Modelling of the Performance Comparison between Circular and Elliptical Double -Tube Heat Exchanger

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ABSTRACT

Heat exchangers are crucial components for various industrial applications, including oil refining, chemical processing, and power generation. Despite extensive research on heat exchanger performance, the impact of tube geometry on heat transfer efficiency requires further investigation. This study aims to address this gap by comparing the thermal performances of circular and elliptical double-tube heat exchangers using computational fluid dynamics (CFD) analysis. Models of both geometries were created using ANSYS software, and simulations were conducted at varying mass flow rates (0.04 kg/s, 0.07 kg/s, and 0.55 kg/s) to evaluate the heat transfer and fluid flow characteristics. The study found that circular tubes consistently outperformed elliptical tubes in terms of the heat transfer efficiency across all tested flow rates. Specifically, the circular tubes exhibited higher temperature increases in cold water and greater temperature decreases in hot water, as visualised in the temperature contours.

1. Introduction

Heat exchangers are used to transfer heat between two or more fluid streams at various temperatures [1]. They are extensively utilised in power generation, chemical processing, electronic cooling, air conditioning, refrigeration, and automotive applications [2]. One of the most critical and essential elements of electricity, utility, and technological installations is the heat-exchange (or heat-utilising) apparatus. Any conversion of energy from one form to another, as well as any transfer of energy from one system to another, results in the conversion of energy to heat [3].

Heat exchangers are classified as either direct or indirect exchangers. Direct-contact heat transfer occurs when two immiscible fluids, such as gas and liquid, come into direct contact with each other. Examples of direct-contact exchangers include cooling towers and jet condensers for water vapour and other vapours that use water sprays. In indirect contact types, such as automobile radiators, hot

and cold fluids are separated by an impervious surface, and they are referred to as surface heat exchangers. There was no mixing of the two fluids [4]. There are three types of heat exchangers: (a) shell and tube, (b) plate-fin, and (c) counterflow [5,6].

The most common types of heat exchangers are shell and tube. Shell and tube heat exchangers consist of two main components, shells and tubes. The shell is a large vessel containing several tubes. The principle of operation is simple: two fluids at different temperatures are brought into close contact without mixing. One fluid flowed through the tubes, whereas another fluid flowed over the tubes (through the shell) to transfer heat between the two fluids [7].

A Plate Fin Heat Exchanger (PFHE) consists of flat plates and finned chambers to transfer heat between the fluids. PFHEs are often categorised as compact heat exchangers owing to their relatively high heat-transfer surface-area-to-volume ratio. PFHEs are commonly used for gas-to-gas heat exchanges. Various fin geometries, such as triangular, rectangular, wavy, louvered, perforated, serrated, and offset strip fins, are used to separate the plates and create flow channels [8]. The common fin thickness ranges from 0.046 mm to 0.20 mm, and the fin heights range from 2 to 20 mm [9].

A plate heat exchanger is a type of heat exchanger that uses metal sheets to transfer heat between the two fluids. Because fluids flow over the surfaces, this design offers a significant advantage over conventional heat exchangers by exposing the fluids to a much larger surface area. This facilitates heat transfer and significantly increases the rate of the temperature change [10]. Plate heat exchangers have become popular, with very small brazed versions used in millions of combination boilers for hot water parts. The high efficiency of heat transfer in such a compact form improves the flow rate of domestic hot water (DHW) in combination boilers. The small plate heat exchanger profoundly impacted the indoor heating and hot water systems [11].

In a counterflow heat exchanger [12,13], the two fluids flow in opposite directions with hot and cold fluids entering the opposite ends. This type of heat exchanger maximises the rate of heat transfer for a given surface area owing to its counterflow arrangement. Consequently, such heat exchangers are widely used for heating and cooling fluids [14]. Several common advantages of a counterflow heat exchanger include a more uniform temperature distribution between the two fluids, which minimises the thermal stresses throughout the exchanger [15]. In addition, the outlet temperature of the cold fluid approached the highest temperature of the hot fluid [16]. A more uniform temperature difference results in a more consistent rate of heat transfer throughout the heat exchanger.

Several factors can affect the heat transfer rate. Thermal conductivity is a bulk property that describes the ability of a material to transfer heat. The higher the thermal conductivity of a material, the more rapidly heat is transferred through it. Materials with relatively high thermal conductivities are referred to as thermal conductors, whereas materials with relatively low thermal conductivities are known as thermal insulators [17]. Therefore, the thermal conductivities of the materials used in the heat exchangers significantly affect the rate of heat transfer.

Not only can the thermal conductivity affect the rate of heat transfer, but the cross-sectional area can also influence it. As the area increases, the rate of heat transfer also increases. When the area increases, the thermal conductivity also increases because a larger area implies more molecules and electrons on each layer, leading to a greater rate of heat flow through the solid [18]. Consequently, as the thermal conductivity increased, the heat transfer rate also increased.

2. Methodology

In fundamental research [2, 19], the double-tube counterflow heat exchanger was modelled using Design Modeller in ANSYS software. Two circular and elliptical tubes were modelled for the double-tube counterflow heat exchanger. The main components consist of an inner tube and an outer tube, where the outer tube with cold water is the domain and the inner tube with hot water is the domain. Figure 1(a) shows the model of the circular tube of the heat exchanger, and Figure 1(b) shows the model of the elliptical tube of the heat exchanger. Table 1 presents the geometries of the circular and elliptical tubes in the double-tube counterflow heat exchangers.
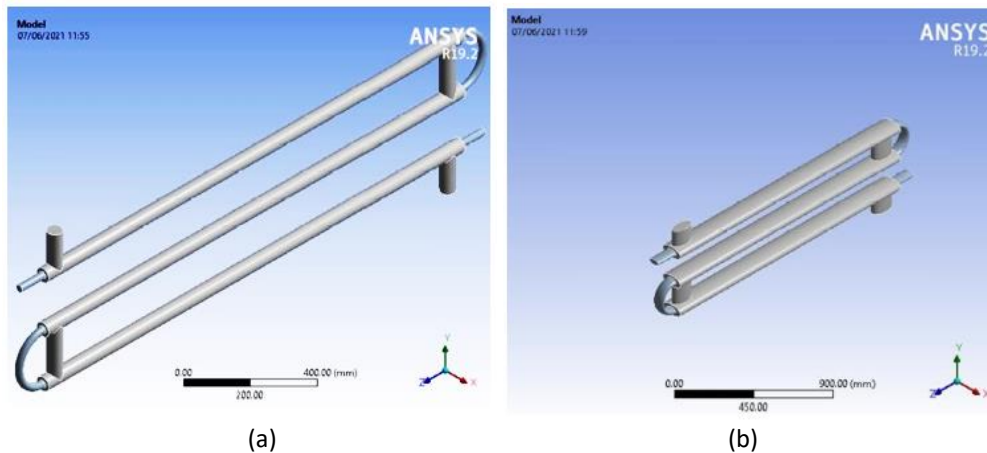

| (a) | (b) |

Fig. 1. Model of heat exchanger (a) Circular shape (b) Elliptical shape tube

Table 1
The geometry of double tube counterflow heat exchanger of circular and elliptical tube

Pipe	Circular tube	Elliptical tube		Length (thickness 2mm)
	Diameter (mm)	Major axis (mm)	Minor axis (mm)	
Inner	25.8	36.48	18.24	1756
Outer	50.6	71.48	35.24	

2.1 Meshing

As the mesh quality increased, the flow solution became more accurate. The overall accuracy of the model depended on the quality of the working cells. Consequently, meshing and simulation processes take longer to achieve the desired mesh quality. A grid independence test (GIT) was used in the project to demonstrate result convergence by controlling variables such as the type of mesh and the number of nodes, and identifying the appropriate element (mesh) size for the geometry. Figure 2(a) shows the meshing for a circular double-tube counterflow heat exchanger and Figure 2(b) shows the meshing for an elliptical double-tube counterflow heat exchanger.

2.3 Boundary Conditions and Parameter Assumptions

The simulations were conducted under steady-state conditions with water serving as the working fluid. Boundary conditions were meticulously defined to ensure accurate results. The inlet temperatures for the hot and cold water were set to 360 K and 300 K, respectively. Three distinct mass flow rates were considered: 0.04 kg/s, 0.07 kg/s, and 0.55 kg/s, to capture the range of flow scenarios. To maintain an incompressible flow, the pressure at the inlets is specified accordingly. The tube walls were subjected to no-slip boundary conditions to ensure that the fluid velocity at the walls

was zero. In addition, a constant heat flux was assumed across the heat exchanger surface, providing a consistent thermal boundary condition throughout the simulations.
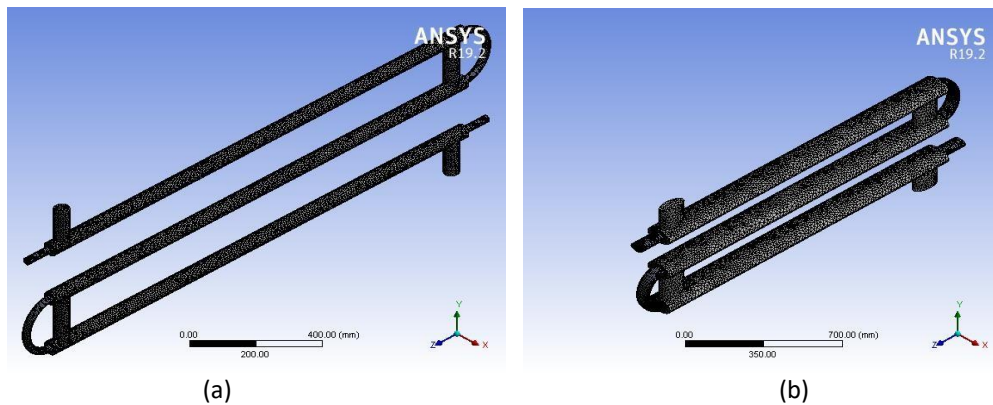

(a)   (b)

Fig. 2. Meshing images (a) Circular double tube counterflow (b) Elliptical double tube counterflow heat exchanger

3. Results

3.1 Circular and Elliptical Tube with 0.04kg/s Mass Flow Rate

Tables 2 and 3 present the results of the CFD simulations for the circular and elliptical tubes at a mass flow rate of 0.04 kg/s. The temperature contours depicted in Figures 3, 4, and 5 further illustrate the thermal performance of both geometries.

Table 2
The result for a circular tube with a flow rate of 0.04kg/s

| Conditions	Cold water inlet	Cold water outlet	Hot water inlet	Hot water outlet
Temperature (K)	300	325.26	360	334.37

Table 3
The result for an elliptical tube with a flow rate of 0.04kg/s

Conditions	Cold water inlet	Cold water outlet	Hot water inlet	Hot water outlet
Temperature (K)	300	322.58	360	336.64

The results indicate that the circular tube exhibits a higher temperature increase at the cold-water outlet and a greater temperature decrease at the hot-water outlet than the elliptical tube. Specifically, the cold-water temperature rises by 25.26 K in the circular tube, whereas it rises by 22.58 K in the elliptical tube. Similarly, the hot-water temperature drops by 25.63 K in the circular tube and by 23.36 K in the elliptical tube. The temperature contours in Figures 3, 4, and 5 provide a visual representation of the heat transfer distribution within the heat exchangers. Figure 3 shows a more uniform and widespread heat transfer in the circular tube, leading to more efficient thermal performance. In contrast, Figures 4 and 5 show that the elliptical tube had a less uniform heat distribution, resulting in a slightly lower heat transfer efficiency.
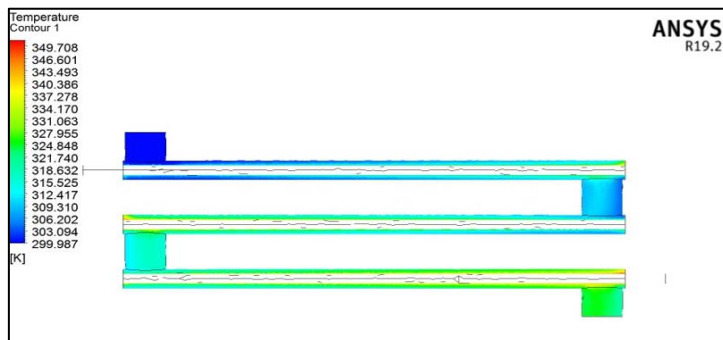
(a)
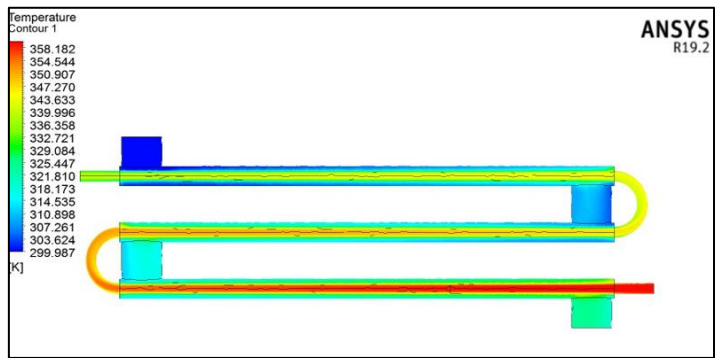
(b)

Fig. 3. Temperature contour (a) Circular tube (b) Elliptical tube (0.04kg/s)

(a)

(b)

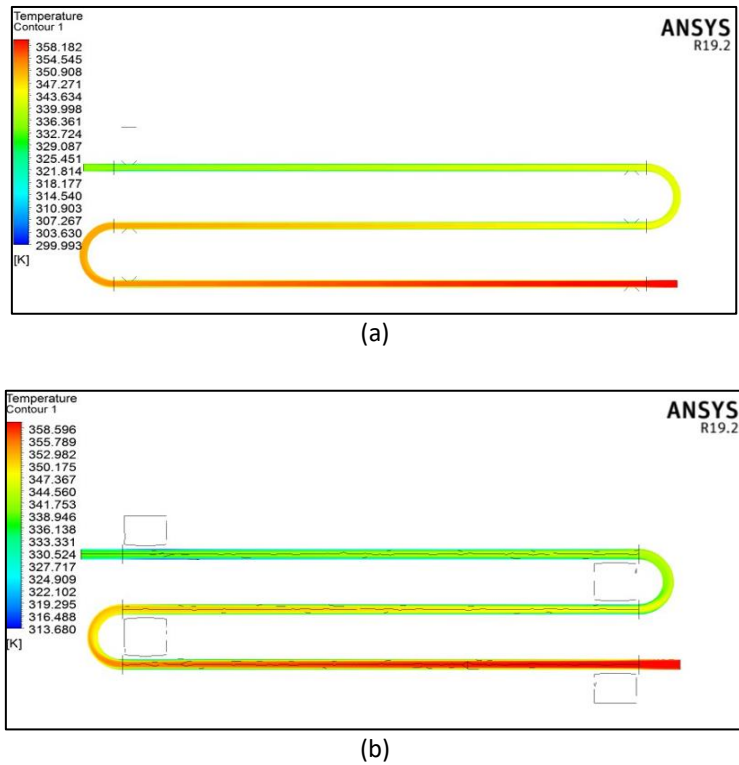**Fig. 4.** Temperature contour (a) Circular tube (b) Elliptical outer tube (0.04kg/s)

(a)

(b)

Fig. 5. Temperature contour for (a) Circular tube (b) Elliptical inner tube (0.04kg/s)

3.2 Circular and Elliptical Tube with 0.07kg/s Mass Flow Rate

Tables 4 and 5 show the simulation results for the circular and elliptical tubes at a mass flow rate of 0.07 kg/s. The overall temperature contours are shown in Figure 6(a) for the circular tube and Figure 6(b) for the elliptical tube. The temperature contour for the cold-water tube is shown in Figure 7(a) for the circular tube and Figure 7(b) for the elliptical tube, and the temperature contour for the hot-water tube is shown in Figure 8(a) for the circular tube and Figure 8(b) for the elliptical tube.

The results show that at a mass flow rate of 0.07 kg/s, the circular tube again demonstrates better heat transfer efficiency than the elliptical tube. The cold-water temperature increases by 21.16 K in the circular tube, compared to a 19.45 K increase in the elliptical tube. The hot-water temperature decreases by 21.29 K in the circular tube and 19.92 K in the elliptical tube. The temperature contours in Figures 6, 7, and 8 provide a visual representation of heat transfer within the heat exchangers. Figure 6 shows a more uniform heat distribution in the circular tube, which contributed to its higher thermal performance.

Table 4
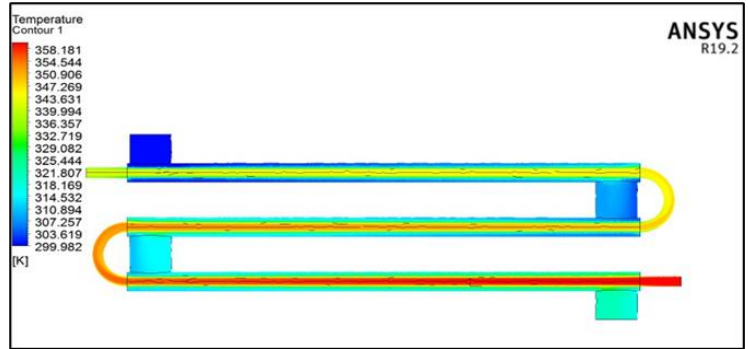The result for a circular tube with a flow rate of 0.07kg/s

Conditions	Cold water inlet	Cold water outlet	Hot water inlet	Hot water outlet
Temperature (K)	300	321.16	360	338.71

Table 5
The result for the elliptical tube with a flow rate of 0.07kg/s

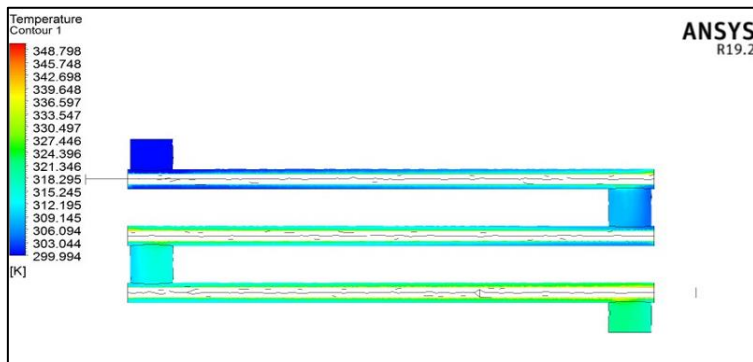| Conditions	Cold water inlet	Cold water outlet	Hot water inlet	Hot water outlet
Temperature (K)	300	319.45	360	340.08

(a)

(b)

Fig. 6. Temperature contour (a) Circular tube (b) Elliptical tube (0.07kg/s)

(a)

(b)

Fig. 7. Temperature contour (a) Circular tube (b) Elliptical outer tube (0.07kg/s)

In contrast, Figures 7 and 8 show that the elliptical tube had a less uniform heat distribution, resulting in a slightly lower heat transfer efficiency. These observations were consistent with the trends observed at the other flow rates. The circular tube consistently provided a more effective heat transfer profile, as evidenced by the more consistent temperature gradients and larger temperature changes in both the hot and cold-water streams. This indicates that circular geometry is better suited for enhancing the heat transfer performance of double-tube heat exchangers under different operating conditions.
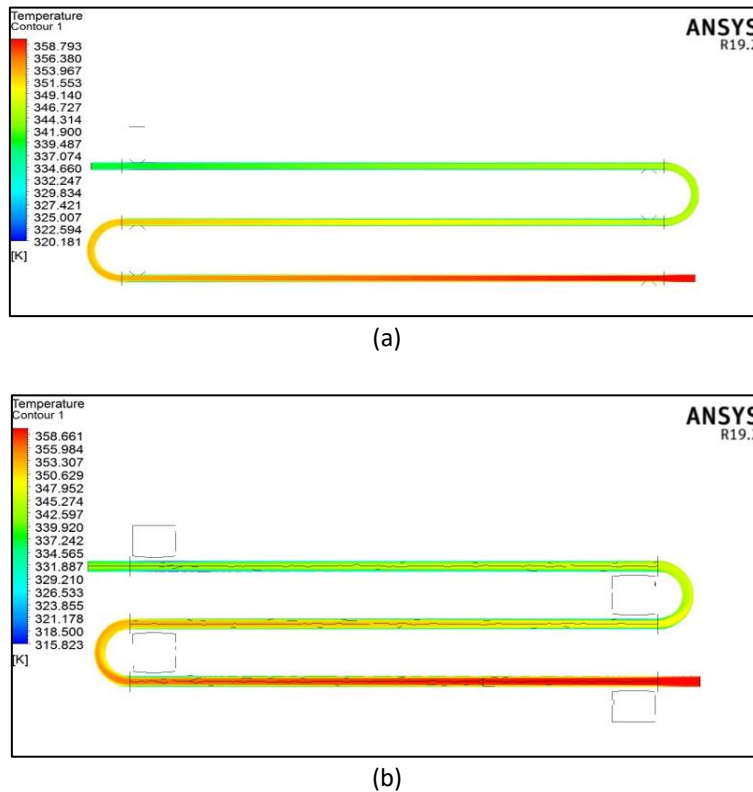

(a)

(b)

Fig. 8. Temperature contour (a) Circular tube (b) Elliptical inner tube (0.07kg/s)

3.3 Circular and Elliptical Tube with 0.55kg/s Mass Flow Rate

Tables 6 and 7 present the simulation results for the circular and elliptical tubes at a mass flow rate of 0.55 kg/s. The overall temperature contours are shown in Figure 9(a) for the circular tube and Figure 9(b) for the elliptical tube. The temperature contour for the cold-water tube is shown in Figure 10(a) for the circular tube and Figure 10(b) for the elliptical tube, and the temperature contour for the hot-water tube is shown in Figure 11(a) for the circular tube and Figure 11(b) for the elliptical tube.

At a higher mass flow rate of 0.55 kg/s, the circular tube continues to outperform the elliptical tube in terms of heat transfer efficiency. The cold-water outlet temperature rises by 13.08 K in the circular tube, compared to a 10.04 K rise in the elliptical tube. The hot-water temperature decreases by 13.12 K in the circular tube and 10.12 K in the elliptical tube.

Table 6

The result for a circular tube with a flow rate of 0.55kg/s

Conditions	Cold water inlet	Cold water outlet	Hot water inlet	Hot water outlet
Temperature (K)	300	313.08	360	346.88

Table 7

The result for the elliptical tube with a flow rate of 0.55kg/s

Conditions	Cold water inlet	Cold water outlet	Hot water inlet	Hot water outlet
Temperature (K)	300	310.04	360	349.88

The temperature contours in Figures 9, 10, and 11 reveal that even at higher flow rates, the circular tube maintained a more effective heat transfer profile. Figure 9 shows a more consistent temperature gradient across the circular tube, indicating better thermal performance. Figures 10 and 11 show that the heat distribution of the elliptical tube was less efficient, with more localised temperature variations and a less uniform heat transfer profile.

In summary, the results across different flow rates consistently demonstrate that circular tubes offer superior heat-transfer performance compared to elliptical tubes. This was attributed to the more effective and uniform heat distribution in the circular tubes, as evidenced by the temperature contours and quantitative data from the simulations.
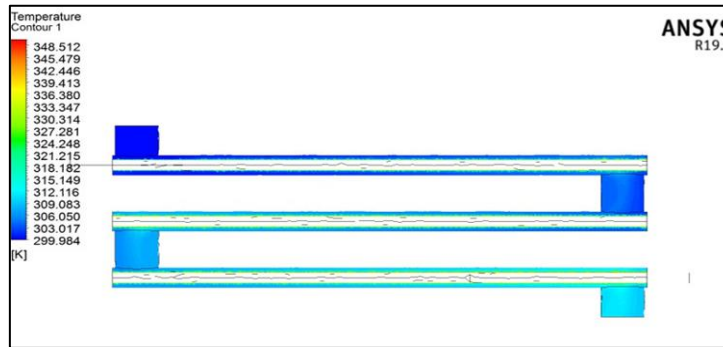

(a)
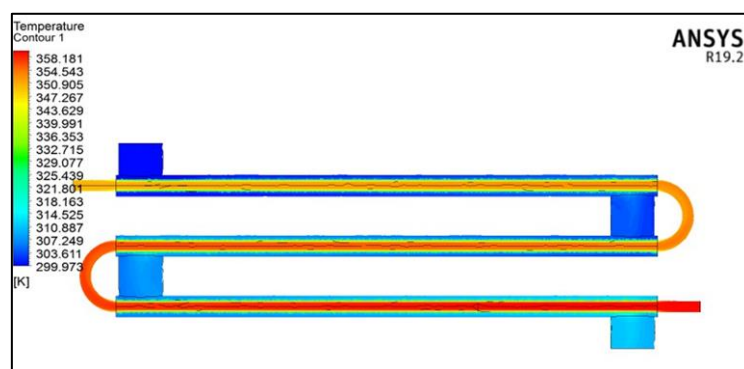
(b)

Fig. 9. Temperature contour (a) Circular tube (b) Elliptical tube (0.55kg/s)
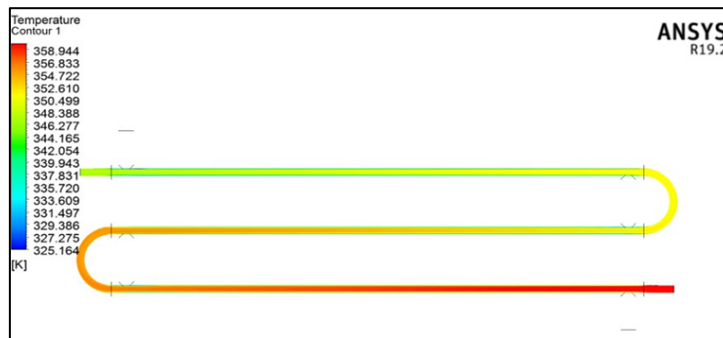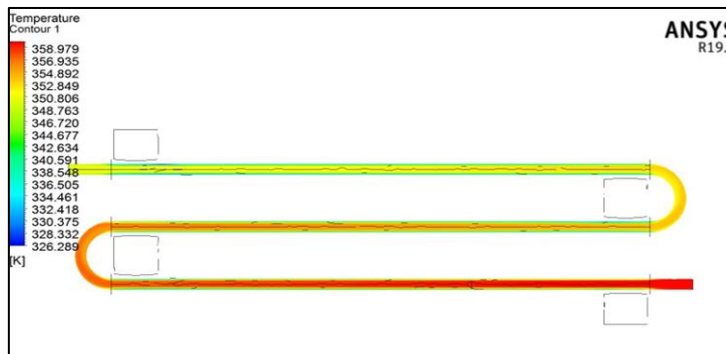
(a)

(b)

Fig. 10. Temperature contour (a) Circular tube (b) Elliptical outer tube (0.55kg/s)

(a)

(b)

Fig. 11. Temperature contour (a) Circular tube (b) Elliptical inner tube (0.55kg/s)

3.4 Comparison between Circular and Elliptical Shape Tube

Based on the temperature comparison between the circular and elliptical tubes, the maximum heat transfer rate was found at a flow rate of 0.04 kg/s with the circular tube. The data indicate that the circular tube is more effective than the elliptical tube in terms of heat transfer rate. At a flow rate of 0.04 kg/s, the hot water passing through the circular tube has cooled down by 25.52 K, which is more than the cooling achieved by the hot water passing through the elliptical tube. By comparing the cooling temperatures of the hot water, the flow rate of 0.04 kg/s has the highest cooling effect at 25.52 K, followed by 0.07 kg/s and 0.55 kg/s. Based on these results, it can be stated that the lower the flow rate, the higher is the cooling rate of the water. The simulation results were compared with those from a previous study. For the results to be validated, the percentage error should be within 5%. Table 4.17 shows the validation results between the simulation and the previous study. The error between the experimental and validation results shown in the table was less than 5%.

4. Conclusions

This study successfully modelled and analysed the performance of circular and elliptical double-tube heat exchangers using CFD simulations. The results demonstrate that circular tubes provide better heat transfer efficiency than elliptical tubes at various flow rates. The validation of the simulation results with the experimental data showed a percentage error of less than 5%, confirming the accuracy of the CFD models. Future work could explore the impact of other geometrical modifications and boundary conditions to further optimise heat exchanger performance.

References
[1] Jangid, Sonam. "Plate type heat exchanger—A review study." *IOSR Journal of Engineering* 8 no. 10 (2018): 2278-8719.
[2] Khayal, O. M. E. S. "Fundamentals of heat exchangers." *International Journal of Research in Computer Applications and Robotics* 6, no. 12 (2018): 1-11.
[3] Edreis, Edreis, and A. Petrov. "Types of heat exchangers in industry, their advantages and disadvantages, and the study of their parameters." In *IOP Conference Series: Materials Science and Engineering*, vol. 963, no. 1 (2020): 012027. https://doi.org/10.1088/1757-899X/963/1/012027
[4] Zohuri, Bahman. *Compact heat exchangers*. Cham, Switzerland: Springer, 2017. https://doi.org/10.1007/978-3-319-29835-1.
[5] Zohuri, Bahman, and Bahman Zohuri. "Heat exchanger types and classifications." *Compact Heat Exchangers: Selection, Application, Design and Evaluation* (2017): 19-56. https://doi.org/10.1007/978-3-319-29835-1_2
[6] Zohuri, Bahman, and Bahman Zohuri. "Thermal Design of the Selected Compact Heat Exchanger." *Compact Heat Exchangers: Selection, Application, Design and Evaluation* (2017): 187-265. https://doi.org/10.1007/978-3-319-29835-1_4
[7] Arsenyeva, Olga, Leonid Tovazhnyanskyy, Petro Kapustenko, Jiří Jaromír Klemeš, and Petar Sabev Varbanov. "Review of developments in plate heat exchanger heat transfer enhancement for single-phase applications in process industries." *Energies* 16, no. 13 (2023): 4976. http://dx.doi.org/10.3390/en16134976
[8] Permana, Ikhwan, Tri Ayodha Ajiwiguna, and Mukhammad Ramdlan Kirom. "Comparison of heat transfer coefficient on single tube and multi tube heat exchanger." In *Journal of Physics: Conference Series*, vol. 1153, no. 1, p. 012138. IOP Publishing, 2019. https://doi.org/10.1088/1742-6596/1153/1/012138
[9] Thakur, Narayan, Advait Inamdar, Deepak Pal, and Akshat Mohite. "Heat Exchangers in Aerospace Applications." *International Research Journal of Engineering Technologi* 8, no. 3 (2021): 266-274.

[10] Taufiq, Abdul, and P. S. Dhakar. "CFD analysis of plate heat exchanger by using Ansys." *International Journal of Research and Analytical Reviews (IJRAR)* 7, no. 3 (2020).

[11] Nair, Ajay Muraleedharan, Christopher Wilson, Ming Jun Huang, Philip Griffiths, and Neil Hewitt. "Phase change materials in building integrated space heating and domestic hot water applications: A review." *Journal of Energy Storage* 54 (2022): 105227. https://doi.org/10.1016/j.est.2022.105227

[12] Bejan, Adrian, Mohammad Alalaimi, Sylvie Lorente, A. S. Sabau, and James W. Klett. "Counterflow heat exchanger with core and plenums at both ends." *International Journal of Heat and Mass Transfer* 99 (2016): 622-629. https://doi.org/10.1016/j.ijheatmasstransfer.2016.03.117

[13] Chekurov, Sergei, Jyrki Kajaste, Kari Saari, Heikki Kauranne, Matti Pietola, and Jouni Partanen. "Additively manufactured high-performance counterflow heat exchanger." *Progress in Additive Manufacturing* 4 (2019): 55-61. https://doi.org/10.1007/s40964-018-0059-x

[14] Simhadri, K., G. V. D. Mohan, and P. Sai Chaitanya. "Comparison of overall heat transfer coefficient value of double pipe heat exchanger without and with various twisted inserts of different twist ratios." *Journal of Mechanical and Civil Engineering* 12 (2015): 115-124.

[15] Ali, Murad, Anwar Ul-Hamid, Luai M. Alhems, and Aamer Saeed. "Review of common failures in heat exchangers–Part I: Mechanical and elevated temperature failures." *Engineering Failure Analysis* 109 (2020): 104396. https://doi.org/10.1016/j.engfailanal.2020.104396

[16] Azam, Syafiqah Ruqaiyah Saiful, Nofrizalidris Darlis, Norrizal Mustaffa, Mohamad Amirur Rahman Azahar, Amirul Syafiq Bin Sadun, Omar Abu Hassan, Ishkrizat Taib, Khairul Nizam Mustaffa, and Muhamad Mohshein Hashim. "CFD Analysis of the Effect of Heat Distribution on Different Heating Pad Piping Arrangements for Flexitank Application." *CFD Letters* 15, no. 2 (2023): 1-15. https://doi.org/10.37934/cfdl.15.2.115

[17] Burger, N., A. Laachachi, M. Ferriol, M. Lutz, V. Toniazzo, and D. Ruch. "Review of thermal conductivity in composites: Mechanisms, parameters and theory." *Progress in Polymer Science* 61 (2016): 1-28. https://doi.org/10.1016/j.progpolymsci.2016.05.001

[18] Annaratone, Donatello. *Engineering heat transfer*. Springer Science & Business Media, 2010.

[19] Fakheri, Ahmad. "Heat exchanger fundamentals: analysis and theory of design." In *Handbook of Thermal Science and Engineering*, pp. 1315-1352. Springer, Cham, 2018. https://doi.org/10.1007/978-3-319-32003-8_19-1