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Heat Exchanger Design for the Production of TiO_2 nanoparticles using precipitation method

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Abstract: This study aims to design a heat exchanger to produce TiO_2 nanoparticles using precipitation method. The calculation shows that the heat exchanger specification is designed to have a tube length of 4,267 m with an inner tube diameter of 21,1836 m, a shell diameter of 254 mm, tube pitch 31,75 mm, and baffle space of 51 m. HE has a laminar flow type. Then, the results obtained through calculations using Microsoft Excel for the effectiveness of the designed heat exchanger is 77,48%. These results can be used as information in designing a suitable heat exchanger for the synthesis of TiO_2 nanoparticles.

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1. Introduction

Heat Exchanger is a device used for the heat exchange process. The Heat Exchanger process can be in the form of a heating process and a cooling process. This heat exchanger process always involves 2 media in the form of a fluid (liquid or gas) to be exchanged for heat. For example, for heating water, it involves a heating medium such as steam with the medium to be cooled, such as water (Ngo et al., 2006; Sadighi Dizaji et al., 2015). Heat exchanger is a tool that greatly affects the activities of industrial processes, the maximum carrying capacity of the tool can affect a process so that the process becomes less than optimal, so an appropriate and economical design plan is needed in the manufacture of the heat exchanger. So that it can be operated properly and run optimally in accordance with the design predictions that have been designed (Nandiyanto et al., 2021).

In previous years, many reports have been published on experimental and theoretical studies of materials regarding the titanium dioxide (TiO_2) semiconductor. Nano-sized TiO_2 has received enormous interest due to a large number of applications in photocatalytic systems (Paz, 2010), sunscreens (Sharma et al., 2019), medical implants (Kunrath et al., 2018), fuel cells (Mihankhah et al., 2018), and solar cells (Meen et al., 2009), sensors (Zhu et al., 2009).

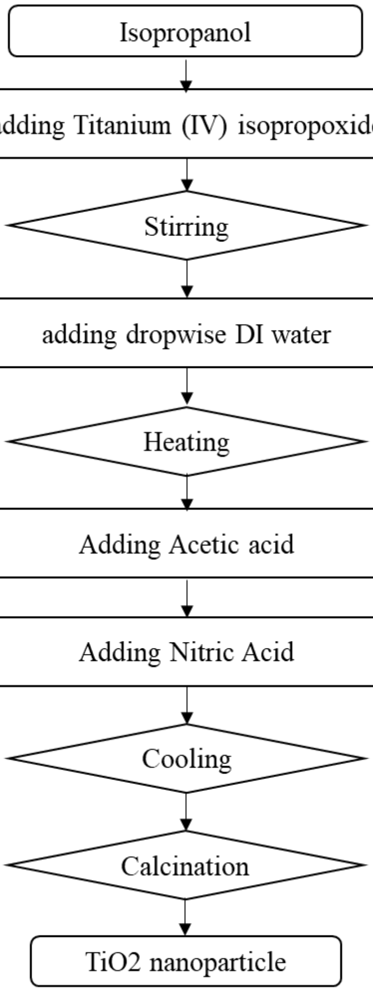

Figure 1. Flow chart of TiO2 nanoparticle production

TiO_2 is one of the widely studied semiconductor materials used in many applications due to its commercial availability at low cost, chemical stability, non-toxic properties and general reactivity (MacWan et al., 2011). Methods that can be used to synthesize TiO_2 include sol-gel, sputtering, chemical vapor deposition, and hydrothermal (Dey et al., 2004; Kaur et al., 2018; Mamakhel et al., 2013). In this article we will discuss the design process, working mechanism, and results of the heat exchanger that we have designed.

2. Methodology

2.1 Synthesis of TiO_2 nanoparticle

TiO_2 powders were also synthesized through the hydrothermal treatment of 2 g TiO_2 powder in 50 ml of 10 M NaOH solution and stirred for 10 min at room temperature. This solution was then transferred into a Tefon-lined stainless steel autoclave and the condition for the hydrothermal

reaction was maintained thoroughly at 150 °C for 48 h. Furthermore, the autoclave was cooled down naturally up to room temperature and resulting in the formation of a white salt cake type of mixture. The upper residual liquid was poured off. The obtained residual dispersion was washed several times with 0.1 M HCl and distilled water until the solution reached pH of 7. The obtained sample was filtered and dried at 80 °C in a vacuum oven for 8 h. To obtain the fne powder, the sample was ground in a mortar pestle and annealed at 500 C for 4 h. figure 1 represents the schematic diagram of the above synthesis route

2.2 Mathematical models for designing a heat exchanger

Table 1 shows the physical and thermal properties for the characteristics of the fluid operating in the HE. Several assumptions are used for the shell and tube type HE design. The hot fluid used is coconut oil, while the cold fluid is water. The hot fluid enters at 80°C and exits at 42°C. The cold fluid enters at 35°C and exits at 40°C. In the process of collecting data regarding specifications, we refer to the Standard Tubular Exchanger Manufacturers Association (TEMA), while thermal analysis is in the form of manual calculations using basic Microsoft Office applications based on equations 1 – 13 shown in table 2.

Table 1. Physical and thermal properties of the fluid

	Hot Fluid (coconut oil) *Z*°C	**Cold fluid (water) pada *Z*°C**
konduktivitas termal λ (W·m^{-1}·K^{-1})	0,16	0,63
viskositas kinematik *v* (mm^{2}·s^{-1})	55	0.91
panas spesifik c_p (J·kg^{-1}·K^{-1})	2100	4178
densitas *ρ* (g·l^{-1})	920	1000

Table 2. Specification of shell and tube heat exchanger and operating condition for coconut oil and water fluid based on calculation result

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 (W) m = the mass flow rate of the fluid (kg/s) Cp = the specific heat	(1)

	ΔT = the fluid temperature difference	
Logarithmic mean temperature differenced (LMTD)	$$\text{LMTD} = \frac{(T_{hi} - Tc_i) - (T_{ho} - Tc_o)}{ln\frac{(T_{hi} - Tc_i)}{(T_{ho} - Tc_o)}}$$ T_{hi} = the temperature of the hot fluid inlet (°C) T_{ho}= the temperature of the hot fluid outlet (°C) Tc_i = the temperature of the cold fluid inlet (°C) Tc_o= the 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)
	$$F = \frac{\sqrt{R^2 + 1} ln\left[\frac{1-P}{1-PR}\right]}{(R-1) ln\left(\frac{2-P(R+1-\sqrt{R^2+1})}{2-P(R+1+\sqrt{R^2+1})}\right)}$$	(5)
Heat transfer field area (A)	$$A = \frac{Q}{U \times LMTD}$$ 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 = constant with a value of 3.14 D_o= the tube diameter (m) l = the tube diameter (m).	(7)

		Shell diameter	$$D_s = 0.63\left(\frac{\sqrt{\frac{CL}{CTP}\times(A\times(PR)^2\times D_o)}}{l}\right)^{\frac{1}{2}}$$ D_s = the shell diameter (m) A = the area of the heat transfer area (m^2) P, R = the correction factor D_o = the 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)
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 rate of water in tube (Gt)	$$Gt = \frac{m_h}{a_t}$$ Gt = the mass flow of water in the tube (kg/m^2s) m_h= the mass flow rate of the hot fluid (Kg/s) a_t = the flow area tube (m^2)	(10)
		Reynold number (R_e, 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 and shell (Kg/m^2s)	(11)

			μ = the dynamic viscosity (kg/ms).	
		Prandtl number (Pr, t)	$$\Pr = \left(\frac{C_p \times \mu}{K}\right)^{\frac{1}{2}}$$ 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)	$$Nu_t = 0.023 \times Re_t^{0.6} \times Pr^{0.33}$$ Re_t = Reynold number Pr = Prandtl number	(13)
		Inside coefficient (hi)	$$hi = \frac{Nu \times K}{d_i, t}$$ di = the convection heat transfer coefficient in the tube (W/m^2°C) K = the thermal conductivity of the material (W/m°C) d_i, t = the inner tube diameter (m).	(14)
3	Shell	Shell flow area (A_s)	$$A_s = \frac{d_s \times C \times B}{P_t}$$	(15)
			$$D_b = d_o \left(\frac{N_t}{k_1}\right)^{\frac{1}{n_1}}$$ 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)	(17)

A_s = the shell flow area (m^2).

Equivalent diameter (d_e)

$$d_e = \frac{4\left(\frac{Pt}{2} \times 0.87Pt - \frac{1}{2}\pi\frac{d_{o,t}}{4}\right)}{\frac{1}{2}\pi d_{o,t}} \quad (18)$$

Pt = tube pitch (1.25× d_o) (m)

π = 3.14

$d_{o,t}$ = tube outside diameter (m).

Reynold number (R_e, t)

$$Re_s = \frac{di_t \times Gt}{\mu} \quad (19)$$

Re_s = the Reynolds number in tube

di_s = the inner tube diameter (m)

Gs = the mass flow of water in the tube and shell (kg/m^2s)

μ = the dynamic viscosity (kg/ms).

Prandtl number (Pr,s)

$$Pr_s = \left(\frac{C_p \times \mu}{K}\right)^{\frac{1}{2}} \quad (20)$$

Pr_s = 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).

Nusselt number (Nu, s)

$$Nu_s = 0.023 \times Re_s^{0.6} \times Pr^{0.33} \quad (21)$$

Re_s = Reynold number

Pr = Prandtl number

Convection heat transfer coefficient (h_o)

$$ho = \frac{Nu \times K}{d_e} \quad (22)$$

ho = the convection heat transfer coefficient ($W/m^2°C$)

K = the thermal conductivity (W/m°C)

			d_e = the equivalent diameter (m).	
4	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 = inside heat transfer coefficient (W/m^2°C) h_o = outside heat transfer coefficient (W/m^2°C), Δr = wall thickness (m) K = thermal conductivity(W/m°C)	(23)
5	Heat rate	Hot fluid rate (C_h)	$$C_h = m_h \,.\, C_{ph}$$ 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). $$Q_{max} = C_{min} \ (T_{h,i} - T_{c,i})$$ Q_{max} = maximum heat transfer (W) 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)	(24)
6	Effectiveness	Heat exchanger effectiveness (ε)	$$\varepsilon = \frac{Q_{act}}{Q_{max}} \times 100\%$$ Q_{act} = actual energy transferred (W) Qmax = 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 = heat transfer area (m^2) C_{min} = minimum heat capacity rate (W/°C).	(26)
		Fouling factor (Rf)	$$Rf = \frac{U_a - U_{act}}{U_a \times U_{act}}$$	(27)

Rf = fouling factor

U_a = overall heat transfer coefficient (W/m^2°C) U_{act} = actual overall heat transfer coefficient (W/m^2°C)

3. Results and Discussion

The heat exchanger is designed by calculating the temperature difference between the input hot temperature and the output cold temperature. The Q value in the shell and tube design for this heat exchanger design is 553812 W. In this design, the Re value indicates less than 2300, informing the type of flow that occurs in the shell in laminar flow. A connected laminar flow heat exchanger may experience non-uniform flow and a reduction in the effective heat exchanger coefficient at the Reynolds number. The thermal performance of this heat exchanger will be directly proportional to the thermal conductivity, viscosity, density, and specific heat of the fluid. If the difference between the input and output temperatures is far enough, the effectiveness value that calculates the amount of heat transferred is also high. The process flow diagram (PFD) for the production of TiO2 nanoparticles is shown in Figure 2.

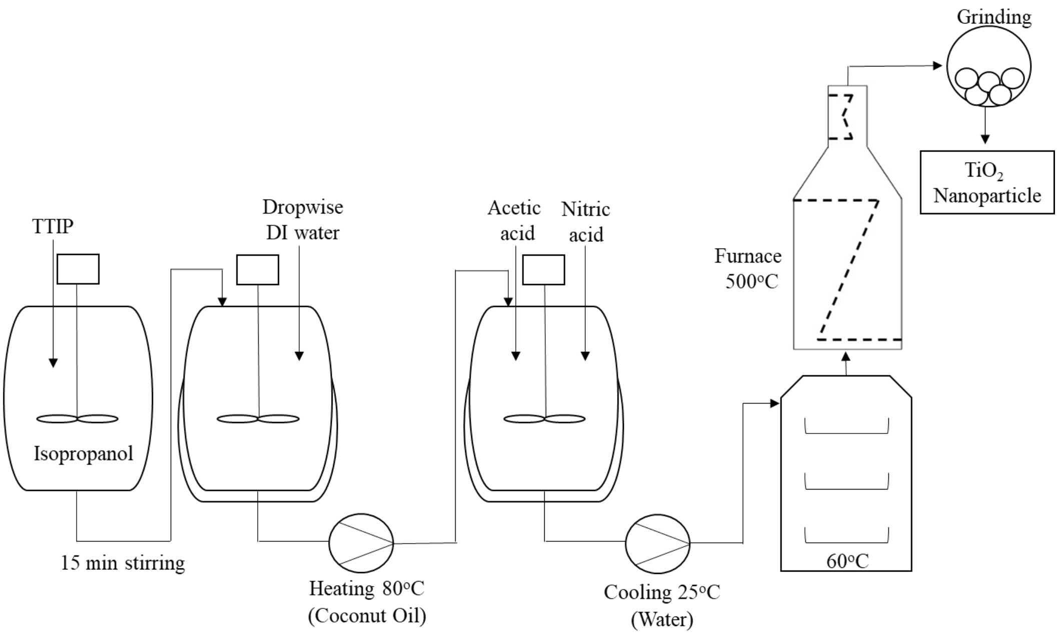

Figure 2. PFD heat exchanger design for production TiO2 nanoparticle

The effectiveness of HE is 77.48%, determined from the calculation of the actual heat transfer rate divided by the maximum possible heat transfer rate. This effectiveness value can measure the amount of heat carried, and will be high if the input and output temperature differences are much different. Another factor that affects the performance of the heat exchanger is the number and spacing of the partitions on the heat exchanger. Close partition spacing can increase the effectiveness of the heat exchanger. The shell and tube heat exchanger specifications based on the calculation results are shown in table 3.

Table 3. Specification of shell and tube heat exchanger and operating condition for diethylene glycol and water based on calculation result.

Description	Type/value
Type of heat exchanger	Single tube pass, and type E shell
Coconut oil inlet temperature (°C)	80
Coconut oil outlet temperature (°C)	42
Water inlet temperature (°C)	35
Water outlet temperature (°C)	40
Tube outside diameter, do (mm)	25,4
Tube inner diameter, di (mm)	21,1836
Pitch, (mm)	27,78
Total tube number, N	254
Total Heat Transfer Surface Area in Tube (m^2)	0,3403
Mass Flow Rate of Fluid in Tube ($kg/m^2.s$)	155,12
Reynold Number in Tube	0,0597
Prandtl Number in Tube	721875
Nusselt Number in Tube	0,3637
Shell inner diameter, Ds (mm)	254
Total Heat Transfer Surface Area in shell (m^2)	0,0403
Mass Flow Rate of Fluid in shell ($kg/m^2.s$)	94,29
Reynold Number in Shell	2676,89
Prandtl Number in Shell	6034,89
Nusselt Number in Shell	484,99
Baffle spacing, B (m)	51

Initial Heat Transfer Rate (W)	553812
Logarithmic Mean Temperature Difference (°C)	61
Area of Heat Transfer (m^2)	86,44
Water heat rate (W/K)	15884,61
HE Effectiveness (%)	77,48
Number of Transfer Unit	3,91

Conclusion

The results of HE with shell and tube type and one pass have several specifications. The results of the designed a shell and tube typed HE with one pass have shell length specifications of 4,267 m, with an inner tube diameter of 21,1836 mm, a shell diameter of 254 mm, tube pitch 31,75 mm, and baffle space of 51 m. HE has a laminar flow type. The effectiveness of HE is 77,48% and NTU is 3,91. However, the results showed that the designed HE does not fulfil the requirements of TEMA standards. The results of this calculation are quite good, so it can be used as information to optimize the manufacture of heat exchanger designs in the future

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