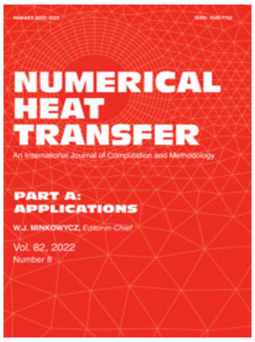

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Experimental comparison and CFD analysis of conventional shell and tube heat exchanger with new design geometry at different baffle intervals

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ABSTRACT

Basically, in the working principle, the transition from high temperature to low temperature is achieved, while the temperature value of the one with the lower temperature rises, this process can continue until the temperature value of the other decreases and reaches equilibrium. Therefore, heat exchangers are highly preferred in the industry where heat transfer is possible, in mass production facilities where nonstop production takes place such as the pharmaceutical and paper industry, and in sectors where energy efficiency is of utmost importance. In the analyses, it is aimed to investigate the changes in the fluid behavior of the conventional one-piece type baffle plate shell and tube heat exchanger at different baffle plate intervals by keeping it constant at different flow rates. Here, water was used as the working fluid to examine the changes in fluid behavior, the direction in which the heat transfer rate per pressure drop changes, the pressure drop and the effects on the body side heat transfer coefficient. As a result, it has been determined that the distance between the baffle plates used in the conventional one-piece type shell and tube heat exchanger varies and the values compared at different flow ranges differ.

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KEYWORDS
Baffle plate; conventional one-piece heat exchanger; heat transfer coefficient; pressure drop

1. Introduction

Cost, physical conditions and environmental factors, as well as energy efficiency elements, show the utmost importance in mass production sectoral segments and other areas of industry where thermal applications, where energy efficiency should be at a high level, are intense, and this is why structural elements we call heat exchangers do not exist if thermal applied systems do not exist. In practice, it can be stated that the fins of the heat exchanger, which vary according to the construction geometry and heat transfer mechanisms, occupy a lot of space in heat transfer-based industries. Although the flow in finned pipes is cross or cross-opposite. It is known that the flow in heat transfer with finned plane plates typically provides flow in the direction parallel to the fin surfaces. It can be said that it depends on the blade geometry and the distances between the blades [1].

Shell and tube heat exchangers are frequently used in industry and regions where heat applications are intense, and they have the opportunity to be preferred in every field due to the wide range of operating temperature and pressure [2].

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Nomenclature

C	centigrade degree (C)
STHE	shell-and-tube heat exchanger

Kottke et al. obtained the local heat transfer coefficient in the outer shell of the shell and tube heat exchangers by adding absorption, chemical and combined color reactions and performing mass transfer measurements. After the heat transfer coefficient was obtained, they found the heat transfer coefficient by making use of the analogy between heat and mass transfer in the second part. In the other work of the team, they conducted research using different types of baffle plates by using the mass transfer technique in order to determine the local heat transfer coefficient. In addition, by determining the pressure drop in the baffle plates, the flow distribution on the body side is revealed, as well as the average heat transfer coefficients for each body and pipe sections [3,4].

It is aimed to determine the thermal performance and pressure losses of the body side of the heat exchanger by using the Bell-Delaware method. In addition, a multi-objective optimization study of a shell-tube heat exchanger in terms of pumping power and heat transfer area was carried out by Thibault et al., using the NSGA-II algorithm in the multi-target genetic algorithm module of MATLAB. Serna et al. also carried out the optimization study of the shell and tube heat exchanger using the same method [5–7]. In the study conducted by Nazari et al., in the research where the economic optimization of the shell and tube heat exchangers was realized by using the Kern method, the body side heat transfer coefficient and pressure losses were determined [8]. In the study of Jacobi et al., they applied the Kern method to calculate the heat transfer coefficient and pressure losses on the body side and performed the optimization of the shell and tube heat exchanger according to the TEMA standards [9]. Together with Munawar et al., they conducted a study to realize the optimal efficiency design of the shell and tube heat exchanger by using a total of ten different strategies on issues such as minimum cost and optimal heat transfer design [10]. Caballero et al. carried out a study planning to design an optimal shell and tube heat exchanger aiming to minimize the negative elements with the use of particle swarm optimization application [11]. Kızılkan conducted a study examining the fluid behavior that causes reactive effects such as pressure drop and heat transfer caused by the baffle plates [12]. Kızılkan conducted a study examining the fluid behavior, which includes reactive effects such as pressure drop and heat transfer caused by the baffle plates on the fluid [12]. They concluded that the optimal model is the k-epsilon in the experimental observation, where optimization studies were performed using the shell and tube heat exchanger [13]. Kiran investigated the pressure drop and heat transfer effects of baffle plates on the fluid [14–16].

2. Materials and methods

The shell-and-tube heat exchanger, in which a conventional one-piece baffle plate is designed and formed, has been investigated in a three-dimensional and continuous regime. Computational fluid dynamics programs were used in the analysis. It was carried out through the ANSYS Fluent program (Figure 1).

2.1. Physical model

In the design of the heat exchanger to be used in the analysis, a shell-and-tube heat exchanger with a single body with a length of 1,200 mm and a radius of 60 mm, with a single pipe passage, was designed as a physical model (Figure 2).

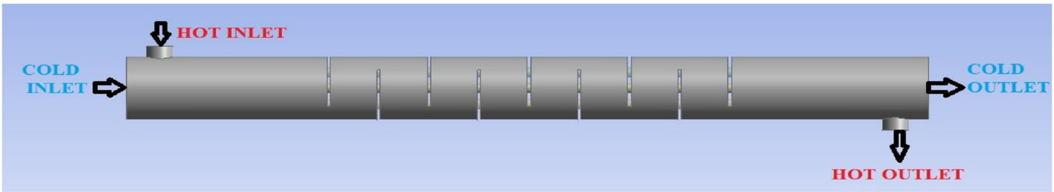

Figure 1. Path of the working fluid at inlet and outlet.

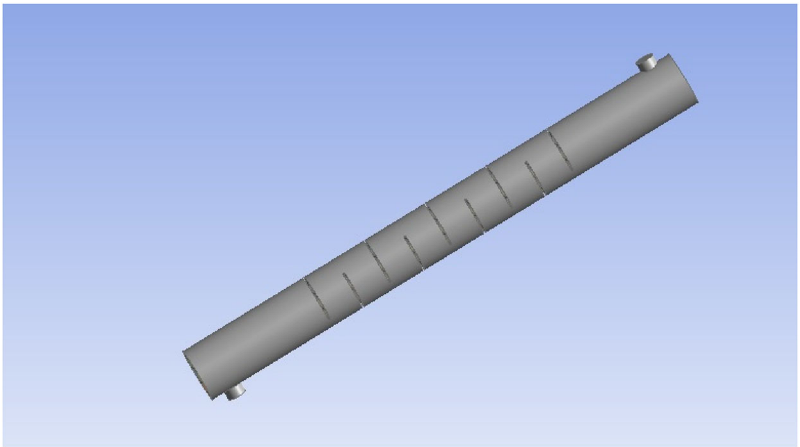

Figure 2. Conventional one-piece baffle plate shell and tube heat exchanger.

The pressure drops, heat transfer rate and variations in fluid behavior that may occur with the variation of the spaces between the designed conventional one-piece baffle plates will be monitored throughout the analysis. The views of the baffle plates are given in Figure 3*a*-, *b*-. Water was preferred as the working fluid used throughout the analysis. Thermophysical properties of water are ρ: 976.1 (kg/m^3), cp: 4191.5 (J/kg °C), µ: 0.000391 (kg/m s), K: 0.665 (W/m °C). On the other hand, the technical details of the heat exchanger in its design are shown in Table 1.

2.2. Governing equations

Analyses were carried out by applying the realizable k-ε turbulence model in the analysis and using the finite volume method as the solution method. The energy and continuity equations used are given below:

Continuity equation:

$$\frac{\partial \mathrm{u_i}}{\partial \mathrm{x_i}} = 0 \tag{1}$$

Energy equation:

$$\frac{\partial \mathrm{u_i}\ T}{\partial \mathrm{x_i}} = \rho \frac{\partial}{\partial \mathrm{x}_i}\left(\left(\frac{\upsilon}{Pr} + \frac{\upsilon \mathrm{t}}{Pr}\right)\frac{\partial T}{\partial \mathrm{x_i}}\right) \tag{2}$$

2.3. Determination of boundary conditions in analysis

In the realization of the analyses, the processes were continued based on pressure and ignoring the effects of gravity in the steady regime. Aside from neglecting the possible leaks between the

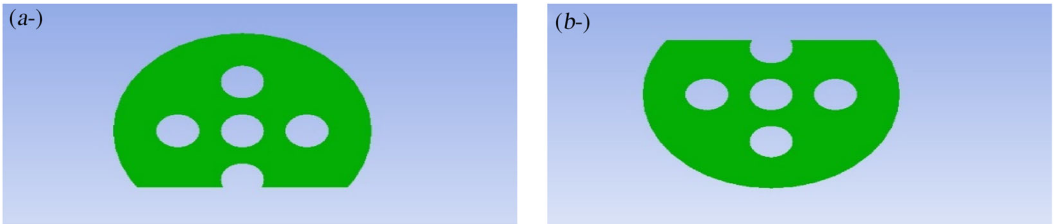

Figure 3. (a-, b-) Conventional one-piece type baffle plates.

Table 1. Geometrical dimensioning.

Description	Dimension	Description	Dimension	Description	Dimension
Body		Pipe		Baffle plate	
Radius (mm)	60	Diameter (mm)	20	Number of baffles	9
Length (mm)	1200	Number of pipes	5	Kalınlık (mm)	5
Number of passes	1	Intermediate distance (mm)	30	Boşluk (mm)	50, 75, 125

inner surface of the body and the baffle plates, which are the intersection points among the items to be neglected. On the other hand, it is assumed that there is no heat transfer between the external environment and the outer surface of the heat exchanger. As the method used in the analyses, the standard wall functions were used in the regions close to the surface and the non-slip boundary condition was applied as a boundary condition on all surfaces. In addition, it is assumed that the pipe surface temperature is 300 K and the water enters the system at a temperature of 345 K. In this study, the differences that may occur with the change of the distances between the designed baffle plates as 50 and 75 mm, the changes in the pressure drop and heat transfer, and the fluid behavior were investigated when each flow rate value is kept constant.

2.4. Mesh independence test

The main purpose of the mesh independence test is to ensure the accuracy of the analyses made through the computational fluid dynamics program. Five different mesh systems with 8,565, 10,901, 16,688, 17,896 and 35,036 elements were created for the heat exchanger formed with a conventional one-piece baffle plate. It has been determined that the difference between the last two mesh systems in terms of pressure drop is around 1% while having the maximum mass flow rate. Therefore, the analysis results are shown in Figure 4, assuming that the network structure with 17,896 elements is sufficient in the context of the flow analysis process and the analyses are performed (Figure 5). Therefore, assuming that the mesh structure with 17,896 elements is sufficient to perform the flow analysis operations and the relevant analyses are performed, the results are shown in Figure 4.

2.5. Data reduction

The basic equation given in the following compact form was used in the preparation of the data obtained from the analyses. The following equation is used to calculate the body side heat transfer coefficient (*hs*) and the body side heat transfer rate:

$$h_s = \frac{[Body\ side\ heat\ transfer\ rate = Q_s = \dot{m}s \cdot cp, s \cdot (Ts, in - Ts, out)]}{\mathrm{N} \cdot \pi \cdot \mathrm{d0} \cdot \mathrm{L} \cdot \left(\frac{[\mathrm{Ts, in} - \mathrm{Tw}] - [\mathrm{Ts}, out - \mathrm{Tw}]}{ln \frac{[\mathrm{Ts, in} - \mathrm{Tw}]}{[\mathrm{Ts}, out - \mathrm{Tw}]}} \right)} \tag{3}$$

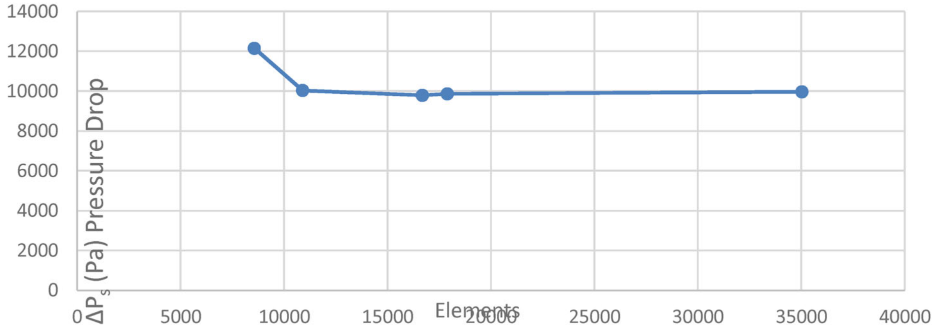

Figure 4. Mesh independence test.

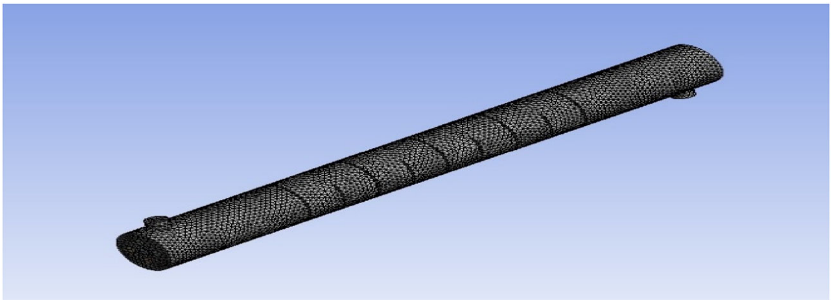

Figure 5. Body mesh view.

3. Results and discussion

The distributions of temperature and pressure on the plane drawn over the center line of the designed heat exchanger are shown using figures and graphics as a result of flow analysis. From the foremost analysis in the heat exchanger equipped with a conventional one-piece type baffle plate, the temperature and pressure distributions were observed at maximum mass flow rate and the distance between the baffle plates is 50mm, and the results are shown in Figures 18 and 19. Then, analyses were carried out on the temperature and pressure distributions in the case where the distance between the baffle plates is 75 mm, and the results are shown in Figures 20 and 21. The conditions that may arise in the fluid behavior as a result of the change in the gap between the baffle plates at different flow rates, which are also kept constant in the ongoing analyses, are given with figures.

In the analyses performed on the outlet temperature in the heat exchanger equipped with conventional one-piece type baffle plate, in cases where the baffle plate spacing is 50 mm and the mass flow rate is 1.2, 1.5, 1.8 and 2.1 kg/s; the outlet temperature obtained is higher than the resulting outlet temperatures when the mass flow rate is 1.2, 1.5, 1.8 and 2.1 kg/s and the baffle plate spacing is 75 mm.

It has been observed that the pressure drop when the mass flow rate is 1.2, 1.5, 1.8 and 2.1 kg/s and the baffle plate gap is 75 mm in the shell and tube type heat exchanger equipped with a conventional one-piece baffle plate is higher than the case where the baffle plate gap is 50 mm and the mass flow rate is 1.2, 1.5, 1.8 and 2.1 kg/s (Figures 6–24).

The analysis results in which the baffle plate gaps are compared at different values and the heat convection coefficient changes with the mass flow rate are given in Figure 22. According to the results of the analysis, it was determined that the changes in the four different flow rates continued to increase, and the heat convection coefficient increased accordingly in all cases. Another observed result is that the heat convection coefficient of the one-piece baffle plate in the shell-tube heat

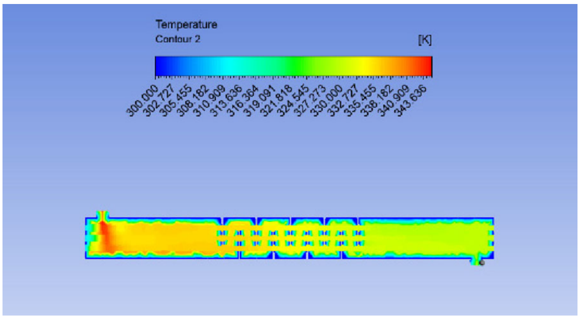

Figure 6. Temperature distribution of conventional one-piece baffle plate type heat exchanger: gap = 50 mm; mass flow rate = 1.2 kg/s.

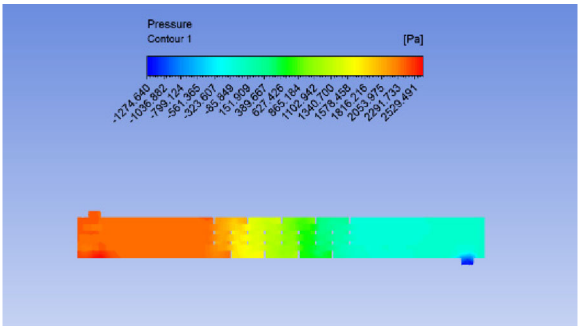

Figure 7. Pressure distribution of conventional one-piece baffle plate type heat exchanger: gap = 50 mm; mass flow rate = 1.2 kg/s.

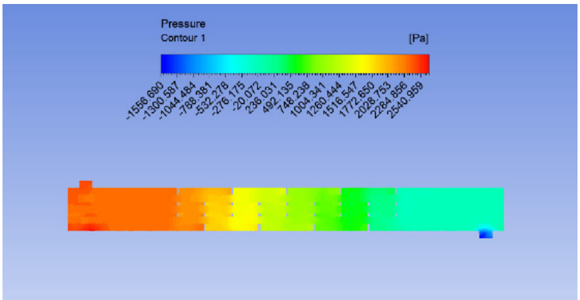

Figure 8. Pressure distribution of conventional one-piece baffle plate type heat exchanger: gap = 75 mm; mass flow rate = 1.2 kg/s.

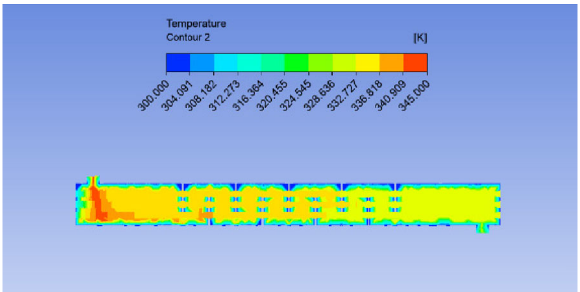

Figure 9. Temperature distribution of conventional one-piece baffle plate type heat exchanger: gap = 75 mm; mass flow rate = 1.2 kg/s.

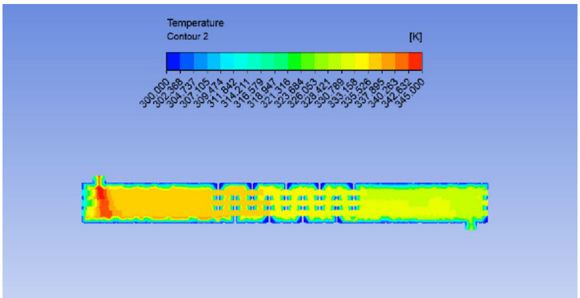

Figure 10. Temperature distribution of conventional one-piece baffle plate type heat exchanger: gap = 50 mm; mass flow rate = 1.5 kg/s.

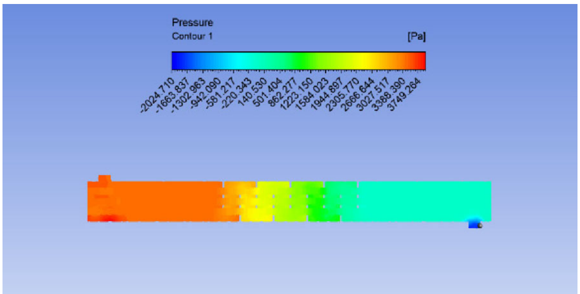

Figure 11. Pressure distribution of conventional one-piece baffle plate type heat exchanger: gap = 50 mm; mass flow rate = 1.5 kg/s.

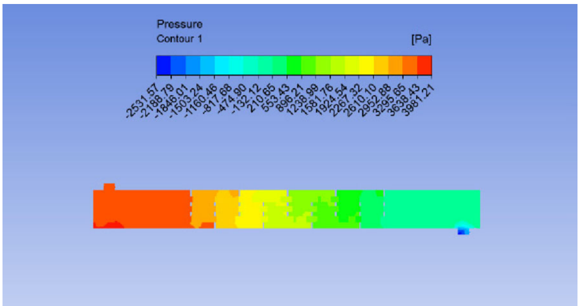

Figure 12. Pressure distribution of conventional one-piece baffle plate type heat exchanger: gap = 75 mm; mass flow rate = 1.5 kg/s.

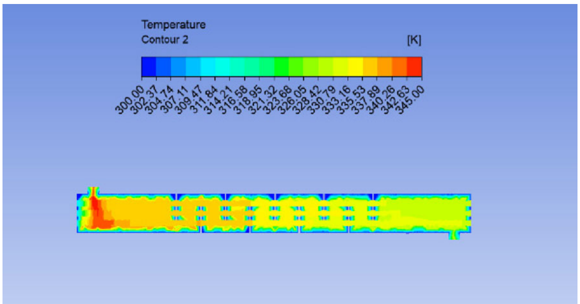

Figure 13. Temperature distribution of conventional one-piece baffle plate type heat exchanger: gap = 75 mm; mass flow rate = 1.5 kg/s.

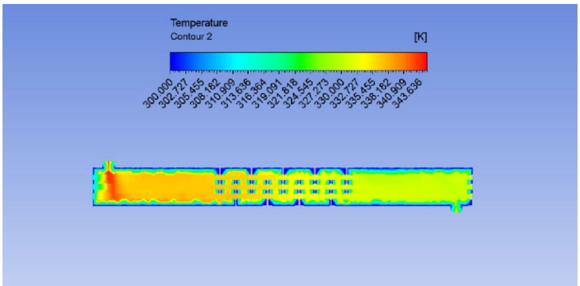

Figure 14. Temperature distribution of conventional one-piece baffle plate type heat exchanger: gap = 50 mm; mass flow rate = 1.8 kg/s.

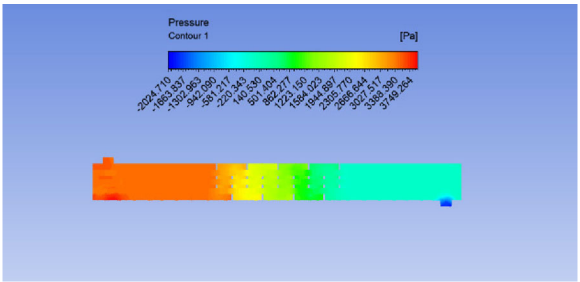

Figure 15. Pressure distribution of conventional one-piece baffle plate type heat exchanger: gap = 50 mm; mass flow rate = 1.8 kg/s.

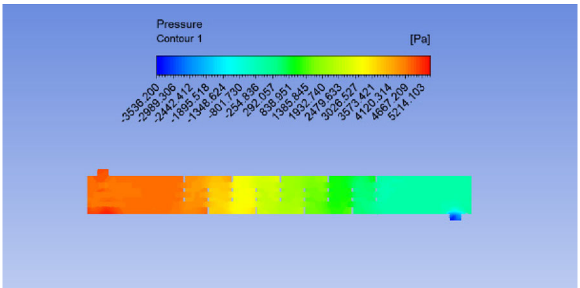

Figure 16. Pressure distribution of conventional one-piece baffle plate type heat exchanger: gap = 75 mm; mass flow rate = 1.8 kg/s.

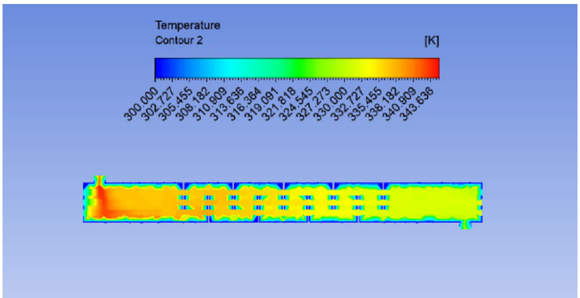

Figure 17. Temperature distribution of conventional one-piece baffle plate type heat exchanger: gap = 75 mm; mass flow rate = 1.8 kg/s.

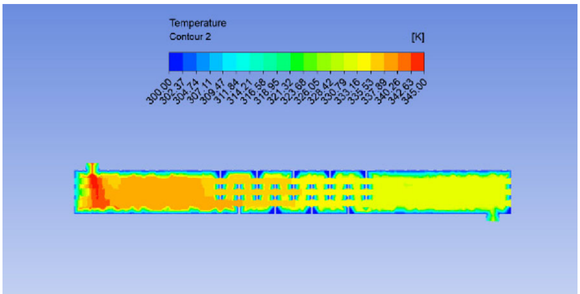

Figure 18. Temperature distribution of conventional one-piece baffle plate type heat exchanger: gap = 50 mm; mass flow rate = 2.1 kg/s.

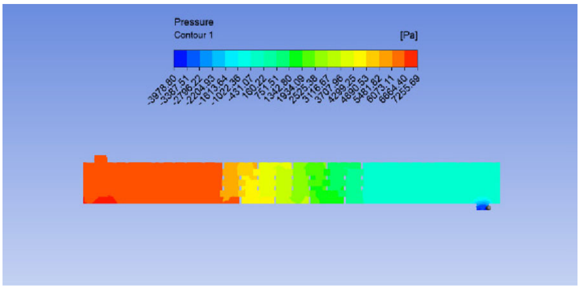

Figure 19. Pressure distribution of conventional one-piece baffle plate type heat exchanger: gap = 50 mm; mass flow rate = 2.1 kg/s.

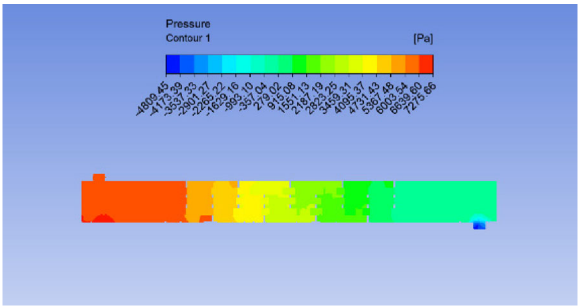

Figure 20. Pressure distribution of conventional one-piece baffle plate type heat exchanger: gap = 75 mm; mass flow rate = 2.1 kg/s.

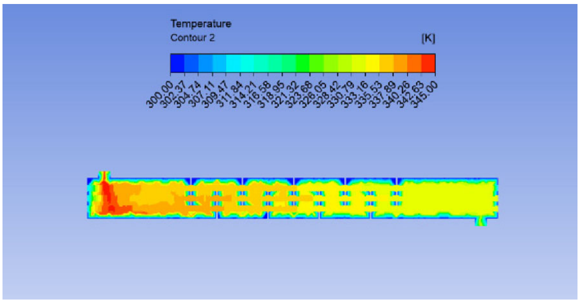

Figure 21. Temperature distribution of conventional one-piece baffle plate type heat exchanger: gap = 75 mm; mass flow rate = 2.1 kg/s.

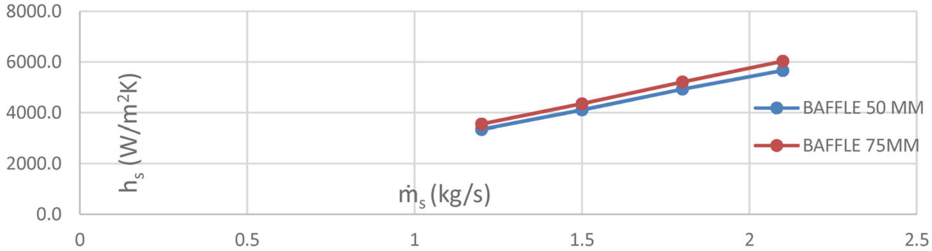

Figure 22. The relationship between heat transfer coefficient and mass flow rate.

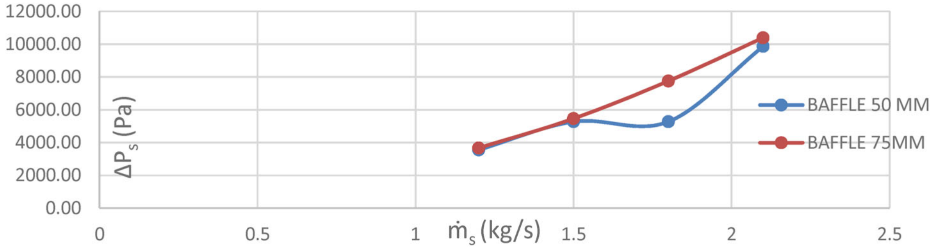

Figure 23. The relationship between pressure drop and mass flow rate.

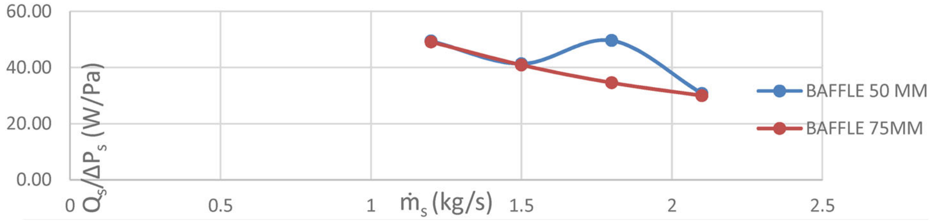

Figure 24. Relationship between heat transfer rate per pressure drop and mass flow rate.

exchanger designed at 75 mm spacing is higher than the heat convection coefficient of the one-piece baffle plate in the shell-tube heat exchanger designed at 50 mm spacing at all flow rates, and this can be explained by the fact that the flow has gained a zigzag structure thanks to the deflector plates.

The analysis results showing the relationship between pressure drop and mass flow rate are given in Figure 23. In the observed result, it can be seen that the pressure drop of the single-piece baffle plate in the shell and tube heat exchanger designed at 75 mm spacing is higher than the pressure drop in the shell and tube heat exchanger designed in the 50 mm spacing of the one-piece baffle plate.

The analysis results showing the relationship between the mass flow rate and the heat transfer rate per pressure drop, which is a criterion that provides information about the thermohydraulic performance of fluids, are shown in Figure 24. According to the analysis result, it can be observed that the heat transfer rate per pressure drop of the one-piece baffle plate in the shell and tube heat exchanger designed at 50 mm spacing is higher than the heat transfer rate per pressure drop per pressure drop of the one-piece baffle plate, which is designed at 75 mm spacing.

4. Conclusions

In this study, one-piece baffle plate designed at 50 mm spacing of the shell-and-tube heat exchanger and one-piece baffle plate designed at 75 mm spacing of the STHE. The pressure drop on the body side and its effects on heat transfer have been investigated numerically by detailing with figures and graphics. In the analyses in which the changes in the fluid behavior are observed, it is seen as a result of the analyses that the effects of the pressure drop and the heat transfer coefficient change with the mass flow rate. Accordingly, both in the shell and tube heat exchanger designed with 50 mm spacing of one-piece baffle plate and in the shell-and-tube heat exchanger designed with 75 mm spacing of one-piece baffle plate, it can be observed that by increasing the mass flow rate of the fluid on the body side, the pressure drop and the heat transfer coefficient increase in the same way.

It has been observed that the heat transfer coefficient and pressure drop in the shell and tube heat exchanger designed at 50 mm spacing of the one-piece baffle plate is lower than the shell and tube heat exchanger designed at 75 mm spacing of the one-piece baffle plate. In addition, it has been determined that the heat transfer rate per pressure drop in the shell and tube heat exchanger designed at 50 mm spacing of the one-piece baffle plate is higher than the shell and tube heat exchanger designed at 75 mm spacing of the one-piece baffle plate.

In another analysis of the heat transfer rate per pressure drop, when the mass flow rate is 1.8 kg/s, the heat transfer rate per pressure drop in the shell-and-tube heat exchanger designed at 50 mm spacing of the one-piece baffle plate was determined to be the highest compared to the cases at other mass flow rates. Thus, it was concluded that the one-piece baffle plate designed at 50 mm spacing can improve the heat transfer rate per pressure drop by 30% compared to the one-piece baffle plate designed at 75 mm spacing.

Although some differences, experimental results and numerical results gave appropriate results, these differences can be explained as following:

The types of baffle plates and the number of holes on the baffle plates differ. The range of the mass flow rate is kept larger. The compatibility of the graphs drawn for the mass flow ranges used in our study and the graphs drawn in the experimental study was observed. The results found in the experimental study should be convergent in CFD.

The equipage used in the experimental study was adjusted according to the baffle plate types so that the average and maximum deviations of shell-side heat transfer coefficient are 10.8% and 15.1%, respectively, and those of shell-side pressure drop are 14.0% and 16.7%, respectively. The flow rate of the uniform flow was varied for different baffle plate types. In the CFD study, the flow is defined as uniform in the inlet region.

Numerical analyses are carried out by comparing experimental results by Liu et al. [17] for eight different baffle plates. These simulations indicate that these studies can be carried out easily with CFD. Numerical valuation is generally consistent with the experimental results. Nevertheless, some deviations are observed. In addition, as a result of these simulations, it has been seen that certain changes in baffle plates geometry can result in major changes to the operating conditions of the heat exchanger, and this can have significant impact on flow characteristics, distribution of pressure and temperature.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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