JOURNAL OF ENERGY SYSTEMS

2023, 7(1)

2602-2052

DOI: 10.30521/jes.1116707

Research Article

Numerical investigations on a triple fluid heat exchanger with helical and sinusoidal coils

Mariappan Suresh
Sri Sivasubramaniya Nadar College of Engineering, Department of Mechanical Engineering, Kalavakkam 603110, Tamilnadu, India, msuresh@ssn.edu.in

Submitted: *23.05.2022*
Accepted: *08.11.2022*
Published: *31.03.2023*

Abstract: A modification is made in the existing concentric heat exchanger design to enhance its heat duty. A standard concentric tube heat exchanger is modified by considering two inner tubes with a combination of helical and sinusoidal coils. Numerical studies are performed in this triple fluid heat exchanger to assess its thermal performance by taking into account mass flow rate, fluid temperatures, heat transfer, which are governed by fundamental heat transfer equations. Computational fluid dynamics simulation methodology together with local and element-by-element method is applied with a MatLab computer code. Hot water and milk fluids are used as working fluids in helical and sinusoidal coils, respectively. Cooling water is used as shell side fluid. The attainment of high heat-load-per-unit-area and high surface-area-to-volume ratio is used as optimizing parameter in the simulations. The helical coil provides an increase in heat transfer rate and overall heat transfer coefficient increases by a percentage 13% for varying hot fluid flow rates, when it is compared with the sinusoidal coil. The pressure drop for the helical coil increases, exponentially compared to the sinusoidal coil, thereby it shows a higher pumping power for the helical coil.

***Keywords**:* *CFD analysis, Helical coil, Numerical simulation, Sinusoidal coil, Triple fluid heat exchanger*

Cite this paper as:	Suresh, M., Numerical investigations on a triple fluid heat exchanger with helical and sinusoidal coils. *Journal of Energy Systems 2023; 7*(1): 46-56, DOI: 10.30521/jes.1116707

1. INTRODUCTION

Enhancement of heat for a heat exchanger is one of the most common tasks confronted by industries employed to the thermal systems. Enhancement techniques include increasing the surface area or increasing heat transfer coefficient by introducing turbulence promoters, inserts, roughness, and other parameters. The helical and sinusoidal coils are known to improve heat transfer without the requirement of additional turbulence or surface area. Many researchers have studied the functioning of tubular heat exchanger with three concentric tubes. Unal [1] conducted theoretical studies on triple concentric tube heat exchangers and developed effectiveness-NTU relations for both parallel and counter flow configurations. Batmaz and Sandeep [2] calculated overall heat transfer coefficients for triple tube heat exchangers and determined temperature profiles for all three streams in the axial direction. Jayakumar *et al.*, [3] reported the numerical results for heat transfer characteristics of a helical coil heat exchanger using CFD simulation software and validated with experimental results after testing the heat duty of a fabricated helical coiled heat exchanger. In addition, correlations were developed in terms of Nusselt number to estimate heat transfer coefficient for helical coil. Garcia-Valladares [4] applied transient one-dimensional analysis of fluid flow in the numerical simulation for the analysis of heat transfer performance of triple concentric tube heat exchangers. Optimum values of heat exchanger efficiency shall be obtained by using this model. Rennie [5] performed numerical and experimental studies on a concentric helical coil heat exchanger with different flow configurations. It was reported that annulus thermal resistance is the single most influencing parameter for heat exchanger performance and heat transfer shall be enhanced by increasing the inner coil diameter. Abdelmagied [6] conducted experiments on a triple spirally coiled tube heat exchanger to study thermal and flow characteristics. It was found that when hot water temperature was increased, it enhanced the heat exchanger duty. Also, heat transfer rate improved when the coil spiral angle was increased. The same author studied the heat transfer and pressure drop characteristics on this heat exchanger by conducting experiments under turbulent flow conditions in Ref. [7]. Aluminium oxide-water nanofluid was used as the working fluid. It was found that heat duty and effectiveness were better than those of concentric spiral coil by more than 100%. Also, heat transfer rate was enhanced when aluminium oxide-water nanofluid was used instead of water. Tiwari *et al.*, [8] introduced various type of inserts like rib, porous plate and twisted tape in a triple tube heat exchanger to improve its heat transfer rate, by carrying out experiments as well as the CFD simulation techniques. Also various metal oxide-water nanofluids were used to evaluate heat exchanger performance. It was concluded that maximum efficiency was realized when the heat exchanger used rib type insert and Tungsten metal oxide nanofluid. Both computational fluid dynamics (CFD) and experimental analyses validated the results. Bahiraei *et al.*, [9] performed theoretical studies on a three-concetric tube heat exchanger with ribs, to evaluate its performance, by employing crimped spiral rib and alumina-water nanofluid. It was observed that this particular type of rib-nanofluid combination enhanced the heat exchanger effectiveness due to the generation of strong swirl flows and vortices. Elsaid *et al.*, [10] compared the performance of triple tube heat exchanger with and without ribs by performing numerical analyses by using CFD. Different shapes of rib geometries and different types of nanofluids were used in the numerical model. It was found that ribbed heat exchanger performed better than heat exchanger without ribs. Also, staggered arrangement of ribs enhanced the heat transfer when compared with inline rib arrangement. Similarly, when a hybrid nanofluid consisting of aluminium, magnesium and silicon oxides was used, heat transfer was improved by percentage 25% compared to other nanofluids.

In a recent paper, Kurt *et al.*, [11] have carried out an exhaustive exploration on pressure drops and temperature variation in parabolic trough solar collector absorber tubes using RNG *k*-epsilon model in a CFD analysis. In their analysis, the superheated steam has been considered as working fluid. Numerical results are in good agreement with the experimental data received from solar test facility in Spain. Sahin *et al.*, [12] studied heat transfer and friction characteristics of concentric tube heat exchangers with coiled wire turbulators, experimentally and numerically and it was concluded that heat transfer enhancement was obtained using turbulators, though at the expense of pressure and pumping power. Sahin *et al.*, [13] also conducted similar explorations by using helical turbulators and obtained better heat transfer enhancement when compared with coiled wire turbulators. Sahin *et al.*, [14] analyzed the performance of similar heat exchangers with spring type turbulator using RNG *k*-epsilon turbulence model with different wall functions and found that standard wall function yielded better results when compared with non-equilibrium wall and enhanced wall functions. In spite of enormous literature on triple concentric tube heat exchangers, there exist renewed research interests on triple fluid, one shell-two tube heat exchangers with various tube configurations and investigations. In the present work, performance of a concentric tube heat exchanger with two inner tubes of helical and sinusoidal configurations is explored numerically by employing both CFD simulations and element-by-element effectiveness-NTU method.

2. NUMERICAL SIMULATION

A schematic diagram of triple fluid heat exchanger with helical and sinusoidal coils is shown in Fig. 1. Hot milk flows through the helical coil and then hot water is sent through the sinusoidal coil. Both fluids are cooled by water flowing through the outer tube or shell.

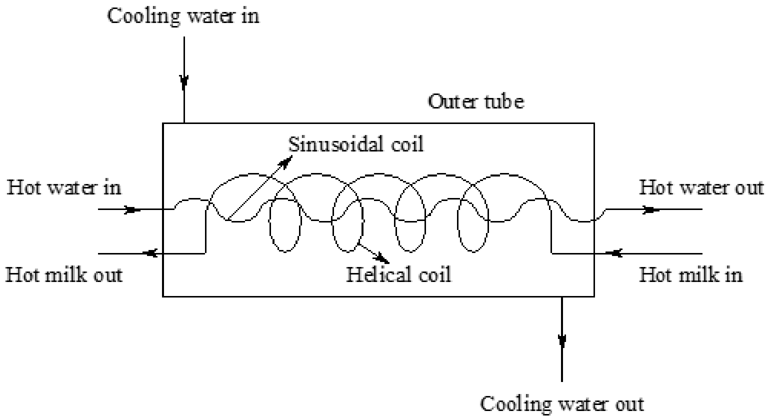


Figure 1. Schematic diagram of a triple fluid heat exchanger.

2.1. CFD Simulation Model

Figs. 2(a-d) show the geometries created using Ansys Workbench Design Modeller for coils and outer tube. The dimensions considered for the heat exchanger are indicated in Table 1. The correlations for friction factor, pressure drop and overall heat transfer coefficient are used in the model similar to Ref. [5]. Figs. 3(a,b) depict the coil mesh and surface components for the heat exchanger.

The well-known k-ε model with an enhanced wall treatment is adjusted for the analyses and no-slip conditions are assumed. The solution method uses simple scheme with a second order upwind for energy, momentum and dissipation. The residual parameters are set to $1.0\text{x}10^{-3}$ for the convergence.

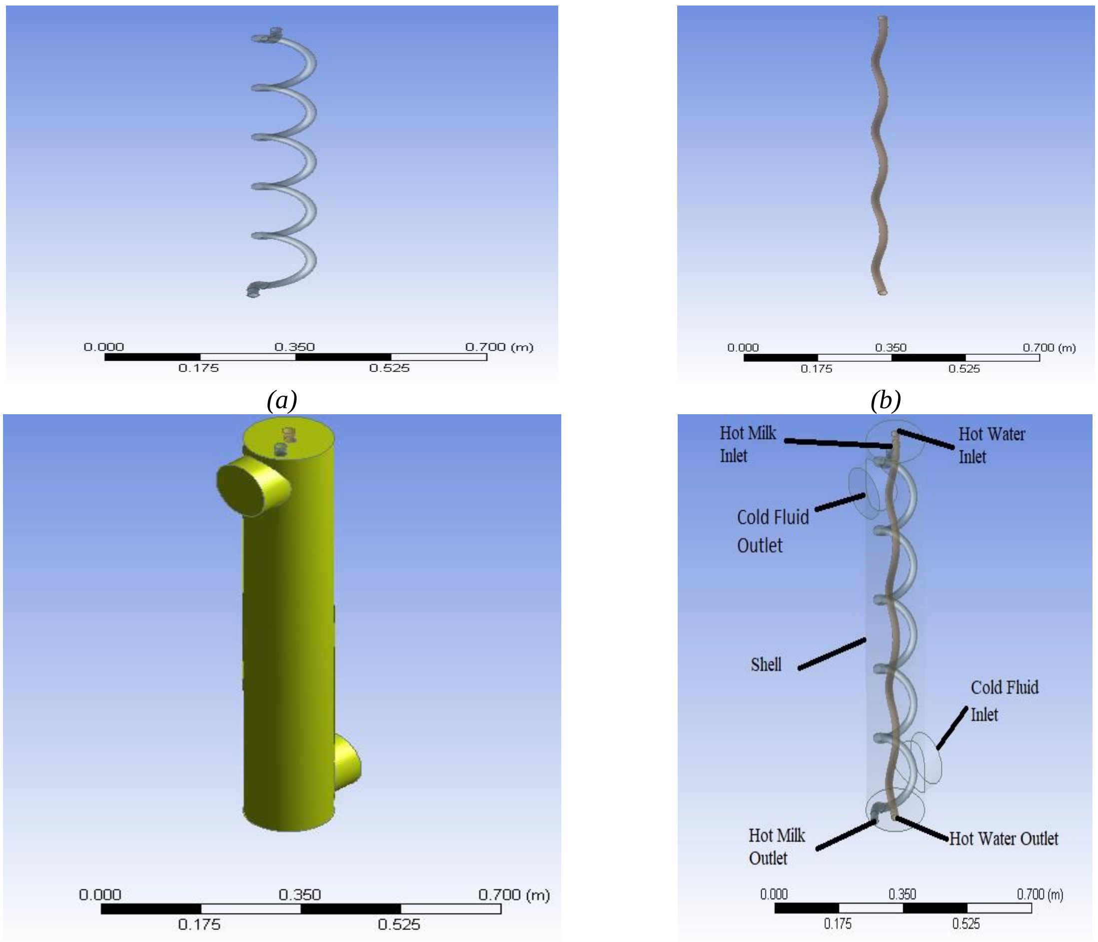
2.2. CFD Simulation Results

2.2.1. Temperature profiles

Figs. 4(a-c) indicate the temperature profiles for hot milk in the helical coil, hot water in the sinusoidal coil and cooling water in the outer tube, respectively. For the same increase in flow rates for both hot milk and water, temperature drop in the helical coil is 2-5 °C more than that in sinusoidal coil due to the increase in flow resistance and heat transfer coefficient, which results in increase in heat transfer rate for the helical coil.

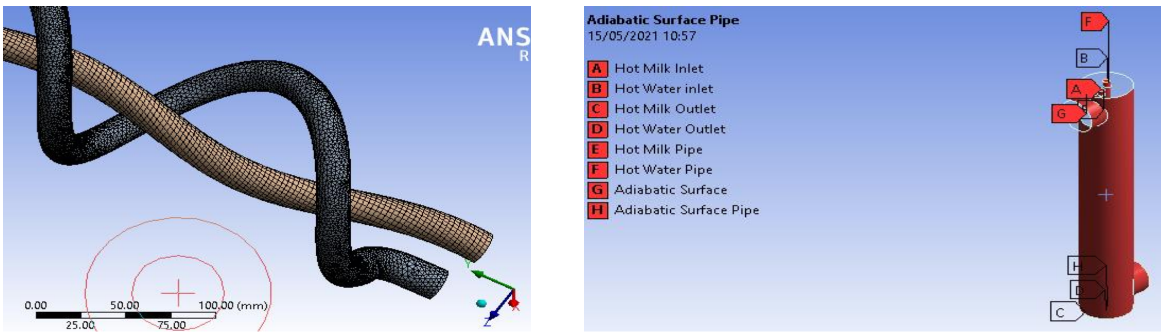
2.2.2. Pressure profiles

Figs. 5(a-c) depict the pressure profiles for hot milk in the helical coil, hot water in the sinusoidal coil and water as cooling medium in the outer shell. For the same increase in flow rates for both hot milk and hot water, the pressure drop in the helical coil is 100-3000 Pa more than one in the sinusoidal coil due to the increase in the flow resistance.



(a) (b) (c) (d)

Figure 2. Geometries of a) helical and b) sinusoidal coils, c) outer tube, and d) heat exchanger.

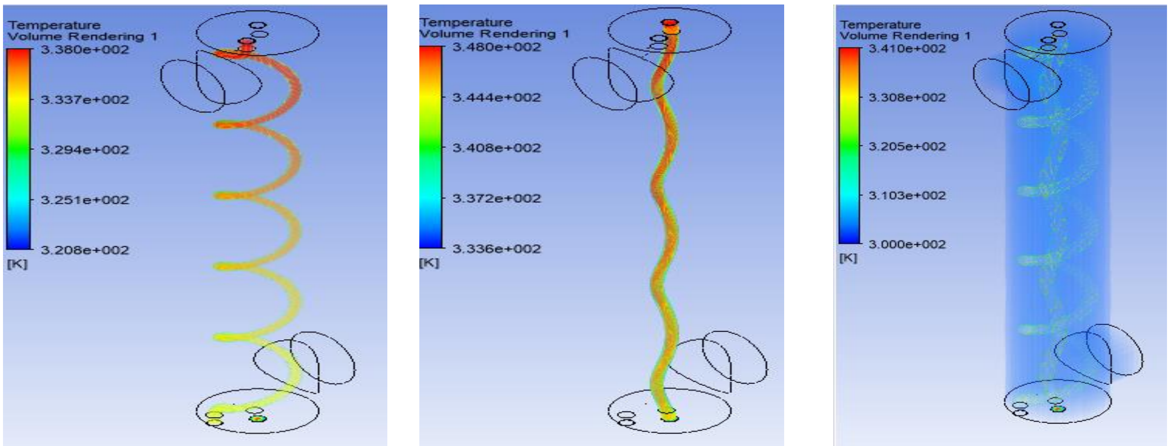


(a) (b)

Figure 3. a) Helical and sinusoidal coil meshes, b) heat exchanger components.

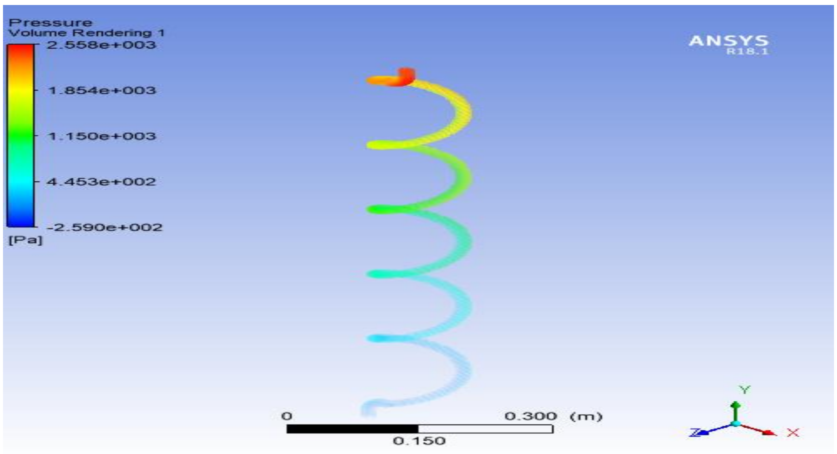
Table 1. The dimensions of the heat exchanger.

Helical coil	
Inner diameter	20 mm
Coil thickness	1 mm
Coil length	1000 mm
Coil pitch	180 mm
No. of turns	5
Inner diameter of helix	76 mm
Outer diameter of helix	124 mm
Sinusoidal coil	
Inner diameter	20 mm
Coil thickness	1 mm
Coil length	1000 mm
Coil pitch	250 mm
No. of turns	4
Inner amplitude of curve	40 mm
Outer diameter of curve	42 mm
Outer tube	
Inner diameter	160 mm
Tube thickness	3 mm

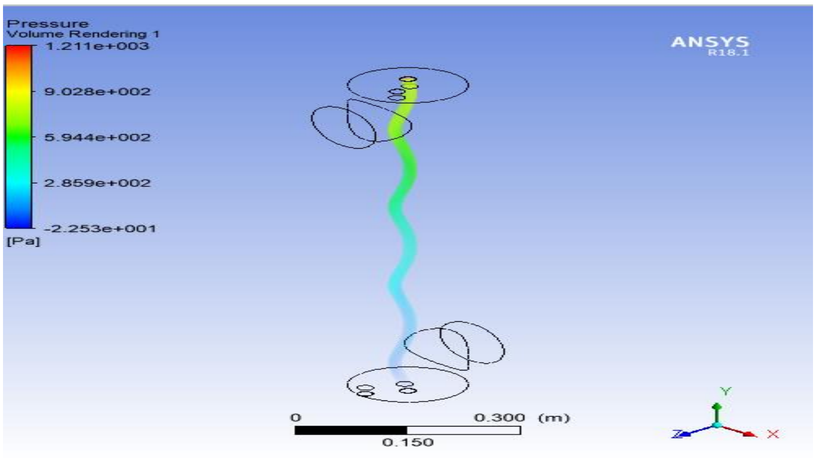


(a) (b) (c)

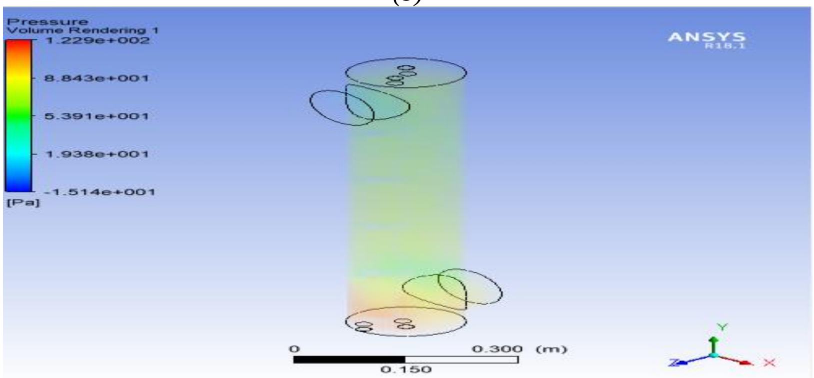
Figure 4. Temperature profiles for a) hot milk in helical coil, b) hot water in sinusoidal coil, and c) cooling water in the outer tube.



(a)



(b)



(c)

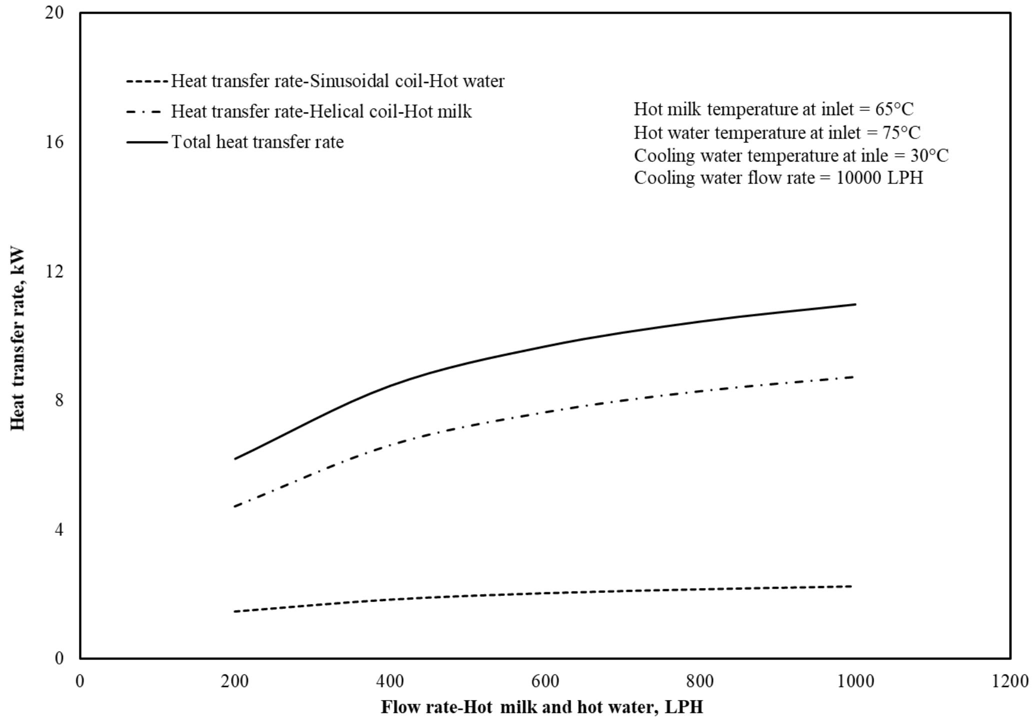
Figure 5. Pressure profiles for a) hot milk in helical coil, b) hot water in sinusoidal coil, and c) cooling water in the outer tube.

2.3. Element-by-element Effectiveness-NTU Simulation Model

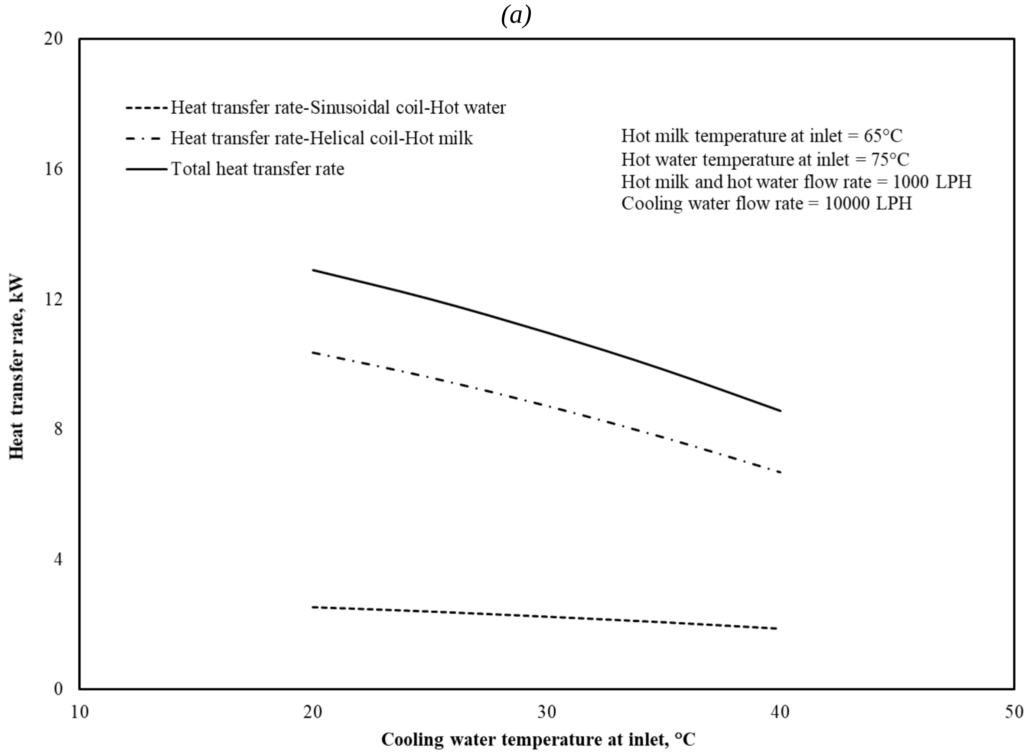
This simulation model calculates all the parameters like pressure, temperature, overall heat transfer coefficient, effectiveness and heat transfer rate for a small section of the heat exchanger and these values are assigned as input parameters for the next small section. This procedure is continued along the flow direction till heat exchanger end. A computer code has been written for this calculation procedure, using MATLAB.

2.4. Effectiveness-NTU Simulation Results

Heat transfer rate of sinusoidal and helical coils are illustrated in Figs. 6(a, b) for varying flow rates of hot fluids and cooling water inlet temperature. The heat transfer rate is enhanced as hot fluid flow rate increases, where it is reduced as cooling water inlet temperature increases. The increase in hot fluid flow rate improves the heat transfer coefficient and maximum possible heat transfer, thereby enhancing the heat exchanger duty, whereas increase in cooling fluid temperature reduces the temperature potential with a decrease in the heat transfer rate. Heat duty of the helical coil is better due to the enhanced heat transfer coefficient resulting from the increased flow resistance. Temperature difference across both coils are depicted in Figs. 7(a,b) for similar variations in hot fluid flow rate and cooling water temperature. The temperature potential across the helical coil is higher due to the enhanced heat transfer, however, the temperature potentials for both coils are reduced at high hot fluid flow rates as well as at high cooling water temperatures. In the first case, it is due to the inverse variation and in the second case, it is due to the reduced heat transfer rate. The effectiveness of both coils are shown in Figs. 8(a,b) for variation in parameters mentioned in Figs. 6 and 7. The effectiveness of the helical coil is better due to the enhanced heat transfer coefficient. The effectiveness of both coils are reduced at high hot fluid flow rates due to the high heat capacity of the fluids, whereas the effectiveness of both coils increase at high temperatures of cooling water due to the enhanced heat transfer coefficient. Regarding to the pressure variation in the heat exchanger, the pressure drop across the sinusoidal coils and heat exchanger shell are negligible, when they are compared with ones across the helical coils (Fig. 9). The reason for considerable pressure drop in helical pipe could be due to the flow resistance caused by turbulence. Though turbulence in the helical coil enhances the heat transfer rate, it results in significant increase in the friction factor. Pressure profile trends in Fig. 9 are good agreement with that of the work of Kurt et. al., [11].

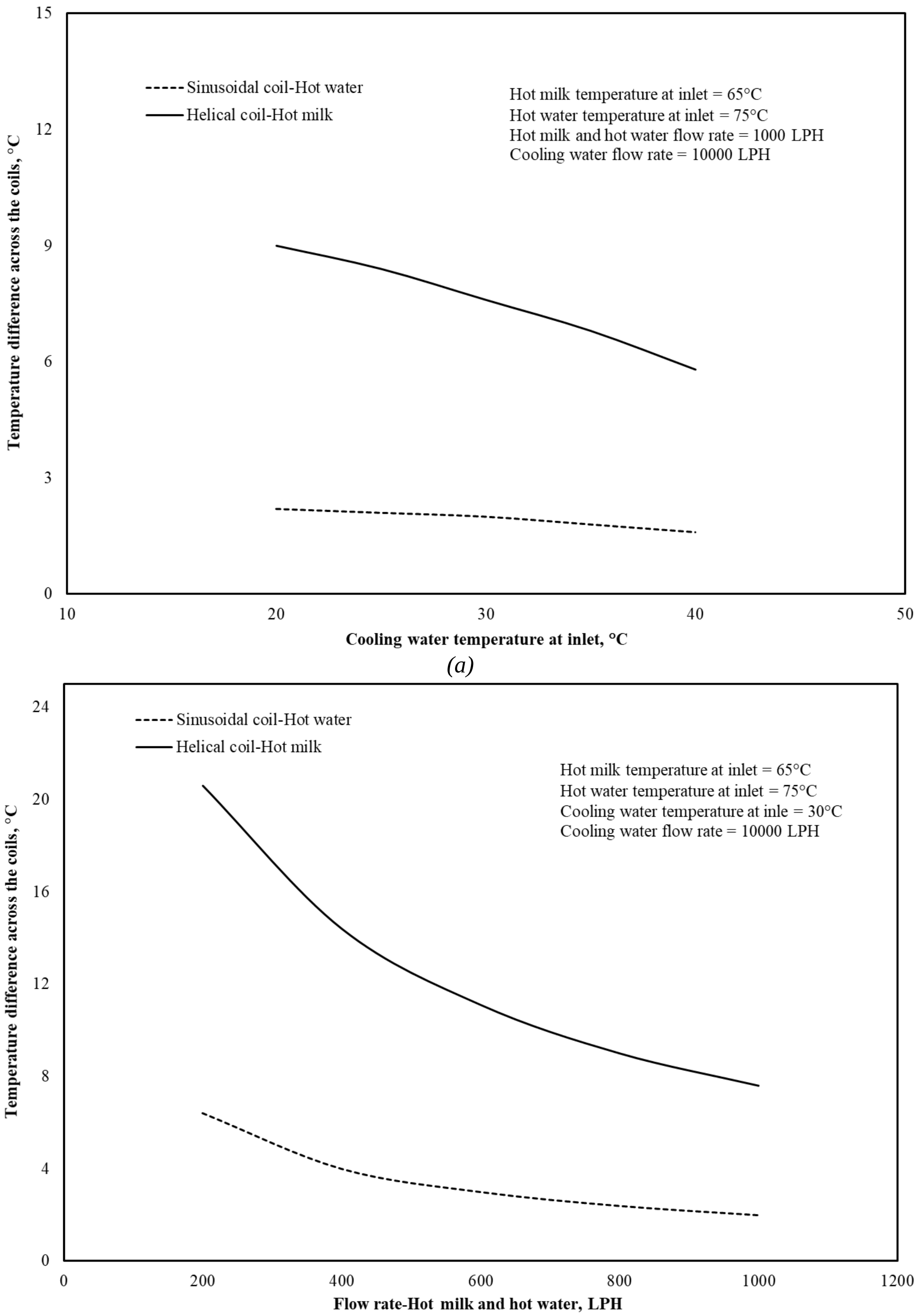


(a)



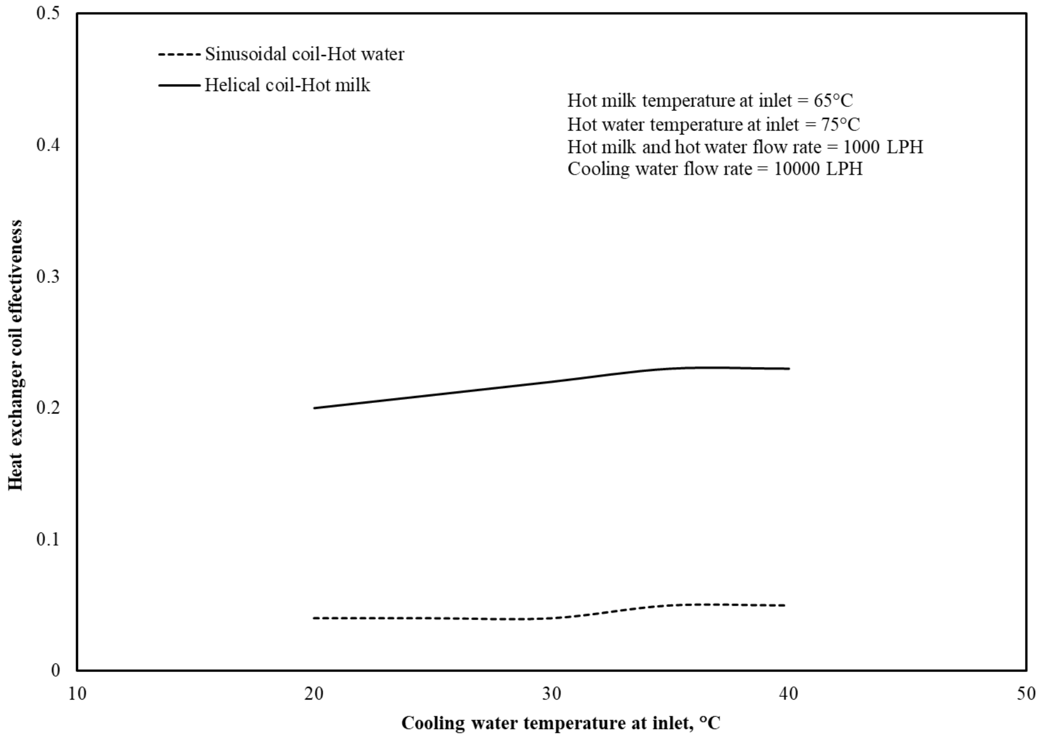
(b)

Figure 6. The heat transfer rate influenced by a) hot fluid flow rate, and b) cooling water inlet temperature.

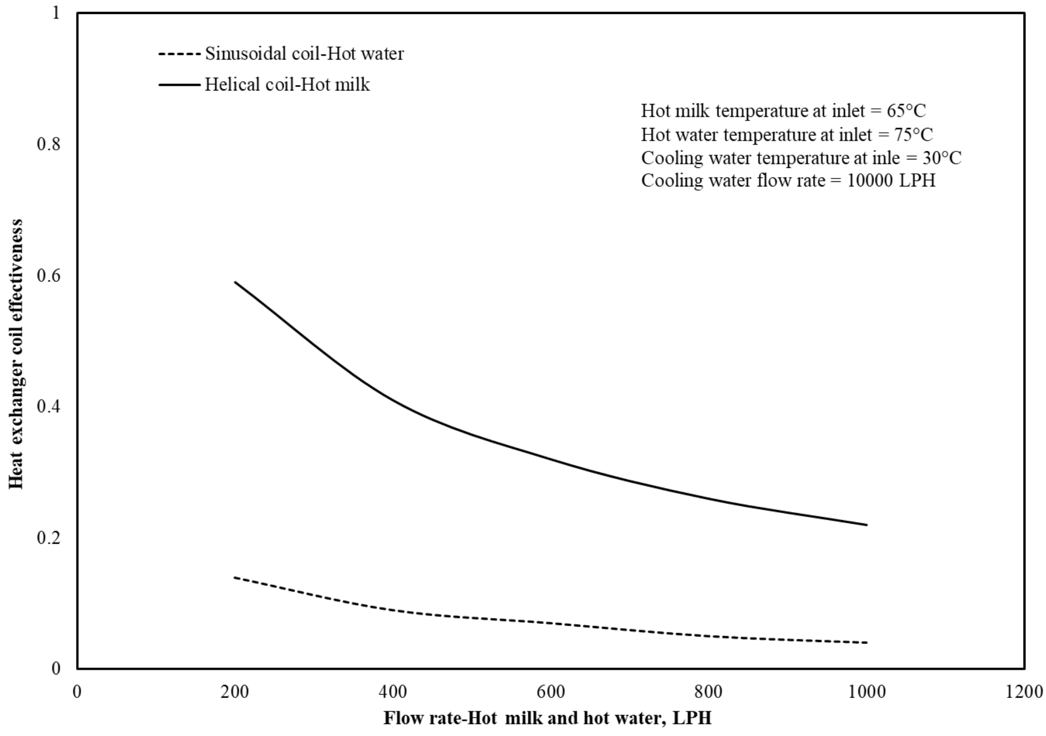


(b)

Figure 7. The temperature difference across the coils influenced by a) hot fluid flow rate, and b) cooling water inlet temperature.



(a)



(b)

Figure 8. The coil effectiveness influenced by a) hot fluid flow rate, and b) cooling water inlet temperature.

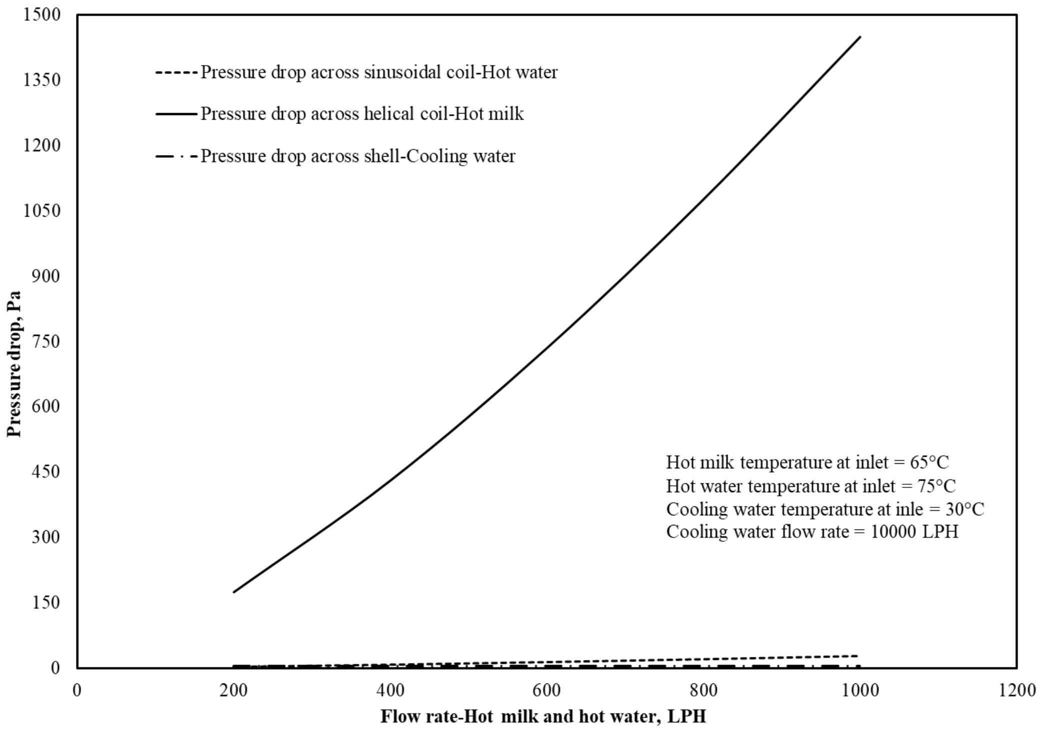


Figure 9. The pressure drop across the coils and shell influenced by hot fluid flow rate.

3. CONCLUSIONS

In the present work, CFD simulations and local and element-by-element method have been employed to analyze the effect of helical and sinusoidal coils on the performance of a triple fluid heat exchanger. The hot water and hot milk fluids are used as working fluids in the helical and the sinusoidal coils, respectively. The cooling water is used as the shell side fluid. The attainment of high heat-load-per-unit area and high surface-area-to-volume ratio are used as the optimizing parameters in the simulations.

The influence of the fluid flow parameters on thermal performance, overall heat transfer coefficient and heat exchanger effectiveness have been explored in detail. The findings prove that the helical coil performs better by removing more heat compared to the sinusoidal coil due to higher flow resistance offered by the helical coil, resulting in turbulence and enhanced heat transfer coefficient. For varying hot fluid flow rates, the helical coil provides an enhanced thermal performance with an improvement of 13% over the sinusoidal coil. However, the pressure drop for the helical coil increases exponentially compared to one for the sinusoidal one, thereby indicating the necessity of higher pumping power for a helical coil. The triple fluid heat exchanger shall be assessed for future engineering applications with the working fluid circuits like hot-hot-cold or hot-cold-cold.

Acknowledgment

The author acknowledges the assistance rendered by the post-graduate energy engineering student of author’s institution, Mr. Putta Venugopal, towards the completion of this work.

REFERENCES

[1] Unal, A. Effectiveness-NTU relations for triple concentric-tube heat exchangers. *International Communications in Heat and Mass Transfer* 2003; *30*: 261-272

[2] Badmaz, E, Sandeep, KP. Calculation of overall heat transfer coefficients in a triple tube heat exchanger. *Heat and Mass Transfer* 2005; *41*: 271-279.

[3] Jayakumar, JS, Mahajani, SM, Mandal, JC, Vijayan, PK, Rohidas Bhoi. Experimental and CFD estimation of heat transfer in helically coiled heat exchangers. *Chemical Engineering Research and Design* 2008; *86*: 221-232.

[4] Garcia-Valladares, O. Numerical simulation of triple concentric-tube heat exchangers. *International Journal of Thermal Sciences* 2004; *43*: 979-991.

[5] Rennie, Timothy J. Numerical and experimental studies of a double pipe helical heat exchanger. Ph.D, McGill University, Montreal, Canada, 2004.

[6] Abdelmagied, M. Experimental study of a triple spirally coiled tube heat exchanger thermo-fluid characteristics. *Applied Thermal Engineering* 2020; *180*: 115803.

[7] Abdelmagied, M. Thermal performance characteristics of a triple spiral tube heat exchanger. *Chemical Engineering & Processing: Process Intensification* 2020; *149*: 107707.

[8] Tiwari, AK, Summaiya, J, Oztop, HF, Said, Z, Pandya, NS. Experimental and numerical investigation on the thermal performance of triple tube heat exchanger equipped with different inserts with WO_3/water nanofluid under turbulent condition. *International Journal of Thermal Sciences* 2021; *164*: 106861.

[9] Bahiraei, M, Mazaheri, N, Hanooni, M. Performance enhancement of a triple-tube heat exchanger through heat transfer intensification using novel crimped-spiral ribs and nanofluid: A two-phase analysis. *Chemical Engineering & Processing: Process Intensification* 2021; *160*: 108289

[10] Elsaid, AM, El-Said, EMS, Abdelaziz, GB, Sharshir, SW, El-Tahan, HR, Abd Raboo, MF. Performance and exergy analysis of different perforated rib designs of triple tubes heat exchanger employing hybrid nanofluids. *International Journal of Thermal Sciences* 2021; *168*: 107006.

[11] Kurt, E, Demirci, M, Sahin, HM. Numerical analyses of the concentrated solar receiver pipes with superheated steam. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* 2022; *236*: 893-910.

[12] Sahin, HM, Baysal, E, Dal, AR, Sahin, N. Investigation of heat transfer enhancement in a new type heat exchanger using solar parabolic trough systems. *International Journal of Hydrogen Energ* 2015; *40*: 15254-15266.

[13] Sahin, HM, Baysal, E, Dal, AR. Experimental and numerical investigation of thermal characteristics of a novel concentric type tube heat exchanger with turbulators. *International Journal of Energy Research*. *2013; 37:* 1088-1102.

[14] Sahin, HM, Dal, AR, Ozkaya, M. Numerical Analysis of a Nested Tube Spring Type Turbulator Heat Exchanger with RNG k-ε Turbulence Model. *Gazi University Journal of Science Part C: Design and Technology*. *2020; 8*: 64-78.