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Design of Heat Exchanger for The Production of Synthesis Nio-Nanoparticles

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ABSTRACTS

The aim of this study is to analyze a heat exchanger in a NiO synthesis process using the sol-gel method. Calculation of the heat exchanger specifications obtained shell length of 0.889 mm, shell diameter of 0.03 mm, outer tube diameter of 0.0254 m, inner diameter of 0.023 mm, wall thickness of 0.000889 mm, tube length of 5.4864, and tube pitch 0.02778. Based on the calculations performed through Microsoft Excel, the results show that the heat exchanger design on the shell and tube that fits is a laminar flow type, with an effectiveness of 96.40%. Therefore, this heat exchanger with shell and tube one meets the requirements and standards based on effectiveness, but without the calculation of the fouling factor. Nevertheless, the results of this analysis can be used as a learning medium in the design process, heat exchanger performance analysis, and operating mechanism.

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1. INTRODUCTION

Heat exchanger is defined as a process that occurs between two fluids with different temperatures and separated by a solid wall. It is commonly used in various engineering applications, such as in air conditioning and space heating, waste heat recovery, electricity production, and processing (Than, et al., 2008). One of the functions of the heat exchanger is for the production of NiO nanoparticles.

NiO nanoparticles are used in various fields, such as fuel cell electrodes (Tomczyk, et al., 1993; Makkus, et al., 1994), electrochromic films (Chigane, & Ishikawa, 1992; Jiao, et al., 2003; Kitao, et al., 1994) and catalysis (Berchmans, et al., 1995). Bulk NiO shows antiferromagnetic character under the Neel temperature of 523 K, and the magnetic properties of NiO itself are modified by reducing its particle size. As proven by Manna et al., the antiferromagnetic properties of NiO become superparamagnetic (300 K) with particle sizes reaching about 100 nm (Manna, et al., 2008). Various approaches have been developed for the synthesis of NiO nanoparticles, including electrospinning technique (Dharmaraj, et al., 2004), microemulsion technique (Palanisamy, & Raichur, 2009), organic solvent method (Li, et al., 2001), solvothermal process (Beach, et al., 2009), and sol-gel method (Alagiri, et al., 2012; Zorkipli, et al., 2016; Thota, & Kumar, 2007; Wu, et al., 2007).

Several studies on the design of heat exchanger tools have been done (Caputo, et al., 2008; Than, et al., 2008; Jegede, & Polley, 1992; Guo, et al., 2010). In contrast to the referred studies, we conducted analysis and evaluation of the processes. Therefore, this study aims to design heat exchanger for the production of NiO nanoparticles. Various kinds of literature on NiO synthesis have been studied (Alagiri, et al., 2012; Wu, et al., 2007). The designed heat exchanger is a shell and tube type. This study is expected to be a useful reference in designing heat exchanger, as well as a learning and teaching method ranging from design process, working mechanism, to performance.

2. METHOD

2.1. Synthesis of NiO nanoparticles

The specific processing conditions and preparation procedures are shown in Figure 1. The procedures taken from the experiments of Wu, et al., (2007) and Alagiri, et al., (2012). To begin, $Ni(NO_3)_2 \cdot 6H_2O$ is dissolved in dilute deionized water. Then, a dropwise of the solution in a suitable proportion is added to the citric acid solution as the ligand. After that, the pH value needs to be adjusted by adding HNO_3 or NH_4OH to the mixed solution. As a result, a fully transparent and homogeneous solution was formed through the stirring and slow evaporation at 70° C until a very viscous residue was produced, after which it was cooled to room temperature. Then it is calcined at a certain temperature: 400; 450; 500; 550, but in the experiment conducted by Alagiri, et al., (2012), the calcination temperature can be carried out at 400 for 3 hours.

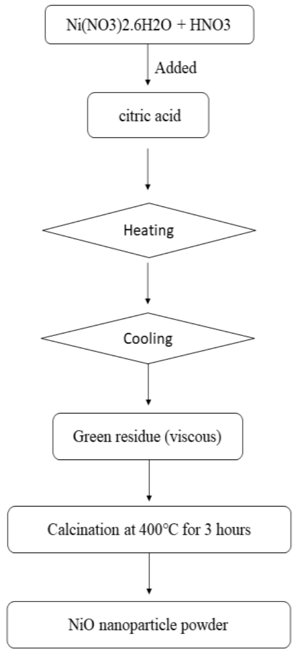

Fig. 1. Schematic diagram of the nano-NiO preparation process using the sol-gel method.

2.2. Mathematical model for designed Heat Exchanger

The hot fluid used is 30% ethylene glycol, while the cold fluid is water. The hot fluid enters at 70°C and leaves at a temperature of 62.5°C. The cold fluid enters at 10°C and leaves at 30°C. The assumptions used for the fluid characteristics operating in the heat exchanger is shown in Table 1. The incoming ethylene glycol flow rate is 21.6 (kg/s) while the incoming water flow rate is 6.78 (kg/s). In data collection, the Tubular Exchanger Manufacturers Association (TEMA) Standard was used as the reference regarding the specifications, while the thermal analysis is in the form of manual calculations using the basic Microsoft Excel application based on equations 1-27, follow what has been done by Nandiyanto, et al., (2022). The heat exchange parameters that were calculated is shown in Table 2.

Table 1. Assumptions of fluid characteristics working on Heat Exchanger.

	Shell side	**Tube side**
	Hot fluid	**Cold fluid**
Inlet Temperature, T_{in} (K)	343,15	283,15
Outlet Temperature, T_{out} (K)	335,65	303,15
Fluid Flow Rate (kg/s)	21,6	6,78
Operating Pressure (atm)	1	1
Specific Heat (kJ/kg.K)	2433	1005
Density (kg/m³)	1.110	997

Table 2. Calculation of heat exchanger parameters.

Section	Parameters	Equation	Eq
Basic Parameters	Energy transferred (Q)	$Q_{in} = Q_{out}$ $m_c \; x \; C_{pc} \; x \; \Delta T_c = m_h \; x \; C_{ph} \; x \; \Delta T_h$ Where, Q = Energy transfer (Wt) T = Fluid temperature difference (°C) Cp = heat specification m = mass fluid flow rate (Kg/s)	(1)
	Logarithmic mean temperature differenced (LMTD)	$LMTD = \frac{(T_{hi} - T_{ci}) - (T_{ho} - T_{co})}{ln \frac{(T_{hi} - T_{ci})}{(T_{ho} - T_{co})}}$ Where, T_{hi} = Inlet hot fluid temperature (°C) T_{ci} = Inlet cold fluid temperature (°C) T_{ho} = Outlet hot fluid temperature (°C) T_{co} = Outlet cold fluid temperature (°C)	(2)
	Correction factor	$R = \frac{T_{hi} - T_{ho}}{T_{ci} - T_{co}}$	(3)
		$P = \frac{T_{hi} - T_{ho}}{T_{ci} - T_{co}}$	(4)
		$F = \frac{\sqrt{R^2 + 1} \ln \left[\frac{1 - P}{1 - PR}\right]}{(R - 1) \ln \left(\frac{2 - P \; (R + 1 - \sqrt{R^2 + 1}}{2 - P(R + 1 + \sqrt{R^2 + 1}}\right)}$	(5)
	Heat Transfer Field Area (A)	$A = \frac{Q}{U \; x \; LTMD}$ Where, Q = Energy transfer (W) LMTD = Logarithmic Mean Temperature Difference U = overall heat transfer coefficient	(6)
	Number of tubes (N)	$N = \frac{A}{\pi \; x \; D_0 x \; l}$ Where, N = Number of tubes A = *Heat Transfer Field Area* π = 3,14 D_0 = Tube diameter (m) l = Tube length (m)	(7)
	Shell Diameter	$D_s = 0{,}63 \left(\frac{\sqrt{\frac{CL}{CTP} \; x \; ((A \; x \; PR^2 \; xD_o}}{l} \right)^{1/2}$ Where,	(8)

		D_s = Shell Diameter (m) A = *Heat Transfer Field Area* (m^2) P, R = correction factor Do = tube diameter (m) CTP = one tube (0.93); two tubes (0.90); three tubes (0.85) CL = 90^o and 45^o = 1,00; 30^o and 60^o = 0,87	
Tube	Total Heat Transfer Surface Area in Tube (A_t)	$$a_t = N_t \frac{a'_n}{n}$$ Where, a_t = total heat transfer surface area in the tube (m^2) Nt = Number of tubes a'_n = area of flow in the tube n = number of passes	(9)
	Mass Flow Rate of Water in Tube (Gt)	$$G_t = \frac{m_h}{a_t}$$ Where, G_t = mass flow of water in the tube (kg/m^2s) m_h = mass flow rate of hot fluid (Kg/s) a_t = total heat transfer surface area in the tube (m^2)	(10)
	Reynolds number (Re, $_t$)	$$Re_t = \frac{di_t\ x\ G_t}{\mu}$$ Where, Re_t = Reynolds number in the tube di_t = inner tube diameter (m) G_t = mass flow of water in the tube (m^2) μ = dynamic viscosity (kg/ms)	(11)
	Prandtl numbers (Pr, $_t$)	$$Pr = \left(\frac{Cp\ x\ \mu}{K}\right)^{1/2}$$ Where, Pr = Prandtl number Cp = specific heat of fluid in the tube μ = dynamic viscosity of the tube liquid (Kg/ms) K = thermal conductivity of the tube material (W/m°C)	(12)
	Nusselt number (Nu, $_t$)	$$Nu = 0{,}023\ x\ {Re_t}^{0,6}\ x\ Pr^{0,33}$$	(13)
	Convection Heat Transfer Coefficient in Tube *(h_i)*	$$hi = \frac{Nu\ x\ K}{d_i, t}$$ Where, hi = convection heat transfer coefficient in the tube (W/m^2°C) K = thermal conductivity of the material (W/m°C) d_i, t = inner tube diameter (m)	(14)
Shell	Shell flow area (A_s)	$$A_s = \frac{d_s\ x\ C\ x\ B}{P_t}$$	(15)

		Where, d_s = shell diameter (m) C = clearance (P_t-d_o) B = shell bundle Pt = tube distance (1,25 x d_o) (m).	
	Mass Flow Rate of Water in Shell (Gs)	$$G_s = \frac{m_c}{a_s}$$ Where, m_c = mass flow rate of cold fluid (Kg/s) a_s = shell flow area (m^2)	(16)
	Diameter equivalent (d_e)	$$d_e = \frac{4\left(\frac{Pt}{2}\ x\ 0{,}87\ Pt\ x\ \frac{1}{2}\pi\frac{d_{o.t}}{4}\right)}{\frac{1}{2}\pi d_{o.t}}$$ Where, Pt = tube distance (1,25 x d_o) (m) $\pi = 3{,}14$ $d_{o.t}$ = outside diameter of tube (m)	(17)
	Reynolds number in shell (Re, s)	$$Re_s = \frac{di_s\ x\ G_s}{\mu}$$ Where, Re_s = Reynolds number in shell di_s = inner tube diameter (m) G_s = mass flow of water in the shell (kg/m^{2}s) μ = dynamic viscosity (kg/ms)	(18)
	Prandtl numbers in shell (Pr, s)	$$Pr_s = \left(\frac{Cp\ x\ \mu}{K}\right)^{1/2}$$ Where, Pr_s = Prandtl Number Cp = specific heat of fluid μ = dynamic viscosity of the liquid (Kg/ms) K = thermal conductivity (W/m°C)	(19)
	Nusselt Number in the shell (Nu, s)	$$Nu = 0{,}023\ x\ Re_s^{0,6}\ x\ Pr^{0,33}$$	(20)
	Convection Heat Transfer Coefficient in the shell (h_o)	$$ho = \frac{Nu\ x\ K}{d_e}$$ Where, ho = heat transfer coefficient (W/m^2°C) K = thermal conductivity of the material (W/m°C) d_e = diameter equivalent (m)	(21)
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, h_i = inside heat transfer coefficient (W/m^2°C)	(22)

		h_o = outside heat transfer coefficient (W/m²°C), Δr = wall thickness (m) k = thermal conductivity (W/m°C)	
Heat Rate	Hot Fluid Rate (C_h)	$C_h = m_h \,.\, Cp_h$ Where, C_h = hot fluid rate (W/°C) m_h = specific heat capacity of hot fluid (J/Kg°C) Cp_h = mass flow rate of hot fluid (Kg/s).	(23)
	Cold Fluid Rate (C_c)	$C_c = m_c \,.\, Cp_c$ C_c = cold fluid rate (W/°C) m_c = specific heat capacity of cold fluid (J/Kg°C) Cp_c = mass flow rate of cold fluid n (Kg/s).	(24)
		$Q_{max} = C_{min}(Th_i - Tc_i)$ Where, Q_{max}= Maximum heat transfer (W) C_{min} = Minimum heat capacity rate (W/°C) Th_i = inlet temperature of hot fluid (°C) Tc_i = Cold fluid inlet temperature (°C).	(25)
Heat Exchanger	Effectiveness (ε)	$\varepsilon = \frac{Q_{act}}{Q_{max}} x\ 100\%$ Where, Q_{act} = actual energy transferred (W) Q_{max} = maximum heat transfer (W)	(26)
	Number Transfer Unit (NTU)	$NTU = \frac{U\ x\ A}{C_{min}}$ Where, U = overall heat transfer coefficient (W/m²°C) A = heat transfer area (m²) C_{min} = minimum heat capacity rate (W/°C).	(27)

3. RESULT AND DISCUSSION

The calculation shows that the transferred energy value (Q) is 394146 W with a shell length of 0.889 mm, a shell diameter of 0.03 mm, an inner diameter of 0.023 mm, and an outer diameter of 0.0254 mm. The wall thickness, tube length and tube pitch were 0.000889 mm, respectively; 5.4864 m; 0.02778. The effectiveness of heat exchanger was found to be 96.40% which indicates the actual heat transfer rate that was divided by the maximum heat transfer rate. The total heat exchanger performance is also determined by the specific heat of the fluid, density viscosity, and thermal conductivity. The complete calculation results are shown in Table 3.

The designed heat exchanger design model is shown in Fig. 2. NiO synthesis requires a heating temperature of 70°C and then cooled at room temperature in the range of 25-27°C. Therefore, the hot fluid used is 30% ethylene glycol and the cold fluid is water. The hot fluid enters at a temperature of 70°C and leaves at a temperature of 62.5°C. The cold fluid enters at 10 and leaves at 30°C. After forming a greenish residue, continued calcination at 400°C for 3 hours.

Table 3. Heat Exchanger performance parameters designed based on calculations.

No	Parameters	Result
1	Transferred energy (Q)	394146 W
2	Logarithmic Mean Temperature Difference (LMTD)	12.7 ℃
3	Overall Fluid Heat Coefficient Assumption (U_a)	140 Btu/h.ft^2.F
4	Heat Transfer Field Area *(A)*	212.21 m^2
5	Number of tube (N)	193
6	Total Heat Transfer Surface Area in the Tube (A_t)	0.44 m^2
7	Mass Flow Rate of Water in Tube (Gt)	543.093 kg/m^2.s
8	Reynolds number (Re_t)	0.7051
9	Prandtl numbers ($Pr,_t$)	167696,42
10	Nusselt number ($Nu,_t$)	2.51
11	Convection Heat Transfer Coefficient in the Tube *(h_i)*	13496.02452 W/m^2°C
12	Bundle Shell *(Db)*	400.974 mm
13	Shell flow area (A_s)	0.44 m^2
14	Mass Flow Rate of Water in Shell (Gs)	21.45 kg/m^2.s
15	Diameter equivalent (d_e)	25835.15 m
16	Reynolds number in shell ($Re,_s$)	93280475.06
17	Prandtl numbers in shell (Pr, s)	0.00873
18	Nusselt numbers in shell (Nu,s)	9628.42
19	Convection Heat Transfer Coefficient in the shell (h_o)	971686.063 W/m^2°C
20	Actual Overall Heat Transfer Coefficient (U_{act})	7.84
21	Effectiveness (ε)	96.40%
22	Number Transfer Unit (NTU)	8.924

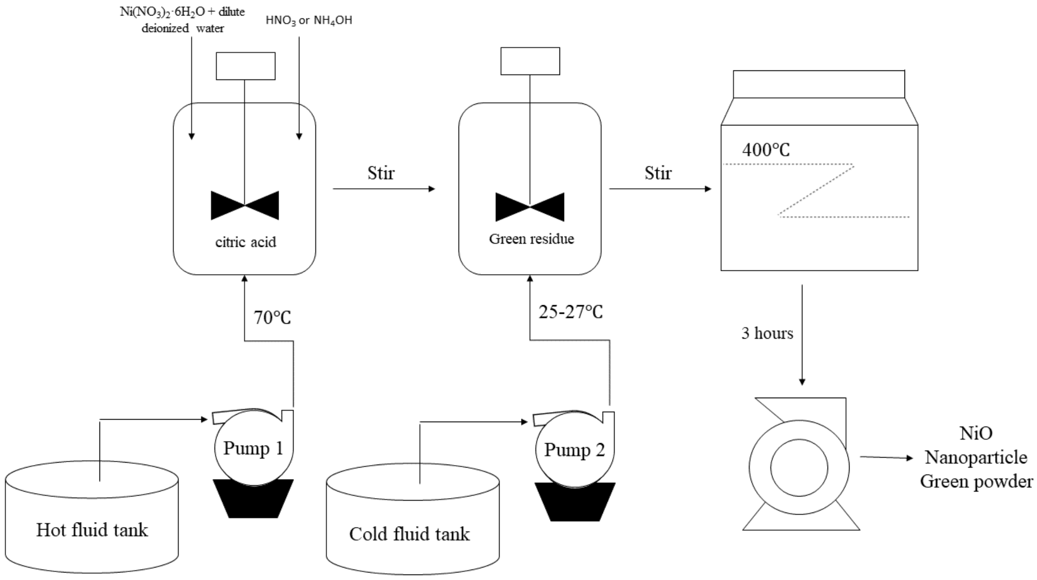

Fig. 2. PFD on the synthesis of NiO-nanoparticles.

Therefore, this heat exchanger with shell and tube one meets the requirements and standards based on effectiveness, but without the calculation of the fouling factor.

4. CONCLUSION

Calculation of the heat exchanger specifications obtained shell length of 0.889 mm, shell diameter of 0.03 mm, inner diameter of 0.023 mm, outer tube diameter of 0.0254 m, wall thickness of 0.000889 mm, tube length 5.4864, and tube pitch 0.02778. Based on the calculations performed through Microsoft Excel, the results show that the heat exchanger design on the shell and tube that fits is a laminar flow type, with an effectiveness of 96.40%. Therefore, this heat exchanger with shell and tube one meets the requirements and standards based on effectiveness, but without the calculation of the fouling factor.

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