Numerical analysis of a modified shell and tube heat exchanger model

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Abstract: In present day shell and tube heat exchanger is the most common type heat exchanger widely used in industries, because it suites high pressure applications. The process involving stimulation consists of modeling existing and newly designed geometry and meshing the new geometry of shell and tube heat exchanger using CFD package 14.0. The objective of the project is to modify the existing heat exchanger in order to reduce the preheating time. We focus on numerical comparison of the existing design with the newly constructed geometry. Analytical data obtained for the new design is compared with the existing one. The actual design consisting of 49 U Tubes with 10mm diameter, length 1225mm and shell diameter 168mm is converted to 18 tubes with 25.4mm diameter, length 2050mm and shell diameter 273.1mm.

1. Introduction

Shell and Tube Heat Exchanger is one of the major type of heat exchangers widely used inorder to control the wide range of temp and pressures. It consists of bundles of tubes mounted inside a cylindrical shell. One fluid flows through the tube and the other flows over. The flow can be parallel, counter or cross flow. Our current topic is correlated with Shell and Tube Heat Exchanger. The work is being done at Brahmapuram Diesel Power Plant, Brahmapuram, Ernakulam. The plant produces electricity using 4 stroke 18 cylinder V-engines (Pe.4.2B V 570). The cylinders are arranged in V of 45 degrees. The power rating is about 1650hp per cylinder. Plant operates basically on diesel cycle fuels used are HSD/LSHS/LSFO. The output shaft of the diesel engine is connected to an alternator thereby producing electricity. Lube oil used is Mobilguard 440. For the engine to operate, the temperature of lube oil is to be maintained at about 90°C for that approximately 8 – 9 hours of pre-heating is been taken. Our aim is to reduce the pre-heating time in order to reduce the cost per unit of electricity.

K.Maheswaridevi and G.V Nagaman[1] made a shell and tube heat exchanger and investigated that the heat transfer rate can be increased by altering the tube material using ANSYS FLUENT TOOL 14.5. They found that the heat transfer rate has increased from 13.6W to 14W per tube by changing the tube material from brass to copper, thereby reducing the preheating time. V.Hariharan, G.Ravindra Reddy and B.Sreehari[2] have done the thermal analysis of water to oil type shell and tube heat exchanger using ANSYS FLUENT and compared the results with theoretical value. They got an error of 0.0274 in effectiveness which was almost negligible. Mohammad Irshad, Mohammad Kaushar and G Rajmohan[3] have designed a shell and tube heat exchanger with segmental baffles. The flow and temperature inside the shell and tube heat exchanger was studied using CFD package ANSYS 14.5. They investigated that the shell and tube heat exchanger with 40 degree inclination angle results in better performance than 0, 20 and 30 degrees respectively. VindhyaVasiny Prasad Dubey, RajRajat Verma, Piyush Shankar Verma and A.K Srivastava[4] have done an experimental study on the
performance analysis of shell and tube heat exchanger under the effect of varied operating conditions. They found that the effectiveness is closely related to turbulence and insulation. Out of other materials, cotton wool and the tape had given the best values of effectiveness. They observed that effectiveness is 50% at pump opening. Shravan H. Gawande et al. [5] have designed and fabricated a shell and tube heat exchanger for industrial applications. The thermal and mechanical design was computed using TEMA/ASME standards theoretically and also by using software. It was found that this proposed design was simple and less time consuming than the existing method used in different Indian industries.

1.1 Existing heat exchanger model

The existing design consists of a shell, 49 U-Tubes along with 9 baffles inside the shell. Shell is made of Carbon Steel and U-Tubes are made of Copper. Lube oil passes through the shell and steam passes through tubes. The hot steam with temperature of 170.4°C passing through copper tubes exchanges heat to the incoming lube oil passing through the shell. The incoming lube oil temperature is around 50°C. The operating temperature of lube oil is around 90°C -100°C. So the lube oil must be heated from 50°C to 90°C. The following figure depicts the 3D model of the present heat exchanger.

![3D Model of old design](image)

**Figure 1.** 3D Model of old design

1.2 Limitations of existing model

We already discussed that the source of power for generating electricity in BDPP is 4 stroke 18 cylinder V diesel engine. In order to start the engine the lube oil must be at a temperature of about 90°C to 100°C. So preheating of lube oil is necessary. It takes about 9 to 10 hours to preheat the entire quantity of lube oil by using the present heat exchanger. Because of this long preheating time plant is running at loss. Five units are there in BDPP. But now only two units are in working condition. Other units are not working because of the cost associated with the preheating of lube oil and cost of diesel.
2. Methodology

2.1 New design model

The numbers of tubes have reduced from 49 to 18. The number of baffles increases from 9 to 21. Instead of U Tubes, here we take straight tubes supported by two flanges on either sides. 18 tubes are at inlet and remaining 18 tubes at outlet. There is a dome attached on the outer side. Tubes are attached to the dome, such that steam take U turn and comes out through 18 tubes at outlet. The tube length and shell diameter have also increased accordingly.

2.1.1 Supporting calculations

| Parameter                  | Value          |
|----------------------------|----------------|
| Tube inside diameter       | 0.834 inch     |
| Tube outside diameter      | 1 inch         |
| Length of tube             | 12 ft          |
| Ti                         | 30°C           |
| To                         | 90°C           |
| Ti                         | 158.83°C       |
| Mass flow rate of steam, m₀| 2000 kg/hr     |
|                             | = 0.555 kg/s   |
|                             | = 4409.22 lbm/h|
| Lube oil                   | m₀ = 3600 l/h  |
|                             | = 3600*(10^-3)*991 kg/hr |
|                             | = 0.991 kg/s   |
|                             | = 7865.17 lbm/hr|

At 30°C , \( C_p = 1922 \, \text{J/kg k} \)

90°C , \( C_{p₀} = 2175 \, \text{J/kg k} \)

Since, \( C_{p₀} = (C_p + C_{p₀})/2 = 2048.5 \, \text{J/kg k} \)

\[ Q = m₀ \times C_{p₀} \times ΔT₀ \]

\[ = 7865.17 \times 0.4893 \times 108 \]

\[ = 415630.189 \, \text{btu/h} \]

\[ Q = mₐ \times C_p \times ΔTₐ \]

\[ 415630.189 = 4409.22 \times 0.9986 \times ΔTₐ \]

\[ ΔTₐ = 94.396 \, °F \]

Since, \( t₀ = 317.894 – 94.396 = 223.498 \, °C \)

\[ = 111.66 \, °C \]

LMTD, \( ΔT_{lm} = \frac{(T₁ – t₂) – (T₂ – t₁)}{\ln \left( \frac{T₁ – t₂}{T₂ – t₁} \right)} \)
\[
\log \left(\frac{317.89 - 194}{223.49 - 86}\right) = 130.57 \, ^\circ F
\]

To find correction factor \( F \),
\[
P = \frac{t_2 - t_1}{T_1 - t_1} = \frac{223.49 - 317.89}{86 - 317.89} = 0.407
\]
\[
R = \frac{T_1 - T_2}{t_2 - t_1} = \frac{86 - 194}{223.49 - 37.89} = 1.144
\]
\[
\Rightarrow F = 0.9
\]
\[
A = \frac{Q}{U \cdot \text{LMTD} \cdot F} = 47.047 \, \text{ft}^2
\]
\[
A = n_t \cdot \Pi \cdot D_0 \cdot L
\]
\[
n_t = 14.97 \approx 18 \text{ tubes}
\]
\[
U_{\text{req}} = \frac{Q}{n_t \cdot \Pi \cdot D_0 \cdot L \cdot (\Delta T_{\text{lm}}) \cdot c_f} = 62.56 \text{ Btu/h ft}^2 \, ^\circ F
\]
Hence, \( U_{\text{req}} = 62.56 \text{ Btu/h ft}^2 \, ^\circ F
\]
\[
Re = \frac{4m \cdot n_p}{\pi \mu n_t} = 2243.83 \, n_p
\]
\[
Re \geq 10^4
\]
Since, \( n_p = 10^4 / 2243 = 4.49 \approx 6 \text{ passes}
\]
\[
n_t = 18
\]
\[
n_p = 6
\]
Shell id = 10 inch

To calculate \( h_i \):
\[
Re = \frac{4mC^{*}B}{\pi D_i \mu} = 13463.02
\]
\[
h_i = \frac{K_i}{D_i} \cdot 0.023 \cdot Re^{0.8} \cdot Pr^{1/3} \left(\frac{H}{\mu w}\right)^{0.14}
\]
\[
h_i = 998.79 \text{ Btu/h ft}^2 \, ^\circ F
\]

To calculate \( h_0 \):
\[
B = 0.2 \, d_1 = 0.2 \times 10 = 2 \text{ inch}
\]

From tables (Design of heat exchanger by Robert W Serth),
\[
P_t = 1.25 \text{ inch}
\]
OD = 1 inch

\[
C^* = 0.25
\]
\[
a_s = \frac{dsc^*B}{144 \, \text{Pt}} = \frac{10 \times 0.25 + 2}{144 + 1.25} = 0.0277 \, \text{ft}^2
\]
\[
G = \frac{m}{as} = 7865.17 / 0.227 = 283941.15 \, \text{lbm/h ft}^2
\]
\[ D_{e} = \frac{de}{12} = 0.99/12 = 0.0825 \text{ ft} \]
\[ Re = \frac{De \cdot G}{\mu} = \frac{(0.0825 \cdot 283941.15)}{1.8} \]

Hence, \( Re = 13013.96 \)

To find \( \mu \) of engine oil:

From tables, \( \mu = 7.445 \times 10^{-2} \text{ Pa s} \)

\[ = 0.7445 \text{ poise} \]
\[ = 1.8 \text{ lbm/ ft h} \]

To find colburn factor, \( J_H \):

\[ J_H = 0.5 \left( 1 + \frac{B_{ds}}{D_{e}} \right) \left( 0.08 Re^{0.6821} + 0.7 Re^{0.1772} \right) \]
\[ = 0.5 \left( 1 + 0.3 \right) \left( 0.08 \times 13013.96^{0.6821} + 0.7 \times 13013.96^{0.1772} \right) \]
\[ = 34.127 \]

\( K \) (engine oil) = 0.1407 W/mK

\[ = 0.0813 \text{ Btu/ h ft}^2 \text{ F} \]

\( C_p = 2047 \text{ J/kg K} \)
\( K = 0.489 \text{ Btu/ lbm}^2 \text{ F} \)

\( \mu = 1.8 \text{ lbm/ ft h} \)

\( Pr = \frac{\mu C_p}{K} = 10.826 \)

\[ h_0 = J_H \cdot \left( \frac{K}{De} \right) \cdot Pr^{0.33} \cdot \left( \frac{\mu}{\mu_w} \right)^{0.14} \]
\[ = 34.127 \times \left( 0.0813/0.0825 \right) \times 10.826^{0.33} \times 1 \]
\[ = 74.397 \text{ Btu/ h ft}^2 \text{ F} \]

To calculate clean overall coefficient,

\[ U_c = \left[ \frac{D_0}{h_i \cdot D_i} + \frac{D_0 \ln D_0}{2K(tube)} + \frac{1}{h_0} \right]^{-1} = 67.56 \text{ Btu/ h ft}^2 \text{ F} \]

Since, \( U_c > U_{req} \), design is safe.

Fouling factors:

\[ Rp = \frac{RD_i \cdot D_0}{D_i} + R_{D_0} \]
\[ = \frac{0.0005+1}{0.834} + 0.001 \]

\( Rp = 0.00156 \text{ ft}^2 \text{ F/ Btu} \)

Design overall Coefficient:

\[ U_D = \left( \frac{1}{U_c} + Rp \right)^{-1} = 65.36 \text{ Btu/ h ft}^2 \text{ F} \]

Over surface = \( \frac{U_c}{U_{req}} - 1 = 16.3\% \)

Over design = \( \frac{U_d}{U_{req}} - 1 = 4.4\% \)
Comparison with the present heat exchanger design:

Old design:

\[ \text{Area of tubes} = nt \frac{\pi}{4} \cdot d^2 \]
\[ = 49 \cdot (\pi/4) \cdot 64 \cdot 10^{-6} \]
\[ = 2.463 \cdot 10^{-3} \text{m}^2 \]

\[ F = 0.9 \]
\[ U = 75 \text{ W/m}^2\text{K} \]

\[ Q = FUAL \Delta T_{\text{in} \text{out}} \]
\[ = 0.9 \cdot 75 \cdot 2.463 \cdot 10^{-3} \cdot 2.45 \cdot 72.54 \]
\[ = 29.54 \text{ W} \]

\[ \Delta T_{\text{in} \text{out}} = \frac{[(158.83 - 90) - (106.387 - 30)]}{\ln \frac{158.83 - 90}{106.387 - 30}} \]
\[ = 72.54^\circ \text{C} \]

New design:

\[ \text{Area of tubes} = 18 \frac{\pi}{4} \cdot 0.0211^2 \]
\[ = 6.294 \cdot 10^{-3} \text{m}^2 \]

\[ Q = 0.9 \cdot 75 \cdot 6.294 \cdot 10^{-3} \cdot 3.657 \cdot 72.54 \]
\[ = 112.7 \text{ W} \]

2.1.2. 3D model of new design

Based on the numerical calculations, we have made a new 3D model using Solid works 2010

![3D Model of new design](image)
Table 1 Dimensions of new design

| Parameters                  | Dimensions |
|-----------------------------|------------|
| Heat exchanger length, L    | 2270mm     |
| Shell inner diameter, D_i   | 266.3mm    |
| Tube outer diameter, d_o    | 25mm       |
| Triangular pitch            | 32mm       |
| Number of tubes             | 18         |
| Number of baffles           | 21         |
| Central baffle spacing      | 63.5mm     |
| Tube length                 | 1825mm     |

2.2 Analysis of new design model using ANSYS 14.0

Analysis of shell and tube heat exchanger using CFD. To study the temperature distribution of shell and tube separately for a 50s flow time with a specific mass flow rate. We have done triangular surface mesh with mesh quality 0.842, skewness factor 0.228 and growth rate 1.2 respectively. The following figure depicts the meshed view.

Figure 3. Meshed view of new design
2.2.1 Problem setup

Simulation was carried out in ANSYS® FLUENT® 14. In the Fluent solver Pressure Based type was selected, transient time was selected for the simulation. In the model option energy calculation was on and the viscous was set as standard k-e, standard wall function (k-epsilon 2 eqn). Engine oil and water vapour were selected as fluid material. Copper and aluminium were selected as solid material. In cell zone conditions, engine oil was selected for shell and water vapour was selected for tubes. Then boundary conditions were applied. The mass flow inlet of engine oil is 1kg/s and temperature is 323K. Lube oil pressure is 4bar and density is 991kg/m³. The mass flow inlet of steam is 0.55kg/s and temperature inlet is 170.4°C. Solution initialization was Hybrid Initialization method and solution was initialize from inlet with 323k temperature.

3. Results and discussion

Variation of temperature distribution across shell

The temperature Contours plots across the cross section along the length of heat exchanger will give an idea of the flow in detail. Variation of temperature from inlet to outlet of the shell is clearly depicted below.

![Temperature distribution across shell](image)

**Figure 4.** Temperature distribution across shell.

Temperature versus position graph across shell inlet and outlet

This graph depicts the temperature distribution of inlet and outlet of the engine oil flowing through the shell. Red dots at the top indicates hot oil out from the shell which is at a temperature of around 390K. White dots at the bottom indicates cold oil in to the shell which is at a temperature of about 323K.
Figure 5. Temperature versus position graph across shell

Temperature versus position graph across tube inlet and outlet

This graph depicts the temperature distribution of inlet and outlet of the steam flowing through the tubes. Red dots at the bottom indicate cold steam out from the tubes which is at a temperature of around 408K. White dots at the top indicate hot oil in to the tubes which is at a temperature of about 443K.

Figure 6. Temperature versus position graph across tubes
4. Conclusions

- Numerical calculations reveal that the heat transfer rate has increased from 29.54W for the old design to 112.7W for the newly designed heat exchanger.

- The overall heat transfer coefficient of the new designed model i.e., $U_c$ and $U_d$ are higher than that of the required heat transfer coefficient. This reveals that our design is safe.

- While doing ANSYS simulation, we only give mass flow rate and inlet temperature of the lube oil and steam as boundary conditions. The outlet is just given as outflow, such that the system will automatically calculate the temperature at the outlet. From the ansys report, it is confirmed that the lube oil temperature at the outlet has reached at the required range i.e., 90°C to 120°C.

- Since the capacity of the new heat exchanger is higher than that of the old model, the quantity of lube oil heating at a particular time interval will be more than that of the old model.

- Area of the tubes are increased from $2.463*10^{-3}$ m$^2$ to $6.294*10^{-3}$.

- The amount of heat transferred will also be more. So by combining these statements, we can say that the preheating time required to heat 36000L of lube oil will be lesser for the new model.

5. References

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