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Design Shell and Tube of Heat Exchanger for the Cooling Process of Lubricant Oil

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Abstract (English)
This study aims to analyze and develop a heat exchanger (HE) application for the cooling process of lubricant oil. This shell and tube- type HE is designed simply, but it still refers to the existing design rules. The design of a shell and tube type HE with one pass shell and tube with turbulence flow. The specifications of the HE apparatus are shell length of 1.06 m in shell length, 0.203 m in shell diameter, 0.01656 m in inner tube diameter, 0.01905 m in outer tube diameter, and 0.016 m in thickness. The results showed an effectiveness value of 27.5% . This informed that although the shell and tube-typed HE does not meet the requirements and standards for being set in industrial applications, it can be useful as a learning method regarding the design process, working mechanism, and analyzing the performance of the HE.

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Heat Exchanger, Performance, Shell and Tube

Abstrak (Indonesia)
Penelitian ini bertujuan untuk menganalisis dan mengembangkan aplikasi heat exchanger (HE) untuk proses pendinginan minyak pelumas. HE tipe shell and tube ini didesain sederhana, namun tetap mengacu pada kaidah desain yang ada. Desain shell and tube tipe HE dengan one pass shell and tube dengan aliran turbulensi. Spesifikasi alat HE adalah panjang cangkang dengan panjang cangkang 1,06 m, diameter cangkang 0,203 m, diameter tabung dalam 0,01656 m, diameter tabung luar 0,01905 m, dan tebal 0,016 m. Hasil penelitian menunjukkan nilai efektivitas sebesar 27,5%. Hal ini menginformasikan bahwa meskipun HE tipe shell and tube belum memenuhi persyaratan dan standar yang ditetapkan dalam aplikasi industri, namun dapat berguna sebagai metode pembelajaran mengenai proses desain, mekanisme kerja, dan analisis kinerja HE.

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Introduction

The heat exchanger (HE) is a heat transfer device that transfers heat energy from one medium to another. A HE is a device that transfers heat from one fluid to another. To reach the ideal thermal in the heat transfer process, two fluids with different temperatures will be separated on the cold side or hot side by a separating medium. The advantage of a HE is that it has high thermal efficiency and is inexpensive. The HE is made up of multiple thin plates that are held together by a frame that runs parallel to the plates. (Ibrahim et al., 2019). HE plays an important role in the operation of many systems, such as power plants, nuclear reactors (Oh et al., 2010), industrial processes (Ma et al., 2016), and as fuel (Magistri et al., 2006 & Dagdas A., 2007). HE plays a significant part in effective energy use since it is utilized in a variety of applications. HE design development, reliability, and maintenance are continually required to increase whole system performance (Abou Elmaaty et al., 2017). HE has many different types, such as; wire on tube Islamoglu., 2003), crossflow type plate HE (Saman and Alizadeh., 2002), type plate HE (Luan et al., 2008), type ground HE (Saeidi et al., 2018), and plate-fin HE using a new type of vortex generators (Samadifar and Toghraie., 2018). Oil cooling refers to a process where oil is used as a coolant. Oil heated by a cooling object and then usually passes through a unit coolers such as oil coolers, usually types radiator, or less commonly a water jacket (Gaos,2008). The cooled oil flows back inside hot object to cool down continuous. The oil cooler is an exchange tool heat which functions to cool the oil using a cooling fluid, namely water. In the oil cooler there are two cycles interrelated, namely the cold fluid cycle (water) and the hot fluid cycle (oil), which both in opposite directions (Counter flow). Oil as a hot fluid is in in the Fins will release heat to water as a cold fluid located outside fin. From the above, it can be seen that is the rate of heat transfer from oil to water through the fin wall is greatly affected by the presence of dirt from the water carried sticking to the pipe is called fouling Therefore, the goal of this study is to develop a HE application for the cooling process of lubricant oil. This shell and tube-typed HE is designed to be simple but still refers to the existing design rules, making it useful as a learning method regarding the design process, the working mechanism, and the performance of the HE (Akhmadi & Romadhon, 2016)

Method

Mechanism of Lubricant Oil in Machine

Oil functions to lubricate all the smallest parts of the components in our engine, especially all components that move against each other, so that erosion does not occur due to objects rubbing against each other, at least the coefficient of friction can be kept as small as possible. The role of this oil is very important, apart from reducing engine heat, this oil also functions to reduce sound/noise, imagine if there was not enough engine oil, various sounds from the engine would definitely appear (Wang et.al., 2017)

Oil is like blood in the body, so oil also needs a pump like the body needs a heart to pump blood throughout the body. The role of the oil pump in the engine is also very important, what good is even good oil if it can't flow to the end of our engine components. After the oil is pumped to flow to all components, it is first passed through the oil filter, this component will ensure that the oil that will become the friction bearing is clean from grams of residual engine friction or other foreign objects. After leaving the oil filter, it will flow into the channels or gaps in the engine components and before returning to the oil pump, there are several types of engines that have an oil cooler. Here the oil will be cooled first before flowing back into the engine crankcase and then into the chamber. The oil pump then flows back into the engine. Remember that engine efficiency is inversely related to engine temperature (the lower the engine temperature, the higher the engine efficiency), indeed no engine has 100% efficiency because the engine when working has a temperature. Well, oil can also reduce engine heat by cooling it before entering the engine crankcase (Septian et al., 2021)

Mathematical models for Designing HE

Data processing on the HE is done using Microsoft Excel by triggering the heat transfer that occurs in the HE. Table 1 shows the heat exchange parameters that were calculated. Several data assumptions are used in the process of obtaining the characteristics for a shell and tube HE, including shell length of 1.06 m in shell length, 0.203 m in shell diameter, 0.01656 m in inner tube diameter, 0.01905 m in outer tube diameter, and 0.016 m in thickness.

Table 1 HE parameter calculation

Section	Parameter	Equation	Eq.
Basic parameters	The energy transferred (Q)	$Q_c = Q_h$ $m_c \times Cp_c \times \Delta T_c = m_h \times Cp_h \times \Delta T_h$ Where, Q = the energy transferred (Wt) *m* = the mass flow rate of the fluid (Kg/s) *Cp* = the specific heat ΔT = the fluid temperature difference (°C).	(1)
	Logarithmic mean temperature differenced (LMTD)	$LMTD = \frac{(T_{hi} - Tc_i) - (T_{ho} - Tc_o)}{ln\frac{(T_{hi} - Tc_i)}{(T_{ho} - Tc_o)}}$ Where, T_{hi} = temperature of hot fluid inlet (°C) T_{ho} = temperature of hot fluid outlet (°C) Tc_i = temperature of cold fluid inlet (°C) Tc_o= temperature of cold fluid outlet (°C)	(2)
	Correction factor	$P = \frac{T_{co} - T_{ci}}{T_{hi} - T_{ci}}$ $R = \frac{T_{hi} - T_{ho}}{T_{co} - T_{ci}}$ $F = \frac{\sqrt{R^2+1}\ \ln[\frac{1-P}{1-PR}]}{(R-1)\ln\left(\frac{2-P(R+1-\sqrt{R^2+1}}{2-P(R+1+\sqrt{R^2+1}}\right)}$ Thus, the value of the temperature change is $\Delta t = F \times LMTD$	(3) (4) (5)
		Where, T_{hi} = temperature of hot fluid inlet (°C) T_{ho} = temperature of hot fluid outlet (°C) Tc_i = temperature of cold fluid inlet (°C) Tc_o= temperature of cold fluid outlet (°C) *P* = temperature efficiency of the heat exchanger *R* = ratio of the product of fluid flow in the shell with specific heat to fluid flow in the tube *F* = correction factor Δt = temperature change LMTD = Logarithmic mean temperature differenced (calculated using Eq. 2)	(6)

Section	Parameter	Equation	Eq.
	Heat Transfer Field Area (A)	$A = \frac{Q}{U \times (LTMD \times F)}$ Where, Q = the energy transferred (W) U = the overall heat transfer coefficient $LMTD$ = the logarithmic mean temperature difference.	(7)

Table 1 (Continue). Heat exchanger parameter calculation.

Section	Parameter	Equation	Eq.
Tube	Number of Tubes (N)	$Nt = \frac{A}{\pi \times D_o \times l}$ Where, N = the number of tubes A = the area of the heat transfer area (m^2), π = 3.14 D_o= tube diameter (m) l = tube diameter (m).	(8)
	Surface Area of Total Heat Transfer in Tube (a$_t$)	$a_t = N_t \frac{a'_t}{n}$ Where, 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)
		And, $a'_t = \frac{\pi}{4} \times (D_{i,t})^2$ Where, $D_{i,t}$ = inner diameter of tube	(10)
	Mass Flow Rate of Fluid in Tube (Gt)	$Gt = \frac{m_{th}}{a_t}$ Where, Gt = the mass flow of water in the tube (kg/m^{2}s) m_h = the mass flow rate of the hot fluid (Kg/s) a_t = the flow area tube (m^2	(11)
	Reynold number (Re,t)	$Re_t = \frac{di_t \times Gt}{\mu}$ Where, Re_t = the Reynolds number in tube di_t = the inner tube diameter (m),	(12)

Section	Parameter	Equation	Eq.
		Gt = the mass flow of water in the tube (m^2) μ = the dynamic viscosity (Kg/ms).	
	Prandtl Number (Pr,t)	$Pr = (\frac{C_p \times \mu}{K})^{\frac{1}{2}}$ Where, 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).	(13)
	Nusselt number (Nu,t)	$Nu = 0.023 \times {Re_t}^{0.6} \times Pr^{0.33}$ Where, Re_t = the Reynolds number in tube Pr = Prandtl number	(14)

Table 1 (Continue). Heat exchanger parameter calculation.

Section	Parameter	Equation	Eq.
	Inside coefficient (h$_i$)	$hi = \frac{Nu \times K}{d_i, t}$ Where, hi = 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).	(15)
Shell	Shell flow area (A_s)	$A_s = \frac{d_s \times C \times B}{P_t}$ Where, d_s = shell diameter (m) C = clearance (P_t-d_o) B = Baffle spacing 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) A_s = the shell flow area (m^2).	(17)
	Equivalent diameter (d_e)	$d_e = \frac{4(\frac{Pt}{2} \times 0.87\, Pt - \frac{1}{2}\pi \frac{{d_{o,t}}^2}{4})}{\frac{1}{2}\pi d_{o,t}}$ Where, P_t = tube pitch (1.25× d_o) (m) π = 3.14 $d_{o,t}$ = tube outside diameter (m).	(18)
	Reynold number (Re,s)	$Re_s = \frac{d_e \times Gs}{\mu}$	(19)

Section	Parameter	Equation	Eq.
		Re_s = Reynold number di_s = inner tube diameter (m) Gs = the mass flow of water in the shell (Kg/m^{2}s) μ = the dynamic viscosity (Kg/ms).	
	Prandtl Number (Pr,s)	$Pr = (\frac{C_p \times \mu}{K})^{\frac{1}{2}}$ Pr_s = Prandtl number Cp = specific heat capacity (kJ/kg°C) μ = dynamic fluid viscosity (Kg/ms) K = thermal conductivity (W/m°C).	(20)
	Nusselt number (Nu,s)	$Nu_s = 0.023 \times {Re_s}^{0.6} \times Pr^{0.33}$ Re_s = Reynold number Pr = Prandtl number	(21)
	Convection Heat Transfer Coefficient (hs)	$hs = \frac{Nu \times K}{d_e}$ ho = convection heat transfer coefficient (W/m^2°C) K = thermal conductivity (W/m°C) d_e = shell diameter (m).	(22)

Table 1 (Continue). Heat exchanger parameter calculation.

Section	Parameter	Equation	Eq.
Heat rate	Hot Fluid Rate (tube) (C_h)	$C_h = m_h . Cp_h$ Where, C_h = hot fluid rate (W/°C) Cp_h = specific heat capacity (J/Kg°C) m_h = mass flow rate of hot fluid (Kg/s).	(23)
	Cold Fluid Rate (shell) (C_C)	$C_C = m_c . Cp_c$ 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)	(24)
Maximum Heat Transfer Rate (Qmax)		$Qmax = C_h(T_{hi,t} - T_{ci,s})$ Q_{max} = maximum heat transfer (W) C_{min} = minimum heat capacity rate (W/°C) $T_{h,i}$ = temperature of hot fluid inlet (°C) $T_{c,i}$ = temperature of cold fluid inlet (°C).	(25)
Effectiveness	Heat Exchanger Effectiveness (ε)	$\varepsilon = \frac{Qact}{Qmax} \times 100\%$ Where, Q_{act} = actual energy transferred (W) Q_{max} = maximum heat transfer (W)	(26)

Section	Parameter	Equation	Eq.
	Number of Transfer Unit (NTU)	$NTU = \frac{U \times A}{C_{min}}$ Where, U = overall heat transfer coefficient (W/m^2°C A = heat transfer area (m^2) C_{min} = minimum heat capacity rate (W/°C).	(27)
Tube Length	Tube Length (Lt)	$Lt = \frac{NTU \times C_{min}}{U \times \pi \times do_{,t} \times Nt \times 2}$ Where Lt = tube length (m) NTU = Number of transfer unit C_{min} =Hot fluid rate (W/K) U = Overall heat transfer ($\frac{W}{m^2}K$) $do_{,t}$ = Outer tube diameter (m) *Nt* = number of tube	(28)

Result and Discussion

The assumptions regarding the fluid characteristics operating on the device are shown in Table 2. Table 3 shows the calculation results of the HE designs. Several assumptions were used to derive the HE designs specifications, while it developed a shell and tube-type HE. The assumptions used are 1.06 m in shell length, 0.203 m in shell diameter, 0.01656 m in inner tube diameter, 0.01905 m in outer tube diameter, and 0.016 m in thickness.

Table 2. Heat exchanger operating data.

Specification	Input Fluid
Tube Side (Hot Fluid)	
Fluid Material	Oil
Mass flow rate (m_{th}; kg/s)	1.5
Dynamic viscosity (μ; Kg/m.s)	6.16×10^{-4}
Inlet Temperature in tube side (T_{hi}; °C)	107
Inlet Temperature in tube side (T_{hi}; K)	380
Outlet Temperature in tube side (T_{ho}; °C)	27
Outlet Temperature in tube side (T_{ho}; K)	300
Heat Capacity (*Cp*; J/Kg.K)	2161
Thermal conductivity of fluid materials (*K*; W/m.K)	16
Tube and Shell material	Stainless SS304
Shell Side (Cold Fluid)	
Fluid Material	Water
Mass flow rate (m_{sh}; kg/s)	1.72
Dynamic viscosity (μ; Kg/m.s)	2.54×10^{-3}
Inlet Temperature in tube side (Tc_i; °C)	27
Inlet Temperature in tube side (Tc_i; K)	300
Outlet Temperature in tube side (Tc_o; °C)	45
Outlet Temperature in tube side (Tc_o; K)	318

Heat Capacity (*Cp*; J/Kg.K)	4174
Thermal conductivity of fluid materials (*K*; W/m.K)	51
Tube and Shell material	Carbon Steel ASTM A106

Table 3 HE specifications based on calculation results

No	Parameter	Results
1	**Initial Heat Transfer Rate (*Q*)**	7117.5 Watt
2	**Logarithmic Mean Temperature Difference (*LMTD*)**	10.51°C
3	**Assumed Overall Fluid Heat Coefficient of Water (U_a)**	1000 W/m^2.°C
4	**Area of Heat Transfer (*A*)**	9.09 m^2
5	**Number of Tube (*Nt*)**	70
6	***CTP***	0.9
7	***CL***	0.87
8	**Total Heat Transfer Surface Area in Tube (a_t)**	0.01099 m^2
9	**Mass Flow Rate of Water Fluid in Tube (*Gt*)**	136.487 kg/m^2.s
10	**Reynold Number in Tube (*Re, t*)**	3669.19
11	**Prandtl Number in Tube (*Pr, t*)**	9.646
12	**Nusselt Number in Tube (*Nu, t*)**	6.688
13	**Convection Heat Transfer Coefficient in the Tube (h_i)**	6461.83 W/m^2.°C
14	**Bundle Shell (*Db*)**	0.269 m
15	**Total Heat Transfer Surface Area in Shell (a_s)**	0.0280 m^2
16	**Mass Flow Rate of Water Fluid in Shell (*Gs*)**	61.4285 kg/m^2.s
17	**Equivalent Diameter (*De*)**	0.0173 m
18	**Reynold Number in Shell (*Re, t*)**	418.39
19	**Prandtl Number in Shell (*Pr, t*)**	4.559
20	**Nusselt Number in Shell (*Nu, t*)**	1.419
21	**Convection Heat Transfer Coefficient in Shell (h_o)**	356.497 W/m^2°C
22	**Actual Overall Heat Transfer Coefficient (U_{act})**	70.7058 W/m^2°C
23	**Heat Capacity Rate for Hot Fluid (C_h)**	3241 W/°C
24	**Heat Capacity Rate for Cold Fluid (C_c)**	7179.28 W/°C
25	**HE Effectiveness (s)**	27.5%
26	**Number of Transfer Unit (*NTU*)**	2.243
27	**Dirt Factor (*Df*)**	0.01314

The principle of a HE or HE is to equalize or equalize the difference between the hot fluid's inlet temperature (Thin) and the cold fluid's input temperature (Tc in), with the effects visible at the outlet temperature. The results show the Initial Heat Transfer Rate (Q) in the design of a shell and tube-type HE of 71175 W. In this design, the Reynolds number shows the value of Re > 2300, so the type of flow that occurs in the shell is turbulent flow. There are various uses for turbulent flow in industrial processes such as heating and cooling. To put it another way, most industrial

HEs use turbulent flow, which has a larger heat convection coefficient than laminar flow and consequently a better heat transfer rate (Hasanpour et al., 2014).

Based on the calculation results, the effectiveness of the HE is 27.5%. HE effectiveness is the actual heat transfer rate divided by the maximum possible heat transfer rate (San et al., 2012). The resulting effectiveness value, which measures the amount of heat carried, will be high if the temperature differences between the input and output are large. So it can also be interpreted that the effective value of the HE is directly proportional to the magnitude of the temperature difference (ΔTLMTD) (Rao et al., 2020).

Other factors that affect the HE's performance include the number and spacing of baffles in the HE's specs. A close baffle distance will increase the effectiveness of the HE as well as a small percentage of baffle cut will increase the effectiveness of the HE (Mohammadi et al., 2020). When computing the overall heat transfer coefficient, fouling is conventionally considered by using an additional thermal resistance value of Rf or the so-called “fouling factor” or “fouling resistance”. The impurity factor responsible for the decrease in the performance of the HE depends on the flow rate. Cutters can reduce overall heat transfer, so an extra surface must be provided to ensure that the required heat transfer is achieved. The standard permissible impurity factor from TEMA for fluid water is 0.0002°C. m2/W, while the value of the impurity factor in this study was 0.01314 °C.m2/W. Therefore, the shell and tube-type HE, does not meet the requirements and standards.

Conclusion

Based on the calculations that have been carried out, it can be concluded that the results of the design of a shell and tube-type HE with one pass shell and tube turbulence flow, with specifications of 1.06 m in shell length, 0.203 m in shell diameter, 0.01656 m in inner tube diameter, 0.01905 m in outer tube diameter, and 0.016 m in thickness, has an effectiveness of 27.5%. Therefore, the shell and tube type HE that has been designed does not meet the requirements and standards that have been set.

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