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Shell and tube heat exchanger design for production graphene oxide nanoparticles from agricultural waste

Diah Indriati[1], Asep Bayu Dani Nandiyanto[2*], Meli Fiandini[3], Risti Ragadhita[4], Teguh Kurniawan[5]
[1,2,3,4] Chemistry Department, Universitas Pendidikan Indonesia, Bandung, Indonesia
[5] Chemical Engineering Department, Universitas Ageng Tirtayasa, Indonesia

*Corresponding author E-mail: nandiyanto@upi.edu

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Abstract

Heat exchangers are used to transfer heat energy, using fluids or gases, both hot and cold, from one area to another due to temperature differences. Almost all agricultural wastes serve as carbon products which are essential to produce graphene oxide, it is very possible to get graphene oxide by synthesizing it from agricultural waste which is expected to reduce the amount of waste on the earth. After carrying out the synthesis, it is necessary to test the characterization of the resulting product. The characterization stage requires a sintering process (20ºC to 98ºC) until the product is completely solidified. This research aims to design a heat exchanger that is highly effective in assisting the sintering process. For the design to be well-directed, several things must be done, such as calculating the main components (shell and tube) and designing a heat exchanger. Based on the TEMA standard and the use of simple calculations that refer to the attached calculation formula using Ms. Excel, hot and cold fluids used in this heat exchanger design are ethylene glycol and water. The length of the shell and tube is 5 m, the inner and outer shell diameters are 254 mm and 279.4 mm; the inner and outer tube diameters are respectively 22.09 mm and 25.40 mm. The calculation results show an excellent design effectiveness value of 86.14%. There is a comparison with previous studies using different fluids, when compared to this study it gives a higher effectiveness value.

Keywords: Heat Exchanger, Shell and Tube, Ethylene Glycol-Water, Graphene Oxide Nanoparticles, Agricultural Waste

1. Introduction

The heat exchanger changes the temperature and phase of a fluid type; this process utilizes the heat transfer of high-temperature fluids to low-temperature. In the design process of the shell and tube, the heat exchanger functions to find out what factors influence the size of the design itself. The shell and tube form is considered to have many advantages in terms of fabrication, cost, and performance [1]. Shell and tube heat exchangers (STHEs) are the most widely used heat exchangers in the industry due to their relatively simple manufacture [2], [3]. A heat pipe (HP) is a simple device for transferring large amounts of heat from a heat source to a cold environment through an enclosed space; it is efficient and does not consume much external energy [4], [5]. This pipe has the basic working principle of a continuous heating process and a condensation process for the liquid filled in it; therefore, the fluid's thermophysical properties significantly influence the pipe's performance [4], [6].

Nanofluids consist of a base fluid and particles or sheets of nanometer dimensions. It is believed that nanoparticles can form Van der Waals forces whose name has a high tendency to form a fouling layer resulting in thermal resistance for a long time with high loads [7], [8]. Nanofluid stabilization requires different physical and chemical treatments [4], [5], [7], [9].

Graphene is a two-dimensional nanomaterial that has heat-limiting and heat-locking mechanisms that differ significantly from one-dimensional zero-dimensional nanoparticles [4], [10], [11]. There is still a need for studies on the effect of GO on PHP performance; therefore, in this study, GO nanofluid is used as a working fluid in PHP. In previous studies, the synthesis of graphene oxide from agricultural waste has been carried out (such as orange peels, bagasse, and rice husks) [12]. Almost all agricultural wastes serve as carbon products which are essential to produce graphene oxide. The topic taken in this study is the design of a heat exchanger for synthesizing graphene oxide from agricultural waste.

2. Research method

2.1. Preparation of agro-wastes powder

The agro-waste used is the part that has a lot of fiber. First, the waste is washed clean using tap water, then rinsed using distilled water. The waste is dried and ground to a fine powder. This preparation acts as a carbon source for graphene oxide synthesis [13].

2.2. Synthesis/fabrication of graphene oxide (GO)

GO synthesis was carried out using the Hummers method. Mixing was carried out between agro-waste powder, 95 – 97% sulfuric acid solution, and 30% sodium nitrate powder until it became homogeneous with a ratio of 9:1 (*v/v*) using mechanical stirrer. Potassium permanganate is added slowly, then stirred until an oxidation reaction occurs (20ºC). The mixing results were diluted with distilled water, hydrogen peroxide was added, and (98ºC). Then wait for it to separate between the solid and liquid phases. The liquid phase was discarded and take the solid paste phase. For characterization, the paste obtained was dried by the sintering process using 150ºC (GO150) [14], [15], Then as shown in Figure 1.

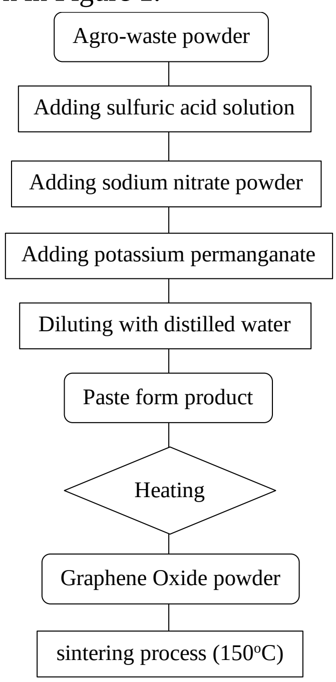


Figure 1. Workflow of GO nanoparticle fabrication

2.3. Mathematical models for HE design

Ethylene glycol and water are used as hot and cold fluids. The data assumptions used to design the shell and tube heat exchanger are listed in table 1. Data collection refers to the standard Tubular Exchanger Manufacturers Association (TEMA), which is used as a design reference and uses Ms. Excel for analysis of simple thermal calculations as shown in the equation. 1-19 [16].

The calculation equation is divided into several parts, namely: Basic parameters (Q; LMTD; A; N; and shell diameter), Tube parameters (a_t; G_t; Re_t; Pr_t; Nu_t; and h_i), Shell parameters (a_s; G_s; de; Re_s; Pr_s; Nu_s; and h_o), shell and tube parameter (U_{act}), Heat rate parameters (C_h and C_c), Effectiveness parameters (ε; NTU; Q_{max}; and Rf). Not all calculations need to be done, in the TEMA standard book there are several parameter values assuming the desired size variation.

The energy transferred (*Q*) was measured by using equation 1.

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

where, *Q* = Energy transferred (*W*)
m = Mass flow rate fluid (*kg/s*)
Cp = Specific heat (*J/kg.K*)
ΔT = Fluid temperature difference (^oC)

The Logarithmic Mean Temperature Difference (*LMTD*) was measured by using equation 2.

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

where, T_{hi} = Temperature hot fluid inlet (°C)
T_{ho} = Temperature hot fluid outlet (°C)
T_{Ci} = Temperature cold fluid inlet (°C)
T_{Co} = Temperature cold fluid outlet (°C)

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

$$A = \frac{Q}{(U \times LMTD)} \tag{3}$$

where, *A* = Heat transfet field area (m^2)
U = Heat transfer coefficient ($W/m^2\,^oC$)
LMTD = Logarithmic mean temperature difference (°C)

The number of tube (*N*) was measured by using equation 4.

$$N_t = \frac{A}{(L \times a'')} \tag{4}$$

where, *N* = Number of tube
L = Length of tube (*m*)
a'' = Outer surface area (m/m^2)

The shell diameter (D_s) was measured by using equation 5.

$$D_s = 0,63\left(\frac{\sqrt{\frac{CL}{CTP} \times A \times PR^2 \times D_o}}{l}\right)^{\frac{1}{2}} \quad (5)$$

where, D_s = Shell diameter (*m*)

D_o = Tube diameter (*m*)

CTP = If, one tube pass (0,93) ; two tube pass (0,90) ; three tube pass (0,85)

CL = If, 90° and 45° (1,00) ; 30° and 60° (0,87)

P,R = Correction factor $R = \frac{T_{hi}-T_{ho}}{T_{Co}-T_{Ci}}$; $P = \frac{T_{Co}-T_{Ci}}{T_{hi}-T_{ho}}$

The total heat transfer surface area in tube (a_t) was measured by using equation 6. Similar formula is used in shell calculations (a_s).

$$a_t = N\frac{a'_t}{n} \quad (6)$$

where, a'_t = Flow area tube (m^2)

n = Number of passes

The mass flow rate of water in tube (G_t) was measured by using equation 7. Similar formula is used in shell calculations (G_s).

$$G_t = \frac{m_h}{a_t} \quad (7)$$

where, m_h = Mass flow hot liquid tube (kg/m^2s)

G_t = Mass flow water in tube (kg/m^2s)

The Reynolds number in tube (Re_t) was measured by using equation 8. Similar formula is used in shell calculations (Re_s).

$$Re_t = \frac{di_t \times G_t}{\mu} \quad (8)$$

where, di_t = Inner tube diameter (*m*)

μ = Dynamic viscosity fluid in tube (kg/ms)

The Prandtl Number in tube (Pr_t) was measured by using equation 9. Similar formula is used in shell calculations (Pr_s).

$$Pr_t = \left(\frac{C_p \times \mu}{K}\right)^{\frac{1}{2}} \quad (9)$$

where, K = Thermal conductivity of the tube material (W/m^oC)

The Nusselt number in tube (Nu_t) was measured by using equation 10. Similar formula is used in shell calculations (Re_s)

$$Nu_t = 0.023 \times Re_t^{0.6} \times Pr_t^{0.33} \quad (10)$$

The heat transfer coefficient in tube (h_i) was measured by using equation 11.

$$h_i = \frac{N_u \times K}{di_t} \quad (11)$$

The equivalent diameter in shell (d_e) was measured by using equation 12.

$$d_e = \frac{4\left(\frac{Pt}{2} \times 0.87Pt - \frac{1}{2}\pi\frac{do_t}{4}\right)}{\frac{1}{2}\pi \times do_t} \quad (12)$$

where, P_t = Tube pitch $(1.25 \times d_o)$ (m)

π = 3.14

do_t = Outer tube diameter (m)

The convection heat transfer coefficient in shell (h_o) was measured by using equation 13.

$$h_o = \frac{Nu \times K}{de} \quad (13)$$

The overall heat transfer coefficient (U_{act}) was measured by using equation 14.

$$U_a = \frac{1}{\frac{1}{h_i} + \frac{\Delta r}{K} + \frac{1}{h_o}} \quad (14)$$

where, Δr = Wall thickness (m)

The hot fluid rate (C_h) was measured by using equation 15. A similar formula is used for cold fluid rate and the result used as C_{min}.

$$C_h = m_h \times Cp_h \quad (15)$$

where, Cp_h = Specific heat capacity (J/kgK)

C_h = Hot fluid rate (W/K)

The heat exchanger effectiveness (ε) was measured by using equation 16.

$$\varepsilon = \frac{Q_{act}}{Q_{max}} \times 100\% \quad (16)$$

where, Q_{act} = Actual energy transferred

The number of heat transfer units (NTU) was measured by using equation 17.

$$NTU = \frac{U \times A}{C_{min}} \quad (17)$$

The energy transferred maximal (Q_{max}) was measured by using equation 18.

$$Q_{max} = C_{min}(T_{hi} - T_{ci}) \quad (18)$$

The convection heat transfer coefficient in shell (Rf) was measured by using equation 19.

$$Rf = \frac{U_a - U_{act}}{U_a \times U_{act}} \quad (19)$$

where, U_{act} = Actual overall heat transfer coefficient ($W/m^2\,^oC$)

Table 1. Physical and thermal properties of the fluid

Properties		Hot Fluid at 98ºC [17]	Cold Fluid at 20ºC [17]
		Ethylene Glycol	Water
Density ρ	(kg/m^3)	1117	997,7
Viscosity v	($kg/m.s$)	0,0161	0,00098
Thermal conductivity λ	($W/m.K$)	0,252	0,604
Heat specific c_p	($J/kg.K$)	2400	4179

3. Results and discussion

The law of the conservation of energy states that energy cannot be destroyed. Energy changes form from one form to another. Energy/heat can move in three ways: radiation, conduction, and flow. In industry, many production processes involve heat exchange, such as boilers, superheaters, oil coolers, condensers, Etc. Heat exchangers are prioritized to exchange the energy of two fluids with two different temperatures. Energy exchange can occur through a field separating the two fluids or by direct contact (fluid mixing). Exchanged energy/heat will cause a change in fluid temperature (sensible heat) or sometimes a phase change (latent heat). The transfer rate is affected by: fluid flow velocity, fluid temperature difference, surface properties of the plane separating the two fluids, and physical properties (viscosity, thermal conductivity, specific case capacity, Etc.) [1].

The standard used in heat exchangers is TEMA (Tubular Exchanger Manufacturers Association) from America. TEMA discusses the types of heat exchangers, performance calculation methods and design strengths, the term heat exchanger parts (parts), and the basis for application ownership in industrial processes. This standard is used as a reference to minimize negative impacts on users, such as the danger of damage, operational failure, security, and estimated costs used. Based on TEMA, the types of heat exchangers are divided into two groups: Class R, for heavy work applications such as heavy oil and chemical industries, and Class C, for general use with small size and heat transfer capacity. This study's shell and tube heat exchanger design chosen is shown in Figure 2. This tool is used for the evaporation or boiling process of fluids outside the pipe; this type is also often called the boiler type [18].

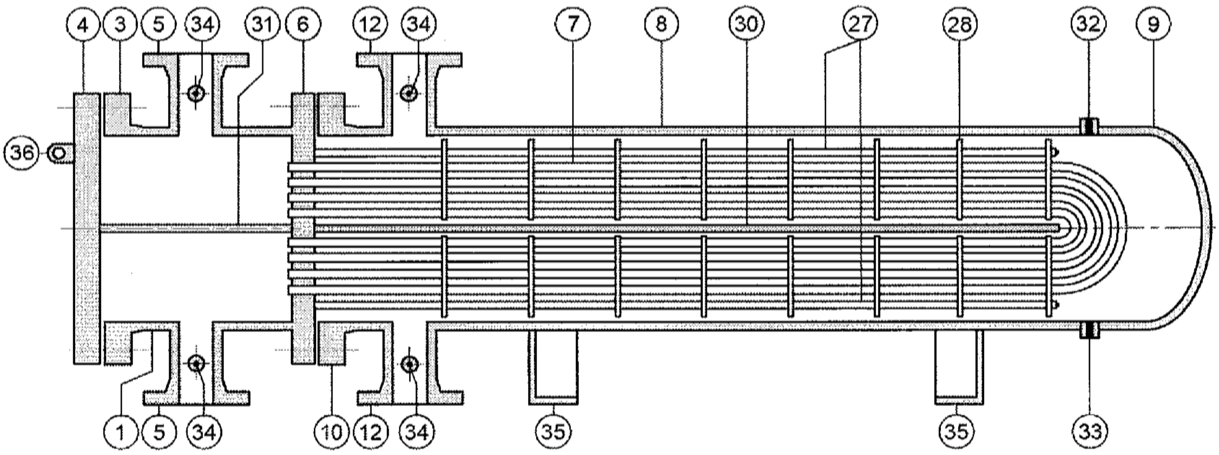
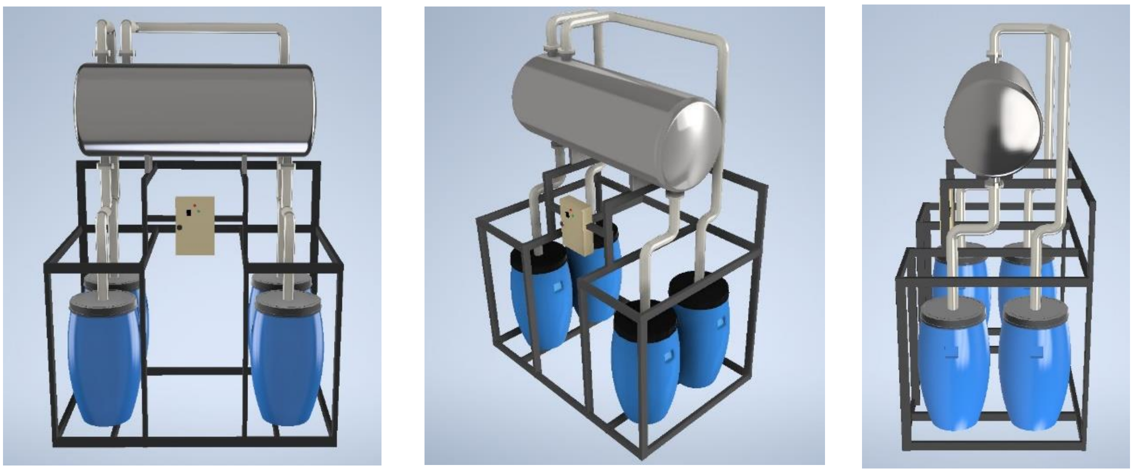


Figure 2. Illustrates design of heat exchanger

Information numbers on the picture:

1	Stationary Head-Channel	27	Tie-rods and Spacers
3	Stationary Head Flange-Channel or Bonnet	28	Transverse Baffles or Support Plates
4	Channel Cover	30	Longitudinal Baffle
5	Stationary Head Nozzle	31	Pass Partition
6	Stationary Tubesheet	32	Vent Connection
7	Tubes	33	Drain Connection
8	Shell	34	Instrument Connection
9	Shell Cover	35	Support Saddle
10	Shell Flange-Stationary Head End	36	Lifting Lug
12	Shell Nozzle		

The shell is one of the two most essential components in heat exchanger design, located on the outermost covering of the tube. In this design, the shell flows water fluid. The shell material used is ASTM A106 Carbon Steel Pipe Seamless with the advantages of thick walls, making it resistant to high temperatures; no welded joints, which means it is more resistant to corrosion and has an excellent cylindrical shape. The tube is the part that flows the ethylene glycol fluid. The tube is located on the inside of the shell. The selected tube material is Stainless SS304 with the advantages of easy to form (weldable), rust resistant, good quality for deep drawing use, able to absorb and conduct heat well, has a long-term value greater than other metals, and able to withstand extreme temperature variations and high durability. The value specifications used in the shell and tube design are listed in table 2. Also, in table 2, the fluid values' specifications are written. The author tries to illustrate a miniature framework of a small heat exchanger designed on a small scale, shown in figure 3.



(a) (b) (c)

Figure 3. Miniature illustration of heat exchanger design on a simple scale

The heat exchanger design in this study uses a single tube pass (shell and tube) type. Placement of the tube in the shell uses a square position (45^o) so that the baffle type is single-segmental. The production of graphene nanoparticles requires heating from room temperature 20^{o}C to 98^{o}C. The use of ethylene glycol and water provides the possibility to increase heating effectiveness both in terms of energy and time. In Nandiyanto's research (2022) [16], the design of the heat exchanger used to produce carbon particles with the size specifications listed in table 3, this research can be compared because it has almost the same goal, namely to produce carbon products, this research produces a value The effectiveness is not good because the fluid used has characteristics that are not quite right when used in a heat exchanger with a temperature difference that is not that far. A small effectiveness value is also produced because the Q value used with the heat exchange output is not very profitable resulting in a low effectiveness value. Whereas for this study using ethylene glycol and water fluids in the use of heat exchangers so that in the calculations it produces a Q value that is quite profitable to change the temperature according to design. Values and size specifications refer to the standards used (TEMA). Processing is carried out using calculations 1-19 with Ms. Excel's assistance, and the results are obtained in table 2. After going through all the costs, the practical value of the heat exchanger was 86.145%. This figure is relatively high in world industry, and it can be assumed that the design is optimal enough to support the macro-scale graphene oxide production process.

Table 2. Specification of heat exchanger based on TEMA standard and the calculation results

Description	**Type / Value**	
Type of heat exchanger	Single tube pass	Shell and tube
Ethylene Glycol inlet temperature in tube	98 ^oC	
Ethylene Glycol outlet temperature in tube	20 ^oC	
Water inlet temperature in shell	20 ^oC	
Water outlet temperature in shell	100 ^oC	
Tube outer diameter	25.400 mm	
Tube inner diameter	22.090 mm	
Length	±5000 mm	
Wall thickness	1.650 mm	
Pitch tube	27.780 mm	
Total tube number	433.250	
Total Heat Transfer Surface Area in Tube	0.0830 m^2	
Mass Flow Rate of Fluid in Tube	36.127 kg/m^2. s	
Reynold Number in Tube	49.586	
Prandtl Number in Tube	153.333	
Tube layout	Square	
Shell outer diameter	279.400 mm	
Shell inner diameter	254 mm	
Total Heat Transfer Surface Area in shell	0.0312 m^2	
Mass Flow Rate of Fluid in shell	64.050 kg/m^2.s	
Reynold Number in Shell	1688504.174	
Prandtl Number in Shell	6.780	
Nusselt Number in Shell	5570.190	
Baffle type	Single-segmental	
Baffle spacing	55.88 mm	
Initial Heat Transfer Rate	651924 W	
Logarithmic Mean Temperature Difference	78.995	
Area of Heat Transfer	383.3324 m^2	
Ethylene Glycol flow rate in tube	3 kg/s	
Water flow rate in shell	2 kg/s	
Ethylene Glycol heat rate in tube	7200 W/K	
Water heat rate in shell	8358 W/K	
HE Effectiveness	86.145 %	
Number of Transfer Unit	14.5139	

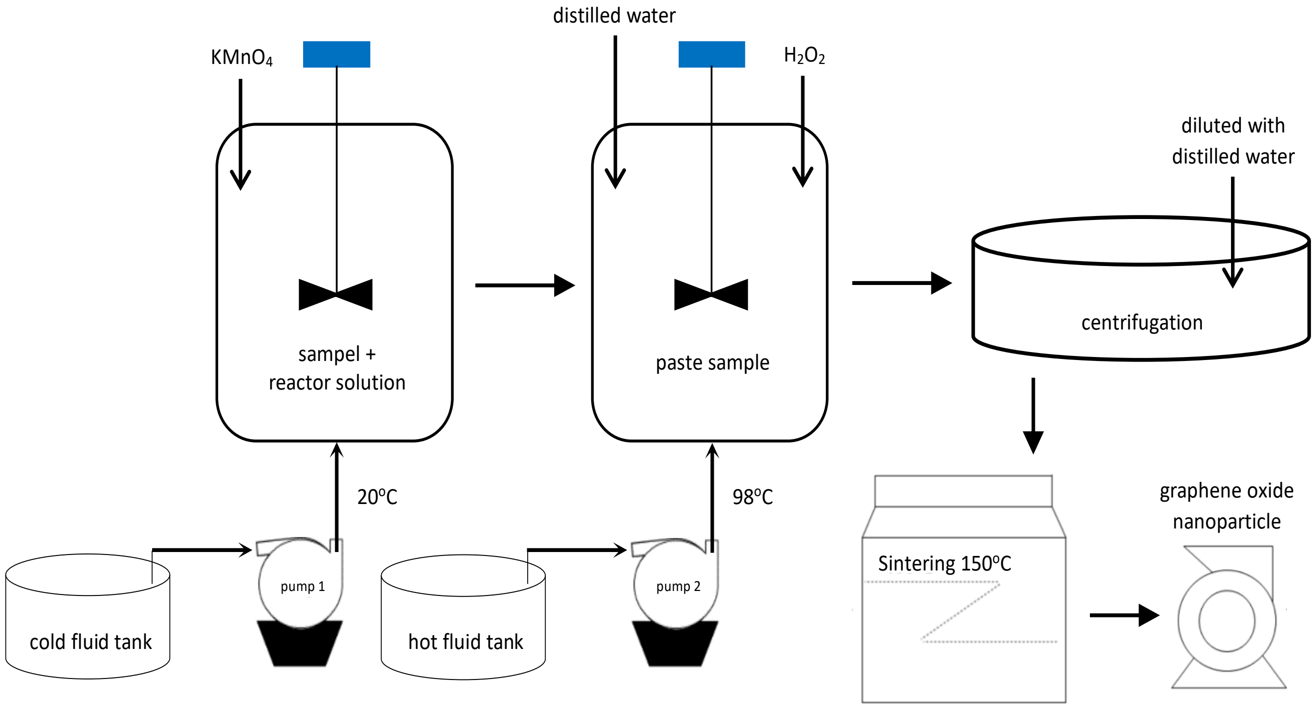


Figure 4. PFD on the synthesis of Graphene Oxide-nanoparticles

Table 3. Comparison of heat exchanger specifications designed in previous studies

Description	**Specification of Shell and Tube Heat Exchanger**	
	(Nandiyanto, 2022) [16]	This Paper
Shell Length	1930 mm	±5000 mm
Shell Diameter	203 mm	279.400 mm
Outer Tube Diameter	22 mm	25.400 mm
Thickness	1.6 mm	1.650 mm
Fluida panas	Hot oil (270°C)	Ethylene Glycol (98°C)
Fluida dingin	Cold oil (180°C)	Water (20°C)
Nilai efektivitas	44.44%	86.145 %

4. Conclusions

- The type of heat exchanger is shell and tube.
- The material suggested in this research for tube making is Stainless SS304, and the material for making the shell is ASTM A106 Seamless Carbon Steel Pipe.
- The cold fluid used is water, and the hot fluid used is ethylene glycol.
- Calculations are performed using a simple application Ms. Excel regarding formulas and values to the TEMA standard.
- Estimated design numbers in this design are outer shell diameter of 279.4 mm, inner shell diameter of 254 mm, inner tube diameter of 22.098 mm, outer tube diameter of 25.4 mm, the wall thickness of 1.6510 mm, tube length of 4.8768 mm, and tube pitch of 27.78 mm.
- The heat transfer rate produced by design is 651924 W.
- Design effectiveness based on the TEMA standard as the primary reference reaches 86.145 %. This figure is quite good mathematically and can be considered for direct application on a macro scale for the graphene oxide synthesis industry from agricultural waste.

Declaration of competing interest

There are no financial or non-financial interests and competition in any material discussed in this paper.

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