A study on the effect of baffle spacing to the performance of a shell and tube heat exchanger

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Abstract. Baffle is commonly used to improve the performance of the shell and tube heat exchangers. In this work, effect of the baffle spacing to the performance of a shell and tube heat exchanger has been examined experimentally and numerically. The length and diameter of the shell of the heat exchanger is 700 mm and 156 mm, respectively. The number of the tube is 8. The inner and outer diameter of the tube is 11.6 mm and 13 mm, respectively. In this study baffle spacing is varied from 40 mm, 50 mm and 60 mm. By using the numerical and experimental data, the heat transfer coefficient and temperature effectiveness have been examined. The temperature distribution, path line and vector velocity are plotted and discussed. The results show that the temperature effectiveness decreases as baffle spacing increases. Temperature effectiveness decreases with increasing baffle spacing. In addition, temperature of the inlet does not affect the heat transfer coefficient. It affects the temperature effectiveness.

1. Introduction
In the recent years, the technologies that can improve energy efficiency and energy conservation are extremely needed. In some industries, some fluids that still have high temperature are released to environment such as exhaust gases. On the other hand, such industries might need heat source that can be recycled. Thus, in these cases heat exchanger can be employed. Heat exchanger is used to exchange a heat between hot stream to cold stream. In many industries, heat exchanger is typically used such are chemical industry, electronics, waste heat recovery, power plat, air conditioning system, and many more [1,2]. There are several type of heat exchangers now in service such as plate heat exchangers, plate fin heat exchangers, shell and tube heat exchanger, etc. Among these, shell and tube heat exchangers are known as the most used heat exchanger. The reasons include its simple in construction, low in maintenance cost and it has high ratio of heat transfer are to volume [1]. In order to improve the performance of a shell and tube heat exchanger many innovations have been proposed. The present paper focus on the improvement in the shell side of the heat exchanger. Typical heat transfer enhancement in the shell side of the heat exchanger is installing baffle. The objective of baffle here is to direct and to enhance the heat transfer rate.
Several studies on the shell and tube heat exchanger with baffles have been found in literature. Due to nature of flow in the shell side of the shell and tube heat exchanger, many of complex flow circulations presence. By using the baffle in the shell side, the flow is becoming more complex [3,4]. Effect of baffle spacing on the pressure drop and local heat transfer in shell and tube heat exchangers for staggered tube arrangement have been reported [5]. It was shown that for the same Reynolds number, the pressure drop and average heat transfer are increased by an increased baffle spacing due to reduced leakage through the baffle-shell clearance. The other issue of the effect of the baffle spacing is the optimization of the baffle spacing. Saffar-Avval and Damangir [6] proposed a general correlation for determining optimum baffle spacing for all types of shell and tube heat exchangers. In particular for shell and tube condenser as a heat exchanger, the effect baffle spacing to minimize the capital and operating costs has been examined [7]. Thermoeconomic optimization of baffle spacing for shell and tube heat exchanger has been reported by Eryner [8]. These studies reveal that many optimization aspects can be used to optimize the shell and tube heat exchangers. The presence of the baffle in the shell side of the shell and tube heat exchanger can be examined not only from the baffle spacing. Several studies of the baffle can be viewed from the effects of the baffle configuration to the heat transfer rate and pressure drop [9,10], effect of baffle clearance on the flow direction in the shell side [11], effect of baffle inclination on the flow characteristics [12,13], and many more.

In this work numerical and experimental studies are carried out to explore the effect of baffle spacing to the performance of the shell and tube heat exchanger. The objective here is to explore the effect of the baffle spacing to the effectiveness of shell and tube heat exchanger. The results are expected to supply the necessary information on developing optimum shell and tube heat exchanger that can be used in industries.

2. Methods
Two different approaches are used in here, they are numerical simulation and experimental methods. In order to provide experimental data a shell-and-tube heat exchanger has been designed and fabricated. The picture of the tube bundle of the heat exchanger is shown in Figure 1(a). In the numerical simulation, the heat exchanger is modelled using design modeler of ANSYS. The isometric view of the heat exchanger is shown in the left side of Figure 1(b). The model is divided by meshing the model and also shown in Figure 1(c).

Figure 1. The tube bundle, isometric view and meshing of the heat exchanger

The dimension of the heat exchanger is explained as follows. The length and diameter of the shell of the heat exchanger is 700 mm and 156 mm, respectively. The number of the tube is 8. The inner and outer diameter of the tube is 11.6 mm and 13 mm, respectively. The tube pitch and
baffle cut is 27 mm and 25%, respectively. In the experiment and the simulation, the flow rate in
the shell side and tube side is 10 L per minute and 1.8 L per minute, respectively. As a note, water
and oil are used as the working fluid. As the cold fluid, water flows in the shell side. On the other
hand, as hot fluid oil flows in the tube side. The numerical analysis is carried out by commercial
CFD code of ANSYS. In the numerical analysis the thermophysical properties of the fluids are
drawn from database provide by ANSYS.

In this study, numerical and experiments, the baffle spacing is varied. They are 40 mm, 50
mm, and 60 mm. However, the baffle cut is fixed at 25% and it is a single segment. In addition,
temperature of the hot fluid is also varied. They are 60°C, 65°C, and 70°C, respectively. On the
other hand, the temperature of the cold fluid is fixed at 27°C.

In the numerical method, three-dimensional computational domain is solved iteratively. The
assumptions here are as follows. It is a steady state flow, all of the thermophysical properties are
constant, and the flow is laminar. In addition, the dissipation rate is negligible. Based, on these
assumptions, three-dimensional governing equations are developed. The conservation of mass is
written in the following equation.
\[ \frac{\partial}{\partial x_i} (\rho u_i) = 0 \] (1)

The conservation of momentum in \( x-, y-, \) and \( z- \)directions is presented in the tensor form as
follows.
\[ \frac{\partial (\rho u_i u_j) }{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \frac{\partial}{\partial x_j} \left( \frac{\partial u_i}{\partial x_i} \right) \right] f_i \] (2)

Where \( i,j,k = 1,2,3 \) referred to \( x,y,z \) axes, respectively. The term of \( f_i \) is the body force in the
\( i- \)direction.

The energy equation is formulated in the tensor form as follows.
\[ \frac{\partial (\rho u_i T) }{\partial x_i} = \frac{\partial}{\partial x_i} \left( k \frac{\partial T}{\partial x_i} \right) - \frac{\partial p}{\partial x_i} u_i + \rho \dot{q} + \] (3)

In the above equation, the term \( \Phi \) is a dissipation function. It is formulate using equation (4) as
shown below.
\[ \Phi = \pi \left[ 2 \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial w}{\partial z} \right)^2 \right] + \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right)^2 + \lambda (\nabla \cdot \vec{v})^2 \] (4)

The governing equations shown above are discretized into a set of algebraic equations using finite
volume method. The discretization is carried out based on the first up-wind scheme. All of the
algebraic equations are solved iteratively using SIMPLE algorithm.

In the experimental study, flow rate and temperatures of the fluid flows are measured and
recorded. The measured temperatures are used to provide the comparison parameter. The
comparison parameters are overall heat transfer coefficient and temperature effectiveness. The
first parameter, overall heat transfer coefficient is calculated by the below equation.
\[ U = \frac{Q}{A \times F \times LMTD} \] (5)

Where \( A \) [m²] and \( F \) is the heat transfer area and correction factor, respectively. The correction
factor of the present heat exchanger is calculated by
\[ F = \frac{\sqrt{R^2 + 1} \times \ln \left[ \frac{\left( 1 - P \right) \left( 1 - RP \right)}{\left( 2 - P \right) \left( R + 1 - \sqrt{R^2 + 1} \right) / \left( 2 - P \right) \left( R + 1 + \sqrt{R^2 + 1} \right) } \right]}{\left( R - 1 \right) \times \ln \left[ \left( 2 - P \right) \left( R + 1 - \sqrt{R^2 + 1} \right) / \left( 2 - P \right) \left( R + 1 + \sqrt{R^2 + 1} \right) \right]} \] (6)

Where the parameter \( R \) and \( P \) are defined as
The second parameter, temperature effectiveness is calculated by the below equation.

\[
R = \frac{(mc_p)_h}{(mc_p)_l} = \frac{(T_{hi} - T_{lo})}{(T_{ci} - T_{ci})}
\]

(7)

\[
P = \frac{(T_{ci} - T_{ci})}{(T_{hi} - T_{hi})}
\]

(8)

The second parameter, temperature effectiveness is calculated by the below equation.

\[
\varepsilon = \frac{Q}{(mc)_{min} (T_{hi} - T_{ci})}
\]

(9)

The above parameters will be examined using the experimental data and numerical simulation data.

3. Results and Discussions

The numerical simulation and experimental have been carried out. The results will be discussed in two subsections. In the first subsection, fluid flow characteristics in the heat exchanger will be presented and discussed. In the second subsection the performance will be discussed.

3.1. Fluid flow characteristics

In order to explore the fluid flow characteristics inside the heat exchanger, the path line and velocity vector at baffle spacing 60 mm are shown in Figure 2. The path line and vector velocity in the Shell side and Tube side are shown in the figure. It can be seen that in the shell side, the fluid flows from the inlet. It is obvious that the baffles direct the fluid flow inside the shell. On the other hand, the flow inside the tube bundle is also shown. The flow is two passes flows. This will affect the heat transfer rate between the fluid in the shell and the fluid in the tubes.

**Figure 2.** Path line and Vector velocity at baffle spacing 60 mm

In order to examine the effect of the baffle spacing to the fluid flow characteristics, temperature distributions in the heat exchanger at different baffle spacing are shown in Figure 3. In the figure, temperature distributions in the shell side and in the tube side are shown at baffle spacing 40 mm, 50 mm, and 60 mm, respectively. It can be seen that the hot fluid flows inside the tube. Its temperature decreases gradually and it becoming lower when it leaving the heat exchanger. On the other hand, temperature of the fluid in the sell side increases. However, the increasing
temperature not as high as increasing temperature in the tube side. This is because the heat capacity of the fluid in the shell side is way bigger than the fluid in the tube side.

![Temperature distributions in the heat exchanger](image)

(a) Baffle spacing 40 mm

(b) Baffle spacing 50 mm

(c) Baffle spacing 60 mm

**Figure 3.** Temperature distributions in the heat exchanger at $T_{h_l} = 65^\circ C$ and $T_{c_l} = 27^\circ C$

The effect of the baffle spacing to the temperature distribution can be examined by comparing the decreasing temperature of the fluid in the tube side. By increasing the baffle spacing from 40 mm to 50 mm, shown by Figure 3(a) and Figure 3(b), the temperature of the fluid in the tube side decreases more slowly. This is because increasing baffle spacing will decrease the heat transfer rate and as a result the temperature difference in the tube side will decrease. The similar trend also shown by comparing the temperature distribution at baffle spacing 50 mm and 60 mm. The effect
of the baffle spacing to the fluid in the shell side can be seen in the figure. By increasing the baffle spacing the temperature different in the shell side of the heat exchanger decreases. This fact suggests that increasing baffle spacing in the shell side of the heat exchanger will decrease the temperature different and as a result the heat transfer rate will decrease.

3.2. Effect to the performance
In order to make a better examination to the baffle spacing to the performance of the heat exchanger, the heat transfer coefficient and temperature effectiveness are shown in Table 1. The results are presented at all temperature inlets. At temperature inlet 60°C, the heat transfer coefficient at baffle spacing 40 mm, 50 mm and 60 mm is 100.89 W/m·K, 98.69 W/m·K, and 96.69 W/m·K, respectively. The similar trends are also shown for temperature inlet 65°C and 70°C. This fact suggests that increasing baffle spacing will decrease the heat transfer coefficient. The effect of the baffle spacing to temperature effectiveness can be examined by using data shown in Table 1. The table shows that at hot inlet temperature of 60°C the temperature effectiveness at baffle spacing 40 mm, 50 mm and 60 mm is 65.18, 62.9, and 57.85, respectively. The temperature effectiveness decreases as baffle spacing increases. This is because at higher baffle spacing results in lower heat transfer rate. The similar trend is also shown at different hot inlet temperature. This fact suggests that higher baffle spacing will decrease the temperature effectiveness. In addition, temperature of the inlet does not affect the heat transfer coefficient. However, it affects the temperature effectiveness.

### Table 1. Heat transfer rate and effectiveness of the heat exchanger

| Baffle spacing | Hot inlet temperature (°C) | Cold inlet temperature (°C) | Heat transfer coefficient (W/m·K) | Effectiveness (%) |
|----------------|----------------------------|----------------------------|-----------------------------------|-------------------|
| 40 mm          | 60                         |                            | 100.89                            | 65.18             |
| 50 mm          |                            |                            | 98.69                            | 62.9              |
| 60 mm          |                            |                            | 96.69                            | 57.85             |
| 40 mm          | 65                         | 27                         | 100.47                            | 62.21             |
| 50 mm          |                            |                            | 98.5                             | 60.39             |
| 60 mm          |                            |                            | 96.42                            | 57.21             |
| 40 mm          | 70                         |                            | 100.72                            | 63.09             |
| 50 mm          |                            |                            | 98.53                            | 62.26             |
| 60 mm          |                            |                            | 96.43                            | 57.35             |

3.3. Numerical and experimental comparison
As a note, in the present work a set of experimental have also been carried out. The results are presented in Table 2. In the table the results from CFD analysis are also shown for comparison. It is obvious that the effect of the baffle spacing to the heat transfer coefficient and to the temperature effectiveness is similar between the experimental and numerical results. At temperature inlet of 60°C, increasing baffle spacing from 40 mm, 50 mm and 60 mm results in decreasing of heat transfer coefficient from 94.32 W/m·K, 92.44 W/m·K, and 90.79 W/m·K, respectively. Thus, the heat transfer coefficient decreases with increasing baffle spacing. Furthermore, temperature effectiveness decreases with increasing baffle spacing. However, there are significant discrepancies between the numerical results and experimental results. This is because in the experimental results the loss of heat to the surrounding still very significant. Which is in the numerical results, the heat loss to the surrounding is assumed to be zero.

### Table 2 Comparison of the result of numerical analysis and experimental
| Baffle spacing | Hot inlet temperature (°C) | Cold inlet temperature (°C) | CFD results | Experimental results |
|----------------|-----------------------------|-----------------------------|-------------|----------------------|
|                |                             |                             | Heat transfer coefficient (W/m².K) | Effectiveness (%) | Heat transfer coefficient (W/m².K) | Effectiveness (%) |
| 40 mm          | 60                          |                             | 100.89      | 65.18                | 94.32                           | 33.50             |
| 50 mm          |                             |                             | 98.69       | 62.9                 | 92.44                           | 32.84             |
| 60 mm          |                             |                             | 96.69       | 57.85                | 90.79                           | 32.22             |
| 40 mm          |                             | 27                          | 100.47      | 62.21                | 94.34                           | 33.36             |
| 50 mm          |                             |                             | 98.5        | 60.39                | 92.5                            | 32.70             |
| 60 mm          |                             |                             | 96.42       | 57.21                | 90.82                           | 32.08             |
| 40 mm          |                             |                             | 100.72      | 63.09                | 94.95                           | 33.38             |
| 50 mm          |                             |                             | 98.53       | 62.26                | 93.1                            | 32.72             |
| 60 mm          |                             |                             | 96.43       | 57.35                | 90.49                           | 31.84             |

4. Conclusions
In this work numerical and experimental works have been carried out to examine the effect of the baffle spacing to the heat transfer coefficient and temperature effectiveness. A shell and tube heat exchanger with diameter of 156 mm and length 700 mm has been analysed. Three baffle spacings have been tested, they are 40 mm, 50 mm, and 60 mm. In the numerical simulation path line and vector velocity have been plotted. The results show that the temperature effectiveness decreases as baffle spacing increases. Temperature effectiveness decreases with increasing baffle spacing. In addition, temperature of the inlet does not affect the heat transfer coefficient. It affects the temperature effectiveness. However, there are significant discrepancies between the numerical results and experimental results.

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