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DESIGN OF SHELL AND TUBE TYPE HEAT EXCHANGER FOR NANOFIBRIL CELLULOSE PRODUCTION PROCESS

Hanif Nur Purnamasari[1], Teguh Kurniawan[2], Asep Bayu Dani Nandiyanto[1*]
[1] Departemen Pendidikan Kimia, Universitas Pendidikan Indonesia, Bandung, Indonesia

[2] Departemen Teknik Kimia, Universitas Sultan Ageng Tirtayasa, Serang, Indonesia

Email: *nandiyanto@upi.edu

Abstract. Heat exchanger plays an important role in industry. In industrial applications, the type of heat exchanger that is often found is the shell and tube type heat exchanger. The aim of this paper is to of tube and shell type heat exchanger for nanofibril cellulose production applications. The method used is to design several assumptions and calculate parameters related to determining the performance of the heat exchanger. The parameters are calculated manually using the Microsoft Excel application. In this design, the TEMA standard is used as a reference. The result of this paper is the heat exchanger has 53 pcs of tubes with the effectiveness up to 89.21%. This indicates that the overall performance of the heat exchanger in cellulose nanofibril production applications can be further improved by selecting the right fluid, fluid flow rate, and other physical properties, as well as the number of tubes that will be required.

Keywords: Effectiveness, Heat Exchanger, Performance, Shell and Tube

1. Introduction

A heat exchanger can be defined as a device that functions to transfer heat between two fluids that are at different temperatures. These two liquids are separated by a wall to prevent mixing with each other [1]. Heat exchangers are often used in engineering applications such as power generation, petroleum refining, chemical engineering processes, air conditioning, food industry and others [2]. There are various types of heat exchangers, one of which is a shell and tube heat exchanger which is commonly used as a gas or liquid medium in a large temperature and pressure range [3]. The diagram of typical shell and tube heat exchanger is shown in Figure 1. Shell and tube heat exchangers are made of tube bundles and may consist of several tubes which are the medium for fluid flow and heat transfer [4,5].

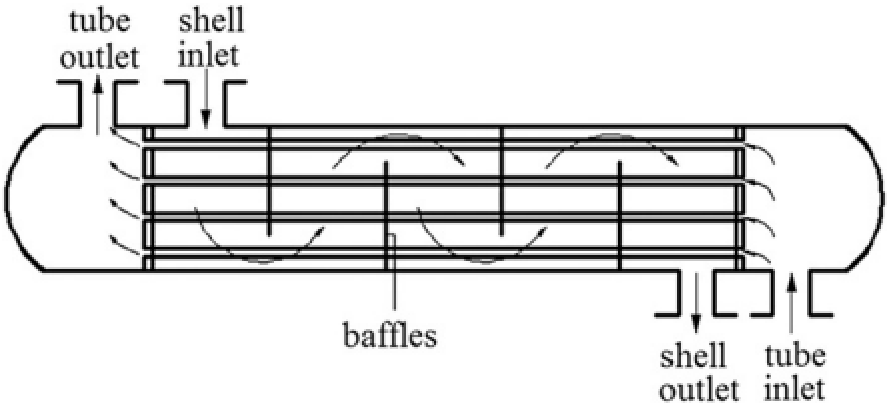

Figure 1. Diagram of a typical shell and tube heat exchanger [6]

In a previous review, Feng et al. [7] designed a shell and tube heat exchanger with the hot water as source of heat for organic fluid evaporation process. The results showed that the complex function has a minimum point with an optimal external diameter of the heat transfer tube. This shows that the complex function has a certain heat transfer performance and greatly improves the fluid flow performance. In Said et al. [8] investigating the efficiency of heat exchangers using stable Cu/water nanofluids. Based on his research results, the convective heat transfer coefficient obtained with nanofluid is slightly higher than that of base fluid for the same fluid inlet temperature and mass flow rate.

This study purpose to focus on the design of shell and tube type heat exchanger for nanofibril cellulose production applications because the design of heat exchangers to produce this nanocrystal is still rare. Based on literature [9], the preparation of cellulose nanofibrils for use in the synthesis of polyvinyl alcohol/cellulose nanofibril hybrid airgel microspheres requires a temperature of 60°C. To determine the performance of the heat exchanger that has been designed, it is necessary to calculate the heat transfer surface area (A) that depend on other parameters, namely thermal load (Q), overall heat transfer coefficient (U) and logarithmic mean temperature difference (ΔTlm).

2. Method

The shell and tube type heat exchanger are designed by specifying the proper dimensions for the heat exchange apparatus. Standard of Tubular Exchanger Manufacturers Association (TEMA) is used in the process of collecting data regarding the specifics and dimensions of the apparatus. After that, the thermal analysis takes the form of an overall calculation heat transfer coefficient (U), LMTD method, heat transfer (Q), and pressure drop is also calculated manually using basic Microsoft Office applications that calculated based on Table 1. Then the calculation results are considered to determine the performance and efficiency of the heat exchanger.

Table 1. Parameter calculation of heat exchanger

Section	Parameter	Equation	No. Eq
Basic parameters	The energy transferred (Q)	$Q_{in} = Q_{out}$ $m_h \times Cp_h \times \Delta T_h = m_c \times Cp_c \times \Delta T_c$ Where, Q : the energy transferred (Wt) m : the mass flow rate of the fluid (Kg/s) Cp : the specific heat ΔT : the fluid temperature difference (°C).	(1)
	Logarithmic mean temperature differenced (LMTD)	$\Delta T_{lm} = \frac{(T_1 - t_2) - (T_2 - t_1)}{ln\frac{(T_1 - t_2)}{(T_2 - t_1)}}$ ΔT_{lm} : log mean temperature difference T_1 : temperature of the hot fluid inlet (°C) T_2 : temperature of the hot fluid outlet (°C) t_1 : temperature of the cold fluid inlet (°C) t_2: temperature of the cold fluid outlet (°C)	(2)
	Correction factor	$R = \frac{T_1 - T_2}{t_2 - t_1}$ $S = \frac{t_2 - t_1}{T_1 - t_1}$	(3)
		$F_t = \frac{\sqrt{R^2+1}\ \ln[\frac{1-P}{1-PR}]}{(R-1)\ln(\frac{2-P(R+1-\sqrt{R^2+1}}{2-P(R+1+\sqrt{R^2+1}})}$	(4)

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Section	Parameter	Equation	No. Eq
			(5)
		$\Delta T_m = F_t \, \Delta T_{lm}$	(6)
	Heat Transfer Field Area (A)	$A = \frac{Q}{U \times \Delta T_{lm}}$ Where, Q : the energy transferred (W) U : the overall heat transfer coefficient ΔT_{lm} : the logarithmic mean temperature difference.	(7)
	Number of Tubes (N)	$N_t = \frac{A}{\pi \times D_o \times l}$ Where, N : the number of tubes A : the area of the heat transfer area (m^2), π : 3.14 D_o : tube diameter (m) l : tube length (m).	(8)
Tube	Surface Area of Total Heat Transfer in Tube (a_t)	$a_t = N_t \frac{a'_t}{n}$ Where, a_t : the total heat transfer surface area in the tube (m^2)	(9)

Section	Parameter	Equation	No. Eq
		N_t : the number of tubes a'_t : the flow area in the tube (m²) n : the number of passes.	
	Mass Flow Rate of Water in Tube (Gt)	$$Gt = \frac{m_h}{a_t}$$ Where, Gt : the mass flow of water in the tube (kg/m²s) m_h : the mass flow rate of the hot fluid (Kg/s) a_t : the flow area tube (m²)	(10)
	Reynold number (Re,t)	$$Re_t = \frac{di_t \times Gt}{\mu}$$ Where, Re_t : the Reynolds number in tube di_t : the inner tube diameter (m), Gt : the mass flow of water in the tube (m²) μ : the dynamic viscosity (Kg/ms).	(11)
	Prandtl Number (Pr,t)	$$Pr = (\frac{C_p \times \mu}{K})^{\frac{1}{2}}$$ Where, Pr : Prandtl number Cp : the specific heat of the fluid in the tube μ : the dynamic viscosity of the fluid in the tube (Kg/ms) K : the thermal conductivity of the tube material (W/m°C).	(12)

Section	Parameter	Equation	No. Eq
	Nusselt number (Nu,t)	$Nu = 0.023 \times {Re_t}^{0.6} \times Pr^{0.33}$	(13)
	Inside coefficient (h_i)	$hi = \frac{Nu \times K}{d_i, t}$ Where, hi : the convection heat transfer coefficient in the tube (W/m²°C) K : the thermal conductivity of the material (W/m°C) d_i, t : the inner tube diameter (m).	(14)
Shell	Shell flow area (A_s)	$D_b = d_o(\frac{N_t}{k_1})^{\frac{1}{n_1}}$ $A_s = \frac{d_s \times C \times D_b}{P_t}$ Where, d_s : shell diameter (m) C : clearance (P_t-d_o) D_b : a shell bundle P_t : tube pitch (1.25× d_o) (m).	(15) (16)
	Mass Flow Rate of Water in Shell (Gs)	$Gs = \frac{m_c}{A_s}$ m_c : the mass flow rate of the cold fluid (Kg/s) A_s : the shell flow area (m²).	(17)

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Section	Parameter	Equation	No. Eq
	Equivalent diameter (d_e)	$$d_e = \frac{4(\frac{Pt}{2} \times 0.87\, Pt - \frac{1}{2}\pi \frac{d_{o,t}}{4})}{\frac{1}{2}\pi d_{o,t}}$$ Where, P_t : tube pitch (1.25× d_o) (m) π : 3.14 $d_{o,t}$: tube outside diameter (m).	(18)
	Reynold number (Re,s)	$$Re_s = \frac{di_s \times Gs}{\mu}$$ Re_s : Reynold number di_s : inner shell diameter (m) Gs : the mass flow of water in the shell (Kg/m²s) μ : the dynamic viscosity (Kg/ms).	(19)
	Prandtl Number (Pr,s)	$$Pr = (\frac{C_p \times \mu}{K})^{\frac{1}{2}}$$ Pr_s : Prandtl number Cp : specific heat capacity (kJ/kg°C) μ : dynamic fluid viscosity (Kg/ms) K : thermal conductivity (W/m°C).	(20)
	Nusselt number (Nu,s)	$$Nu_s = 0.023 \times {Re_s}^{0.6} \times Pr^{0.33}$$ Re_s : Reynold number Pr : Prandtl number	(21)
	Convection Heat Transfer Coefficient (ho)	$$ho = \frac{Nu \times K}{d_e}$$	(22)

Section	Parameter	Equation	No. Eq
		ho : convection heat transfer coefficient (W/m²°C) *K* : thermal conductivity (W/m°C) d_e : equivalent diameter (m).	
Shell and Tube	Actual Overall Heat Transfer Coefficient (U_{act})	$$U_{act} = \frac{1}{\frac{1}{h_i} + \frac{\Delta r}{k} + \frac{1}{h_o}}$$ Where, *hi* : inside heat transfer coefficient (W/m²°C) *ho* : outside heat transfer coefficient (W/m²°C), Δr : wall thickness (m) *K* : thermal conductivity(W/m°C)	(23)
Heat rate	Hot Fluid Rate (C_h)	$$C_h = m_h . Cp_h$$ Where, C_h : hot fluid rate (W/°C) Cp_h : specific heat capacity (J/Kg°C) m_h : mass flow rate of hot fluid (Kg/s).	(24)
	Cold Fluid Rate (C_C)	$$C_C = m_c . Cp_c$$ C_c : cold fluid rate (W/°C), Cp_h : specific heat capacity (J/Kg°C), m_c : mass flow rate of cold fluid (Kg/s).	(25)
		$$Q_{max} = C_{min}(T_{h,i} - T_{c,i})$$ Q_{max} : maximum heat transfer (W)	(26)

Section	Parameter	Equation	No. Eq
		C_{min} : minimum heat capacity rate (W/°C) $T_{h,i}$: temperature of the hot fluid inlet (°C) $T_{c,i}$: temperature of the cold fluid inlet (°C).	
Effectiveness	Heat Exchanger Effectiveness (ε)	$\varepsilon = \frac{Qact}{Qmax} \times 100\%$ Where, Q_{act} : actual energy transferred (W) Q_{max} : maximum heat transfer (W)	(27)
	Number of Transfer Unit (NTU)	$NTU = \frac{U \times A}{C_{min}}$ Where, U : overall heat transfer coefficient (W/m^2°C) A : heat transfer area (m^2) C_{min} : minimum heat capacity rate (W/°C).	(28)
	Fouling factor (Rf)	$Rf = \frac{U_a - U_{act}}{U_a \times U_{act}}$ Where, Rf : fouling factor U_a : overall heat transfer coefficient (W/m^2°C) U_{act} : actual overall heat transfer coefficient (W/m^2°C)	(29)

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3. Results and Discussion

In the design of heat exchanger performance, there are several things that need to be assumed. It is assumed that the heat exchanger is made of carbon steel material with tube and shell (one-pass) type. The fluid flow used is a counter-current flow system, and water-water as hot and cold fluids. It is assumed that the hot fluid is on the tube side, and the hot fluid is on the shell side. It is also assumed that there is no heat leakage during the heat exchange process. The overall coefficient (U) for hot and cold fluid water is 800 W/m°C. In Table 2 showed the dimensions heat exchanger according to the TEMA standard.

Table 2. Dimensional specifications of shell and tube type heat exchanger based on TEMA standard

Parameters	Specification
Conductivity Material (W/m°C)	43
Tube Outer Diameter (m)	0.024
Tube Inner Diameter (m)	0.018
Wall Thickness (m)	0.00087
Tube Length (m)	4.245
Tube arrangements	Triangular
Pitch Tube (m)	0.030
Tube-side passes	1 pass
Tube Characteristic Angle (°)	31
Shell Outer Diameter (m)	0.152
Shell Inner Diameter (m)	0.136
Baffle Cut	25%

Overall performance and the effectiveness of heat exchangers depends on density, viscosity, thermal conductivity, and specific heat of the fluids are used [10]. Table 3 shows these parameters and other specification of hot and cold fluid are used for this paper.

Table 3. Specific hot and cold fluids parameter

Parameters	Tube side (Water)	Shell side (Water)
Inlet temperature ($T_{h,in}$; °C)	75	-
Outlet temperature ($T_{h,out}$; °C)	55	-
Inlet temperature ($T_{c,in}$; °C)	-	30
Outlet temperature ($T_{c,out}$; °C)	-	70
Density (kg/m^3)	974.68	995.71
Viscosity (Ns/m^2)	0.000378	0.000798
Fluid flow rate (kg/s)	2	1
Thermal conductivity (W/m.K)	0.67	0.53
Heat specific (J/kg.K)	4193	4178
Operating pressure (bar)	1.013	1.013

Table 4 shows the calculation results after applying the assumptions in table 2 following the equations listed in Table 1. The values of several parameter such as LMTD, area of heat transfer, number of tubes and heat exchanger effectiveness are 12.43℃, 16.87 m², 53 pcs, and 89.21%, respectively.

Table 4. Performance parameters of heat exchangers designed based on calculation

No	Parameter	Results
1	Initial Heat Transfer Rate (*Q*)	167720 W
2	Logarithmic Mean Temperature Difference (*LMTD*)	12.43°C
3	Assumed Overall Fluid Heat Coefficient of Water (U_a)	800 W/m².K
4	R	0.5
5	S	0.89
6	Ft	1.63
7	ΔTm	20.21°C
8	Area of Heat Transfer (*A*)	16.87 m²
9	Number of Tube (*Nt*)	53
10	Total Heat Transfer Surface Area in Tube (a_t)	0.0226 m²
11	Mass Flow Rate of Water Fluid in Tube (*Gt*)	88.50 m/s
12	Reynold Number in Tube (*Re, t*)	4214.08
13	Prandtl Number in Tube (*Pr, t*)	1.18
14	Convection Heat Transfer Coefficient in the Tube (h_i)	135.34 W/m².K
15	Bundle Shell (*Db*)	1.85 m
16	Total Heat Transfer Surface Area in Shell (a_s)	0.06 m²
17	Mass Flow Rate of Water Fluid in Shell (*Gs*)	17.76 m/s
18	Equivalent Diameter (*De*)	0.96 m
19	Reynold Number in Shell (*Re, s*)	400.57
20	Prandtl Number in Shell (*Pr, s*)	3.15
21	Nusselt Number in Shell (*Nu, s*)	1.08
22	Convection Heat Transfer Coefficient in Shell (h_o)	0.5934 W/m².K
23	Overall Heat Transfer Coefficient Actual (U_{act})	0.5932 W/m².K
24	HE Effectiveness (ε)	89.21%
25	Number of Transfer Unit (*NTU*)	3.23
26	Fouling Resistance	1.68 °C.m²/W

The thermal efficiency is an important indicator of energy performance for heat exchangers [11]. The design of the heat exchanger is said to be successful when the percentage of effectiveness obtained is more than 70%. There are fouling resistance value obtained that do not meet the standard that should be 0.0002℃.m²/W, but other parameters including the effectiveness value show pretty good results.

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4. Conclusion

The shell and tube type heat exchanger has been successfully designed based on the TEMA standard, indicating that 113 pipes are needed, with the heat transfer rate generated by the apparatus is 167720 W. Heat exchanger designed with one-passes type. The effectiveness of this heat exchanger design reaches 89.21%, so it can be characterized as having good performance.

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