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Heat Exchanger Design for Silicon Dioxide Nanoparticles Production

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Abstract

Developing and analyzing a heat exchanger design for the production of silicon dioxide nanoparticles is the aim of this research. In designing the heat exchanger design for the production of silicon dioxide nanoparticles, shell and tube heat exchangers are used. The specifications of the equipment used for the design of the heat exchanger are tube outer diameter of 0.0254 m, tube inside diameter of 0.0212 mm, tube length of 5.49 m, and thickness of 0.002 m. The results of calculations performed using Microsoft Excel show that the design of the heat exchanger on the shell and tube shows an effectiveness value of 96.09%. This value indicates that the shell and tube in the heat exchanger design is a laminar type. Therefore, judging from its effectiveness, this shell and tube heat exchanger meets the requirements and standards to be used in the production of silicon dioxide nanoparticles.

Keywords: Silicon dioxide, Heat exchanger, Shell and tube, Effectiveness.

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1. Introduction

Heat exchanger is a heat transfer system between two or more liquids at different temperatures [1-3]. This heat exchanger can be used in the heating or cooling process [4]. The liquid in the heat exchanger is separated so as not to mix between the production fluid and the fluid fluid. Shell and tube heat

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exchangers are the most common type of heat exchanger. In a shell and tube heat exchanger one fluid will flow through the tube and the other fluid will flow across the tube boundary, to transfer heat between the two fluids [5-7].

Shell and tube heat exchangers have several advantages including: having the ability to transfer large amounts of heat, and lower costs than other types of heat exchangers [5]. In this journal, we will discuss about shell and tube heat exchanger for the production of silicon dioxide.

Silicon dioxide is needed in many industries. Silicon dioxide can be applied in the manufacture of glass, ceramics, abrasives, concrete products, fillers in rubber products, production of silica refractories and others [8-9]. Silicon dioxide with high purity can also be used as the main material in the manufacture of optical fibers, semiconductor processing and solar cells [10].

In previous studies, experimental investigation of viscosity and specific heat of silicon dioxide nonofluids [11], measurement of thermal conductivity of silicon dioxide nanofluid [12]., comparative study of silicon dioxide and kaolinite for temperature and humidity variations of earth enabled cooling system have been discussed. and traditional cooler [9]. From the studies on silicon dioxide, there is still no discussion on the design of heat exchangers for the production of silicon dioxide, so it is necessary to do further research on the design of heat exchangers for the production of silicon dioxide.

2. Materials and methods

2.1. Synthesis of silicon dioxide

The synthesis of silicon dioxide was carried out by the sol-gel method [13-14]. Prepared 125 mL of ethanol then added 25 mL of distilled water. Stirred for almost 15 minutes with the help of a magnetic stirrer at 600 rpm. Added 12 mL of tetraethyl orthosilicate and mixed for about 2 hours. Added 30 mL and mixed for 4 hours. After that add 30 mL of liquid ammonia to the flask, and the solution will thicken. Continue the mixing process for 1 hour by adjusting the stirring temperature until it becomes a thick gel. After the gel thickens, a hydrolysis process is carried out to remove excess water, so a filtration process is necessary. After filtration, the solid gel precipitate was collected and washed. After washing, it is put into the muffle furnace at 100℃ for 1 hour. After that take it out. The resulting thick gel solution needs to be calcined to form granules. Take a small portion of the gel and put it in the heating furnace for 2 hours. After 2 hours, take it out and crush it using a mortar as finely as possible and form nanoparticle silicon dioxide (SiO_2) [15]. The silicon dioxide synthesis process is presented in **Fig 1**.

2.2. Mathematical models for designing a heat axchanger

In this heat exchanger design, water is used as the cold fluid and tetra ethylene glycol as the hot fluid. Hot liquid enters at 75℃ and cold liquid enters at 30℃. The fluid characterization used for this heat exchanger process is assumed in Table 1. The flow rate for tetra ethylene glycol is 113.04 kg/h and the flow rate for water is 37 kg/h. Data collection was carried out using the Standard Tubular Exchanger Manufacturers Association (TEMA), while thermal analysis was carried out by processing data using Microsoft Excel based on equations 1-27 in **Table 1**. The data processing process based on these equations has been carried out by [16-17].

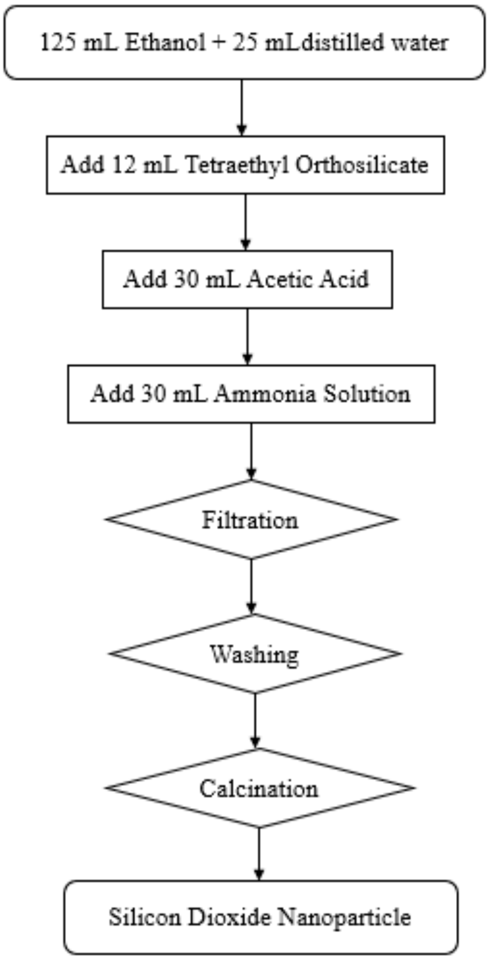

Fig 1. Schematic diagram of the nano-SiO_2 preparation process using the sol-gel method

Table 1. Calculation of heat exchanger parameters

No	Section	Parameter	Equation	Eq
1	Basic parameters	The energy transferred (Q)	$Q_{in} = Q_{out}$ $m_c \times Cp_c \times \Delta T_c = m_h \times Cp_h \times \Delta T_h$ 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)	$LMTD = \frac{(T_{hi} - T_{Ci}) - (T_{ho} - T_{Co})}{ln\frac{(T_{hi}-T_{Ci})}{(T_{ho}-T_{Co})}}$ T_{hi} = the temperature of the hot fluid inlet T_{ho} = the temperature of the hot fluid outlet T_{Ci} = the temperature of the cold fluid inlet T_{Co} = the temperature of the cold fluid outlet All temperature units are in °C	(2)
		Correction factor	$R = \frac{(T_{hi} - T_{ho})}{(T_{Co} - T_{Ci})}$ $P = \frac{(T_{Co} - T_{Ci})}{(T_{hi} - T_{Ci})}$ $F = \frac{\sqrt{R^2+1}\ln[\frac{1-P}{1-PR}]}{(R-1)\ln(\frac{2-P(R+1-\sqrt{R^2+1}}{2-P(R+1+\sqrt{R^2+1}})}$	(3) (4) (5)
		Heat Transfer Field Area (A)	$A = \frac{Q}{U \times LMTD}$ Q = the energy transferred (W) U = the overall heat transfer coefficient $LMTD$ = the logarithmic mean temperature difference	(6)
		Number of Tubes (N)	$N = \frac{A}{\pi \times D_o \times l}$ N = the number of tubes A = the area of the heat transfer area (m^2) π = the value of 3.14 D_o = the tube diameter (m) l = the tube length (m)	(7)
		Shell Diameter	$D_s = 0{,}63\ (\frac{\sqrt{\frac{CL}{CTP} \times ((A \times (PR)^2 \times D_o}}{l})^{\frac{1}{2}}$ D_s = the shell diameter (m) A = the area of the heat transfer area (m^2) PR = the correction factor D_o = the tube diameter (m) CTP = the constant (one tube pass = 0.93; two tube pass = 0.90; and three tube pass = 0.85) CL = the constant (CL at 45 and 90° = 1.00; CL at 30° and 60° = 0.87)	(8)

2	Tube	Surface Area of Total Heat Transfer in Tube (a_t)	$a_t = N_t \frac{a'_t}{n}$ 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)
		Mass Flow of Water in Tube (Gt)	$Gt = \frac{m_h}{a_t}$ Gt = the mass flow of water in tube (Kg/m^{2}s) m_h = the mass flow rate of the hot fluid (Kg/s) a_t = the flow area tube (m^2)	(10)
		Reynold Number (Re_t)	$Re_t = \frac{di_t \times Gt}{\mu}$ Re_t = the Reynolds number in tube di_t = the inner tube diameter (m) Gt = the mass flow of water in the tube (m^2) μ = the dynamic viscosity (Kg/ms)	(11)
		Prandtl Number (Pr, t)	$Pr = (\frac{C_p \times \mu}{K})^{\frac{1}{2}}$ Pr = Prandtl Number C_p = 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)
		Inside coefficient (h_i)	$h_i = \frac{Nu \times K}{d_i, t}$ h_i = the convection heat transfer coefficient in the tube (W/m°C) K = the thermal conductivity of the material (W/m°C) d_i, t = the inner tube diameter (m^2)	(14)
4	Shell	Shell Flow Area (A_s)	$A_s = \frac{d_s \times C \times B}{P_t}$ $D_b = d_o(\frac{N_t}{k_1})^{\frac{1}{n_1}}$ d_s = the shell diameter (m) C = clearance ($P_t - d_o$) B = the a shell bundle P_t = the tube pitch ($1.25 \times d_o$) (m)	(15) (16)

		Mass Flow Rate of Water in Shell (G_s)	$G_s = \frac{m_c}{a_s}$ m_c = the mass flow rate of the cold fluid (Kg/s) A_s = the shell flow area (m^2)	(17)
		Equivalent Diameter (d_e)	$d_e = \frac{4 \times (\frac{P_t}{2} \times 0,87\, P_t - \frac{1}{2}\pi\frac{d_{o,t}}{4})}{\frac{1}{2}\pi d_{o,t}}$ P_t = the tube pitch ($1.25 \times d_o$) (m) π = the value of 3.14 $d_{o,t}$ = the tube outside diameter (m)	(18)
		Reynold Number (Re, s)	$Re_s = \frac{di_t \times Gt}{\mu}$ Re_s = the Reynold number di_t = the inner tube diameter (m) Gt = the mass flow of water in the shell (kg/m^2s) μ = the dynamic viscosity (Kg/ms).	(19)
		Prandtl Number (Pr, s)	$Pr = \left(\frac{C_p \times \mu}{K}\right)^{\frac{1}{2}}$ Pr = the Prandtl number C_p = the specific heat capacity (kJ/kg°C) μ = the dynamic fluid viscosity (Kg/ms) K = the thermal conductivity (W/m°C)	(19)
		Nusselt Number (Nu, s)	$Nu_s = 0,023 \times Re_s^{0,6} \times Pr^{0,33}$ Nu_s = the Nusselt number Re_s = the Reynold number Pr = the Prandtl number	(20)
		Convection Heat Transfer Coefficient (*h*o)	$ho = \frac{Nu \times K}{d_e}$ ho = the convection heat transfer coefficient (W/m^2.°C) K = the thermal conductivity (W/m°C) d_e = the equivalent diameter (m)	(21)
5.	Shell and Tube	Actual Overall Heat Transfer Coefficient (U_{act})	$U_{act} = \frac{1}{\frac{1}{h_i} + \frac{\Delta r}{K} + \frac{1}{h_o}}$ h_i = the inside heat transfer coefficient (W/m^2 .°C) ho = the outside heat transfer coefficient (W/m^2.°C) Δr = the wall thickness (m) K = the thermal conductivity (W/m°C)	(22)
6.	Heat rate	Hot Fluid Rate (C_h)	$C_h = m_h.Cp_h$ C_h = the hot fluid rate (W/°C) m_h = the specific heat capacity (J/kg.°C) Cp_h = the mass flow rate of hot fluid (kg/s)	(23)

		Cold Fluid Rate (C_c)	$C_c = m_c.Cp_c$ C_c = the cold fluid rate (W/°C) m_c = the specific heat capacity (J/kg.°C) Cp_c = the mass flow rate of cold fluid (kg/s) $Q_{maks} = C_{min}\left(T_{h,i} - T_{c,i}\right)$ Q_{maks} = the maximum heat transfer (W) C_{min} = the minimum heat capacity rate (W/°C) $T_{h,i}$ = the temperature of the hot fluid inlet (°C) $T_{c,i}$ = the temperature of the cold fluid (°C)	(24)
7.	Effectiveness	HE Effectiveness (ε)	$\varepsilon = \frac{Q\ act}{Q\ max} \times 100\%$ $Q\ act$ = the actual energy transferred (W) $Q\ max$ = the maximum heat transfer (W)	(25)
		Number of Transfer Unit (NTU)	$NTU = \frac{U \times A}{C_{min}}$ U = overall heat transfer coefficient (W/m^2.°C) A = the heat transfer area (m^2) C_{min} = the minimum heat capacity rate (W/°C)	(26)
		Fouling factor (Rf)	$Rf = \frac{U_a - U_{act}}{U_a \times U_{act}}$ Rf = the fouling factor U_a = the overall heat transfer coefficient (W/m^2.°C) U_{act} = the actual overall heat transfer coefficient (W/m^2 .°C)	(27)

3. Results and discussion

From the results of calculations that have been carried out for the design of the heat exchanger for the production of silicon dioxide, the transferred energy value (Q) is 188280 W, with a tube outer diameter of 0.0254 m, tube inside diameter 0.0212 mm, tube length 5.49 m, thickness of 0.002 m.

The type of flow that occurs is laminar flow with shell and tube heat exchanger type is single tube pass, type E. The NTU value in this operating condition is 20.46. Laminar flow is caused by the value of Re < 2300 [18]. In this laminar flow the heat exchange process is not uniform and there is a reduction in the heat exchange coefficient at the Reynolds number. Laminar flow is a flow with fluid moving in layers or laminae with each layer moving without intersecting [19]. In this flow there is no friction so that the stress generated is only caused by the viscosity. This laminar flow is the most ideal fluid flow because the pressure drop that occurs in this flow is very small. Pressure drop is a decrease in pressure that occurs due to friction in the flowing fluid. Pressure drop will cause heat, because the pressure energy turns into heat. The pressure drop is obtained from the difference between the total inlet pressure and the total outlet pressure.

The performance of the heat transfer process is also determined by several factors, including heat specificity of the fluid, viscosity, density and thermal conductivity whose values are presented in **Table 2**. The overall calculation results using Microsoft Excel are presented in **Table 3**.

Table 2. Physical and thermal properties of the fluid

Side	**Shell Side** [20]	**Tube Side** [20]
Fluid Type	Tetra Ethylene Glycol	Water
Inlet Temperature (°C)	30	75
Outlet Temperature (°C)	60	60
Density (kg/m^3)	1120	997
Viscosity (N-s/m^2)	0.0583	0.00089
Heat specific J/Kg.K	2177.14	4184
Thermal conductivity (W/m.K)	0.191	0.598

Table 3. Heat exchanger performance parameters designed based on calculations

No	**Parameters**	**Result**
1	Transferred energy (Q)	188280 W
2	Logarithmic Mean Temperature Difference (LMTD)	21,64°C
3	Area of Heat Transfer (A)	123.74 m^2
4	Number of Tube (Nt)	282.79
5	Total Heat Transfer Surface Area in Tube (a_t)	0.44 m^2
6	Mass Flow Rate of Water Fluid in Tube (Gt)	60,23 Kg/m^{2}s
7	Reynold Number in Tube (Re, t)	1433.63
8	Prandtl Number in Tube (Pr, t)	6.23
9	Nusselt Number in Tube (Nu, t)	3.293
10	Convection Heat Transfer Coefficient in the Tube (h_i)	2596.09 W/m^2°C
11	Bundle Shell (Db)	476.69 mm
12	Shell flow area (A_s)	0.02 m^2
13	Mass Flow Rate of Water Fluid in Shell (Gs)	95.68 Kg/m^{2}s
14	Equivalent Diameter (d_e)	25835.15 m

15	Reynold Number in Shell (Re, t)	42399.43
16	Prandtl Number in Shell (Pr, t)	664.54
17	Nusselt Number in Shell (Nu, t)	1829.19
18	Convection Heat Transfer Coefficient in Shell (h_o)	79025.98
19	Actual Overall Heat Transfer Coefficient (U_{act})	7.813
20	Effectiveness (ε)	96.09%
21	Number of Transfer Unit (NTU)	20.46

From the resulting data, the effectiveness value of the shell and tube on the heat exchanger design was 96.09%. The value of this effectiveness shows the result of the heat transfer rate divided by the maximum transfer rate [21]. The resulting effectiveness value shows the amount of heat carried. Where the value will be high if the difference between the inlet temperature and the outlet temperature is large. So it can be concluded that the effectiveness value of the shell and tube in this heat exchanger design is directly proportional to the magnitude of the temperature difference between the inlet temperature and the outlet temperature [22]. Another factor that influences the effectiveness of the heat exchanger design is the number and spacing of baffles in the heat exchanger specifications. The closeness of the baffle spacing will affect the value of the effectiveness of the heat exchanger design to be higher and the small percentage of baffle cutting will also increase the value of the effectiveness of the heat exchanger design [23]. The effectiveness value obtained was 96.09% indicating that the shell and tube heat exchanger design meets the standard requirements for use in the production of silicon dioxide nanoparticles.

Conclusion

The designed shell and tube heat exchanger has a tube outer diameter of 0.0254 m, tube inside diameter 0.0212 mm, tube length 5.49 m, thickness 0.002 m and effectiveness of 96.09%. These results indicate that the heat exchanger which is designed to have a laminar flow type with a single tube pass type E. The effectiveness value obtained shows that the design results meet the requirements and standards for the production of silicon dioxide.

Conflict of Interest

This study was conducted without any commercial or financial relationship with any institution.

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