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# Design of Shell and Tube Heat Exchanger for Magnetite ($Fe_3O_4$) Particle Production Process

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## ABSTRACTS

Shell and tube heat exchangers are one of the most widely used types of heat exchangers in industry. The low cost of manufacture and use is one of the reasons this heat exchanger is widely used. The purpose of this research is to design a shell and tube heat exchanger (two-pass) type for application in the production of magnetite particles on an industrial scale. To design a heat exchanger, the method used is mathematical calculations using more than 20 equations that are used which are derived based on the influence of dimensional and fluid specifications. In the production of magnetite particles, two heat exchangers are used, namely the reaction process and the crystallization process. The results of this study indicate the effectiveness of the two heat exchangers designed to have a high enough value and exceed 70%. This high effectiveness value indicates that both heat exchangers have good performance. Therefore, this design has the potential to be applied to the magnetite particle synthesis process on an industrial scale.



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## 1. INTRODUCTION

Heat Exchanger is a heat exchanger that serves to change the temperature of the phase of a type of fluid. This process occurs by utilizing the heat transfer process from a high temperature fluid to a low temperature fluid (Septian *et al.*, 2021). Shell-and-tube heat exchangers (STHEs) are the most widely used heat exchangers in process industries because of their relatively simple manufacturing and their adaptability to different operating conditions (Patel & Rao, 2010).

Thermal design of shell-and-tube heat exchangers (STHEs) is done by sophisticated computer software. However, a good understanding of the underlying principles of exchanger design is needed to use this software effectively (Mukherjee, 1998).

The purpose of this article is to design a shell and tube type heat exchanger for applications in the production of magnetite nanoparticles. Magnetite nanoparticle production method is based on research conducted (Meng *et al.*, 2013), namely by coprecipitation method using basic materials $FeCl_2.4H_2O$ and $FeCl_3.6H_2O$. **Figure 1** shows an illustration of the synthesis of magnetite particles in laboratory scale. Based on the illustration, the production process requires a heating device at a temperature of 50$^o$C to mix the main precursor and the product crystallization process requires a temperature of 90$^o$C. Assuming that the laboratory scale synthesis scheme can be directly used on an industrial scale, the heat generated in the process reaction and crystallization will be managed with a heat exchanger. Therefore, here we evaluated heat exchanger performance that is applied in the magnetite production industry. To analyse the performance of the designed heat exchanger, there are several parameters that need to be considered and of course will be the focus of this heat exchanger design consideration. The calculated parameters are heat transfer surface area (A), thermal load (*Q*), overall heat transfer coefficient (*U*), and logarithmic mean temperature difference (*ΔTlm*) to see whether the designed heat exchanger meets the standard or not.

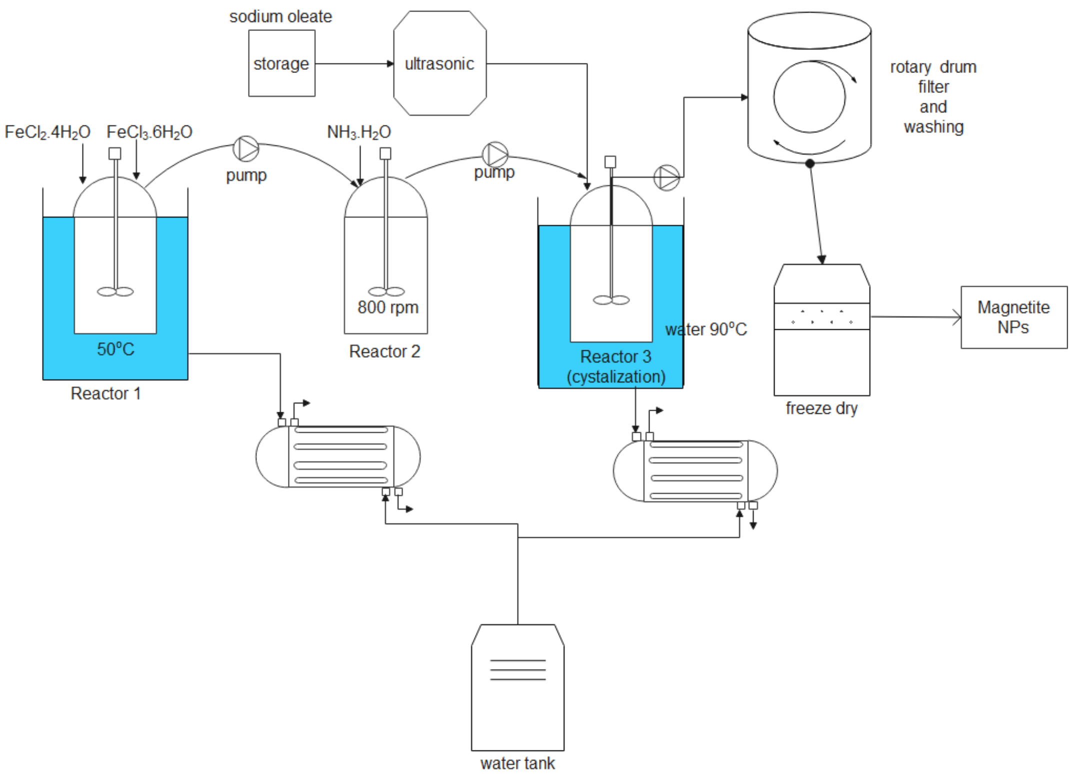


**Figure 1**. Illustration of magnetite particle synthesis process

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## 2. METHODS

The method used in writing this article is a mathematical calculation for each parameter used in the shell and tube heat exchanger design process.

According to flow regime, the tube side heat transfer coefficient ($h_t$) is computed from following correlation.

$$h_t = \frac{Nu \times K}{d_i,t} \tag{1}$$

where, *K* is thermal conductivity of material, di is inner diameter of tuber and *Nu* is Nusselt number given as equation no. 2.

$$Nu = 0.023 \times Re_t^{\ 0.6} \times Pr_t^{\ 0.33} \tag{2}$$

$P_{rt}$ is Prandtl number and computed as equation no. 3.

$$Pr_t = (\frac{C_p \times \mu}{K})^{\frac{1}{2}} \tag{3}$$

And $Re_t$ is the tube side Reynolds number and given by equation no. 4.

$$Re_t = \frac{di_t \times Gt}{\mu} \tag{4}$$

*Gt* is mass flow rate of fluid in tube, given by equation no. 5.

$$Gt = \frac{m_h}{a_t} \tag{5}$$

Surface area of total heat transfer in tube ($a_t$) is found by equation no. 6.

$$a_t = N_t \frac{a'_t}{n} \tag{6}$$

Where, $a_t$ is the total flow area in tube, n is the number of passes, and $N_t$ is the number of tubes as given by equation no. 7.

$$N_t = \frac{A}{\pi \times d_o \times l} \tag{7}$$

Do is the outer diameter of tube, *l* is the lenght of the tube, and *A* is the heat exchanger surface area and given by equation no. 8.

$$A = \frac{Q}{U \times LTMD} \tag{8}$$

Kern's formulation for segmental baffle shell and tube exchanger is used for computing shell side heat transfer coefficient $h_s$, given by equation no. 9.

$$h_s = \frac{Nu \times K}{d_e} \tag{9}$$

Where, $d_e$ is the shell hydraulic diameter and computed as given by equation no. 10

$$d_e = \frac{4(\frac{Pt}{2} \times 0.87\ Pt - \frac{1}{2}\pi \frac{d_{o,t}}{4})}{\frac{1}{2}\pi d_{o,t}} \tag{10}$$

$P_t$ is tube pitch and for triangular tube arrangements is (1,25 x $d_o$).

Cross section area normal to flow direction is determined by equation no. 11.

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$$A_s = \frac{D_s \times C \times B}{P_t} \quad (11)$$

Diameter of bundle of the tube can obtain from equation no. 12.

$$D_b = d_o \left(\frac{N_t}{k_1}\right)^{\frac{1}{n_1}} \quad (12)$$

*N* and *k* are constants for that equation. These constants are shown in **Table 1** for different flow arrangements.

Prandtl number for shell side follows equation no. 13.

$$Pr = \left(\frac{C_p \times \mu}{K}\right)^{\frac{1}{2}} \quad (13)$$

Reynolds number for shell side follows equation no. 14.

$$Re_s = \frac{di_s \times G_s}{\mu} \quad (14)$$

Where $G_s$ is the mass flow rate of water in shell, given by equation no. 15.

$$Gs = \frac{m_c}{A_s} \quad (15)$$

The overall heat transfer coefficient (*U*) depends on both the tube side and shell side heat transfer coefficients and fouling resistances are given by equation no. 16.

$$U_{act} = \frac{1}{\frac{1}{h_t} + \frac{\Delta r}{k} + \frac{1}{h_s}} \quad (16)$$

Considering the cross flow between adjacent baffle, the logarithmic mean temperature difference (*LMTD*) is determined by equation no. 17.

$$LMTD = \frac{(T_{hi} - Tc_i) - (T_{ho} - Tc_o)}{ln \frac{(T_{hi} - Tc_i)}{(T_{ho} - Tc_o)}} \quad (17)$$

The correction factor F for the flow configuration involved is found as a function of dimensionless temperature ratio for most flow configuration of interest.

$$F = \frac{\sqrt{R^2+1}\, ln ln \left[\frac{1-P}{1-PR}\right]}{(R-1) ln ln \left(\frac{2-P(R+1-\sqrt{R^2+1}}{2-P(R+1+\sqrt{R^2+1}}\right)} \quad (18)$$

Where R is the correction coefficent given by equation no. 19.

$$R = \frac{T_{hi} - T_{ho}}{T_{co} - T_{ci}} \quad (19)$$

P is the efficiency given by equation no. 20.

$$P = \frac{T_{co} - T_{ci}}{T_{hi} - T_{ci}} \quad (20)$$

The heat transfer rate is given by equation no. 21.

$Q_{in} = Q_{out}$

$$m_c \times Cp_c \times \Delta T_c = m_h \times Cp_h \times \Delta T_h \quad (21)$$

Based on total heat exchange surface area (*A*), the tube lenght is,

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$$L = \frac{A}{\pi d_o N_t} \quad (22)$$

Then, hot fluid rate ($C_h$) and cold fluid rate ($C_c$) given by equation no. 23 and no. 24.

$$C_h = m_h . Cp_h \quad (23)$$

$$C_C = m_c . Cp_c \quad (24)$$

Furthermore, the effectiveness of the heat exchanger that has been made is calculated through the equation no. 25.

$$\varepsilon = 2\left\{1 + c + \sqrt{1 + c^2}\ \frac{1 + expexp\,[-NTU\sqrt{1+c^2}]}{1 - expexp\,[-NTU\sqrt{1+c^2}]}\right\}^{-1} \quad (25)$$

Where, *NTU* adalah number of transfer unit, given by equation no. 26.

$$NTU = \frac{U \times A}{C_{min}} \quad (26)$$

Where, $C_{min}$ is the minimal heat capacity of the fluid.

And the fouling factor can obtain from equation no. 27.

$$Rf = \frac{U_a - U_{act}}{U_a \times U_{act}} \quad (27)$$

## 3. RESULTS AND DISCUSSION

To design a shell and tube heat exchanger, several assumptions are used to design and estimate the performance of the heat exchanger that has been made. Some of the assumptions used are that the fluid system used in this heat exchanger is water-water fluid, the heat exchanger designed is a shell and tube heat exchanger with a two-pass type, then the material used in the design of this heat exchanger is carbon steel, flow system of the fluid used is counter-current flow, then the overall coefficient (*U*) is 900 W/m$^2$.°C, the orientation of the geometry of the shell is horizontal, the baffle used is single segmental, and it is assumed that no heat is wasted during the heat exchange process. All the assumptions used above apply to the two heat exchangers used during the reaction process and also for the crystallization process.

Then the specification of the tool that will be used for the design of the heat exchanger also uses some assumptions. The assumptions used are valid for the two heat exchangers designed for the reaction and crystallization sections, this assumption refers to the standard used by TEMA. **Table 1** shows the dimensions of the designed heat exchanger apparatus.

Furthermore, specifications related to the fluid system used in the heat exchanger are required. In this article the fluid used is a water-water system. Because the magnetite particle production process has 2 heat exchangers and both have different temperatures, so the fluid specifications of each heat exchanger will be different. **Table 2** shows the specifications of the fluid used in the heat exchanger in the reaction process, while the specifications of the fluid used for the heat exchanger in the crystallization process are shown in **Table 3**.

To determine the performance of the heat exchanger that we have designed, it is necessary to evaluate several parameters. This evaluation is carried out through mathematical calculations of several previously assumed parameters. Calculations are made based on the equations listed in the methods section of this article. This equation is used to calculate the parameters used to see the performance of the designed heat exchanger. These parameters include the thermal load (*Q*), the league rhythmic temperature difference (*LTMD*), number of tube (*Nt*) of the heat exchanger, to the effectiveness of the heat exchanger. The data used in this mathematical calculation are data from dimension specifications and also fluid specifications which are presented in **Tables 1-3**. Based on these data, after the calculations have been carried out, the results of calculations for various parameters are presented in **Table 4**. **Table 4** has been presented results for the design of the heat exchanger in the reaction process and also in the crystallization process.

**Table 1.** Specifications of the heat exchanger apparatus based on TEMA standard.

| Parameter | Spesification |
|---|---|
| Conductivity Material (W/m°C) | 43 |
| Tube outer diameter (m) | 0.03 |
| Tube inner diameter (m) | 0.0268 |
| Wall thickness (m) | 0.0032 |
| Tube lenght (m) | 4.88 |
| Tube arrangemets pitch | Triangle |
| Pitch tube (m) | 0.0375 |
| Tube-side pass | 2 |
| Tube characteristic angle (°) | 45 |
| Shell outer diameter (m) | 0.6421 |
| Shell inner diameter (m) | 0.65 |
| Baffle cut | 25% |

**Table 2.** Specification of hot and cold fluids used in the reaction process

| Parameters | The specification in Tube Side | The specification in Shell Side |
|---|---|---|
| Inlet Temperature ($T_{h,in}$; °C) | 50 | - |
| Outlet Temperature ($T_{h,out}$; °C) | 30 | - |
| Inlet Temperature ($T_{c,in}$; °C) | - | 25 |
| Outlet Temperature ($T_{c,out}$; °C) | - | 30 |
| Fluid Flow Rate (kg/s) | 10 | 20.004785 |
| Density (kg/m$^3$) | 988.02 | 997.05 |
| Viscosity (Nm.s/m$^2$) | 0.0005465 | 0.000891 |
| Thermal Conductivity (W/m.K) | 0.6305 | 0.5948 |
| Heat Spesific (J/kg.K) | 4181 | 4180 |
| Operating Pressure (bar) | 1.013 | 1.013 |

The dimensional specifications of the heat exchanger used in this calculation are based on the standards of The Tubular Exchanger Manufacturers Association (TEMA). **Figures 2** and **3** are illustrations of the 2D tube layout used, namely triangular and shell illustrations used for the two-pass type. The length of the shell used for the designed heat exchanger is 4.88 m, these results are obtained based on calculations using equation (22). Based on the calculation results, the initial heat transfer value for the reaction process was 836200 W and for the crystallization process was 1892250 W (see **Table 3**).

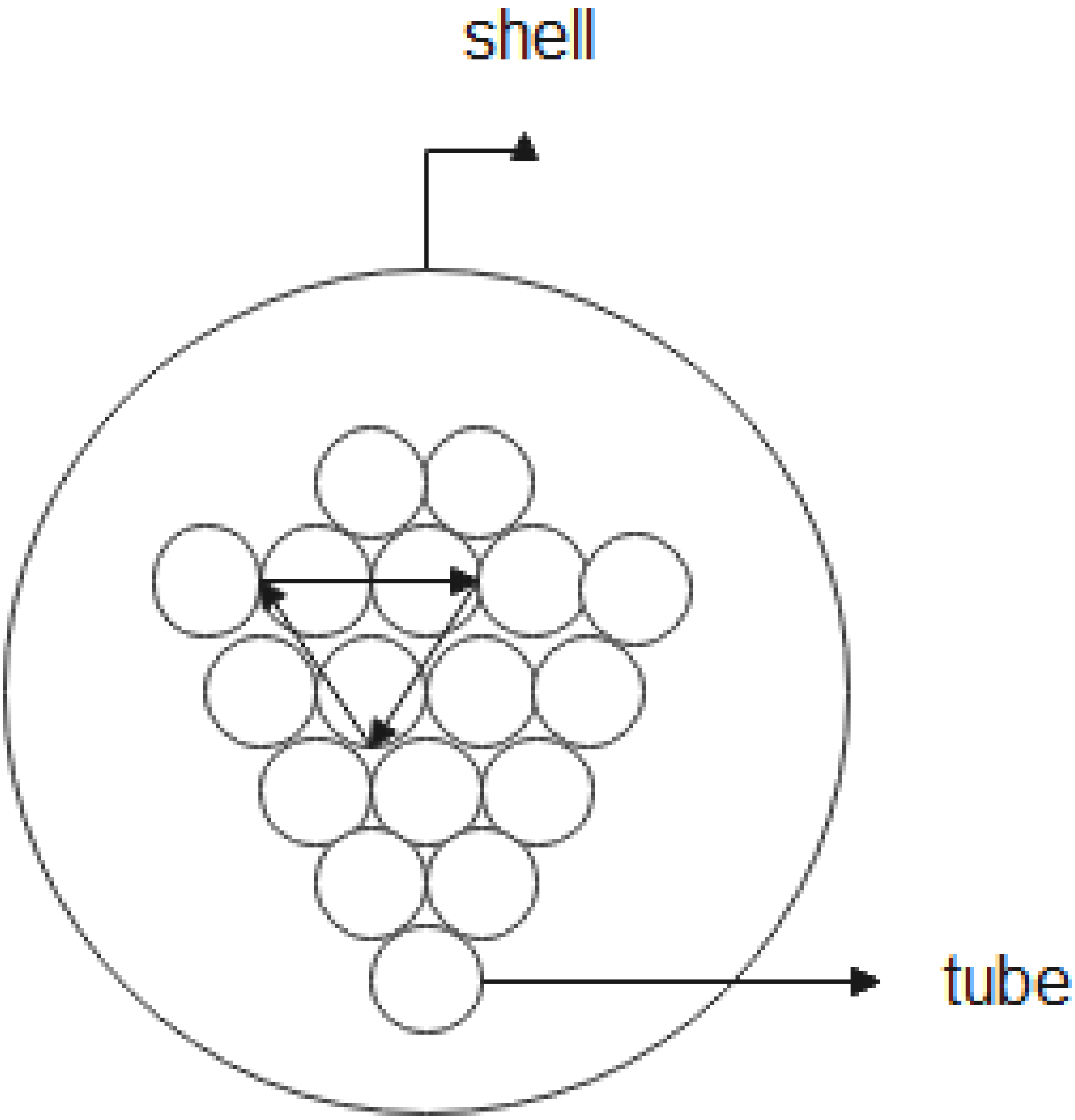


**Figure 2.** 2D tube layout

**Table 3.** Specification of hot and cold fluids used in the crystallization process.

| Parameters | The specification in Tube Side | The specification in Shell Side |
|---|---|---|
| Inlet Temperature ($T_{h,in}$; °C) | 90 | - |
| Outlet Temperature ($T_{h,out}$; °C) | 45 | - |
| Inlet Temperature ($T_{c,in}$; °C) | - | 25 |
| Outlet Temperature ($T_{c,out}$; °C) | - | 45 |
| Fluid Flow Rate (kg/s) | 10 | 45.269139 |
| Density (kg/m$^3$) | 965.06 | 997.05 |
| Viscosity (Nm.s/m$^2$) | 0.0003142 | 0.000891 |
| Thermal Conductivity (W/m.K) | 0.6613 | 0.5948 |
| Heat Spesific (J/kg.K) | 4205 | 4180 |
| Operating Pressure (bar) | 1.013 | 1.013 |

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**Table 4.** Performance parameters of heat exchanger designed based on calculations

| No | Parameter | Results for reaction process | Results for crystallization |
|---|---|---|---|
| 1 | Q (W) | 836200 | 1892250 |
| 2 | LMTD (°C) | 10.82 | 30.82879328 |
| 3 | Ua (W/m$^2$. K) | 900 | 900 |
| 4 | R | 4 | 2.25 |
| 5 | S | 0.2 | 0.307692308 |
| 6 | Ft | 0.8134 | 0.8062784 |
| 7 | ΔTm | 8.801 | 24.85659013 |
| 8 | A (m$^2$) | 105.558 | 84.58521419 |
| 9 | Nt | 230 | 184.0025021 |
| 10 | at (m$^2$) | 9.313 | 5.9799 |
| 11 | Gt (m/s) | 0.0123 | 0.0154 |
| 12 | Ret | 6045.607 | 13122.68 |
| 13 | Prt | 3.624 | 1.9979 |
| 14 | ht (W/m$^2$.K) | 4143.970 | 6480.152 |
| 15 | Baffle spacing (m) | 0.1337 | 0.1211 |
| 16 | Db (m) | 0.6614 | 0.5982 |
| 17 | as (m$^2$) | 0.017899 | 0.0146 |
| 18 | de (m) | 0.0214 | 0.0213 |
| 18 | Res | 26784.55 | 73909.678 |
| 20 | Prs | 6.26156 | 6.2615 |
| 21 | hs (W/m$^2$.K) | 4545.461 | 10238.387 |
| 22 | Uact (W/m$^2$.K) | 906.939 | 1132.635 |
| 23 | $\varepsilon$ | 76.4% | 89.02% |
| 24 | NTU | 22.728 | 18.212 |
| 25 | Fouling Resistance (°C.m$^2$/W) | -0.000008 | 0.00023 |

Several other parameters such as LMTD, number of tubes, bundle diameter, overall heat transfer coefficient, and the effectiveness of the designed heat exchanger for sequential reaction sections are 10.82oC, 230 pieces, 0.6614 m, 906.939 W/m$^2$. K and an effectiveness of 76.4 %. while the parameter values for the heat exchanger in the crystallization section are 30,828°C, 184 pieces, 0.5982, 1132.635 W/m$^2$. K and the effectiveness is 89.02%. the high overall heat transfer coefficient shows how easy it is for heat to move from a hot fluid to a cold fluid (Singh & Sarkar, 2020). From the results obtained, the value of U in the crystallization process is greater than the value of U in the reaction process, so it can be said that in the crystallization process heat is more easily transferred than in the reaction process. Then the effectiveness of the two heat exchangers obtained is more than 70%, even the heat exchanger in the crystallization process is almost 90%. These results indicate the effectiveness of the heat exchanger used, the value of this effectiveness is related to the difference in temperature at the time of entering and leaving the heat exchanger. The effectiveness and this temperature difference have a linear relationship, the greater the temperature difference, the greater the effectiveness of the heat exchanger (Lukitobudi et al., 1995).

**Figure 3** above shows an illustration of the shell layout that will be used. This layout conforms to the standards set by TEMA and the layout is a two-pass type shell layout.

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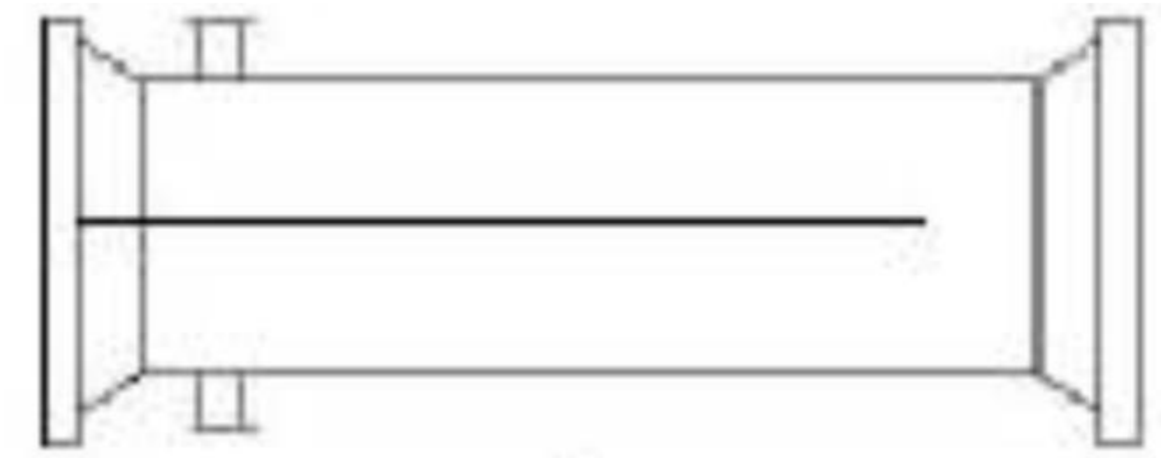

**Figure 3.** Illustration of the shell shape that will be used.

## 4. CONCLUSION

Based on the mathematical calculations that have been done, the two heat exchangers were successfully designed with the shell and tube two-pass type and the number of tubes was 230 for the reaction section and 184 for the crystallization section. Then the overall heat transfer coefficient for the reaction process is 906.939 $W/m^2$. K and for the crystallization process are 1132.635 $W/m^2$. K. Meanwhile, the effectiveness of the two heat exchangers that have been designed reaches more than 70%. Therefore, these two heat exchangers have good performance and potential to be applied on an industrial scale.

## 5. ACKNOWLEDGMENT

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## 6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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