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RESEARCH PAPER

Design of heat exchanger for producing nickel ferrite ($NiFe_2O_4$) nanoparticles using coprecipitation method

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Abstract: This study examines the design of a heat exchanger (HE) in the production process of nickel ferrite ($NiFe_2O_4$) nanoparticles using the coprecipitation method by determining the shell and tube heat exchanger. The Microsoft Excel application is used as a manual calculating machine to facilitate the analysis of heat exchanger (HE) data calculations. The research flowchart starts with a literature study, preparation of tools and materials for design, calculation of the main shell and tube components, and then fabrication. Based on the calculation results, the design specification data for a shell and tube heat exchanger has a shell diameter of 0.032 m, a shell length of 4.267 mm, a thickness of 0.002 m with an initial heat transfer rate (Q) of 460130 W resulting in a heat transfer efficiency of 95.706% and an NTU of 6.165. The high effectiveness value makes the design of the one shell and tube type turbulent flow heat exchanger (HE) considered to have met the standards of high effectiveness and good performance. The design and design process is complete if the device functions properly. This study can be used as a reference for researchers in designing heat exchangers during production to make them more effective, reliable, and economical.

Keywords: Heat Exchanger (HE), Nickel ferrite ($NiFe_2O_4$) nanoparticles, Shell and tube, Effectiveness

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INTRODUCTION

The development of science and technology today, globally, has influenced modernization in various fields, especially in production. One of them is the use of a heat exchanger (HE). HE plays an essential role in the industrial world [1] to meet the needs of technicians for various products produced, such as in the synthesis of nickel ferrite ($NiFe_2O_4$) nanoparticles by raising or lowering the temperature [2] process in its work. In its application, the shell and tube type is the most common heat exchanger [1]. HE is a heat energy transfer device [3] based on the difference in temperature and liquid temperature through the heating and cooling fluid sides, which are separated by a dividing wall [4]. HE has advantages in terms of high thermal efficiency at low cost [3] from fabrication to performance tests [5]. Therefore it is widely used in various application systems, such as nuclear reactors and power plants [6], as fuel and industrial processing processes [7-8]. There are various types of heat exchangers (HE) that can be used, but the most commonly used is the shell and tube type of heat exchanger (HE) [9]. Several parameters that affect the performance of the shell and tube type heat exchanger (HE) are the effectiveness and heat transfer coefficient. The parameters that must be considered to obtain maximum heat transfer effectiveness are the fluid type, temperature, heat transfer rate, flow rate, pressure drop, shell and tube dimensions, pitch distance, baffle distance, tube arrangement, and type of material [2]. One of the functions of the heat exchanger (HE) in industrial processing is to produce nanoparticles by breaking large particles into nanometer-sized particles, top-down or bottom-down.

Nanoparticles are dispersed particulates that are nanometer in size with a diameter of 1-1000 nm [10]. Small particle sizes are the subject of research because they have the potential in various applications, usually utilized in several fields such as information technology, energy production, and storage. After all, nanostructured materials have a high magnetic density as a constituent of magnetic fluids [11]. In addition, nanoparticles are also useful as detectors, catalysts, surface coating agents, and antibacterials. One of the nanoparticles that have been developed and are increasingly in demand is spinel ferrite nanoparticles. Spinel ferrite nanoparticles are inorganic soft magnetic materials that have a cubic crystal structure with the structural formula MFe_2O_4, where M is a divalent metal cation of 3d transition elements (Co^{2+}, Ni^{2+}, Zn^{2+}, and other metal cations) [12] and has good electrical, magnetic, optical, dielectric [13], resistivity and electrical permeability properties.

One of the spinel ferrite nanoparticles is nickel ferrite ($NiFe_2O_4$). Nickel ferrite ($NiFe_2O_4$) nanoparticles are a soft ferrite material that is typically ferromagnetic, originating from an anti-parallel pair between the magnetic moments of Fe^{3+} ions in the tetrahedral position and the magnetic moments of Ni^{2+} ions and Fe^{3+} ions in octahedral positions [14] with high permeability, high resistivity [15] low coercivity and saturation magnetization. The properties of magnetic nanoparticles can be modified by controlling the synthesis process of the materials used. Several approaches have been developed to synthesize nickel ferrite ($NiFe_2O_4$) nanoparticles, namely the coprecipitation method [16-18], the combustion method [12], the sol-gel auto combustion method, and the hydrothermal method [19]. Among these methods, the method used to synthesize nickel ferrite ($NiFe_2O_4$) nanoparticles is the coprecipitation method. Coprecipitation is a simple method that converts a metal salt into a precipitate using a hydroxide or carbonate base precipitator, which is then converted to its oxide form by heating [20] to produce relatively narrow grain particles [21] and small. In addition, this method is also one of the most efficient methods [21] and can be performed under normal environmental conditions [22] or low temperatures [20].

Several researchers have carried out various literature studies regarding the design of heat exchangers [5, 23-25] as temperature controllers in manufacturing nanoparticles. However, researchers have not carried out research studies regarding the design of shell and tube heat exchangers (HE) to produce nickel ferrite ($NiFe_2O_4$) nanoparticles. Simple heat exchanger (HE) technology engineering is designed based on the type of shell and tube for the laboratory scale while still referring to existing design rules, so the writing of this article is expected to be a useful reference source as a method for developing heat exchanger (HE) designs starting from the design process, working mechanism to performance test.

MATERIALS AND METHODS

Synthesis of nickel ferrite ($NiFe_2O_4$) nanoparticles

Nickel ferrite ($NiFe_2O_4$) nanoparticles were synthesized using the coprecipitation method, which refers to a study conducted by [16] and [18]. $NiCl_2$, $FeCl_3$, NaOH, oleic acid, and distilled water were the precursors used. The synthesis process begins by dissolving each of the anhydrous salts $NiCl_2$ and $FeCl_3$ in distilled water until 0.2 M nickel (II) chloride ($NiCl_2.6H_2O$) and 0.4 M iron (III) chloride ($FeCl_3.6H_2O$) are formed as solutions homogeneous salt. Then the two solutions were mixed and added to the 3 M NaOH solution slowly (drop by drop) while stirring using a magnetic stirrer until a liquid precipitate formed which reached a pH > 11 (base), then added 2-3 drops of oleic acid as a surfactant. The precipitation process was carried out by heating at 80℃ and stirring for 40 minutes, and then the precipitate was cooled at room temperature until the temperature was equal. They were then washed twice with distilled water and ethanol. Then it was centrifuged for 15 minutes and dried in a furnace for 24 hours at 80℃, and heating produced solid pieces of nickel ferrite ($NiFe_2O_4$) nanoparticles. The substance obtained is then crushed until smooth [16] and then calcined at a temperature of 600℃ to 1000℃. However, in the experiment [19], the calcination process was carried out at 600℃ for 10 hours, and an inverted cubic nickel ferrite ($NiFe_2O_4$) product was obtained with a size of 28 nm as a result of X-ray diffraction confirmation [16].

Mathematical modeling for heat exchanger (HE) design

In this study, the hot and cold fluids used in the heat exchanger (HE) design are air. Hot fluid enters at 80℃ and exits at a temperature of 45℃. Cold fluid enters at 25℃ and leaves at 47.5℃. In **Table 1**, it is assumed that some characteristics of the heat exchanger (HE) fluid [26]. The Tubular Exchanger Manufacturers Association (TEMA) tabulation is used as a reference for data specifications, while the analysis of performance calculations is carried out in the form of manual calculations using the Microsoft Excel application based on equations 1-15, as has been done by [27]. The calculation of the first heat exchanger (HE) parameter is energy transfer (Q) which is measured using equation (1).

$$Q_{in} = Q_{out}$$

$$m_c\ x\ Cp_c\ x\ \Delta T_c = m_h\ x\ Cp_h\ x\ \Delta T_h \quad (1)$$

Where *Q* is the energy transferred (Wt), *m* is the mass flow rate of the fluid (Kg/s), *Cp* is the specific heat, and ΔT is the fluid temperature difference (℃).

The Logarithmic Mean Temperature Difference (LMTD) was determined using equation (2).

$$LMTD = \frac{(Th_i - Tc_i) - (Th_o - Tc_o)}{\ln\left(\frac{Th_i - Tc_i}{Th_o - Tc_o}\right)} \quad (2)$$

Where Th_i is the temperature of the hot fluid inlet (℃), Th_o is the temperature of the hot fluid outlet (℃), Tc_i

is the temperature of the cold fluid inlet (℃), and Tc_o is the temperature of the cold fluid outlet (℃).

The heat transfer field area (*A*) was calculated using equation (3).

$$A = \frac{Q}{U_d \; x \; \Delta T_{LTMD}} \quad (3)$$

Q is the energy transfer (W), U_d is the overall heat transfer coefficient, and ΔT_{LTMD} is the logarithmic mean temperature difference (℃).

The number of tubes (N_t) was calculated using equation (4).

$$N_t = \frac{A}{L \; x \; a''} \quad (4)$$

Where *A* is the heated area (ft^2), *L* is the tube length, and a'' is the outer surface area (ft^3).

The total heat transfer surface area in the tube *($a_{s,t}$)* was determined using the equation (5).

$$a_t = N_t \frac{a't}{n} \quad (5)$$

Where it is the flow area in the tube (m^2) and *n* is the number of passes.

The mass flow of water in the tube (G_t) is determined by equation (6)

$$G_t = \frac{m_h}{a_t} \quad (6)$$

Where m_h is the mass flow rate of hot fluid (Kg/s), and G_t is the mass flow of fluid in the tube (Kg/m^2.s).

The Reynolds number (Re_t) can be calculated using equation (7).

$$Re_t = \frac{di_t \; x \; G_t}{\mu} \quad (7)$$

Where di_t is the inner tube diameter (m), and μ is the dynamic viscosity of the fluid in the tube (Kg/m.s).

Prandtl Number (*Pr*) in the tube was calculated by using equation (8).

$$Pr = \left(\frac{Cp \; x \; \mu}{K}\right)^{1/2} \quad (8)$$

K is the thermal conductivity of the tube material (W/m.℃).

The Nusselt number (*Nu*) can be determined from the Reynolds number (*Re*) and the Prandtl number (*Pr*) in equation (9).

$$Nu = 0.023 \; x \; Re_t^{\;0.6} \; x \; Pr^{\;0.33} \quad (9)$$

The Actual Overall Heat Transfer Coefficient (U_{act}) was calculated using equation (10).

$$U_{act} = \frac{1}{\frac{1}{h_i} + \frac{\Delta r}{k} + \frac{1}{h_o}} \quad (10)$$

Where h_i and h_o is inside and outside heat transfer coefficient (W/m^2.℃), and Δr is wall thickness (m).

The hot fluid rate (C_h) was measured by using equation (11).

$$C_h = m_h \; x \; Cp_h \quad (11)$$

Where m_h is the mass flow rate of hot fluid (Kg/s), Cp_h is specific heat capacity (J/Kg.K), and C_h is a hot fluid rate (W/K).

Then the, equation (12) below is used to measure the cold fluid rate.

$$C_c = m_c \; x \; Cp_c \quad (12)$$

Where m_c is the mass flow rate of cold fluid (Kg/s), Cp_c is specific heat capacity (J/Kg.K), and C_c is the cold fluid rate (W/K).

To determine the value of the number of heat transfer units (NTU), equation (13) can be used.

$$NTU = \frac{U \; x \; A}{C_{min}} \quad (13)$$

Finally, determining the effectiveness of the heat exchanger (HE) can be calculated using equation (14), and Q_{max} was measured by equation (15).

$$\varepsilon = \frac{Q_{act}}{Q_{max}} \; x \; 100\% \quad (14)$$

$$Q_{max} = C_{min}(Th_i - Tc_i) \quad (15)$$

Where, Q_{act} is the actual energy transferred, Th_i and Tc_i is the temperature of the hot and cold fluid inlet.

Table 1. Characteristics of the fluid that is assumed to work on the heat exchanger (HE)

Parameters	Shell side (hot fluid) Water (80℃)	Tube side (cold fluid) Water (25℃)
Inlet temperature, T_{in} (K)	335.15	298.15
Outlet temperature, T_{out} (K)	318.15	310.65
Thermal conductivity, λ (W/m.K)	0.670	0.607
Viscosity, ν (Kg/m.s)	0.0003	0.0009
Heat specific, C_p (J/Kg.K)	4197	4180
Density, ρ (Kg/m^3)	971.80	997.00

RESULTS AND DISCUSSION

The design of the heat exchanger (HE) used in the production of nickel ferrite ($NiFe_2O_4$) nanoparticles were generated from heat exchanger (HE) specification data using standards (TEMA) and is illustrated in Figure 2. through the PFD scheme for manufacturing nickel ferrite ($NiFe_2O_4$) nanoparticles. Some things that need to be known when designing a heat exchanger (HE) are understanding the characteristics of the material to be used, knowing the amount of material as a fluid and the type of flow to facilitate dimensional measurements, designing a heat exchanger (HE) design and setting up a performance testing mechanism. The results of the calculation of several parameters in equations 1-15 are presented in **Table 2.** as the operating conditions of heat exchanger (HE) performance.

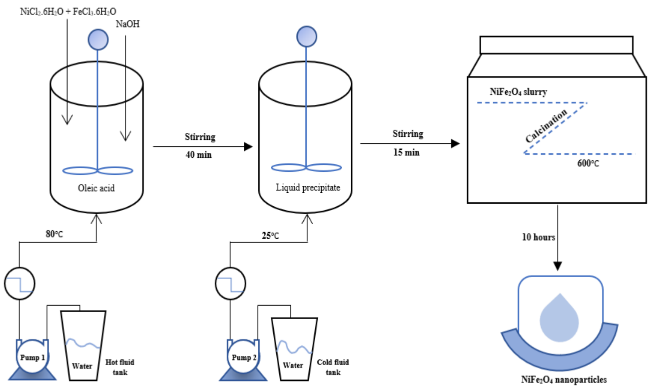

Figure 2. PFD scheme for the process of synthesis of nickel ferrite ($NiFe_2O_4$) nanoparticles

A heating and stirring process was carried out in synthesizing nickel ferrite ($NiFe_2O_4$) nanoparticles for 40 minutes. It aims to optimize the homogenization process and increase the reaction rate in the mixed solution. Furthermore, the solution was precipitated with NaOH until the pH was alkaline and the formation of nickel ferrite ($NiFe_2O_4$) was optimal. Then it was calcined at 600℃ for 10 hours to obtain brown nickel ferrite ($NiFe_2O_4$) nanoparticles [28]. To maintain a fluid flow without changing the existing phase, when synthesizing nickel ferrite ($NiFe_2O_4$) nanoparticles, a heat exchanger (HE) is designed to streamline the fluid flow because it can work two functions: heating and cooling the fluid simultaneously. The two fluids used in synthesizing nickel ferrite ($NiFe_2O_4$) nanoparticles are water. During synthesis, the hot fluid will heat up at 80℃ and leave at 45℃ with a flow rate of 2 Kg/s, while the cold fluid will cool down at 25℃ from an exit temperature of 37.5℃ with a flow rate of 3 Kg/s. After that, a product was formed as nickel ferrite ($NiFe_2O_4$) nanoparticle powder.

Table 2. Specification of heat exchanger (HE) based on TEMA standard and the operating condition based on the calculation results

Description	Type/Value
Type of heat exchanger (HE)	Single tube pass, type shell, and tube heat exchange
Water inlet temperature (℃)	80.0
Water outlet temperature (℃)	45.0
Water inlet temperature (℃)	25.0
Water outlet temperature (℃)	37.5
Outside diameter tube (mm)	31.750
Inner diameter tube (mm)	27.534
Length (m)	4.267
Wall thickness (mm)	2.108
Pitch tube (mm)	27.780
Tube number	168.424
Total heat transfer surface area in the tube (m^2)	0.050
The mass flow rate of fluid in the tube ($Kg/m^3.s$)	59.862
Reynold Number in tube	4649.426
Prandtl Number in tube	2.266
Tube layout	Triangular
Shell outer diameter (mm)	269
Shell inner daimeter (mm)	254
Total heat transfer surface area in the shell (m^2)	0.029
The mass flow rate of fluid in the shell ($Kg/m^3.s$)	69.098
Reynold Number in shell	7868287.937
Prandtl Number in shell	6.262
Nusselt Number in shell	18482.822
Baffle type	Single-segmental
Baffle spacing (mm)	53.800
Initial heat transfer rate (Q)	460130
The logarithmic mean temperature difference	21.853
Area of heat transfer (m^2)	71.651
The water flow rate in the tube (Kg/s)	3
The water flow rate in the shell (Kg/s)	2
Water heat rate in the tube (W/K)	12582
Water heat rate in the shell (W/K)	8366
HE effectiveness (%)	95.706
Number of Transfer Units (TNU)	6.165

Table 2 shows that the Reynolds number greater than 2300 indicates that the shell and tube use a turbulent flow type. Initial heat transfer rate (Q) of 460130 W, shell diameter of 0.032 m, shell length of 4.267 mm, and 0.002 m of thickness resulted in an effectiveness of 95.706% and NTU of 6.165. The heat exchanger's (HE) effectiveness value is determined by the heat transfer rate divided by the maximum heat transfer rate [29]. The high percentage of effectiveness of the heat exchanger (HE) indicates that the heat exchanger (HE) has good performance in the manufacture of nickel ferrite ($NiFe_2O_4$) nanoparticles.

CONCLUSION

The results of the design of a heat exchanger (HE) on the synthesis of nickel ferrite ($NiFe_2O_4$) nanoparticles with a turbulent flow type yield specifications for an initial heat transfer rate (Q) of 460130 W, a shell diameter of 0.032 m, a shell length of 4.267 mm, 0.002 m of thickness and a transfer efficiency heat of

95.706% as well as the resulting NTU of 6.165. Therefore, using a shell and tube heat exchanger (HE) can be categorized as meeting high standards of effectiveness and good performance.

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