Biomedical and Mechanical Engineering Journal (BIOMEJ)
e-ISSN: 2776-1983, p-ISSN: 2829-5242
Vol. 4, No.1, May 2024, pp 1-9

Analysis of Efficiency and Heat Transfer Coefficient in the Performance Evaluation of Shell and Tube Heat Exchanger

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Abstract.
Heat transfer is the process of energy transfer from a region of higher temperature to a region of lower temperature, occurring through conduction, convection, and radiation mechanisms. Understanding heat transfer is crucial in various industrial and thermodynamic applications. One commonly used device in this process is the heat exchanger, which allows heat transfer between two fluids with different temperatures without direct mixing. This research aims to evaluate the heat transfer phenomena in heat exchangers and their performance under various operational conditions. The study measured the average temperature difference, kinematic viscosity, Reynolds number, fluid velocity, heat exchanger efficiency, the average heat released and received, and the heat transfer coefficient. The results showed a high heat exchanger efficiency, with an average value of 99.53%. The heat transfer coefficient also showed significant values, varying based on fluid flow type and operational conditions. This study emphasizes the importance of selecting the appropriate type and design of heat exchanger to improve thermal system efficiency and reduce energy consumption.
Keyword: Heat Transfer, Heat Exchanger, Thermal Efficiency, Heat Transfer Coefficient

1. Introduction

If there is a temperature difference in a system, energy transfer from the higher temperature area to the lower temperature area will occur. This energy transfer process is called heat transfer. Heat transfer is the science that studies the mechanisms of energy transfer due to temperature differences between objects or materials. Heat transfer examines how heat moves through various media, such as conduction in solids, convection in fluids, and radiation through a vacuum. Understanding heat transfer is essential in various applications, from machine design, temperature control in buildings, to industrial processes requiring precise temperature control (Agustina & Astuti, 2015).

Additionally, heat transfer is also a focus in the discipline of thermodynamics, which studies the relationship between heat and other forms of energy. Thermodynamics explains how thermal energy can be converted into mechanical energy and vice versa, as well as the principles governing these energy changes. One important application of heat transfer and thermodynamic principles is the heat exchanger. A heat exchanger is a device that allows heat flow between two or more fluids with different temperatures without direct mixing. This device is widely used in industries to improve thermal efficiency, such as in cooling systems, heaters, and various chemical processes (Sudrajat, 2017).

The purpose of this research is to understand the heat transfer phenomena in heat exchangers and evaluate the performance of these devices under various operational conditions. Through this research, students are expected to calculate the heat transfer rate, heat transfer coefficient, and heat exchanger efficiency. This study also provides insights into the importance of selecting the appropriate type and design of heat exchanger for specific applications to improve thermal system efficiency and reduce energy consumption.

2. Literature Review

2.1 Definition of Heat Transfer

Heat transfer is the process by which thermal energy moves from one place to another due to a temperature difference. This concept was introduced by Joseph Fourier in the early 19th century with his mathematical theory of heat conduction. Heat energy flows from an area with higher temperature to an area with lower temperature until thermal equilibrium is achieved. Heat transfer can occur through three main mechanisms: conduction, convection, and radiation (Tirta Maulana et al., 2022).

2.1.1 Heat Transfer by Conduction

Conduction is the transfer of energy from more energetic particles to less energetic particles within a substance due to interactions between particles. In gases, heat transfer occurs through random translational motion and internal molecular rotation and vibration. In solids, conduction occurs through atomic vibrations and the movement of free electrons, while in liquids, it occurs through interactions among randomly moving molecules (Bergman et al., 2017). Fourier's law is used to calculate the rate of heat conduction:

$$q_x^n = -k\frac{dT}{dx}$$

2.1.2 Heat Transfer by Convection

Convection involves the transfer of heat through the mass movement of fluid, which also carries energy from random molecular motion. When fluid touches a surface with a different temperature, hydrodynamic and thermal boundary layers form, causing energy transfer. On a hot plate, convection causes a temperature gradient depending on the fluid velocity (Holman, 2010). The heat transfer rate is calculated using Newton's law of cooling:

$$q = hA(T_\omega - T_\infty)$$

where h is the convective heat transfer coefficient, A is the surface area, T_ω is the surface temperature, dan T_∞ is the fluid temperature.

2.1.3 Heat Transfer by Radiation

Thermal radiation is the energy emitted by matter with a temperature above absolute zero. Radiation does not require a medium and occurs most efficiently in a vacuum. Emission can be related to changes in the electron configuration of atoms or molecules, and the intensity increases with the object's temperature (Johan et al., 2015). The heat transfer rate by radiation is calculated using the Stefan-Boltzmann law:

$$P = e\sigma AT^4$$

where e is emissivity, σ is the Stefan-Boltzmann constant, A is the surface area, dan T is the temperature.

2.2 *Heat Exchanger*

A heat exchanger is a device designed to transfer heat between fluids with different temperatures without direct mixing. It allows heat flow from the hotter fluid to the cooler fluid, enabling temperature control in various industrial systems. Heat exchangers are essential in heating and cooling applications, improving energy efficiency and maintaining optimal operating temperatures. For example, in cooling systems, they help remove excess heat from processes or machinery, preventing overheating and damage. In heating applications, they help heat fluids to the desired temperature for production or processing. Proper selection and design of heat exchangers can enhance process performance, reduce energy consumption, and lower operational costs (Hadi Sunandrio & Sutarjo, 2023).

2.3 *Shell and Tube Heat Exchanger*

This type of heat exchanger is known as a shell and tube heat exchanger, characterized by its unique construction. It consists of a bundle of tubes mounted inside a large cylindrical shell. Two types of fluids, exchanging heat, flow separately, one through the tube side and the other through the shell side. The first fluid flows inside the tubes, while the second fluid flows through the space around the tubes, inside the shell. This design allows efficient heat transfer between the two fluids without direct mixing.

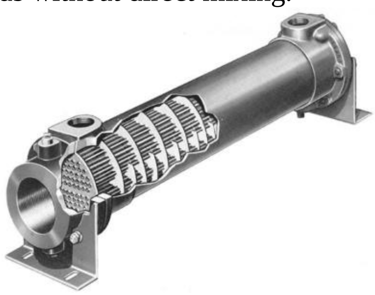

Figure 1 Shell and Tube Heat Exchanger (Holman, 2010)

2.4 Types of Flow in Shell and Tube Heat Exchanger

2.4.1 Parallel Flow

Parallel flow in a heat exchanger is when hot and cold fluids enter from the same end and flow in the same direction. In this configuration, the temperature difference between the two fluids decreases along the heat exchanger as heat transfers from the hotter fluid to the cooler fluid through conduction and convection. Consequently, heat transfer in this configuration tends to be less efficient compared to counterflow because the temperature difference between the two fluids continually decreases along the flow (Suryadi et al., 2023).

2.4.2 Counter Flow

In counterflow, two fluids with different temperatures flow in opposite directions and are separated by a pipe wall. This flow pattern is very efficient because it can maintain a larger temperature difference between the two fluids along the heat exchanger, enhancing the overall heat transfer rate. This configuration is suitable for heavy industrial applications such as power plants and oil refineries, where thermal efficiency and the ability to handle high pressure and temperature differences are crucial (Suryadi et al., 2023).

2.4.3 Cross Flow

Cross flow occurs when the fluids flow perpendicularly to each other in the heat exchanger. One fluid flows across the tubes or main surface, while the other fluid flows across the space between the tubes. Cross flow enables effective heat exchange by transferring heat from the hotter fluid to the cooler fluid through the separating wall. This makes cross flow useful in applications such as heating and cooling systems and industrial processes requiring efficient heat exchange (Husen et al., 2020).

2.5 Performance Parameters of Heat Exchanger

2.5.1 Logarithmic Mean Temperature Difference

The logarithmic mean temperature difference (LMTD) is used to calculate the average temperature difference between two fluids in a heat exchanger, particularly with counterflow direction. LMTD is expressed by the formula:

$$\Delta Tm = \frac{[(T_1 - t_2) - (T_2 - t_1)]}{\left[ln((T_1 - t_2) \big/ (T_2 - t_1)) \right]}$$

where T and are the temperatures of the hot and cold fluids at the inlet and outlet points.

2.5.2 Calculating Heat Released and Absorbed

The heat released by the hot fluid and absorbed by the cold fluid can be calculated using the equation:

$$Q_w = q_w$$

$$W \times C_p \times (T_1 - T_2) = w \times c_P \times (t_2 - t_1)$$

Where W and w are mass flow rates, C_p and c_P are specific heat capacities, and T and t are the temperatures of the hot and cold fluids.

2.5.3 Physical Properties of Water

The kinematic viscosity of water at 20°C is about 1.002 x 10^{-6} m^2/s, which is low and facilitates the flow. This viscosity is important in heat transfer because it affects fluid flow and the formation of thermal boundary layers, as well as improves the efficiency of convection in heat exchangers.

2.5.4 Calculating Reynolds Numbers

Reynolds' number, which determines the type of fluid flow (laminar or turbulent), is crucial in the design of heat exchangers. Turbulent flow increases heat transfer. The calculations for hot and cold fluids are:

$$Re_h = \left(\frac{D \times v_h}{Vh}\right)$$

$$Re_c = \left(\frac{D \times v_c}{Vc}\right)$$

Where D is the diameter, v is the velocity, and v is the kinematic viscosity.

2.5.5 Calculating the Heat Transmission Coefficient (U)

The heat transmission coefficient (U) determines how efficiently a heat exchanger transfers heat, calculated by:

$$U = \frac{q}{A_{HE} \times \Delta T_m} \times 20$$

2.5.6 Heat Exchanger Efficiency Values (η_h)

Heat exchanger efficiency (ηh) measures the effectiveness of heat transfer and is calculated as:

$$\eta_h = \frac{(W.C_p.(T_1 - t_2))}{(W.C_p.(T_1 - t_1))} \times 100\%$$

3. Materials & Methods

In a shell and tube type heat exchanger with counter flow, heat transfer occurs when two fluids with different temperatures flow in opposite directions in the heat exchanger. The system consists of several main components. In the middle of the diagram, there is a shell and tube heat exchanger (1) which serves as the main tool for heat exchange between hot and cold water. This heat exchanger is connected to the hot water inlet (2) and the hot water outlet (3). The hot water inlet pipe (2), marked in red, is connected to a hot water pump (6) that moves hot water from the heating tank to the heat exchanger. The heater inside this system heats the water in the tank before it is flowed to the heat exchanger and requires an electrical connection for its operation. The cold water inlet pipe (4) is connected to the cold water pump (7), which controls the flow of cold water to the heat exchanger to cool the hot water. At the bottom of the diagram, there are two bucket containers (4 and 5) that serve as cold water outlets or hot water and cold water reservoirs after the heat exchange process is complete.

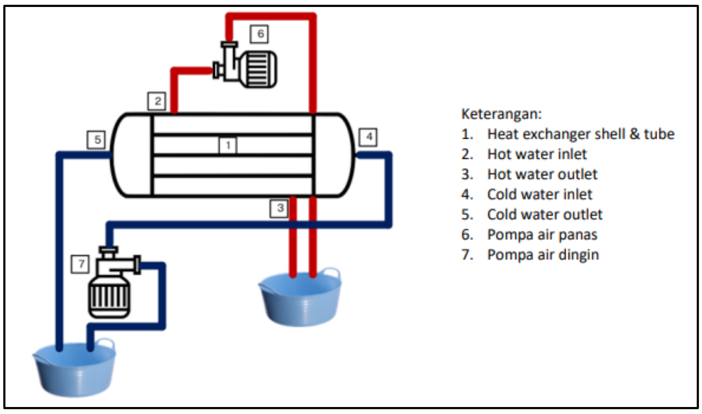

Figure 2 Research Tool Scheme

In the initial stage, the first step is to measure the temperature of the hot water in the head tank using TEMP. SET is available on the control unit to ensure that the hot water temperature in the heating tank reaches a stable condition before starting the practicum. The next step is to set the cold water flow speed which is 45° and the hot water flow speed which is 90°. This is done by opening the cold and hot water valves slowly until the desired water discharge is reached. This process is important to ensure that the flow of cold water flows at the right rate according to the needs of the practicum. After the water flow arrangement is completed, temperature data is collected at several points, namely T_1, T_2 for hot water and t_1, t_2 for cold water, as well as hot water discharge (W) and cold water discharge (w).

4. Results and Discussion

4.1 Observating Result

The following are the data that have been taken from heat exchanger research and determination of hot and cold fluid flow rates. The data taken from the study and are needed for further analysis of heat transfer and heat exchanger efficiency, namely the inlet and outlet temperature of hot fluids, the inlet and outlet temperatures of cold fluids.

Table 1 Data That Has Been Retrieved

Hot Fluid Temperature (°C)				Cold Fluid Temperature (°C)			
Inlet T1 (°C)	Average	Outlet T2 (°C)	Average	Inlet T1 (°C)	Average	Outlet T2 (°C)	Average
79		59		29,8		30,2	
78,9	78,63	59,2	59,23	29,8	29,8	30,3	30,03
78		59,5		29,8		29,6	
75,6		62,8		30,8		32,5	
75,8	75,36	64	63,56	30,6	30,66	32,3	32,26
74,7		63,9		30,6		32	
70,3		69,6		29,9		32,1	
70,1	70,4	69,8	69,77	30	30	32,4	32,1
70,8		69,9		30,1		31,8	

73,1		64,1		29		30,5	
73,1	73,1	64,1	64,1	29	29	30,5	30,5
73,1		64,1		29		30,5	

Table 2 Flow Rate

Hot fluid flow rate (kg/h)	Cold fluid flow rate (kg/h)
1296	2340
1980	1980
1980	2340
2340	1980

4.2 Data Results

The data that has been processed are the average value of temperature difference, kinematic viscosity of hot and cold fluids, Reynolds number of hot and cold fluids, speed of hot and cold fluids, heat exchanger efficiency, average heat released and received, and heat transmission coefficient. The following is the data that has been processed:

Table 3 Processed Data (1)

ΔTm (°C)	V_h (m^2/s)	V_c (m^2/s)	v_h (m/s)	v_c (m/s)	Re_h	Re_c
38,21702	4,16634 x 10^{-7}	8,0476 x 10^{-7}	1,146497	2,070064	55036,16	51445,52
37,77074	4,13286 x 10^{-7}	7,81832 x 10^{-7}	1,751592	1,751592	84764,18	44807,38
39,03039	4,09592 x 10^{-7}	7,8788 x 10^{-7}	1,751592	2,070064	85528,64	52547,69
38,72904	4,1868 x 10^{-7}	8,08175 x 10^{-7}	2,070064	1,751592	98885,24383	43346,86

Table 4 Processed Data (2)

η_{HE}(%)	q ($^{kcal}/_{h}$)	$A_{HE}(m^2)$	U ($^{kcal}/_{m^2.jam.°C}$)
99,53	12840,3	0,003768	4458,38
96,42	13266	0,003768	4660,62
94,80	3080,7	0,003768	1047,38
96,60	12015	0,003768	4116,67

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In the figure below, it can be seen that the relationship between heat transfer efficiency and fluid flow parameters. The data that has been obtained from the results of efficiency calculations are 99.53%, 96.42%, 94.80%, 96.60%.

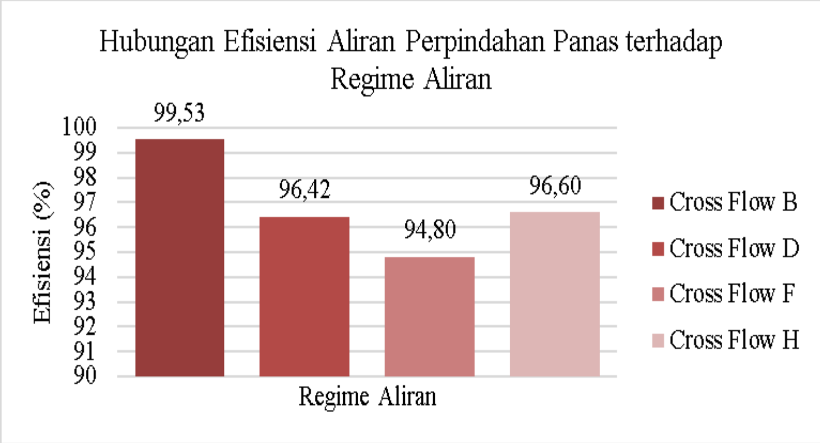

Figure 3 The Relationship between Heat Transfer Efficiency and Flow Regime

Based on the graph image, it can be seen that the highest efficiency value is cross flow B with an efficiency of 99.53%, while the lowest efficiency value is found in cross flow F with an efficiency of 94.80%. This can happen because heat transfer in a fluid is greatly influenced by the temperature difference between hotter and cooler fluids. The greater the temperature difference, the faster and more efficient the heat transfer process will occur (Pratama et al., 2023). Not only is the temperature difference a factor that affects efficiency, Reynolds number is also an important parameter that determines the flow of fluid in a heat exchanger. A high Reynolds number value will indicate turbulent fluid flow, which is associated with higher displacement. It can be seen that Reynolds numbers of hot fluids and cold fluids show turbulent fluid flows. Fluid flow is also closely related to the efficiency of the heat exchanger, as the fluid flow rate affects the flow velocity, which is an influence on Reynolds' number. An increase in flow rate tends to increase Reynolds' number, which can change the flow regime from laminar to turbulent.

In the figure below, the relationship between the heat transfer coefficient and the flow regime. The data that has been obtained from the calculation results for the heat transmission coefficient (U) is 4458,38 $kcal/m^2 hours°C$, 4660,62 $kcal/m^2 hours°C$, 1047,38 $kcal/m^2 hours°C$, and 4116,67 $kcal/m^2 hours°C$.

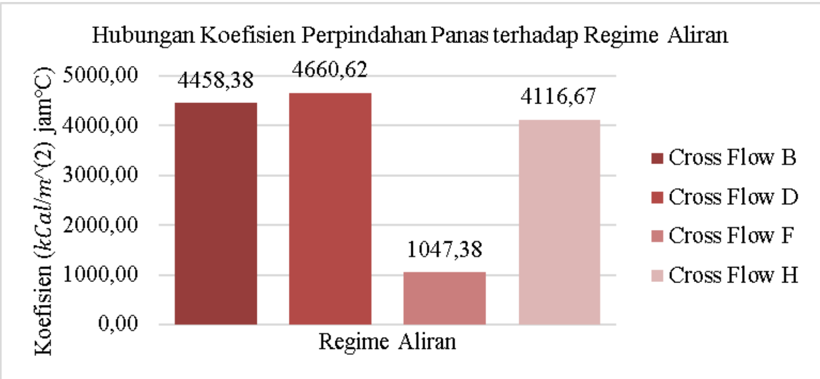

Figure 4 The Relationship of Heat Transfer Complexity to Flow Regime

The Relationship of Heat Transfer Coefficients to Regime Based on the graph image, it can be seen that the highest value of the transfer coefficient is cross flow D with 4660,62 $kcal/m^2 hours°C$, hile the lowest value of the heat transfer coefficient is crossflow F with

1047,38 $kcal/m^2 hours°C$. This can happen because of the influence of Reynolds' number, the more turbulent a fluid is, the more efficient the heat transfer will be. Another influencing factor is the temperature difference. The greater the temperature difference, the higher the rate of heat transfer. Therefore, although higher temperatures may result in a larger temperature gradient between the tube and the fluid, the heat transfer coefficient tends to decrease due to the opposite effects of changes in the physical properties of the fluid and flow characteristics (Ramlan & Mursadin, 2019). Another factor is the difference in the flow rate that is regulated. Higher flow rates typically result in turbulent flow and result in an increased heat transfer coefficient. From the data that has been determined, the heat transfer coefficient to the flow regime has different results.

5. Conclussion

a) Variations in the flow rate of hot water in the heat exchanger affect the efficiency of heat transfer, with the temperature difference between hotter and cooler fluids being the main factor. The greater the temperature difference, the faster and more efficiently the heat transfer process occurs. In addition, Reynolds' number is also an important parameter that determines efficiency, with high values indicating turbulent flow leading to more efficient heat transfer.

b) The heat transfer coefficient in a heat exchanger is affected by several factors, including Reynolds' number, the temperature difference between fluids, and the flow velocity. Turbulent fluid flow increases the heat transfer coefficient, while large temperature differences also affect the heat transfer rate. In addition, higher flow rates tend to produce turbulent flow and increase the heat transfer coefficient.

c) The decrease in the temperature of the hot fluid and the rise in the temperature of the cold fluid after passing through the heat exchanger are closely related to the heat exchange mechanism in it. In heat exchange, the heat energy from the hot fluid is transferred to the cold fluid, causing the temperature of the hot fluid to decrease and the temperature of the cold fluid to increase. In counterflow, where the fluid flows in the opposite direction, the heat exchange efficiency increases due to the larger temperature gradient.

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