Optimization of manganese ferrite/distilled water parameter design on heat exchanger using RSM and CFD

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Abstract. Nanofluid is the new fluid in nanotechnology development. Its features carry the ability of fastly discharging heat transfer. Thus, it becomes beneficial for various applications, such as heat transfer, refrigeration, and some devices or machines. This study aims to investigate the performance of a response parameter in a heat exchanger with MnFe$_2$O$_4$ – H$_2$O nanofluid as its cold fluid on various input parameters of tube number, cold fluid flow, and nanoparticle volume fraction to identify the optimum value of heat transfer rate. This study used Response Surface Methodology (RSM) that usually adopted to know the optimum value of a response from an influencing factor. Besides, it also used Computational Fluid Dynamics (CFD) to analyze the heat transfer on the fluid flow computationally. The results of this research show that the optimum parameter value of the heat transfer rate is 42.8022 Watt with 0.075% nanoparticle volume fraction, 0.6l/min nanofluid flow, and three heat exchanger tubes. The rate of heat transfer encounters an increase following the addition of MnFe$_2$O$_4$ nanoparticle volume fraction, cold fluid or nanofluid flow, and the number of heat exchanger tubes.

Keywords: MnFe$_2$O$_4$, nanoparticle, nanofluid, heat exchanger, RSM, CFD.

1. Introduction
The fast advancement of science and technology has placed the performance of machines’ warming and cooling system in the primary needs of various industries, including in energy and automotive companies. The thermal properties of the fluid feature hold an essential role in the energy efficiency of heat exchanger related tools. However, many of them still use conventional fluids, such as oil, coolant, water, and ethylene glycol, that generally possessed low heat transfer properties and required substantial effectivity improvement in the fourth generation of technology advancement [1].

Nanofluid becomes a new fluid class in the nanotechnology development that carries the considerable potential to be applied in heat transfer or cooling. Nanofluid represents a mixture of two phases, where the liquid and dispersed phases are from less than 50 nm nanoparticles [2]. Nanofluid’s characteristic that quickly channels heat transfer carries beneficial for any application, such as for heat transfer, refrigeration, and many types of equipment or machines [3].
A heat exchanger with computational fluid dynamics (CFD) methods reveals that the convective heat transfer coefficient of two nanofluids can be improved by adding nanoparticle, as well as the flow rate, especially the turbulent flow [4]. The heat transfer on the heat exchanger relies not only on the fluid used but also on the tube design that affects the heat exchangers’ efficiency [5]. Optimization of the design and fluid of shell heat exchanger during the heat transfer process using Response Surface Methodology (RSM) has always become the primary purpose of engineer and designer. The aim of this expansion is to identify and investigate the quantitative estimation of various design parameters that affect the thermal performance of the heat exchanger [6].

Therefore, a study on MnFe$_2$O$_4$ nanofluid with water as the primary fluid is required to determine the heat exchanger scale of concentration, flow, and design optimized with the RSM method. After that, it is simulated using the CFD method that capable of creating heat exchanger design, as well as analyzing and identifying the characteristics of heat transfer, temperature, and flow rate.

2. Research methodology

2.1 Computational fluid dynamic (CFD)
This study was simulated using CFD. It used three different tubes of 1 tube, 2 tubes, and three tubes. The material of those tubes was from copper metal with outside and inside diameter of 7.45 mm and 6.45 mm, respectively. At the same time, the outside and inside diameter of the shell heat exchanger were 21.45 mm and 20.45 mm with a shell and tube total length of 380 mm, as presented in Figure 1. Before the simulation was carried out, a three-dimension geometry design was developed. The geometry design was produced using a CFD software, Ansys Fluent version 14.5. The stages of developing geometry design were pre-processing, processing, and post-processing.

![Design of heat exchanger's tubes](image)

**Figure 1.** Design of heat exchanger’s tubes. a) 1 Tube, b) 2 Tube, c) 3 Tube, d) Double pipe
2.2 Preparation of nanofluid material
Manganese ferrite (MnFe₂O₄) nanoparticle form sigma aldrich with the size of 50nm is the spinel ferrite material used for the construction of nanofluid due to its relatively high thermal conductivity and heat capacity; thus, it generates well heat resistant [7], as illustrated in Figure 1. The nanoparticle used for nanofluid with distilled water basic fluid had three fraction volume of 0.025%, 0.05%, and 0.075%. The nanoparticles were weighted with the required ratio and mixed with the basic fluid. After that, the nanofluids were stirred using a magnetic stirrer for two to three hours to dissolve all particles. The properties of manganese ferrite nanoparticle and distilled water are shown in Table 1.

| Table 1. Characteristics of manganese ferrite nanoparticle and distilled water |
|------------------------|------------------------|------------------------|
| Characteristic        | Manganese Ferrite      | Distilled Water         |
| Purity                | 99 %                   | 99.5 %                  |
| Density               | 4870 kg m⁻³            | 997.1 kg m⁻³            |
| Thermal Conductivity  | 12,552 W m⁻¹ K⁻¹      | 12,552 W m⁻¹ K⁻¹        |
| Specific Heat         | 857 J kg⁻¹ K⁻¹         | 857 J kg⁻¹ K⁻¹          |

2.3 Thermophysical properties of nanofluid
Thermophysical properties refer to the physical features of nanofluid used in the heat exchanger machine. It consists of density, specific heat, and thermal conductivity of the nanofluid.

\[ \rho_{nf} = (1 - \varnothing) \rho_{bf} + \varnothing \rho_{np} \]  
Where \( \rho_{nf} \) represents the nanofluid’s density (kg m⁻³), \( \rho_{bf} \) is the density of the basic fluid (kg m⁻³), \( \rho_{np} \) means the nanoparticle’s density (kg m⁻³), and \( \varnothing \) is the nanofluid’s volume fraction (%) [8].

\[ C_{pnf} = (1 - \varnothing) C_{pbf} + \varnothing C_{pnp} \]  
Where \( C_{pnf} \) is the nanofluid’s specific heat (J kg⁻¹ °C⁻¹), \( C_{pbf} \) means the basic fluid’s specific heat (J kg⁻¹ °C⁻¹), and \( C_{pnp} \) is specific heat of the particle (J kg⁻¹ °C⁻¹)[9].

\[ \mu_{nf} = \frac{t_{nf} \cdot \rho_{nf}}{t_{0} \cdot \rho_{0}} \]  
Where \( \mu_{nf} \) represents the nanofluid’s viscosity (kg m⁻¹ s⁻¹), \( \mu_{0} \) is basic fluid’s viscosity (kg m⁻¹ s⁻¹), \( t_{nf} \) is the nanofluid’s viscometer time (s), \( t_{0} \) means the basic fluid’s viscometer time (s)[10].

\[ k_{nf} = \frac{k_{np} + 2k_{bf} + 2\varphi(k_{bf} - k_{np})}{k_{np} + 2k_{bf} - \varphi(k_{bf} - k_{np})} \]  
In which \( k_{nf} \) means the nanofluid’s thermal conductivity (W m⁻¹ °C⁻¹), \( k_{bf} \) is the basic fluid’s thermal conductivity (W m⁻² K⁻¹), and \( k_{np} \) is the thermal conductivity of the nanoparticle (W m⁻² K⁻¹) [11].

2.4 Heat transfer characteristics
Heat transfer is a science employed to identify the energy transfer caused by the temperature differences between fluids, objects, or materials [12].

\[ U = \frac{1}{A_{0} \frac{1}{r_{0}} + \frac{A_{0} \cdot \ln \left( \frac{r_{i}}{r_{0}} \right)}{2\pi k L} + \frac{1}{h_{2}}} \]  
In formula 5, the \( U \) represents the total heat transfer coefficient (W m⁻² K⁻¹), \( r_{0} \) is the radius of outside tube (m), \( r_{i} \) is the radius of inside tube (m), \( A_{0} \) means the surface area of outside pipe (m²), \( A_{i} \) represents the surface area of inside pipe (m²), \( h_{1} \) is the nanofluid’s heat transfer coefficient (W m⁻² K⁻¹), \( h_{2} \) is the thermal fluid’s heat transfer coefficient (W m⁻² K⁻¹), and \( L \) represents the tube’s length (m).
In addition, Formula 6 is an LMTD (Log-Mean Temperature Difference) formula or usually referred to temperature differences. The temperature difference is obtained by subtracting the temperature difference of one heat exchanger’s end by the temperature difference at its other end and divided by the logarithm of the comparison between those temperature differences through formula 6. In Formula 6, $\Delta T_1$ represents the inlet temperature difference ($^\circ$C), $\Delta T_2$ is the outlet temperature ($^\circ$C). In contrast, Formula 7 shows the rate of heat transfer, in which $Q$ means the heat transfer (Watt) and $A$ is the total surface area ($m^2$) [13].

\[ Q = U \cdot A \cdot \Delta T_{LMTD} \]  

(7)

2.5 Response Surface Methodology (RSM)

RSM is a combination of mathematics and statistics based on polynomial estimation (empirical model) with experiment data. This method generates a polynomial function to identify the area of local optimum, model the curvature of response in the optimum area, interpret results of an experiment, and determine the factor declared produce optimum response [14]. Generally, the relation between response and independent variable is unknown [15]. The most common shape is low-order polynomial (the first or second-order). At the same time, the simplest model that could be used is based on the linear function of Formula 8.

\[ Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \varepsilon \]  

(8)

The water level of the polynomial model has to consists of an additional term that illustrates interactions between different experimental variables. Therefore, a model for the second level interaction presents this following Formula 9.

\[ Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \varepsilon \]  

(9)

In addition, the polynomial function requires quadratic term in accordance with Formula 10 to decide the critical points (maximum and minimum)

\[ Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{1 \leq i \leq j \leq k} \beta_{ij} x_i x_j + \varepsilon \]  

(10)

The experiment design of RSM is an efficient procedure to plan an experiment. Consequently, the obtained data could be analyzed to generate valid and objective conclusions, as well as to ensure the accuracy and efficiency of the experiment. Table 2 shows the design of this research using the Box-Behnken experiment model design.

| Table 2. Factors and Level of Experiment Design |
|------------------------|------------------|------------------|
| Factor                 | Level            |
| Number of HE Tube      | 1 tube           | 2 tube           | 3 tube           |
| Nanofluid flow (cold fluid ) | 0.2 l min$^{-1}$ | 0.4 l min$^{-1}$ | 0.6 l min$^{-1}$ |
| Nanoparticle volume fraction | 0.025%          | 0.05%           | 0.075%           |

3. Results and discussion

3.1 Results of thermophysical properties calculation

Table 3 shows the effects of the addition of MnFe$_2$O$_4$ nanoparticle volume fraction toward nanofluid thermophysical properties. The increase occurs in the nanofluid density, up to 1287.57 kg m$^{-3}$. The addition of nanoparticle volume fraction to liquid fluid raises the thickness of that nanofluid since nanoparticles have a higher density than water fluid. Research conducted by
Shahrul et al. (2014) reveals a raise of nanofluid’s density following the increase of nanoparticle volume fraction of its basic fluid [9].

**Table 3. Thermophysical Properties of MnFe$_2$O$_4$ – H$_2$O Nanofluid**

| Volume fraction (%) | Density (kg m$^{-3}$) | Specific heat (J kg$^{-1}$ °C$^{-1}$) | Viscosity (kg m$^{-1}$ s$^{-1}$) | Thermal conductivity (W m$^{-1}$ K$^{-1}$) |
|---------------------|----------------------|-----------------------------------|---------------------------------|----------------------------------------|
| 0.025               | 1093.923             | 4095.95                           | 0.000966875                    | 0.625998                               |
| 0.05                | 1190.745             | 4012.9                            | 0.00102375                     | 0.638456                               |
| 0.075               | 1287.5675            | 3929.85                           | 0.001080625                    | 0.650407                               |

In addition, the upsurge on nanofluid’s viscosity reaches 0.00108 kg m$^{-1}$ s$^{-2}$. The addition of nanoparticle volume fraction into its basic fluid escalates the viscosity value of that nanofluid. That occurs since the solid material from nanoparticle on the basic fluid causes the increase in the nanofluid consistency. The same statement is also found in a research report from Senthilraja et al. (2015) that shows the rise in nanofluid’s viscosity due to the addition of nanoparticle volume fraction [11]. Besides, another growth occurs in nanofluid thermal conductivity that reaches 0.6504 W m$^{-1}$ K$^{-1}$, yet, there is a decrease in nanofluid specific heat, up to 3929.85 Joule/kg°C. The addition of nanoparticle volume fraction into its basic fluid is also completed by Amani (2017), who states that the upsurge of nanofluid thermal conductivity happens due to the higher thermal conductivity of nanofluid than its basic fluid [3].

**3.2 Heat transfer rate of nanofluid**

Table 4 exhibits the experiment design model of Box-Behnken using Minitab 19 software, where 3 factors and 3 levels were formulated in 15 experiments within the stimulated experiment.

![Figure 2. Results of CFD Simulation for Parameter Design No 8 (with 3 tubes, 0.4 l min$^{-1}$ nanofluid Flow and 0.075% Nanoparticle Volume Fraction)](image-url)
As presented in the results of ANOVA in Table 5, this model is presumed to be compatible with predicting the rate of heat transfer (Q) on the optimum performance of heat exchanger, in which the coefficient of determination (R-square) is 94.18%. It indicates that the model describes the rate of heat transfer data (Q). The response value significantly affects the tube number and nanofluid flow parameter \((P<0.05)\). In contrast, the nanoparticle volume fraction gives no significant effect on the response \((P>0.05)\), caused by the significant thermophysical properties difference between one volume fraction and the others.

Table 4. Results of Box-Behnken design with RSM method

| Number of Experiment | A  | B  | C  | Pipe Tube | Nanofluid Flow | Nanoparticle Volume Fraction |
|----------------------|----|----|----|-----------|----------------|-----------------------------|
| 1                    | -  | 1  | 0  | 1 tube    | 0.2 l min\(^{-1}\) | 0.05 %                     |
| 2                    | 1  | -  | 0  | 3 tube    | 0.2 l min\(^{-1}\) | 0.05 %                     |
| 3                    | -  | 1  | 0  | 1 tube    | 0.6 l min\(^{-1}\) | 0.05 %                     |
| 4                    | 1  | 1  | 0  | 3 tube    | 0.6 l min\(^{-1}\) | 0.05 %                     |
| 5                    | -  | 0  | 1  | 1 tube    | 0.4 l min\(^{-1}\) | 0.025 %                    |
| 6                    | 1  | 0  | -  | 3 tube    | 0.4 l min\(^{-1}\) | 0.025 %                    |
| 7                    | -  | 1  | 0  | 1 tube    | 0.4 l min\(^{-1}\) | 0.075 %                    |
| 8                    | 1  | 0  | 1  | 3 tube    | 0.4 l min\(^{-1}\) | 0.075 %                    |
| 9                    | 0  | -  | 1  | 2 tube    | 0.2 l min    | 0.025 %                    |
| 10                   | 0  | 1  | -  | 2 tube    | 0.6 l min\(^{-1}\) | 0.025 %                    |
| 11                   | 0  | -  | 1  | 2 tube    | 0.2 l min\(^{-1}\) | 0.075 %                    |
| 12                   | 0  | 1  | 1  | 2 tube    | 0.6 l min\(^{-1}\) | 0.075 %                    |
| 13                   | 0  | 0  | 0  | 2 tube    | 0.4 l min\(^{-1}\) | 0.05 %                     |
| 14                   | 0  | 0  | 0  | 2 tube    | 0.4 l min\(^{-1}\) | 0.05 %                     |
| 15                   | 0  | 0  | 0  | 2 tube    | 0.4 l min\(^{-1}\) | 0.05 %                     |

Table 5. ANOVA of heat transfer rate (Q)

| Source              | DF | Contribution | F-Value | P-Value |
|---------------------|----|--------------|---------|---------|
| Model (R-squared)   | 3  | 94.18%       | 59.29   | 0.00    |
| Number of Tube      | 1  | 51.74%       | 97.73   | 0.00    |
| Nanofluid Flow      | 1  | 41.53%       | 78.43   | 0.00    |
| Volume Fraction     | 1  | 0.91%        | 1.71    | 0.218   |
| Error               | 11 | 5.82%        |         |         |
| Total               | 14 | 100%         |         |         |
According to Table 5, the contributing factor toward the heat transfer rate, the factors of a number of the tube has a significant effect on the heat transfer rate, 51.7%. Meanwhile, the nanofluid flow and nanoparticle volume fraction affect the heat transfer rate of 41.53% and 0.91%, respectively.

\[ \text{Heat Transfer Rate} = f(\text{Number of Tubes}, \text{Flow}, \text{Nanoparticle Volume Fraction}) \]

![Figure 3. Comparison of heat transfer rate (Q) using CFD experiment with regression equation from RSM](image)

The coefficient of determination (R-squared) value of heat transfer rate (Q) is 94.18%. In other words, the independent variables can explain the dependent variable. Besides, the results of the CFD experiment and results of the RSM regression equation of the heat transfer rate also reveal a similar value, as illustrated in Figure 3. Figure 3 is a reasonable probability plot or commonly known as a respond normality test. It shows points or data from this research that is conducted through the CFD experiment on heat transfer rate (Q) to identify if the analyzed regression in this research is normally distributed or not. The points are located close to the diagonal line. Thus, the residual values are normally distributed.

![Figure 4. Normal probability plot of heat transfer rate (Q) response](image)

Figure 5 is a contour plot chart created using Minitab 19 software. This figure shows the RSM that identifies the effect of variables, including the number of tubes, flow, and nanoparticle volume fraction, toward the heat transfer (Q) rate. The contour plot reveals the maximum condition with color ranges that inform the optimum point location of the heat transfer rate (Q).
response. Each of the colors shows the amount of response. As clearly depicted by Figure 5, the heat transfer rate (Q) increases if their nanofluid flow, nanoparticle volume fraction, and tube number variation in the heat exchanger also rise. The increasing number of tubes escalates the heat transfer rate since it enlarges the surface area until it reaches the optimum points of heat transfer [19].

![Contour Plots of Heat Transfer](image)

**Figure 5.** Surface characteristics of heat transfer rate (Q) response in contour plot

The optimization plot is a graph that exhibits the response optimum value. In other words, it attains the highest value of heat transfer rate (Q). Figure 6 illustrates that the chart of variables optimum values toward heat transfer rate (Q) is 91.3742 Watt with a parameter of 3 tubes, 0.6 l/min flow, and MnFe$_2$O$_4$ nanoparticle volume fraction of 0.075%. This shows that the addition of tube, flow, and nanoparticle volume fraction accelerate the heat exchanger’s heat transfer characteristics [3].

![Optimization plot of heat transfer rate (Q) response](image)

**Figure 6.** Optimization plot of heat transfer rate (Q) response

4. **Conclusion**
According to an investigation of MnFe$_2$O$_4$ – H$_2$O nanofluid on heat exchanger tool using RSM and CFD methods, several conclusions are made:

- Generally, the effect of MnFe$_2$O$_4$ nanoparticle volume fraction addition toward the nanofluid thermophysical properties increases the nanofluid’s density, viscosity, and thermal conductivity. Thus, the addition of nanoparticle volume fraction is capable and feasible to be used as an application of the heat exchanging process.
• The heat transfer rate encounter an upsurge following the increase in MnFe$_2$O$_4$ nanoparticle volume fraction on nanofluid, an increase of cold fluid flow in the heat exchanger, and an increase in the number of tubes, as it enlarges the tube surface area.
• The optimum value of the heat transfer rate of 91.3742 Watt is discovered at the MnFe$_2$O$_4$ nanoparticle volume fraction of 0.075 % with three tubes heat exchanger and nanofluid (cold fluid) flow of 0.6 l m$^{-1}$.

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