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SHELL AND TUBE HEAT EXCHANGER DESIGN FOR NANO ZEOLITE PRODUCTION PROCESS

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Abstract. Heat exchangers are often found in the chemical process industry, but of all types of heat exchangers, the Shell and Tube Heat Exchanger (STHE) is the most commonly used. The design of heat exchangers has also been done a lot because it can reduce production costs. Therefore, this study purpose to design a tube and shell type heat exchanger for applications in producing nano zeolite. The TEMA standard is used as a reference for data collection regarding equipment specifications and dimensions. The parameters are calculated using basic Microsoft Office applications. Shell and Tube type heat exchanger (one pass) with 43 pcs of tubes has been successfully designed. The effectiveness of the heat exchanger reaches 80.02% so it is hoped that this research can be used as a reference in designing a heat exchanger with a better design.

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

1. Introduction

Heat exchanger is a device used for transferring thermal energy between a solid and a fluid, or between two or more fluids. The fluids may be separated by a solid wall to prevent mixing or may be in direct contact [1]. Specific applications of heat exchangers are commonly found in the chemical process industry as well as power production, waste heat recovery, cryogenic, air conditioning (AC) and petrochemical industries [2]. Among these all types of heat exchangers, Shell and Tube Heat Exchanger (STHE) is the most commonly used. This system has a wide range of applications consisting of different operating temperatures and pressures such as heating and air conditioning, power generation, refrigeration, chemical processes, manufacturing and medical applications [3]. A typical STHE schematic is shown in Fig. 1 [4,5].

Heat exchanger systems are developing very rapidly in the chemical industry sector. Feng, et al., [6] conducted research on the STHE type heat exchanger for the evaporation process of organic fluid. A Complex function (CF) considering the heat transfer and fluid flow performance (HTFFP) of STHE. The results show that the total heat transfer rate, total pumping power and complex function after optimization are decreased. The complex function has its double minimum with an optimal mass flow rate of the hot water or an optimal total tube number. In addition, Arani and Moradi [7] designed and optimized STHE using an AI-based optimization method known as cohort intelligence (CI). The results obtained are that the quality and robustness of the CI solution at a reasonable computational cost is considered to be able to solve complex mechanical engineering problems associated with large-scale assembly optimization.

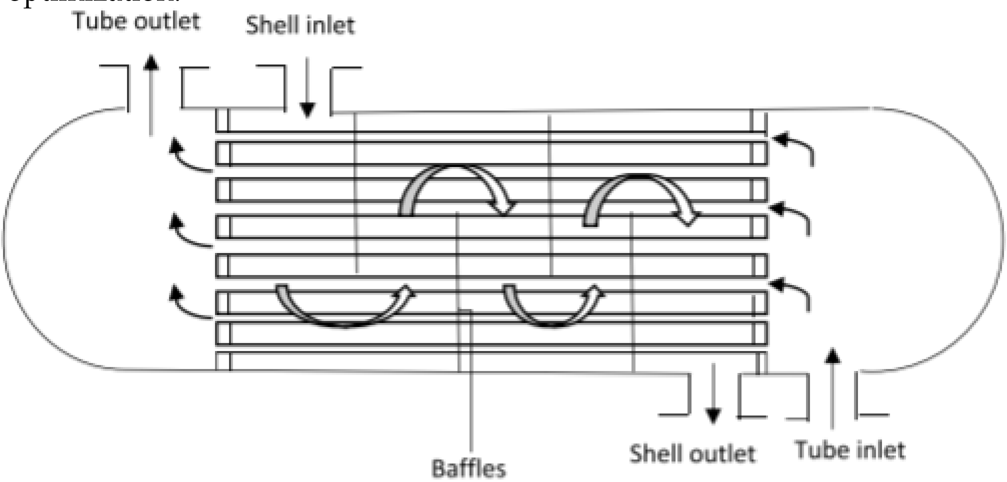

Figure 1. Shell and Tube Heat Exchanger systematic [4,5].

This study purpose to design a tube and shell type heat exchanger for applications in producing nano zeolite. Mastropietro, et al., [8] produced nanosized NaY zeolite crystals from organic free gel by using supported seeds at low temperature. In his research, nanocrystalline products were obtained with high yields in a relatively short reaction time and a low temperature of 30°C. To determine the performance of the designed heat exchanger, it is necessary to calculate the heat transfer surface area (*A*) which depends on other parameters, namely the thermal load (*Q*), the overall heat transfer coefficient (*U*) and the logarithmic mean temperature difference (ΔTlm) to obtain the standard dimensions of the designed heat exchanger.

2. Method

Design of the shell and tube type heat exchanger is used for the exact dimensions of the heat exchanger. Standard of Tubular Exchanger Manufacturers Association (TEMA) is used as a reference for data collection regarding specifications and dimensions of the apparatus. After designing, thermal analysis is carried out in the form of calculating the overall heat transfer coefficient (*U*), LMTD method, heat transfer (*Q*), and pressure drop manually using basic Microsoft Office applications based on the equations in Table 1. The results obtained are used to determine heat exchanger performance and efficiency.

Table 1. Heat Exchanger Calculation Parameters

Section	Parameter	Equation	Eq
Basic parameters	**The energy transferred (Q)**	$Q_{in} = Q_{out}$	**(1)**

Section	Parameter	Equation	Eq
		$m_c \times Cp_c \times \Delta T_c = m_h \times Cp_h \times \Delta T_h$ 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).	
	Logarithmic mean temperature differenced (LMTD)	$LMTD = \frac{(T_{hi} - Tc_o) - (T_{ho} - Tc_i)}{ln\frac{(T_{hi} - Tc_o)}{(T_{ho} - Tc_i)}}$ Where, T_{hi}: temperature of the hot fluid inlet (°C) T_{ho}: temperature of the hot fluid outlet (°C) Tc_i: temperature of the cold fluid inlet (°C) Tc_o: temperature of the cold fluid outlet (°C)	(2)
	Correction factor	$R = \frac{T_{hi} - T_{ho}}{T_{co} - T_{ci}}$	(3)
		$S = \frac{T_{co} - T_{ci}}{T_{hi} - T_{ci}}$	
		$F_t = \frac{\sqrt{R^2+1}\ \ln[\frac{1-P}{1-PR}]}{(R-1)\ln(\frac{2-P(R+1-\sqrt{R^2+1}}{2-P(R+1+\sqrt{R^2+1}})}$	(4)
		$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln(\frac{\Delta T_2}{\Delta T_1})}$	(5)

Section	Parameter	Equation	Eq
		$\Delta T_m = F_t \Delta T_{lm}$	(6)
	Heat Transfer Field Area (A)	$A = \dfrac{Q}{U \times LTMD}$ Where, Q: the energy transferred (W) U: the overall heat transfer coefficient *LMTD*: the logarithmic mean temperature difference.	(7)
	Number of Tubes (N)	$N = \dfrac{A}{\pi \times D_o \times l}$ Where, *N*: the number of tubes *A*: the area of the heat transfer area (m²), π: 3.14 D_o: tube diameter (m) l: tube length (m).	(8)
Tube	Surface Area of Total Heat Transfer in Tube (a_t)	$a_t = N_t \dfrac{a'_t}{n}$ Where, a_t: the total heat transfer surface area in the tube (m^2) N_t: the number of tubes a'_t: the flow area in the tube (m^2) *n*: the number of passes.	(9)

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Section	Parameter	Equation	Eq
	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)
	Nusselt number (Nu,t)	$$Nu = 0.023 \times {Re_t}^{0.6} \times Pr^{0.33}$$	(13)

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Section	Parameter	Equation	Eq
	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)	$$A_s = \frac{d_s \times C \times B}{P_t}$$	(15)
		$$D_b = d_o(\frac{N_t}{k_1})^{\frac{1}{n_1}}$$ Where, d_s: shell diameter (m) C: clearance (P_t-d_o) B: a shell bundle P_t: tube pitch (1.25× d_o) (m).	(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)
	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	(18)

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Section	Parameter	Equation	Eq
		$d_{o,t}$: tube outside diameter (m).	
	Reynold number (Re,s)	$$Re_s = \frac{di_t \times Gt}{\mu}$$ Re_s: Reynold number di_s: inner tube 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)	$$ho = \frac{Nu \times K}{d_e}$$ ho: convection heat transfer coefficient (W/m²°C) K: thermal conductivity (W/m°C)	(22)

Section	Parameter	Equation	Eq
		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) C_{min}: minimum heat capacity rate (W/°C) $T_{h,i}$: temperature of the hot fluid inlet (°C)	(26)

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Section	Parameter	Equation	Eq
		$T_{c,i}$: 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/m²°C A: heat transfer area (m²) 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/m²°C) U_{act}: actual overall heat transfer coefficient (W/m²°C)	(29)

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3. Results and Discussion

Assumptions used to design and estimate the performance of heat exchangers, including:

a) The heat exchanger design is a shell and tube (one-pass) type.
b) The material for the design of the heat exchanger is carbon steel.
c) The fluid used is a water-water fluid system.
d) The flow system in this heat exchanger is a counter-current flow.
e) The hot fluid is assumed to be on the tube side and the cold fluid is assumed to be on the shell side.
f) The specifications for the type of stationary head, shell, and rear head of the heat exchanger are AEW, respectively.
g) Overall coefficient (U) for hot and cold fluids water is 800 W/m^2.K.
h) The orientation of the shell geometry is horizontal.
i) The baffle type is single segmental with orientation perpendicular.

Hot fluid is located in tube side and cold fluid is located in shell side.

In shell and tube heat exchanger, there are several number of shells and tubes arranged in parallel where one fluid flows in the tube, while the other fluid flows in the shell. In this study, the dimensional specifications of the heat exchanger designed according to the TEMA standard are shown in Table 2. While the specifications of the fluid working on the heat exchanger are shown in Table 3.

Table 2. Dimensional specifications of the heat exchanger apparatus based on the TEMA standard.

Parameters	Specification
Conductivity Material (W/m°C)	**43**
Tube Outer Diameter (m)	**0.020**
Tube Inner Diameter (m)	**0.016**
Wall Thickness (m)	**0.0009**
Tube Length (m)	**4.25**
Tube arrangements	**Triangular**
Pitch Tube (m)	**0.035**
Tube-side passes	**1 pass**
Tube Characteristic Angle (°)	**30**
Shell Outer Diameter (m)	**0.152**
Shell Inner Diameter (m)	**0.136**
Baffle Cut	**25%**

Table 3. Specifications of hot and cold fluids

Parameters	The specification in Tube Side	The specification in Shell Side
Inlet Temperature ($T_{h,in}$; °C)	50^{o}C	-
Outlet Temperature ($T_{h,out}$; °C)	40^{o}C	-
Inlet Temperature ($T_{c,in}$; °C)	-	25^{o}C
Outlet Temperature ($T_{c,out}$; °C)	-	45^{o}C

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Fluid Flow Rate (kg/s)	2.0	1.0
Density (kg/m³)	988.02	997.13
Viscosity (N.s/m²)	0.000547	0.000891
Thermal Conductivity (W/m.K)	0.64	0.61
Heat Specific (J/kg.K)	4181	4180
Operating Pressure (bar)	1.013	1.013

In this study, a water-water fluid system with different temperatures was used. Cold air is on the shell side and hot air is on the tube side. After obtaining the data in Table 2 and 3, the heat exchanger design was calculated using basic Microsoft Office applications which included thermal load (*Q*), logarithmic mean temperature difference (*LMTD*), heat transfer surface area (*A*), and number of tubes (N_t) of the heat exchanger as shown in Table 4.

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

No	Parameter	Results
1	Initial Heat Transfer Rate (*Q*)	83620 W
2	Logarithmic Mean Temperature Difference (*LMTD*)	9.1°C
3	Assumed Overall Fluid Heat Coefficient of Water (U_a)	800 W/m².K
4	R	0.5
5	S	0.8
6	F_t	1.87
7	ΔTm	16.99°C
8	Area of Heat Transfer (*A*)	11.48 m²
9	Number of Tube (*Nt*)	43 pcs
10	Total Heat Transfer Surface Area in Tube (a_t)	0.0258 m²
11	Mass Flow Rate of Water Fluid in Tube (*Gt*)	77.52 kg.m/s²
12	Reynold Number in Tube (*Re, t*)	2550.91
13	Prandtl Number in Tube (*Pr, t*)	1.78
14	Convection Heat Transfer Coefficient in the Tube (h_i)	123.3 W/m².K
15	Bundle Shell (*Db*)	3.77 m
16	Total Heat Transfer Surface Area in Shell (a_s)	0.34 m²
17	Mass Flow Rate of Water Fluid in Shell (*Gs*)	2.90 m/s
18	Equivalent Diameter (*De*)	0.6536 m
19	Reynold Number in Shell (*Re, s*)	443.26
20	Prandtl Number in Shell (*Pr, s*)	3.05
21	Nusselt Number in Shell (*Nu, s*)	1.14
22	Convection Heat Transfer Coefficient in Shell (h_o)	1.06 W/m².K
23	Overall Heat Transfer Coefficient Actual (U_{act})	1.05 W/m².K
24	HE Effectiveness (ε)	80.02%
25	Number of Transfer Unit (*NTU*)	2.20
26	Fouling Resistance	0.9494 °C.m²/W

Based on the calculation results obtained, the initial heat transfer rate generated by the heat exchanger equipment is 83620 W. In addition, several other parameters such as LMTD, surface area, and heat transfer coefficient are 9.1°C, 11.48 m^2, and 1.05 $W/m^2.K$. The number of tubes required in the designed heat exchanger is 43 pcs with a total heat surface area of 0.0258 m^2. The effectiveness value of a successful heat exchanger should be more than 70%. The heat exchanger designed in this study obtained an effectiveness value of 80.02% which is assumed to provide good performance in terms of heat exchange. The fluid flow on the tube side shows turbulent flow, while the fluid flow on the shell side shows laminar flow. Fluid flow is determined by the Reynolds Number (Re), if $Re < 2300$ then the fluid flow is laminar flow, but if $Re > 2300$ then the fluid flow follows turbulent flow [9]. Based on the TEMA standard, the impurity resistance value for water fluid obtained is 0.9494 °C.m^2/W.

4. Conclusion

The Shell and Tube type heat exchanger (one pass) with AEW type and the number of tubes as many as 43 pcs has been successfully designed in accordance with TEMA standards. The resulting heat transfer rate is 83620 W with turbulent flow on the tube side and laminar flow on the shell side. The effectiveness of the heat exchanger reaches 80.02% so that the design of the heat exchanger in this study is assumed have good performance.

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