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Design of Shell and Tube Heat Exchanger for Production Aluminium Nitride Nanoparticle in Application Industry

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Abstract
The current industrial implementation process is required to be carried out efficiently and environmentally friendly, this can be done with the presence of a heat exchanger. However, heat exchangers in the production of aluminum nitride nanoparticles are still rare. The purpose of this research is to analyze and improve the heat exchanger design in the production process of aluminum nitride nanoparticles at low cost. The heat exchanger can be designed based on several parameters of the TEMA standard by dimensional specification and specifications of hot and cold fluids. The method is calculated using a Microsoft excel application to evaluate the heat exchanger design according to the TEMA standard. The results showed that the shell and tube heat exchanger was designed with 39 tubes and an effective value of 85.72%. These results have met the TEMA standard and it is hoped that the design and evaluation of this heat exchanger can be used as a reference in the aluminum nitride nanoparticle production industry.

Keywords: Aluminum nitride nanoparticle; Fluids; Heat exchanger; Industry

1. Introduction

According to a report from the International Energy Agency (IEA), World energy demand grew by around 2.1% in 2017, a doubling of the previous year. In detail, the production of carbon emissions results from most of the energy consumption in the form of thermal and most of the heat energy production process [1]. In order to minimize this energy consumption and reduce carbon emissions, heat exchangers are found to be an important tool part used in thermal energy systems such as power plants, refrigeration systems, and petrochemical units [2].

A heat transfer device that moves heat energy from one medium to another is called a heat exchanger. Two fluids with different temperatures will be separated on the hot side or the cold side by a separating medium in order to achieve the ideal thermal in the heat transfer process. An advantage of a heat exchanger is that it is affordable and has high thermal efficiency [3].

A heat exchanger is a device that functions as a flow of heat energy between two or more fluids at different temperatures [4]. Heat exchangers are widely used in various industrial applications, such as food processing, pharmaceutical industry, heat removal from nuclear reactors, etc [5], [6]. In addition, heat exchangers are used in process, electricity, transportation, air conditioning and refrigeration, cryogenics, heat recovery, alternative fuels, and manufacturing industries [7].

Until now, there have been many papers that explain the rapid development of heat exchangers in the industrial world. Fattahi *et al.* [8] investigating the application of aluminum nitride as an advanced ceramic for making heat exchangers. The results showed that the heat exchanger fabrication made of AlN showed an increase in heat effectiveness by 26% from the maximum value. Nekahi *et al.* [9] investigating effectiveness can measure the ideal performance of a heat exchanger, whereby it transfers the maximum amount of heat. Shirvan *et al.* [10] also proposed a new model for the analysis of heat transfer sensitivity and effectiveness of a heat exchanger in the form of a double pipe heat exchanger. Gasia *et al.* [11] investigating the effect of convection forces in a cylindrical shell-and-tube heat exchanger in which water is used as PCM and circulated during the smelting process. By increasing the PCM, the flow rate in the heat exchanger, the melting period, effectiveness and heat transfer rate are improved.

This study aims to design and design the types of tubes and shells of heat exchangers in the production of Aluminum Nitride (AlN) nanoparticles. **Figure 1** shows a laboratory scale production of AlN production which requires a 70 °C heat device to mix all the precursors. Assuming industrial-scale production processes, laboratory-scale heating is replaced by heat exchangers. It is necessary to design a heat exchanger for aluminum nitride nanoparticles because there is still little research on heat exchangers in this industry. To evaluate the performance of a heat exchanger, focus on calculations based on thermal load (Q), logarithmic mean temperature difference (LTMD), heat transfer surface area (A), and number of tubes (Nt) of the heat exchanger to obtain dimensional spesification and specifications of hot and cold fluids in the design of heat exchanger device.

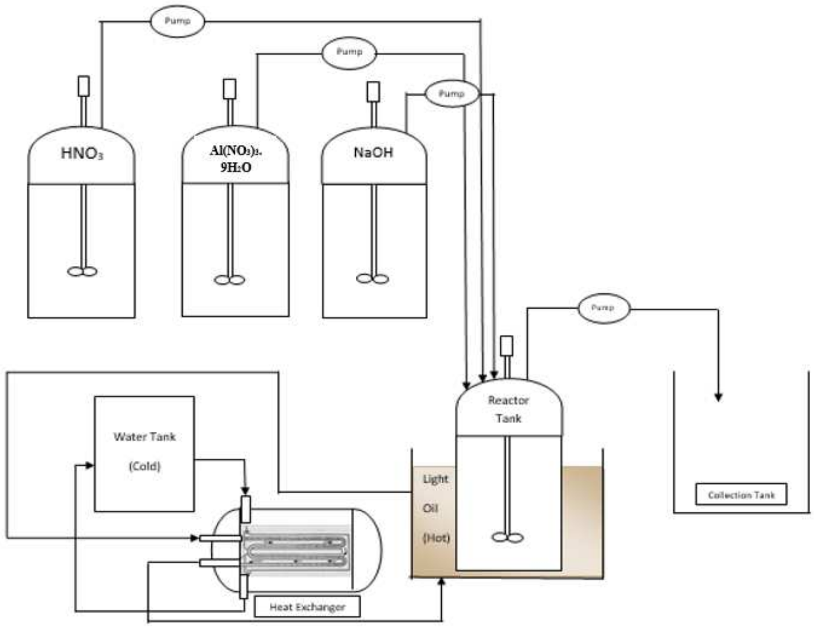

Figure 1. Illustration of Aluminium Nitride Particle Production

2. Method

The design of the heat exchanger chosen in this study is a shell and tube type heat exchanger. This type was chosen because it is easy to manufacture in various sizes and flow configurations, easy to use at various operating temperatures and pressures [12], and its adaptability to different operating conditions [13]. Shell and tube heat exchangers also have a larger heat transfer surface to volume ratio than other heat exchangers [12].

This heat exchanger is designed according to several parameters of the Standard of Tubular Exchanger Manufacturers Association (TEMA) to obtain data regarding the specifications and evaluate the performance of the heat exchanger design according to the standard. These parameters are listed in **Table 1**.

Table 1. Calculation of Heat Exchanger Parameters

Section	Parameter	Equation	Eq
Basic parameters	The energy transferred (Q)	$Q_{in} = Q_{out}$ $m_c \times Cp_c \times \Delta T_c = m_h \times Cp_h \times \Delta T_h$ Where, Q = the energy transferred (Wt) m = the mass dflow rate of the fluid (Kg/s) Cp = the specific heat ΔT = the fluid temperature difference (°C).	(1)
	Logarithmic mean temperature difference (LMTD)	$LMTD = \frac{(T_{hi} - Tc_i) - (T_{ho} - Tc_o)}{ln \frac{(T_{hi} - Tc_i)}{(T_{ho} - Tc_o)}}$ 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)
		$P = \frac{T_{co} - T_{ci}}{T_{hi} - T_{ci}}$	(4)
		$F = \frac{\sqrt{R^2 + 1}\ ln\ ln\ [\frac{1 - P}{1 - PR}]}{(R - 1)\ ln\ ln\ (\frac{2 - P(R + 1 - \sqrt{R^2 + 1}}{2 - P(R + 1 + \sqrt{R^2 + 1}})}$	(5)
	Heat Transfer Field Area (A)	$A = \frac{Q}{U \times LTMD}$ Where, Q = the energy transferred (W) U = the overall heat transfer coefficient $LMTD$ = the logarithmic mean temperature difference.	(6)
	Number of Tubes (N)	$N = \frac{A}{\pi \times D_o \times l}$ 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 diameter (m).	(7)
	Shell Diameter	$D_s = 0.63(\frac{\sqrt{\frac{CL}{CTP} \times ((A \times (PR)^2 \times D_o}}{l})^{\frac{1}{2}}$ Where, D_s = shell diameter (m) A = the area of the heat transfer area (m^2) P, R = the correction factor D_o = tube diameter (m). For CTP value (one tube pass = 0,93; two tube pass = 0,90; and three tube pass = 0,85) and CL value (90° and 45° = 1,00; and 30° and 60° = 0,87).	(8)
	Baffle spacing	Baffle spacing = 0,2 $x\ Ds$ Where, D_s = shell diameter (m)	
Tube	Surface Area of Total Heat	$a_t = N_t \frac{a'_t}{n}$	(9)

Section	Parameter	Equation	Eq
	Transfer in Tube (a_t)	Where, a_t = the total heat transfer surface area in the tube (m²) 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)
	Nusselt number (Nu,t)	$Nu = 0.023 \times {Re_t}^{0.8} \times Pr^{0.33}$	(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)	$A_s = \frac{d_s \times C \times B}{P_t}$ $D_b = d_o(\frac{N_t}{k_1})^{\frac{1}{n_1}}$ 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).	(15) (16)
	Mass Flow Rate of Water in Shell (Gs)	$Gs = \frac{m_c}{a_s}$ Where, m_c = the mass flow rate of the cold fluid (Kg/s) A_s = the shell flow area (m²).	(17)
	Equivalent diameter (d_e)	$d_e = \frac{4(\frac{Pt}{2} \times 0.87\, Pt - \frac{1}{2}\pi \frac{d_{o,t}}{4})}{\frac{1}{2}\pi d_{o,t}}$	(18)

Section	Parameter	Equation	Eq
		Where, P_t = tube pitch (1.25× d_o) (m) π = 3.14 $d_{o,t}$ = tube outside diameter (m).	
	Reynold number (Re,s)	$$Re_s = \frac{di_t \times Gt}{\mu}$$ Where, 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)	$$Pr = (\frac{C_p \times \mu}{K})^{\frac{1}{2}}$$ Where, 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)	$$Nu_s = 0.023 \times {Re_s}^{0.6} \times Pr^{0.33}$$ Where, Re_s = Reynold number Pr = Prandtl number	(21)
	Convection Heat Transfer Coefficient (ho)	$$ho = \frac{Nu \times K}{d_e}$$ Where, ho = convection heat transfer coefficient (W/m²°C) K = thermal conductivity (W/m°C) d_e = equivalent diameter (m).	(22)
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)	$$C_C = m_c.Cp_c$$ Where, 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). $$Q_{max} = C_{min}(T_{h,i} - T_{c,i})$$ Where, Q_{max} = maximum heat transfer (W) C_{min} = minimum heat capacity rate (W/°C)	(25)

Section	Parameter	Equation	Eq
		$T_{h,i}$ = 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)	(26)
	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).	(27)
	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)	(28)

3. Results and Discussion

When designing a heat exchanger, we must determine the materials used to make the heat exchanger according to the type of material and the amount of material with fluid as a heating medium in measuring dimensions. Various designs are determined in estimating the best heat exchanger performance design, such as:

a. The heat exchanger design is shell and tube type (two shell pass and four tube pass).
b. The material for the heat exchanger design is carbon steel.
c. The fluid used is a light oil-water fluid system.
d. The flow system in this heat exchanger is counter flow.
e. The hot fluid is assumed to be on the shell side and the cold fluid is assumed to be on the tube side.
f. The specifications for the stationary head type (indicating front end), shell (indicating shell type), and rear head (indicating rear end type) of the heat exchanger are AEW respectively.
g. It is assumed that there is no heat leakage during the heat exchange process.
h. The overall coefficient (U) for light oil-hot and cold water fluids is 650 W/m2.°C.
i. The orientation of the shell geometry is horizontal
j. The baffle type is single segmental with perpendicular orientation
k. The hot fluid is located on the tube side and the cold fluid is located on the shell side.

The dimensions of the heat exchanger are designed using several assumptions. Table 2 shows the dimensions of the heat exchanger according to the TEMA standard and Table 3 shows the specifications of the fluids acting on the equipment.

Evaluation of equipment performance is necessary in designing heat exchangers. The performance of the heat exchanger consists of the thermal load (Q), the logarithmic average temperature difference (LTMD), the heat transfer surface area (A), and the number of tubes

(Nt) of the heat exchanger. Table 2 and Table 3 data are used to model the heat exchanger. Based on the assumptions and calculation analysis, the designed heat exchanger follows the specifications in Table 4. The specifications of the equipment used are based on the standards of The Tubular Exchanger Manufactures Association (TEMA). Based on the calculation results, the resulting heat transfer rate is 690000 W (see Table 4).

Table 2. Dimensional specifications of heat exchangers based on TEMA standards

Parameters	Specification
Conductivity Material (W/m°C)	43.77
Tube Outer Diameter (m)	0.025
Tube Inner Diameter (m)	0.02
Wall Thickness (m)	0.000889
Tube Length (m)	7.267
Tube arrangements	triangular
Pitch Tube (m)	0.02799
Tube-side passes	four passes side
Tube Characteristic Angle (°)	30
Shell Outer Diameter (m)	0.145
Shell Inner Diameter (m)	0.129
Baffle Cut	25%
Baffle Spacing (m)	0.2214

Table 3. Specification of hot and cold fluids

Parameters	The specification in Tube Side (Cold Fluid)	The specification in Shell Side (Hot Fluid)
	Water	Light Oil
Inlet Temperature ($T_{h,in}$; °C)	150	-
Outlet Temperature ($T_{h,out}$; °C)	100	-
Inlet Temperature ($T_{c,in}$; °C)	-	35
Outlet Temperature ($T_{c,out}$; °C)	-	95
Fluid Flow Rate (kg/s)	4	2
Density (kg/m^3)	895.7	995
Viscosity (Nm.s/m^2)	0.28	0.00031
Thermal Conductivity (W/m.K)	0.155	0.597
Heat Spesific (J/kg.K)	2325	4196
Operating Pressure (bar)	2.768	1.013

Other parameters such as LMTD, surface area, number of tubes, overall heat exchanger transfer coefficient, and the effective with values of 45,53°C, 22,10 m2, 39 pcs, 650 W/m^2.K, and 85.72%, respectively (see Table 3). Although the effectiveness value is quite good, some parameters do not meet the standards. Figure 2 illustrate the tube arrangement and 2D tube layout drawing.

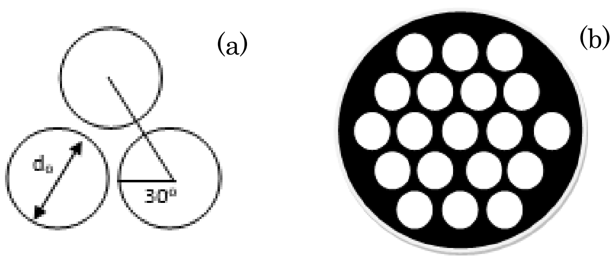

Figure 2.
(a) Tube arrangement: Triangular 30°; (b) Two dimensional tube layout

Table 4. Performance Parameters of Heat Exchanger Designed Based On Calculations

No	Parameter	Results
1	Initial Heat Transfer Rate (*Q*)	690000 W
2	Logarithmic Mean Temperature Difference (*LMTD*)	45,53°C
3	Assumed Overall Fluid Heat Coefficient of Water (U_a)	650 $W/m^2.K$
4	Pressure Drop in Tube	0.83 atm
5	Pressure Drop in Shell	0,52 atm
6	Shell Inside Diameter (d_s)	0.80 m
7	ΔTm	70 °C
8	Area of Heat Transfer (*A*)	22,10 m^2
9	Number of Tube (*Nt*)	39
10	Total Heat Transfer Surface Area in Tube (a_t)	4,78 m^2
11	Mass Flow Rate of Water Fluid in Tube (*Gt*)	1,04 m/s
12	Reynold Number in Tube (*Re, t*)	0,0648
13	Prandtl Number in Tube (*Pr, t*)	3,85
14	Nusselt number *(Nu,t)*	0,004
15	Convection Heat Transfer Coefficient in the Tube (h_i)	9,041 $W/m^2.K$
16	Baffle Spacing	0.049 m
17	Bundle Shell (*Db*)	0,245 m
18	Total Heat Transfer Surface Area in Shell (a_s)	0.0592 m^2
19	Mass Flow Rate of Water Fluid in Shell (*Gs*)	16,876 m/s
20	Equivalent Diameter (*De*)	0,00065 m
21	Reynold Number in Shell (*Re, t*)	0.039028
22	Prandtl Number in Shell (*Pr, t*)	1.05
23	Nusselt Number in Shell (*Nu, t*)	0.0038
24	Convection Heat Transfer Coefficient in Shell (h_o)	3.069 $W/m^2.K$
25	Overall Heat Transfer Coefficient Actual (U_{act})	2.507 $W/m^2.K$
26	Hot Fluid Rate *(Ch)*	2325 W/°C
27	Cold Fluid Rate *(Cc)*	12558 W/°C
28	HE Effectiveness (ε)	85.72%
29	Number of Transfer Unit (*NTU*)	1,7077
30	Fouling Resistance	0,398 $°C.m^2/W$

4. Conclusion

Based on the hypothesis that the heat exchanger design for the production of aluminum nitride nanoparticle which refers to the TEMA standard has been successfully designed with good calculations. The design uses the Shell and Tube type (two shell passes-four tube passes) with a total of 39 tubes. The heat transfer rate by the tool is 690000 watts with turbulent flow in the shell and laminar flow in the tube. The effectiveness of the heat exchanger design reaches more than 85%. So, the heat exchanger design has good performance. And it is hoped that with the manufacture of heat exchangers in industry, it can make production at low costs and can reduce carbon emissions so that it is environmentally friendly.

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