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Heat exchanger design for the production of synthesized gold nanoparticles

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Abstract – *This study aims to develop and analyze the design of heat exchangers in the production of gold nanoparticles (AuNPs) by the biosynthesis method using Sargassum horneri (SH) extract. The simple design of this heat exchanger (HE) uses the shell and tube type, the one-pass tube, and the fluids are water. These specifications pertain to the design of a heat exchanger (HE). The tube length of 4.267 m, shell diameter of 254 mm, outer tube diameter of 22.225 mm, inner tube diameter of 21.184 mm, and wall thickness of 2.1082 mm describe the physical dimensions of the tubes in the heat exchanger. The pitch tube of 31.75 mm refers to the distance between the centers of adjacent tubes in the heat exchanger. Based on manual calculations using Microsoft Excel, the results show that this design has laminar flow as indicated by the Reynolds value. In addition, the HE designs has an effectiveness value of 98.98% with an NTU value of 11.50. In this study, the HE designs results have a high effectiveness value, so it can be considered effective for use in producing gold nanoparticles with SH extract. Therefore, this HE designs analysis can be used as a learning medium in the HE designs process, the operating mechanism, and the performance analysis of the HE.*

***Keywords**: Reynolds number, Shell and tube, Specific heat capacity, Sargassum Horneri.*
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I. Introduction

The heat exchanger (HE) is a device that transfers thermal energy, especially heat, between two streams at different temperatures. It is widely used in industrial processes as an integral part of the process or for heat recovery. Heat exchangers are essential components in processing, power production, power generation, transportation, refrigeration, electronics, chemical or food industries, and manufacturing [1-2].

One of the existing heat exchanger types is shell and tube. The shell and tube-type heat exchangers were used in many applications. As its name suggests, this type consists of a large cylindrical reservoir (shell) at high pressure and a bundle of tubes inside it. This exchanger utilizes two fluids, where one fluid is permitted to flow in the tube and the other fluid flows outside the tube (in the vessel). The fluid runs through the tubes and the hot stream flows on the tubes and inside the shell [2-3].

The existence of this heat exchanger can then be utilized in the production process of nanoparticle materials, including gold nanoparticles (AuNPs). Gold nanoparticles have unique optical, electronic, and thermal properties that depend on their size and shape, making them useful in a variety of fields, such as biomedicine, electronics, and catalysis. Due to their small size, gold nanoparticles exhibit different properties than bulk gold and can be used to create new materials with specific desired properties. Their biocompatibility and stability make them particularly attractive for use in medical applications, such as imaging and drug delivery [4].

Gold nanoparticles are getting more attention because of their excellent plasmonic properties, ease to synthesize, ability to functionalize with different materials for the desired purpose, low toxicity, high biocompatibility, and easy access to their nano dimensions [5].

Based on these advantages, gold nanoparticles are widely used as catalysts [6–8], biosensors [9-10], X-ray imaging [11], drug delivery [12], bioelectric devices [13], and so on. Currently, many researchers have developed gold nanoparticle synthesis. There are various techniques for carrying out the synthesis of AuNPs by dividing them into chemical, physical, and biological techniques [14]. The use of biological techniques to synthesize gold nanoparticles using plant species is a green and eco-friendly alternative to traditional chemical methods. This approach has the advantage of being less hazardous, as it reduces or eliminates the use of toxic chemicals [15].

Several studies have carried out the biosynthesis of gold nanoparticles using Citrus limetta Risso peels [16], Tecoma capensis [17], Ceiba pentandra leaves [18], Punica granatum peels [19] Gracilaria crassa leaves [15], Sargassum horneri [7], Dittrichia viscosa [20], Annona muricata leaves [21], Galaxaura elongata [21], Musa acuminata colla flowers [22], Persea americana fruit peel [23], etc.

The extracellular biosynthesis of gold nanoparticles using plant extracts or whole plants offers several advantages over other methods of nanoparticle synthesis. The ability to control the size, shape, and dispersion of the nanoparticles is important for optimizing their properties and applications.The plants used can also be increased for the large-scale synthesis of nanoparticle materials [24]. Therefore, this study aims to design a heat exchanger to produce gold nanoparticles. As a model for the heat exchanger design, in this study, we use the process of producing gold nanoparticles with biological techniques or biosynthesis using *Sargassum horneri* (SH) extract which has been done before [7].

The type of heat exchanger designed in this article is the shell and tube type. The heat exchanger selection represents significant importance in the design of the heat recovery system. It is essential to design the type of heat exchanger with the maximum degree of compactness concerning process parameters such as temperature, process fluid composition, proximity to impurities, and potential operational problems [25].

The study of the specifications of a heat exchanger can provide valuable insights into the design and performance of heat exchangers on an industrial scale. It can serve as a reference for engineers and designers, who can use the information to optimize the design of heat exchangers, improve their efficiency, and address any potential performance issues.

II. Methodology

The method followed in the study is likely based on the protocol described by [7]. In the manufacture of gold nanoparticles only a few materials are needed, such as Sargassum horneri extract, ethanol, hydrogen tetrachloroaurate (III) trihydrate, $HAuCl_4.3H_2O$.

II.1. Gold Nanoparticle Synthesis

The gold nanoparticle biosynthesis process is shown in Figure 1 and the process flow diagram is shown in Figure 2. The production of gold nanoparticles begins by adding 1 mL of filtered SH extract (2 mg/mL) to a $HAuCl_4.3H_2O$ (1 M) solution, then incubating for 15 minutes at 80°C in water. After 15 minutes, the colloid tube was cooled for 5 minutes. The change in the color of the suspension to dark purple indicated the success of SH-AuNPs biosynthesis. The specific details of the procedure can be found in the study referenced in [7].

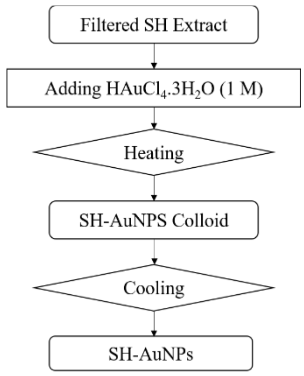

Figure 1. Schematic diagram of the gold nanoparticles biosynthesis.

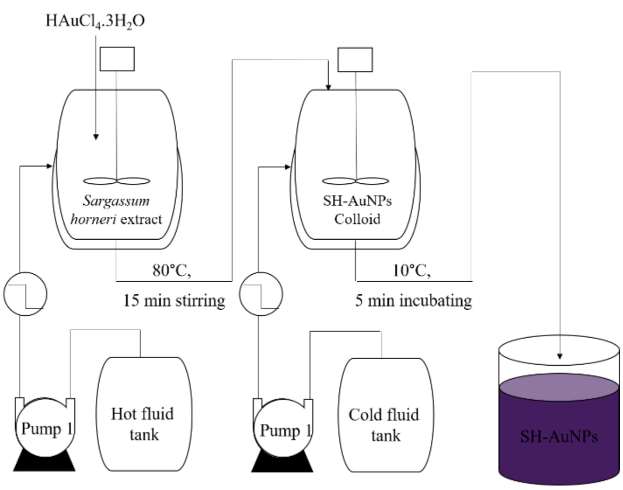

Figure 2. Process flow diagram of SH-AuNPs manufacturing.

II.2. Mathematical model on heat exchanger design

The fluid characteristics assumptions used in the heat exchanger are presented in Table 1. Some of these assumptions are used to design shell and tube-type heat exchangers. The hot fluid enters the heat exchanger at a temperature of 80°C and leaves at a temperature of 30°C, while the cold fluid enters at a temperature of 10°C and leaves at a temperature of 20°C. The incoming water flow rate for the hot fluid is 3.05 kilograms per second, and the incoming water flow rate for the cold fluid is 2.2 (kg/s). The process of collecting specification data for a thermal analysis typically involves manual calculations using mathematical equations (1-15) [26]. The heat exchange parameters are calculated according to Table 2.

Basic parameters calculation for heat exchanger shows by equation 1-4. To measure the energy transferred (Q), some variables need to be determined, as mentioned below.

$$Q_{in} = Q_{out} \\ m_c \times Cp_c \times \Delta T_c = m_h \times Cp_h \times \Delta T_h \quad (1)$$

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 (°C).

To calculate the Logarithmic mean temperature differenced (LMTD) the result has to be determined by:

$$LMTD = \frac{(T_{hi} - T_{Ci})(T_{ho} - T_{Co})}{ln\frac{(T_{hi} - T_{Ci})}{(T_{ho} - T_{Co})}} \quad (2)$$

Where, T_{hi} is temperature of the hot fluid inlet (°C), $T_{ho}$is temperature of the hot fluid outlet (°C), T_{Ci} is temperature of the cold fluid inlet (°C), and $T_{Co}$is temperature of the cold fluid outlet (°C).

To measure the heat transfer field area (A), it has to be determined using below equation.

$$A = \frac{Q}{U_d \times \Delta T_{LMTD}} \quad (3)$$

Where Q is the energy transferred (W) U_d is the overall heat transfer coefficient, and ΔT_{LMTD} is the logarithmic mean temperature difference (F).

To determine the Number of tube (Nt) use the eq. 4.

$$Nt = \frac{A}{L \times a''} \quad (4)$$

Where, A is the heat transfer area (ft^2), L is the Length of tuber, and a$''$ is the outer surface area (ft/ft^2).

Shell and Tube parameters calculation for heat exchanger shows by equation 1-4. To calculate the surface are of heat transfer in tube (a_t), it can be determined by this equation below.

$$a_{s,t} = N_{s,t}\frac{a'_{s,t}}{n} \quad (5)$$

Where, a'_t is the flow area in the tube (m^2) and n the number of passes. The result of a'_t will use to calculate mass flow rate of water in tube (G_t).

$$G_{s,t} = \frac{m_{h,c}}{a_{s,t}} \quad (6)$$

These two values were needed to calculate the Reynolds number. The Reynolds number can be determined by using Eq. 7, where μ is the dynamic viscosity of the fluid in the tube.

$$Re_{s,t} = \frac{di_{s,t} \times G_{s,t}}{\mu} \quad (7)$$

Prandtl Number (Pr) in the tube can be determined by using Eq. 8, where K is the thermal conductivity of the tube material.

$$Pr = \left(\frac{C_p \times \mu}{K}\right)^{\frac{1}{2}} \quad (8)$$

The value of Reynolds number and Prandtl number was used to determine the Nusselt number (Nu).

$$Nu = 0.023 \times {Re_{s,t}}^{0.6} \times Pr^{0.33} \quad (9)$$

Actual Overall Heat Transfer Coefficient (U_{act}) can be determined by using eq. 10.

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

Where, h_i is inside heat transfer coefficient, h_o is outside heat transfer coefficient, and Δr is wall thickness.

To measure the hot and cold fluid rate, it has to be determined using the eq. 12 as mentioned below.

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

Where, C_h is hot fluid rate (W/K), $Cp_h$is specific heat capacity (J/Kg K), and m_h is mass flow rate of hot fluid (Kg/s). This calculation also applied to calculate the cold fluid rate.

$$C_c = m_c Cp_c \tag{12}$$

When, C_c is cold fluid rate (W/K), $Cp_c$is specific heat capacity (J/Kg K), and m_c is mass flow rate of cold fluid (Kg/s). this result used as C_{min}.

Number of heat transfer units, NTU can be determined by using Eq. 13.

$$NTU = \frac{U \times A}{C_{min}} \tag{13}$$

Heat exchanger effectiveness, ε can be determined by using Eq. 14.

$$\varepsilon = \frac{Q_{act}}{Q_{max}} \times 100\% \tag{14}$$

$$Q_{max} = C_{min}(T_{hi} - T_{ci}) \tag{15}$$

Q_{act} is actual energy transferred, T_{hi} is temperature of the hot fluid inlet and T_{ci} is temperature of the cold fluid inlet.

Table 1. Physical and thermal properties of the fluid.

	Hot Fluid water at 80°C	**Cold fluid water at 10°C**
Thermal conductivity, λ ($W \cdot m^{-1} \cdot K^{-1}$)	0.671	0.585
Viscosity, v ($mm^2 \cdot s^{-1}$)	0.000339	0.00131
Heat Specific, c_p ($J \cdot kg^{-1} \cdot K^{-1}$)	4193	4195
Density, ρ ($g \cdot l^{-1}$)	971.6	999.2

III. Results and Discussion

The study used SH extract as a reducing and capping agent for the synthesis of AuNPs (gold nanoparticles) [7]. The synthesis of nanoparticles using algae or microorganisms is a fast, harmless, cost-effective, and environmentally friendly method, and by controlling the synthesis time and temperature, it is possible to reduce the size of the nanoparticles and increase their dispersion. [21].

The design of the heat exchanger for SH-AuNPs, begins with selecting cold and hot fluids. In this study, water was used as cold and hot fluids. Water is the most popular base fluid for heat transfer in various industries. This is because water has a high specific heat, widely available, and cheap [2]. Therefore, the physical and thermal properties of the two fluids are needed in designing a heat exchanger, as shown in Table 1.

The calculation results, using equations 1-15, show that the heat exchanger operates on the production of SH-AuNPs, based on the data obtained and adjusted for the fluid in the hot and cold water, as shown in Table 2. The HE designs concept calculates the temperature difference between the hot fluid temperature inlet and the cold fluid temperature inlet by looking at its effect on the output temperature [26, 27]

Based on the calculation results, the Q value in the shell and tube type HE design is 639432.5 W with the Reynolds number on the tube as 2183.98. Reynolds number in this design shows a number less than 2300, so the type of flow that occurs in the shell is laminar flow [28]. Besides that, the heat exchanger design specifications are shell and tube type, with one pass tube type, tube layout is triangular (30°), baffle type is single-segmental, and other specifications are shown in Table 2 based on calculation results using Microsoft Excel.

In addition, with the number of NTU operating conditions of 31.79, the effectiveness of this heat exchanger design is high when the hot fluid inlet temperature is 80°C, and the outlet temperature is 30°C with the cold fluid inlet temperature is 10°C, and the outlet temperature is 20°C. The effectiveness of a heat exchanger (HE) can be determined by dividing the actual heat transfer rate by the maximum possible heat transfer rate as shown in Eq. 15, and the result of this heat exchanger effectiveness is 98.98%. Therefore, the results of this analysis provide information that is expected to help optimize the modeling of shell and tube type heat exchangers in producing gold nanoparticles with *Sargassum horneri* extract.

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

Description	**Type/value**
Type of heat exchanger	Shell and tube
Tube type	One pass
Water inlet temperature (°C) (hot fluid)	80
Water outlet temperature (°C) (hot fluid)	30
Water inlet temperature (°C) (cold fluid)	10
Water outlet temperature (°C) (cold fluid)	20
Tube outside diameter, OD (mm)	22.225
Tube inner diameter, ID (mm)	21.184
Pitch tube (mm)	31.75
Length (m)	4.267
Wall thickness (mm)	2.1082
Total tube number, N	495
Total Heat Transfer Surface Area in Tube (m^2)	0.2978
Mass Flow Rate of Fluid in Tube ($kg/m^2.s$)	34.95
Reynold Number in Tube	2183.98
Prandtl Number in Tube	2.118
Tube layout	Triangular
Shell inner diameter, Ds (mm)	254
Total Heat Transfer Surface Area in shell (m^2)	0.03136
Mass Flow Rate of Fluid in shell ($kg/m^2.s$)	70.15
Reynold Number in Shell	1059259.704
Prandtl Number in Shell	9.394
Nusselt Number in Shell	4370.234
Baffle type	Single-segmental
Baffle spacing, B (mm)	56
Initial Heat Transfer Rate (W)	639432.5
Logarithmic Mean Temperature Difference (°C)	24.8534
Area of Heat Transfer (m^2)	147.545
Water mass flow rate in tube (kg/s)	3.05
Water mass flow rate in shell (kg/s)	2.2
Water heat rate in tube (W/K)	11000
Water heat rate in shell (W/K)	7920
Number of Transfer Unit	11.50
HE Effectiveness (%)	98.98

IV. Conclusion

In conclusion, the design of HE with shell and tube and one pass tube type has several specifications, These specifications are important parameters that affect the performance of the heat exchanger such as length is 4.267 m, inner tube diameter is 21.184 mm, tube outside diameter is 22.225 mm, wall thickness is 2.1082 mm, pitch tube is 31.75 mm, inner shell diameter is 254 mm, and the total tube number is 495. Based on the calculations performed through Microsoft Excel, the appropriate heat exchanger design results are laminar flow type, with an effectiveness of 98.98% and an NTU of 11.50.

Although the HE effectiveness value is high (98.98%) without calculating the fouling factor, the analysis result on this heat exchanger design can provide an initial reference in optimizing the HE models with shell and tube type, and the base fluid is water for producing gold nanoparticles.

Declaration

- The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.
- The authors declare that this article has not been published before and is not in the process of being published in any other journal.
- The authors confirmed that the paper was free of plagiarism.

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