cold Outlet MAE (°C)	Hot Outlet MAE (°C)
Regular Tubes	1.17	2.83
Helical	0.43	3.12

Finned Tubes

The comparatively low values of MAE with an average difference of about 2°C would suggest that the CFD model is good at predicting the thermal behaviour of the STHE. The lesser MAE for the helical finned tubes indicates that the CFD model has accurately predicted the improvement of heat transfer characteristics brought about by the helical fins.

The agreement between the experimental and numerical outlet temperatures proves the validity of the CFD model. This is further confirmed by the MAE analysis, which states that the predictions of CFD are within acceptable limits of error, especially due to the helical finned tubes, since the MAE was 0.43°C at the cold outlet and 3.12°C in the case of the hot outlet. These values confirm that CFD is a reliable tool for forecasting and optimizing the STHE thermal behaviour without wide physical prototyping.

Moreover, helical fins not only extend the thermal transmission space but also affect the fluid dynamics of the STHE. The enhanced level of turbulence around the fins is depicted and analyzed in CFD velocity contour plots. Indeed, due to this characteristic of turbulence, a good heat transfer presents and causes mixing within the fluid layers and provides a constant interaction of hotter and cooler fluid elements with the heat exchange surfaces. The heat transfer increases owing to the elimination of the thermal partition layer on the surface of the tubes by these turbulence buses, which in turn reduces the insulating effect of the stagnant fluid.

4. Conclusions

This paper vividly shows the rise in heat transfer rate for STHEs when using the helical finned tubes compared to the regular ones. The experiments, coupled with CFD simulations, have established that helical finned tubes offer enhanced dissipation and regulation of temperature. Helical finned tubes show improvements in outlet temperatures and STHE efficiency. The study validated the CFD simulations through experimental data to confirm the solidity and correctness of the model. The credibility of the results was further reinforced through the analysis of MAE. A higher temperature differential between the inlet and outlet fluid in the helical finned tubes than in the regular tubes was observed, indicating increased heat dissipation. Several recommendations also come out of this study. Future research should investigate the optimized helical fin configurations, including changing height, thickness, and spacing, which could maximize the heat transfer rate. Further, integrating alternative materials with high thermal conductivity will improve the efficiency of exchangers with reduced weight and cost. Even more futuristic turbulence versions, such as Large Eddy Simulation or the Reynolds Stress Models - might have yielded CFD results with even higher accuracy, especially for those involving more complex flow conditions. Another benefit of this study would be to get a cost-benefit analysis that could give industries quantitative measures on the economic benefit of adopting helical finned tube configurations.

References

[1] Zhang J, Zhu X, Mondejar M E and Haglind F 2019 A review of heat transfer enhancement techniques in plate heat exchangers *Renewable and Sustainable Energy Reviews* **101** 305–28

[2] Omidi M, Farhadi M and Jafari M 2017 A comprehensive review on double pipe heat exchangers *Applied Thermal Engineering* **110** 1075–90.

[3] He L and Li P 2018 Numerical investigation on double tube-pass shell-and-tube heat exchangers with different baffle configurations *Applied Thermal Engineering* **143** 561–9.

[4] Yang Z, Ma Y, Zhang N and Smith R 2020 Design optimization of shell and tube heat exchangers sizing with heat transfer enhancement *Computers & Chemical Engineering* **137** 106821.

[5] Abbasian Arani A A and Moradi R 2019 Shell and tube heat exchanger optimization using baffle and tube configuration Applied Thermal Engineering **157** 113736.

[6] Kucuk H, Unverdi M and Yilmaz M S 2019 Experimental investigation of shell side heat transfer and pressure drop in a mini-channel shell and tube heat exchanger *International Journal of Heat and Mass Transfer* **143** 118493.

[7] Yang X, Wang X, Liu Z, Luo X and Yan J 2022 Effect of fin number on the melting phase change in a horizontal finned shell-and-tube thermal energy storage unit *Solar Energy Materials and Solar Cells* **236** 111527.

[8] Sadeghianjahromi A and Wang C-C 2021 Heat transfer enhancement in fin-and-tube heat exchangers – A review on different mechanisms *Renewable and Sustainable Energy Reviews* **137** 110470.

[9] Mohsen O A, Muhammed R and Hasan B O 2020 Heat transfer enhancement in a double pipe heat exchanger using different fin geometries in turbulent flow *Iranian Journal of Science and Technology, Transactions of Mechanical Engineering* **45** 2 461–71.

[10] Liu X, Wang M, Liu H, Chen W and Qian S 2021 Numerical analysis on heat transfer enhancement of wavy fin-tube heat exchangers for air-conditioning applications *Applied Thermal Engineering* **199** 117597.

[11] Li K, et al. 2020 Application of entransy theory on structure optimization of serrated fin in plate-fin heat exchanger *Applied Thermal Engineering* **173** 114809.

[12] Abeykoon C 2020 Compact heat exchangers – Design and optimization with CFD *International Journal of Heat and Mass Transfer* **146** 118766.

[13] Sharifi K, Sabeti M, Rafiei M, Mohammadi A H and Shirazi L 2018 Computational fluid dynamics (CFD) technique to study the effects of helical wire inserts on heat transfer and pressure drop in a double pipe heat exchanger *Applied Thermal Engineering* **128** 898–910.

[14] Nagaosa R S 2017 Turbulence model-free approach for predictions of air flow dynamics and heat transfer in a fin-and-tube exchanger *Energy Conversion and Management* **142** 414–25.

[15] Darbandi M, Abdollahpour M-S and Hasanpour-Matkolaei M 2021 A new developed semi-full-scale approach to facilitate the CFD simulation of shell and tube heat exchangers *Chemical Engineering Science* **245** 116836.

[16] Saviers K R, Ranjan R and Mahmoudi R 2019 Design and validation of topology optimized heat exchangers *AIAA Scitech 2019 Forum* **1465**.

[17] Rodrigues M K, Vaz J, Oliveira Rocha L A, Domingues dos Santos E and Isoldi L A 2022 A full approach to Earth-Air Heat Exchanger employing computational modeling, performance analysis and geometric evaluation *Renewable Energy* **191** 535–56.

[18] Alfwzan W F, Alomani G A, Alessa L A and Selim M M 2023 Sensitivity analysis and design optimization of nanofluid heat transfer in a shell-and-tube heat exchanger for solar thermal energy systems: a statistical approach *Arabian Journal for Science and Engineering* **49** 7 9831–47.

[19] Amagour M E H, Bennajah M and Rachek A 2021 Numerical investigation and experimental validation of the thermal performance enhancement of a compact finned-tube heat exchanger for efficient latent heat thermal energy storage *Journal of Cleaner Production* **280** 124238.

[20] Saleh-Abadi M, Rostami M and Farajollahi A H 2023 Successive expansion and contraction of tubes (SECTs) in a novel design of shell-and-tube heat exchanger: a comparison between basic,

finned and non-finned designs *Journal of the Brazilian Society of Mechanical Sciences and Engineering* **45** 9.

[21] Raja B D, Patel V and Jhala R L 2017 Thermal design and optimization of fin-and-tube heat exchanger using heat transfer search algorithm *Thermal Science and Engineering Progress* **4** 45–57.

[22] Ko J Y, et al 2024 A critical review on Colburn j-factor and f-factor and energy performance analysis for finned tube heat exchangers *Energy* **287** 129609.