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RESEARCH ARTICLE

Design of A Counter-Flow Shell and Tube Heat Exchanger: Effect of The Number of Plates on Heat Transfer and Determination Thereof

Nesrin ADIGÜZEL[1,*] Muhammet ÖZGERİŞ[1] Fadime ŞİMŞEK[1] Büşra BAYRAKTAR[1]

[1] *Post-Graduate Student (Doctorate), Ataturk University, Erzurum, Türkiye*
[2] *Department of Mechanical Engineering, Faculty of Engineering, Ataturk University, 25240 Erzurum, Türkiye*

** Corresponding author E-mail: nesrin.adiguzel@atauni.edu.tr*

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ABSTRACT

In this study, the variation of heat transfer characteristics was observed by means of plates attached to the copper tube of a counter-flow shell and tube heat exchanger designed in SolidWorks. The heat exchanger body, i.e. the shell, and the plates were defined as made of 304 stainless steel, and the thin-wall inner tube as copper. With respect to the number of plates and the positioning thereof, the outlet temperatures of the hot and cold fluids were examined and compared in terms of heat transfer. As a result of the data obtained from the analyses, the heat transfer was shown to increase linearly with the number of plates to a certain number, and the optimum number of plates was determined to be 7, having increased the heat transfer by 24% - 52% compared to the case without plates. The positioning of the plates, on the other hand, found to have an insignificant effect.

Contents

1. Introduction

One of the mechanical elements open to continuous improvement and development in engineering terms is heat exchangers. Heat exchangers are mechanical systems that transfer (exchange) heat between two or more fluids having same, similar or completely different properties but which are at different temperatures, generally without mixing them. Heat exchangers are actively used in many fields in industry. In cases where the fluids present in the heat exchangers should not come into contact with each other during the heat transfer, the fluids are separated from each other by thin-wall tubes or metal sheets. However, heat exchanger types in which fluids are mixed are also widely used.

Pourahmad et al. investigated in their study the thermal performance of a double pipe heat exchanger by concurrently using active and passive methods. Using a double twisted-tape turbulator, they inject air bubbles into the working fluid and evaluated the effects of these two interventions on the Nusselt number (Nu) and pressure drop. As a result of the study, the Nu was observed to have increased with the decrease in the twist rate of the turbulator whereas the bubble injection flow rate, cold water flow rate and Reynolds number (Re) increased with the increase in the twist rate. They also revealed that the simultaneous use of the two methods could increase the Nu by 98–114%, 3–14%,

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and 20–39%, compared to a ordinary tube heat exchanger. Besides increasing the heat transfer, another important finding of the study was that the implementation of this method increased the pressure drop and increased the pump power consumption [1].

Salhi et al. conducted a numerical simulation for the investigating hot fluid properties for a horizontal concentric double pipe heat exchanger (DPHE) equipped with turbulators operating in turbulent regime at Re 3000 to 17,000. The heat exchanger was designed to ensure an efficient heat transfer with less heat loss, exchanging heat between the primary fluid (hot air) and the secondary fluid (cold water). Thermal parameters such as Nu, friction factor, thermal performance factor, turbulent viscosity, temperature domain and velocity domain were evaluated and as a result, it was observed that the structure of the flow was strongly influenced by the shape and dimensions of the separators placed. It was found that the Nu and friction factor increased with the pitch and that the heat transfer was positively affected [2].

Xiong et al. conducted a study showing the effect of conical and fusiform turbulators placed in a DPHE on heat transfer and turbulent flow patterns. A total of 21 configurations, comprising of conical and fusiform turbulator inserts and of DPHE configurations with circular and rectangular tubes, were simulated at four Re numbers (4000, 7000, 10000 and 13000) using fluent software. The maximum convective heat transfer coefficient was reported to have been reached with a circular inner pipe [3].

Yadav et al. investigated in their experimental study the pool boiling heat transfer properties of multi-scale functionalized copper surfaces produced using the nanosecond laser surface treatment (NLSP) technique. Experiments were carried out under atmospheric pressure and saturated pool boiling conditions. The increase in the heat transfer coefficient from the laser-treated surfaces, compared to the reference flat surface, was reported to be 93%, 62% and 52% for 1064nm, 355nm and 532nm wavelengths, respectively [4].

Armatsombat and Chinsuwan studied the heat transfer behavior of immersed tubes used in in the aerated recycling chamber at the bottom of supply and return chambers of a conventional loop seal with heat exchanger (LSHE). The heat transfer behavior of immersed tubes with and without side aeration was investigated and it was revealed that the average heat transfer coefficient around the tubes was higher with side aeration and that the thermal stress induced by the temperature difference was lower without side aeration [5].

Due to their small diameter, DPHEs are mostly used in high temperature and high pressure applications. Numerous techniques have been devised to achieve the required heat transfer rate at an economical pumping capacity within the specified design and duration of the heat exchanger. The most popular and efficient techniques for the efficacy of heat exchangers are helical inserts. Focused on improving the thermal efficiency of heat exchangers, Padmanabhan et al. investigated the performance of a DPHE with helical inserts using ANSYS CFX and made a comparative analysis of the heat flow and temperature distribution along the pipe with and without helical inserts [6].

Raghulnath et al. investigated the effect of circumferential turbulators on the heat transfer rate in a shell and helical coil heat exchanger. The performance evaluation of heat exchangers was made through the heat transfer coefficients, Re, Nu, temperature distribution, and pressure drop values. The helical coil imparts more turbulence to the fluid flowing through it. And the turbulence in the cold fluid flow was induced by the implementation of a circumferential turbulators around to coil, i.e. between the coil and the shell, where the cold fluid flows through. For constant cold fluid mass flow rate, different hot fluid mass flow rates (0.03kg/s, 0.06kg/s, 0.09kg/s and 0.12kg/s) were tested and performance parameters were calculated through the measurements. As a result of the study, performance of the system was reported to have decreased when the mass flow rate of the cold fluid exceeded that of the hot fluid [7].

Vivekanandan et al. investigated the thermal, hydraulic and thermodynamic performances of the spiral coil heat exchanger by cascading placement of the coil inside the cylindrical shell. Experiments with variable flow conditions were carried out to determine the optimum flow rate in the spiral heat exchanger. The volume flow rate through the spiral tube was varied from 2L/min to 6 L/min versus two volume flow rates through the shell: 4L/min and 10L/min. Efficiency, Nu, Prandtl number, heat transfer rate, total heat transfer coefficient and exergy efficiency were analyzed at various flow rates in the experimental part in order to verify the CFD results. As a result, 10L/min flow rate through the shell was found to be better in providing higher efficiency at all flow rates between 2 to 6 L/min through the spiral coil. The results obtained from the CFD analyses and experiments were reported to be in good agreement [8].

Bahiraei et al. sought to examine the effects of an innovative crimped-spiral rib in a triple-pipe heat exchanger (TPHE) using alumina-water nanofluid on the efficiency of the system with respect to the second law efficiency. While the water-alumina nanofluid was the hot fluid flowing inside the intermediate pipe where the ribbed side of the internal tube was, the other two fluids were water. Experiments have shown that the implementation of crimped spiral ribs was effective, reducing the thermal entropy generation of the nanofluid by about 22.92% by means of the stronger swirl flow induced by crimped ribs. Total entropy generation, hence total exergy destruction, decreased with the increase in the volume fraction of the nanofluid, with the decrease in the rib pitch, and with the increase in the crimp intensity or rib height. Accordingly, the second law efficiency of the system was found to be higher than 0.6 for all cases [9].

Lara-Montaño et al. addressed the optimization of shell and tube heat exchangers (STHE), an important equipment used in the industry, through evaluation of four case studies designed using Kern's and Bell-Delaware methods, as mathematical models describing the thermo-hydraulic behavior of the system create a complex search domain. A total of 16 optimization problems (four per case study) comprising discrete and continuous pipe diameters were addressed using metaheuristic methods. In conclusion, the metaheuristic algorithms with the best global performance were reported to be differential evolution and gray wolf optimization [10].

Marzouk et al. experimentally investigated the thermal, hydraulic and thermodynamic performances of a STHE equipped with circular rod inserts on top of the tube and compared all data obtained in their experiments with the conventional ordinary STHE. Experimental results showed that the proposed insert configurations induced a significant improvement in thermal and thermodynamic performance of the heat exchanger despite a decline in the hydraulic performance. The percentage of the improvement achieved in U, NTU, ε and exergy efficiency were reported to be (210–280%), (132–149%), (185–224%) and (130–210%), respectively, in comparison to the conventional STHE [11].

Yıldız and Ersöz [12] studied chevron type plate heat exchanger and examined the parameters affecting the efficiency by making energy and exergy analyzes for a total of 15 plates with a thickness of 0.3 mm. Cold fluid mass flow rate at the smallest and hot water flow rate at the highest were found to be the most efficient combination, providing a 0.94 energy efficiency. With regards to exergy efficiency, on the other hand, cold fluid flow rate at the smallest and hot water flow rate at the smallest were the most efficient providing a 0.53 efficiency.

Gomaa et al. presented the results of their experimental and numerical examinations of the concentric TPHE, especially with reference to a DPHE. A numerical CFD model developed using the finite volume discretization method was validated and expanded to cover more design parameters and four flow patterns were executed: counter-flow, co-flow, co-flow vs counter-flow, and counter-flow vs co-flow. Correlations of the Nu, dimensionless design parameters, friction factor and heat exchanger efficiency were also presented. As a result, TPHE was found to provide higher efficiency and greater energy savings per unit length, compared to DPHE [13].

Turgut and Yardımcı investigated the effects of semicircular striped turbulators placed in the inner tube of a DPHE on heat transfer (Nu), friction factor (f) and thermal performance factor (TPF). With the determined design parameters, Nu and f increased by 5.43 and 4.71 times, respectively, compared to the plain pipe, and the TPF increased up to 3.72. Taguchi Experimental Design, Analysis of Variance (ANOVA), and Gray Relational Analysis (GRA) were implemented in the study and the arrangement of the turbulators was found to have the strongest effect (32.94%) and similar to heat transfer, the pitch had the weakest effect on the friction factor. According to this analysis, the most effective parameter on multiple performance characteristics was the Re [14].

Nakhchi et al. in 2021 experimentally investigated the effect of a novel Double-Perforated Inclined Elliptic (DPIE) turbulator on the heat transfer and thermal efficiency of a DPHE. Perforated turbulators have the potential to significantly increase the flow disturbances and to disrupt the thermal boundary layer so as to increase heat transfer without a remarkable impact on friction loss. Experiments revealed that the average Nu increased by 217.4% using DPIE turbulators compared to the tube without vortex generators. Thanks to the recirculation through the perforations of the elliptical turbulators, the fluid mixing between the walls and the core area was increased. A 14.0% increase in friction factor was observed for DPIE turbulators with $d/b = 0.25$ compared to typical elliptical inserts [15].

Studying on plate heat exchangers, Büyükaşik [16] examined plate types with respect to efficiency by designing own plates and compared them with the existing plate types to decide on the most suitable plate geometry. Making a comparison, by means of ANSYS CFD software, between radial edged plates and sharp-edged plates, he concluded that the Nu for both types increased by 20% to 25% in direct proportion to the wave amplitude. The friction factor was reported to be directly proportional to the wave amplitude and the internal edge space. The most suitable geometry was found to be at 0.3 wave amplitude and 0.7 internal space values.

In another study aimed at increasing heat transfer rate, the frictional behaviors of a STHE was investigated introducing different number of swirl vanes at different locations along the pipe length in a simulated model by making use of ANSYS FLUENT CFD methods. Each pipe was equipped with 3 and 6 swirl vanes with different diameters (10mm, 15mm, 19mm) and different vane angles (15°, 30°, 45°) as distributed along the length of the pipe. It was revealed in the study that six swirl vanes with a 19mm diameter and 45° vane angle provided maximum heat transfer improvement, friction factor and thermal improvement factor compared to the plain tube [17].

Luo and Song proposed a new twisted annulus, having same twist pitch, between two counter-twisted oval tubes for a DPHE. A numerical analysis of the thermo-hydraulic performance of annuli were conducted with different aspect ratios and twist ratios and a strong secondary flow was shown to have occurred in the twisted annulus, which can induce a remarkable increase in the heat transfer. The Nu and f of the twisted annuli were reported to be 157% and 118% higher compared to straight counterparts. The maximum value of the thermal performance factor in the devised system was 1.98. Correlations Nu and f as a function of Re, twist ratio and aspect ratio were proposed and their deviations were reported to be ±10% and ±8%, respectively [18].

2. Materials and Methods

In the heat exchanger designed in SolidWorks, the inner tube defined as of copper and the heat exchanger surface of 304 stainless steel.

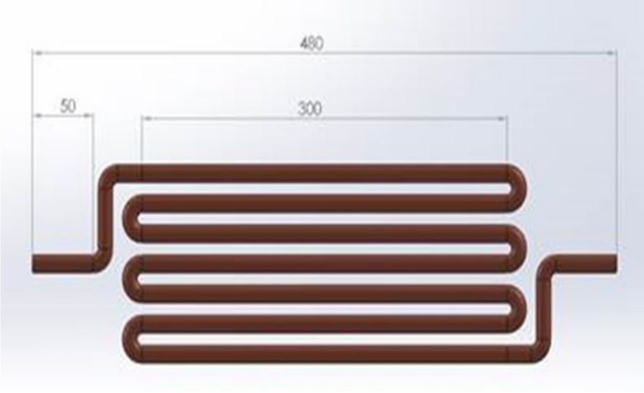

Figure 1 The dimensions of copper pipes

Copper pipe has an inner diameter of 10mm and a wall thickness of 1mm. The dimensions of the copper pipe were as shown in Figure 1. The copper pipe was placed inside the 304 stainless steel shell and thus heat exchange without mixing the fluids was thus ensured.

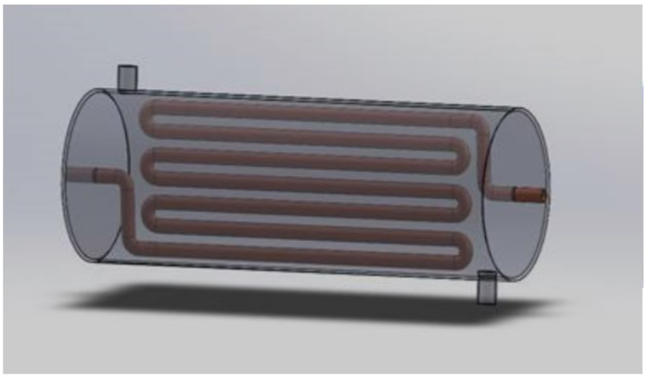

Figure 2 Heat exchanger: without plates

Hot fluid runs through the copper pipe and cold fluid passes through the shell. Figure 2 shows the assembled heat exchanger. In order to improve the heat transfer within the designed heat exchanger, a plate design was made (Figure 3.a) and incorporated into the exchanger as shown inFigure 3.b, in different numbers. The plates were defined as made of the same material as the shell of the heat exchanger. The plates were positioned one upside down and one upright so as to force the cold fluid stay longer in contact with the hot fluid, by directing the flow through the pass ways on the plates.

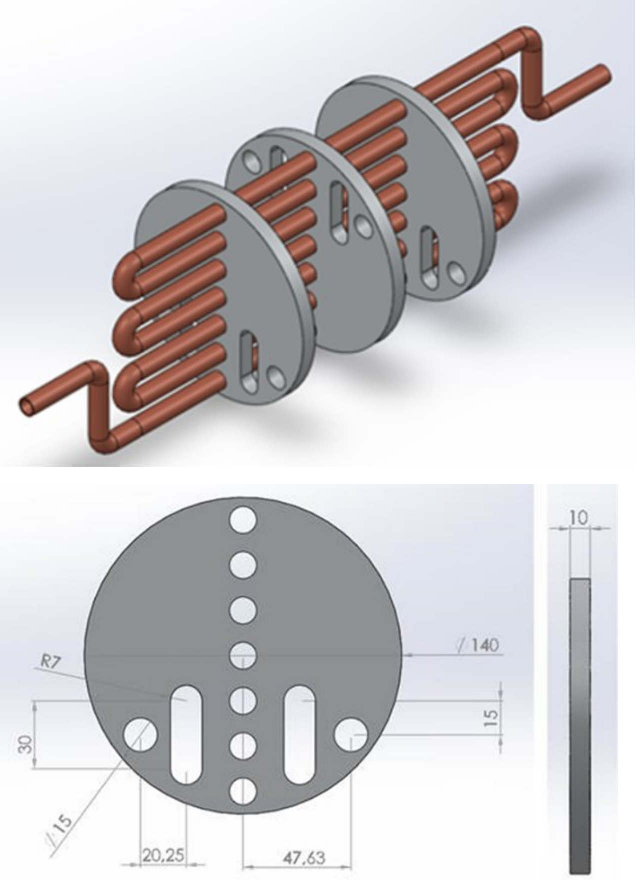

Figure 3 **(a)** Design and dimensions of the plates) and **(b)** the placement of plates (3 plates in this case) in the shell and around the copper pipe.

With the implementation of plates, the total time it takes the cold fluid entering the shell from the top to circulate through the exchanger was aimed to be extended and thus the heat transfer from the hot fluid to the cold fluid be improved.

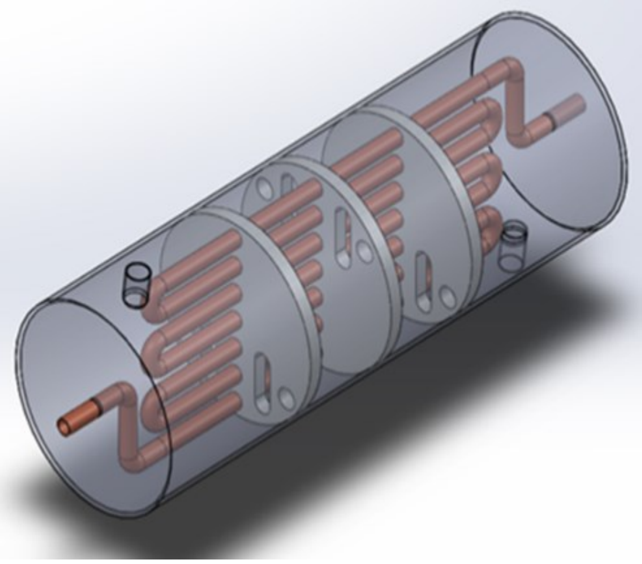

Figure 4 General assembly with 3 plates

A general assembly of the heat exchanger with three plates is shown in Figure 4. The diameter of cold fluid inlet and outlet is 10mm and the wall thickness is 1.5mm. The inner and outer diameter of the shell are 140mm, 145mm, respectively whereas the length of the shell is 430mm. These values were constant for all assemblies and only the number of plates placed inside was changed.

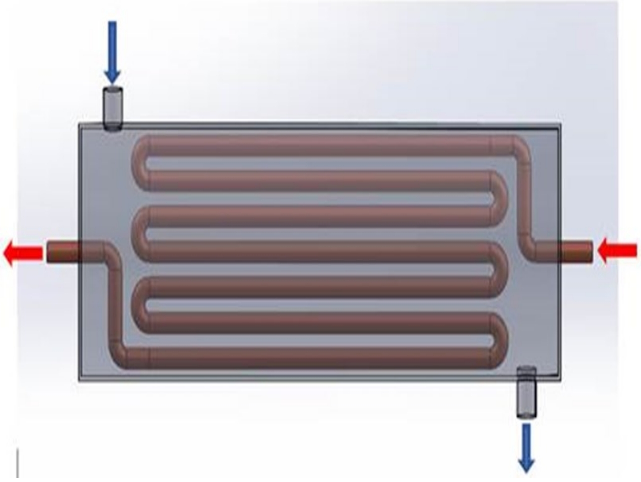

Figure 5 Fluid inlet and outlet directions

Further, the fluids entering the heat exchanger were defined as water in all analyses and the velocities of the hot water entering the copper pipe and of the cold water entering the shell were set constant as 0.2m/s and 0.25m/s, respectively, in all analyses. The flow directions were as seen in Figure 5, blue denoting the cold fluid, and red denoting the hot.

The analyses were done for the heat exchanger without plates first, and then the repeated for 2, 3, 4, 5, 6, 7 and 8 plates adding one at a time. The data were acquired and plotted as temperature against different research parameters to reflect their effects on the input and output values.

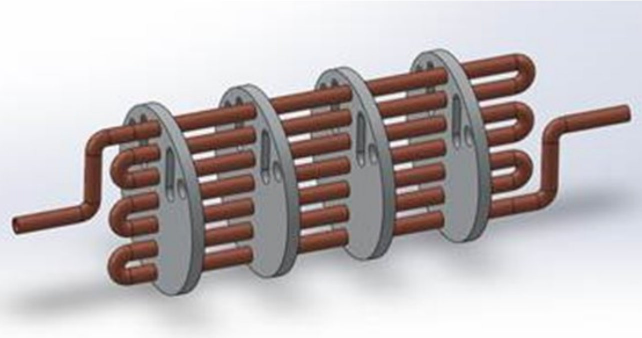

Figure 6 The assembly to inspect the effect of positioning of plates

Lastly, the positioning of the plates was changed to align all pass ways on the plates on a straight line (Figure 6) so as to investigate the effect of positioning on heat transfer. Analyzes were made repeatedly by changing the number of plates.

3. Findings and Discussion

Within the scope of the design and analyses, plates that vertically divide the shell were placed to the counter flow shell and tube heat exchanger aiming to increase the heat transfer by redirecting the fluid to increase the duration of contact of the hot fluid running through the inner copper pipe with the cold fluid passing through the shell of the exchanger.

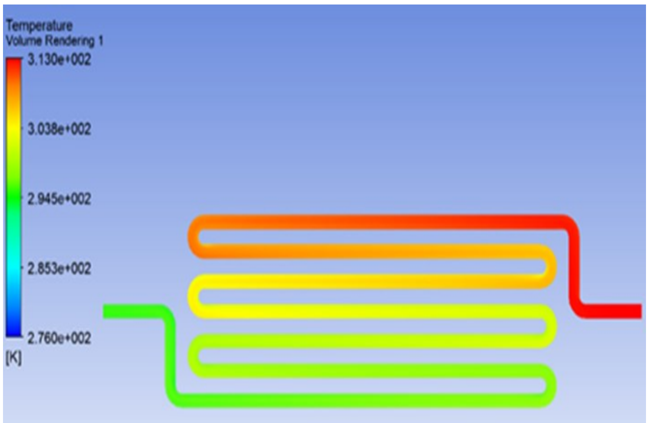

Figure 7 Temperature distribution of the hot fluid in the copper pipe: for the 3-plates case

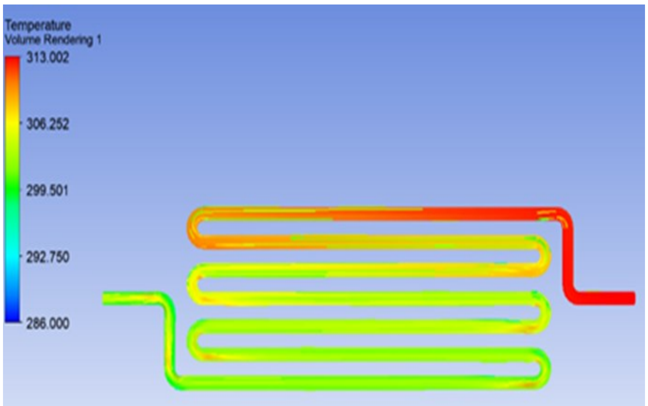

Figure 8 Temperature distribution of the hot fluid in the copper pipe: for 2-plates case

Seen in Figure 7 and Figure 8 are the temperature distribution of the how fluid throughout the copper pipe with 2-plates and 3-plates, respectively. The effect of the number of plates on the heat transfer are presented below in the Figures based on these results.

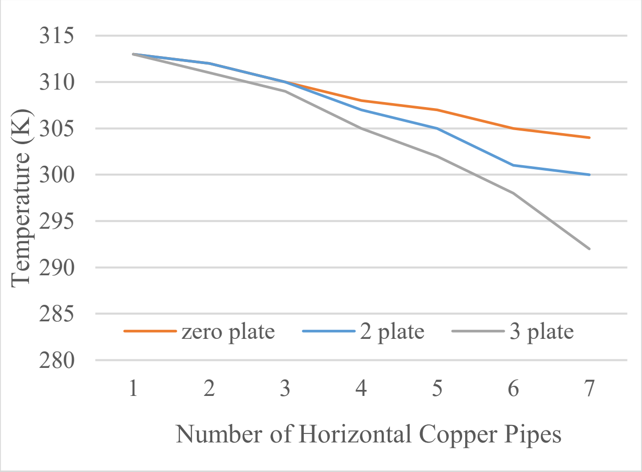

Figure 9 Variation of hot fluid temperature throughout the copper pipe for the reference case (without plates), 2-plates and 3-plates.

The results of the numerical analyses are given in Figure 9. Compared to the reference case, i.e. without plates, the difference in the output temperature of the hot fluid is 4 Kelvin with 2-plates, and 9 Kelvin with 3-plates. As seen in Figure 9, the number of plates positively affects the heat transfer from the hot fluid.

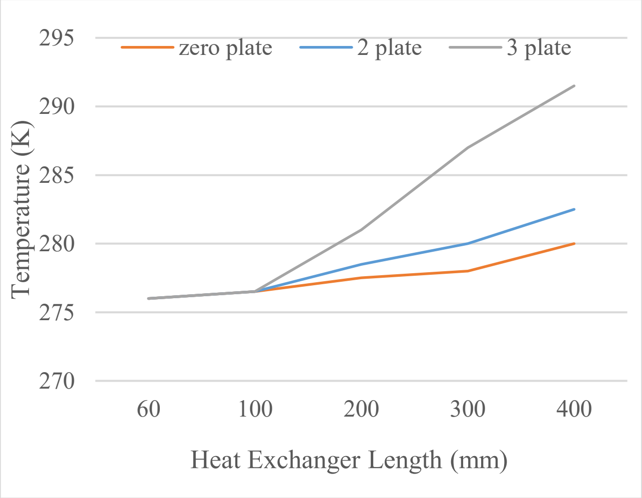

Figure 10 Variation of the cold fluid temperature across the heat exchanger shell for the reference case (without plates), 2-plates and 3-plates.

The variation of the temperature of cold fluid across the length of the shell against the number of plates placed inside the heat exchanger is presented in Figure 10. The variation of the cold fluid temperature with the number of plates is positive, i.e. the heat transferred to the cold fluid increased with the increase of the number of plates. The analyses were repeated by adding one plate at a time until the optimum number of plates was determined.

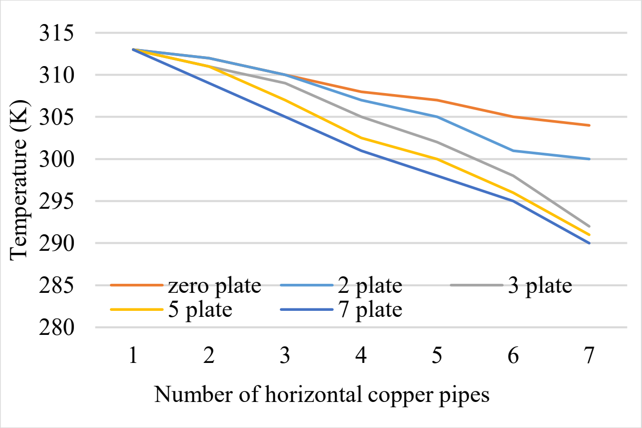

Figure 11 Temperature variation of hot fluid in the copper pipe for different number of plates

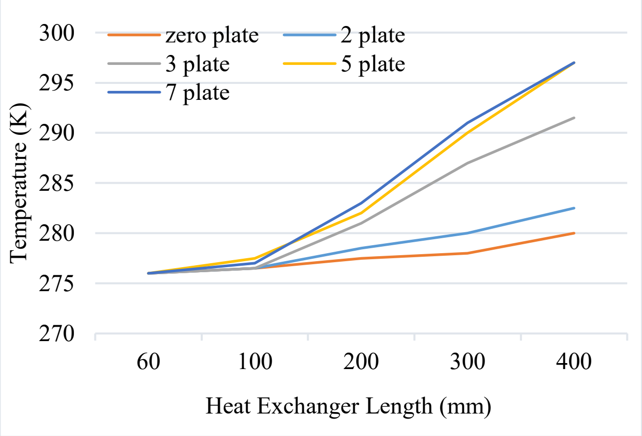

Figure 12 Temperature variation of cold fluid across the heat exchanger shell for different number of plates

The variations of the hot fluid and cold fluid temperatures with the number of plates are shown in Figure 11 and Figure 12, respectively. The analyzes carried out for both the hot fluid and cold fluid properties showed that the change in the output temperature was very small after 7 plates for the hot fluid and after 6 plates for the cold fluid. It has been observed that the decrease in the output temperature of the hot fluid, and accordingly the increase in the output temperature of the cold fluid, was marginal after the optimum number of plates. Accordingly, considering the heat transfer improvement to cost ratio, 7-plates case was determined to be the optimum for the overall performance of the designed heat exchanger.

Figure 13 Designed heat exchanger with the placement of optimum number of plates, i.e. 7 plates

The schematic view of the heat exchanger with 7-plates is as shown in Figure 13, and the heat transfer improvement induced by the placement of the plates was also examined against the positioning of the plates being aligned on a straight line as all upright or being staggered one upside down and one upright. In this respect, the output temperature of the cold fluid was examined with 7-plates for both cases and the results are presented in Figure 14.

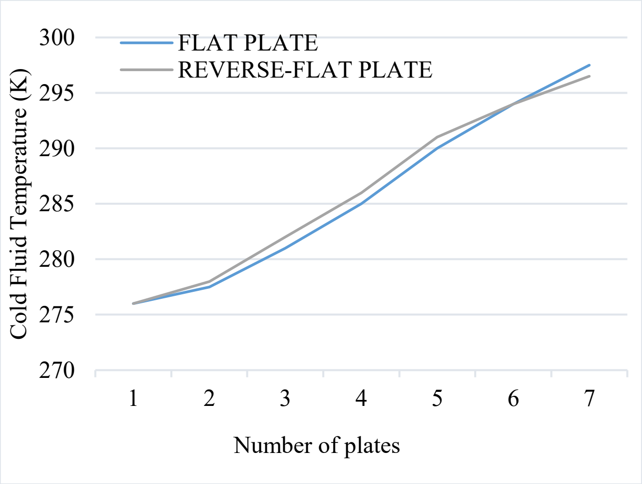

Figure 14 The effect of the position of the plates on the heat transfer

As can be seen in Figure 14, the effect of the positioning of plates on the heat transfer improvement, hence the output temperature of the cold fluid, was found to be insignificant as it did not induce big differences.

4. Conclusions

Having examined in detail the improvement in the heat transfer for hot and cold fluids in different configurations. It has been concluded from the findings of the study that the increase in the number of plates had a positive effect on the heat transfer. Nevertheless, the improvement was found to stop after a certain number of plates. The optimum number of plates for the hot fluid was 7 plates, after which the improvement attained is marginal and hence regarded as not efficient considering the heat transfer/cost ratio. For the cold fluid, the optimum number of plates was found to be 6, after which the additional plates did not induce a significant improvement in the heat transfer. In the light of these findings, the ideal number of plates to be employed in the designed heat exchanger was determined to be 7.

Comparing the performance obtained with the optimum number of plates with that of the reference case, i.e. without the plates, the output temperature of the cold water entering the shell at 276K was recorded as 297 K and 281K, respectively, in the reference case and in the case with optimum number of plates, i.e. 7 plates. On the other hand, the hot water entering the system at 313K, cooled down to 306K in the reference case, and to 298K in the case when 7-plates were placed inside the system. As a result of the incorporation of the plates in the heat exchanger, the cold water drew more heat from the hot water and left the system warmer. As a result of the analyses, the heat transfer efficiency for the optimum case (7 plates), was shown to have increased by approximately 24% - 52% compared to the reference case.

The effect of the positioning of the plates in the shell on the heat transfer was also examined by carrying out separate the analyses, it was revealed that the positioning of the plates did not induce a significant effect on the heat transfer.

Authors' Contributions

Nesrin ADIGÜZEL and Muhammet OZGERİŞ: Data curation, Writing- Original draft preparation, Visualization, Software, Validation

Fadime ŞİMŞEK and Büşra BAYRAKTAR: Conceptualization, Methodology, Investigation, Writing-Reviewing and Editing

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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