Design of a heat exchanger of three concentric tube layer on contrary flow

Z Lubis¹, T U H S G Manik¹*, M Rinkanto¹ and T B Sitorus¹
¹Mechanical Engineering, Universitas Sumatera Utara, Medan - Indonesia

Email: terang1@usu.ac.id*

Abstract. Heat exchangers is a device that produces heat transfer from one fluid to another fluid. This study was conducted to design and build triple concentric tube heat exchangers with counterflow which is used to reduce the temperature of the hot fluid. The hot fluid flows in the annulus section on the second copper tube, then the cold fluid each flows through the first copper tube and annulus portion to the third copper tube. The hot fluid which is water with temperature 60ºC, to heat fluid used water heater with power 1000 watt while cold fluid which is air with temperature 25ºC. These four concentric tube heat exchangers with a total length of the first 2.57 m copper tube with ½ inch diameter. The second copper tube is 2.22 m in diameter of 1 inch. The copper tube is 1.74 m long with a diameter of 1 ¾ inch. The fluid in and out fluid temperature gauges on the heat exchanger can be measured thermocouple which are then processed by software instacall and Tracerdag from a computer through the data acquisition module.

1. Introduction

To develop a technology, especially a heat exchanger, it is necessary to strengthen the technology. In this case the development with a triple concentric tube heat exchanger. This type has an advantage concerning efficiency and performance (double tube heat exchanger) [1,2]. Then it needs to be developed and studied further. Its development has configuration transformation of the form which aims to improve the efficiency following its work function [3,4,5]. A heat exchanger is a viral media in the industrial world. For that purpose, had been planned a tube heat exchanger model a water cooling, but still refers to the existing design rules [6,7]. Therefore, the advantage obtained as a method of design, mechanism, and the performance. Heat exchanger manufacture is used to lower hot water or as a coolant. It is designed as a practice device for designing, manufacturing and analyzing the equipment and materials that used in it. This research was conducted to design and build triple concentric tube heat exchangers with counter flow which is used to reduce the temperature of the hot fluid.

2. Methodology design

2.1. Designing a heat exchanger device of triple tube concentric
In designing a heat exchanger, first determines the capability and the purpose of its design. It is designed for cooling, with assumptions about tube I and tube III coolant is water flow, and then tube II is a flow of hot water to be cooled. After determining the use of this device, then create or design according to the flow to be tested whether parallel or counter.

2.2. *Drawing with software*

The software that used is Autocad for drawing technique, for example, building or construction design. It can image processing in two or three-dimensional form.

2.3. *Scheme of heat exchanger*

Heat exchanger scheme, three layers of concentrate tube using different fluid water temperature, 60°C hot and 25°C cold. Each fluid in the tank will flow when the globe valve was opened. The fluid flowing from the valve will be measured through the flow meter then to the heat exchanger. This device is connected to the Cole-Parmer data via thermocouple cable that placed at each of end of the copper pole, which applies to measure the inlet and outlet temperature. Instacall software and Tracerdaq computer processed the result derived from the data acquisition software and tracerdaq computer. The scheme experimental as shown figure 1 and the scheme of a heat exchanger of counter flow as shown figure 2.

![Figure 1. Scheme of heat exchanger](image-url)
3. Flowchart of heat exchanger manufacture

In the design of heat exchangers device, required a stage in the manufacturing process to produce the finished tool model as desired. Figure 3 shows the flowchart of heat exchanger manufacture.

![Flowchart of heat exchanger manufacture](image)

**Figure 2.** Scheme of a heat exchanger of counter flow

**Figure 3.** The flowchart of heat exchanger manufacture
4. Data Analysis and Discussions

4.1. Designing the heat exchanger

The pipe dimensions of the heat exchanger design are distinguished into three types based on their function namely ½ inch copper brass for cold fluid flow path, 1 inch as hot fluid flow channel as well as the heat exchanger, and 1¾-inch copper pipe for cold flow path and also as annular.

![Copper pipe on a heat exchanger](image)

The reason for the use of copper and the PVC pipe for flow connectivity to the heat exchanger because copper has higher thermal conductivity as shown table 1. Besides pipe connection to heat exchanger was used PVC pipe due to its small thermal conductivity.

| No | Material       | Conductivity, W/m .K |
|----|----------------|-----------------------|
| 1. | Copper         | 401                   |
| 2. | PVC pipe       | 0.19                  |

Table 1. Material conductivity [4]

In designing the dimension of the heat exchange device, first determining the fluid data to be included in it and then analyzed to calculate the dimension of the design. The parameters are used in designing of the triple-tube exchanger as shown in table 2.

| No | Parameter                             | Symbol | Value   | Unit   |
|----|---------------------------------------|--------|---------|--------|
| 1. | The inlet temperature of the hot fluid| \(T_{\text{Hi}}\) | 60      | ºC     |
| 2. | The outlet temperature of the hot fluid| \(T_{\text{Ho}}\) | 43      | ºC     |
| 3. | Cold inlet Fluid temperature pipeline 1| \(T_{\text{C1 in}}\) | 25      | ºC     |
| 4. | Cold inlet Fluids temperature pipeline 2 | \(T_{\text{C2 in}}\) | 25      | ºC     |
| 5. | The fluid flow rate of heat            | \(m_{\text{h}}\) | 0.041   | Kg/s   |
| 6. | Fluid flow rate 1                      | \(m_{\text{c1}}\) | 0.025   | Kg/s   |
| 7. | Cold fluid flow rate 2                 | \(m_{\text{c2}}\) | 0.025   | Kg/s   |
| 8. | The diameter of pipeline 1             | \(d_{\text{n1}}\) | 0.0127  | m      |
| 9. | Diameter of pipeline 2                 | \(d_{\text{n2}}\) | 0.0254  | m      |
| 10.| The diameter of pipeline 3             | \(d_{\text{n3}}\) | 0.04    | m      |
| 11.| Copper thermal conductivity            | \(C_u\) | 401     | W/m K  |

Table 2. Data parameter
To calculate the average temperature of the cold fluid is used iteratively, an assumption is required that $T_{c1\text{\ out}} = T_{c2\text{\ out}} = 30.9 \ ^\circ \text{C}$ and then the average temperature of the fluid could be calculated. To determine the average temperature of the cold fluid tube I:

$$T_f = \frac{T_{c1\text{\ in}} + T_{c1\text{\ out}}}{2} \quad (1)$$

The average temperature of the cold fluid in the tube I, $T_f = 300.95 \ \text{K}$. Table 3 shows the fluid properties of cold water in tube I.

| No | Parameter          | Symbol | Value     | Unit   |
|----|--------------------|--------|-----------|--------|
| 1  | Density            | $\rho_{c1}$ | 997.008   | Kg/m$^3$ |
| 2  | Thermal conductivity | $K_{c1}$ | $613 \times 10^{-3}$ | W/m k  |
| 3  | Specific heat      | $C_{p\ c1}$ | 4179     | J/kg k  |
| 4  | Viscosity          | $\mu_{c1}$ | $855 \times 10^{-6}$ | Pa.s   |
| 5  | Prandtl number     | $Pr_{c1}$ | 5.83     | -       |

Then we calculate flow velocity in the tube I [8] as follows:

$$V_{c1} = \frac{m_{c1} \times 4}{\rho_{c1} \times \pi \times d_{\text{in}}^2} \quad (2)$$

After obtaining the flow velocity, subsequently determine the Reynolds number [9] for cold I tube water by using the equation as follows:

$$Re_{c1} = \frac{\rho_{c1} \times V_{c1} \times d_{\text{in}1}}{\mu_{c1}} \quad (3)$$

Where $Re$ is Reynolds number, $\rho$ is density (kg/m$^3$), $V$ is average velocity of fluid (m/s), $D$ is pipe diameter (m), and $\mu$ is viscosity dynamic (N.s/m$^2$).

The formula to find Nusselt number using the equation as follows [10]:

$$Nu_{c1} = \frac{(f/2) \times (Re_{c1} - 1000) \times Pr_{c1}}{1 + 1.27 \times (f/2)^{5/3} (Pr_{c1})^{2/3} - 1} \quad (4)$$

Calculates the heat flow convection coefficient on the tube with the equation as follows:

$$h_{c1} = \frac{Nu_{c1} \times K_{c1}}{d_{\text{in}1}} \quad (5)$$

Where $Nu_{c1}$ is Nusselt tube number, $h_{c1}$ is heat transfer coefficient of inside tube convection (W/m$^2$ K), $d_{\text{in}1}$ is pipe diameter (m), and $K_{c1}$ is thermal conductivity (W/m.K).

4.2. A coefficient of heat transfer in tube II.

To determine the average temperature of heat fluid in tube II

$$T_f = \frac{T_{\text{in}1} + T_{\text{out}1}}{2} \quad (6)$$
The average temperature of the hot fluid in tube II, $T_f = 324.5 \text{ K}$

**Table 4. The fluid properties heat water in tube II**

| No. | Parameter         | Symbol | Value | Unit   |
|-----|-------------------|--------|-------|--------|
| 1   | Density           | $\rho_{h1}$ | 987   | Kg/m³  |
| 2   | Thermal conductivity | $K_{h1}$ | 0.644 | W/m·k  |
| 3   | Specific heat     | $C_p \cdot h_{1}$ | 4181.8 | J/kg·k |
| 4   | Viscosity         | $\mu_{h1}$ | 532.9 | Pa·s   |
| 5   | Prandtl number    | $Pr_{h1}$ | 3,455 |        |

Then we calculate the flow velocity in tube II as follows:

$$V_{h1} = \frac{\rho_{h1} \cdot x \cdot 4}{\rho_{h1} \cdot N_{h1} (d_{in}^2 - d_{out}^2)^2}$$  \hspace{1cm} (7)

Before calculating the Reynolds number in tube II, the hydraulic diameter [2] using the equation as follows:

$$d_h = d_{in2} - d_{out1}$$ \hspace{1cm} (8)

Where $D_h$ is hydrolic diameter (m), $D_o$ is outside tube diameter (m), $D_i$ is inside tube diameter (m).

After obtaining the flow velocity, then looking for the Reynolds number [10] for the tube II of hot water, the equation as follows:

$$Re_{h1} = \frac{\rho_{h1} \cdot x \cdot V_{h1} \cdot d_{h1}}{\mu_{h1}}$$ \hspace{1cm} (9)

Where $Re$ is Reynolds numeral, $\rho$ is density (kg/m³), $V$ is average velocity of fluid (m/s), $D$ is pipe diameter (m), and $\mu$ is dynamic viscosity (N·s/m²).

After getting Reynolds number, then find for nusselt number [11,12]:

$$Nu_h = 2.718 \cdot Re_h^{0.597} \cdot Pr_1^{1/3} \left( \frac{d_{h1}}{d_1} \right)^{2/3}$$ \hspace{1cm} (10)

From the value of the Nusselt number, we can calculate the heat flow convection coefficient on the annular tube II form of the equation as follows:

$$h_{in} = \frac{Nu_h \cdot x \cdot K_h}{d_h}$$ \hspace{1cm} (11)

Where $Nu_h$ is Nusselt tube numbers, $h_{in}$ is heat transfer coefficient of inside tube convection (W/m²·K), $D_h$ is hydraulic diameter (m), and $k$ is thermal conductivity (W/m·K).

4.3. The coefficient of heat transfer in tube III.

To determine the average temperature of the cold fluid in tube III:

$$T_f = \frac{T_{c2in} + T_{c2out}}{2}$$ \hspace{1cm} (12)
The average temperature of the cold fluid in tube III, \( T_f = 300.95 \) K.

| No | Parameter                             | Symbol | Value       | Unit     |
|----|---------------------------------------|--------|-------------|----------|
| 1  | Density                               | \( \rho_{c2} \) | 997.008     | Kg/m\(^3\) |
| 2  | Thermal conductivity                   | \( K_{c2} \) | \( 613 \times 10^{-3} \) | W/m.k    |
| 3  | Specific heat                          | \( C_{p,c2} \) | 4179        | J/kg.k   |
| 4  | Viscosity                              | \( \mu_{c2} \) | \( 855 \times 10^{-6} \) | Pa.s     |
| 5  | Prandtl number                         | \( Pr_{c2} \) | 5.83        | -        |

Then we calculate the flow velocity in tube III as follows:

\[
V_{c2} = \frac{m_{c2}x^4}{\rho_{c2}x\pi\left(d_{\text{inc2}}-d_{\text{out2}}\right)^4} \tag{13}
\]

Before calculating the Reynolds number in tube III, we calculate the hydraulic diameter by using the equation as follows:

\[
d_h = d_{\text{in3}} - d_{\text{out2}} \tag{14}
\]

After getting the flow velocity in the tube III, then find the Reynolds number for cooling fluid flow by using the equation as follows:

\[
Re_{c2} = \frac{\rho_{c2}xV_{c2}x^4d_h}{\mu_{c2}} \tag{15}
\]

Where \( Re \) is Reynolds number, \( \rho \) is density (kg/m\(^3\)), \( V \) is average velocity of fluid (m/s), \( D \) is pipe diameter (m), and \( \mu \) is dynamic viscosity (N.s/m\(^2\)).

After getting Reynolds number, then find the Nusselt number [13,14]:

\[
Nu_{c2} = 0.51 \times Re_{c2}^{0.5} \times Pr_{c2}^{1/3} \times \left( \frac{Pr_{c2}}{Pr_{c2}} \right)^{0.25} \tag{16}
\]

Afterward, we calculate the heat flow convection coefficient in tube III using the equation as follows:

\[
h_{c2} = \frac{Nu_{c2}xK_{c2}}{d_h} \tag{17}
\]

Where \( Nu \) is Nusselt tube numbers, \( h \) is heat transfer coefficient of inside tube convection (W/m\(^2\) K), \( D_h \) is hydraulic diameter (m), \( k \) is thermal conductivity (W/m.K)

4.4. Calculates the overall heat transfer coefficient. There are two coefficients of on triple concentric tube heat exchanger. To calculate thermal heat transfer coefficient outside and center of pipe 2 to pipe 1 by using the equation as follows:

\[
\frac{1}{U_{o1}} = \frac{d_{\text{out1}}}{d_{\text{in1}}xh_{c1}} + \frac{d_{\text{out1}}x\ln(d_{\text{out1}}/d_{\text{in1}})}{2xk_{\text{coper}}} + \frac{1}{h_{\text{in}}} \tag{18}
\]

The comprehensive heat transfer coefficient in pipe 2 to pipe 3

\[
\frac{1}{U_{\text{in2}}} = \frac{1}{h_{\text{in}}} + \frac{d_{\text{in2}}x\ln(d_{\text{out2}}/d_{\text{in2}})}{2xk_{\text{coper}}} + \frac{d_{\text{in2}}}{d_{\text{out2}}xh_{c2}} \tag{19}
\]
Where \( U \) is average heat transfer coefficient (W/m².K), \( h_i \) is heat transfer coefficient of inside pipe convection (W/m².K), \( h_o \) is heat transfer coefficient of outside convection pipe (W/m².K), \( T \) is tube thickness (m), \( k \) is thermal conductivity of material (W/m.K).

Calculating the average temperature difference logarithmically opposite LMTD (Logarithmic mean temperature difference), using the equation [4] as follows:

\[
\Delta T_{lm} = \frac{(T_{hi} - T_{di}) - (T_{ho} - T_{co})}{\ln\left(\frac{T_{hi} - T_{di}}{T_{ho} - T_{co}}\right)}
\]  

(20)

Where \( \Delta T_{lm} \) is difference temperatures of average logarithmic (°C), \( T_{hi} \) is heat of inlet fluid Temperatures (°C), \( T_{ho} \) is temperature of inlet heat fluid (°C), \( T_{ci} \) is temperature of outlet heat fluid (°C), and \( T_{co} \) is temperature of outlet cold fluid (°C).

Calculates the heat transfer rate by using the equation:

\[
Q_h = \dot{m}_h \cdot C_{p,h} (T_{hi} - T_{ho})
\]

(21)

Where \( Q \) is heat transfer rate (W), \( \dot{m}_h \) is fluid mass flow rate (kg/s), \( C_{p,h} \) is heat fluid (J/kg.K), \( T_{hi} \) is temperature of inlet heat fluid (°C), \( T_{ho} \) is temperature of outlet heat fluid (°C)

Calculates the rate of heat transfer in cold fluid as follows:

\[
Q = \dot{m}_c \cdot C_{p,c} (T_{ci} - T_{co})
\]

(22)

Where \( Q \) is heat transfer rate W), \( \dot{m}_c \) is fluid mass flow rate (kg/s), \( C_{p,c} \) is specific heat of cold fluid (J/kg.K), \( T_{ci} \) is temperature of inlet cold fluid (°C), and \( T_{co} \) is temperature of outlet cold fluid (°C).

4.5. Calculates the length of the heat exchanger

Find the length of the heat exchanger, using the equation as follows:

\[
Q = U A \Delta T_{lm}
\]

(23)

Where \( Q \) is heat transfer rate (W), \( U \) is comprehensive heat transfer coefficient (W/m² °C), \( A \) is extensive of the vertical cross section (m²), and \( \Delta T_{lm} \) is different temperatures of average logarithmic (°C). The length of the pipe is 2.57 m by dividing it into three pipes 0.857m is shown figure 5.

![Figure 5. The design of a heat exchanger](image)

Figure 6 shows the heat exchange device that has been created and installed the flowmeter, and also a temperature sensor on it.
4.6. Design the framework of heat exchanger
The framework of the heat exchanger was made using iron elbow with the thickness of 3mm. Frames are made with different dimensions as shown table 6.

### Table 6. Frame dimension

| No | Dimension       | Quantity | Unit |
|----|-----------------|----------|------|
| 1  | 1200 x 33 x 33  | 4        | mm   |
| 2  | 500 x 33 x 33   | 4        | mm   |
| 3  | 1500 x 33 x 33  | 4        | mm   |

Figure 7 shows the design of framework or buffer of a heat exchanger.

4.7. Design of valve
This design is using the ½ inch ball valve, with the primary material of plastic that easily connected to PVC pipe. This ball valve selection is due to the lowest coefficient of minor losses among all other valves, and the operation is more accessible and less time-consuming than the gate valve as shown table 7.
Table 7. Type of valve and the coefficient of minor loss

| No | Type of valve                       | A coefficient of minor loss |
|----|------------------------------------|-----------------------------|
| 1  | Globe valve, fully open            | 10                          |
| 2  | Angle valve, fully open            | 2                           |
| 3  | Gate valve, fully open             | 0,15                        |
| 4  | Valve gate, ¼ closed               | 0,26                        |
| 5  | Gate valve, ½ closed               | 2,1                         |
| 6  | Gate valve, ¾ closed               | 17                          |
| 7  | Fully open ball valve              | 0,05                        |
| 8  | Gate valve, ½ closed               | 5,5                         |

5. Conclusions

This research has designed and manufactured the concentric of a heat exchanger with three concentric tubes of reverse flow as the water cooler. The materials that used for the manufacture is copper because this device is resistant to corrosion, and the copper has a high conductivity. The heat exchanger component consists of three copper tubes that are having the same concentric center. If the test using the fluid other than water, we should pay attention to the temperature and fluid content that used as it has the potential damage the appliance.

Reference

[1] Bisoniya T S 2015 Design of earth-air heat exchanger. Geothermal Energy.
[2] Sitorus T B et al. 2016 TAE - Proceedings of 6th International Conference on Trends in Agricultural Engineering.
[3] Ariani F et al 2017 IOP Conf. Ser.: Mater. Sci. Eng. 277 012045.
[4] Incropera F and Dewitt D P 1996 Introduction to Heat Transfer. 7th Edition. New York: John Wiley & Sons.
[5] Cengel Y A and Boles M A 2006 Heat transfer, Mc Graw Hill. Inc, Singapore, pp.84-686.
[6] Holman J P 1997 Perpindahan kalor, edisi ke-2. Jakarta, Erlangga.
[7] Irvan et al 2017 IOP Conf. Ser.: Mater. Sci. Eng. 206 012028.
[8] Arjuna J et al 2018 IOP Conf. Ser.: Mater. Sci. Eng. 309 012088.
[9] Ahmed A et al. 2016 Earth-Air Heat Exchanger Thermal Performance in Egyptian Condition: Experiment Result, Mathematical Model, and Computation Fluid Dynamic Simulation. Jurnal Konversi dan Manajemen Energi, vol. 25:38.
[10] Paepe D M and Janssens A 2003. Thermo-hydraulic design of earth-air heat exchangers. Energy Build 35:389-397.
[11] Gauthier C et al. 1997 Numerical simulation of soil heat exchanger storage system for the greenhouse. Sol Energy 60(6):333-346(10).
[12] Sitorus T B et al. 2017 Journal of Engineering and Technological Sciences, Vol. 49, No. 5, 657-670.
[13] Bisoniya T S et al. 2013 Experimental and analytical studies of the earth-air heat exchanger (EAHE) systems in India: a review. Renew Sustain Energy Rev 19:238-246.
[14] Sitorus T B et al 2018 IOP Conf. Ser.: Mater. Sci. Eng. 309 012089.