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Design of Shell and Tube Heat Exchanger Using MATLAB and Finding the Steady State Time Using Energy Balance Equation

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Abstract

Design of shell and tube heat exchangers are done by formulating a standard procedure where the parameters required for building a HX is calculated using numerical method until the dimensions satisfy the condition for maximum overall heat transfer coefficient, this is done using a MATLAB code in which the calculations are iterated by varying the TEMA specified values for tube length and tube outer diameter. The output of this calculation is proposed to be the effective parameters for design of shell and tube heat exchanger for given boundary conditions. Energy balance over the heat exchanger for the designed HX was completed using partial differential equations, which was solved using second order Runge-Kutta method. Since Runge-Kutta method is very robust and efficient, so thermal diffusion term is not included in the energy balance equation. By plotting a temperature v/s tube length graph in MATLAB using the energy balance differential equation and analyzing the same, time required for the shell and tube heat exchanger to reach a steady state condition is obtained. The present work proposes a standard steps to design and analyze the working and performance of a shell and tube heat exchanger.

Keywords: Shell and tube heat exchanger, energy balance equation, steady state time.

1. Introduction

A variety of heat exchangers are used in industries, such as shell-and-tube heat exchangers, plate-fin heat exchangers, fin and tube heat exchangers etc. The shell-and-tube heat exchanger (STHX) has relatively simple manufacture and multi-purpose application possibilities for gaseous and liquid media in a large temperature and pressure range, so they are still widely used in chemical industry, power production, food industry, environment engineering, waste heat recovery, air-conditioning, and refrigeration and so on. A standard procedure for design of STHX is derived in this journal and is coded in MATLAB in such a way that the design configurations are obtained for maximum value of overall heat transfer coefficient is obtained. By solving the energy balance equation and a plot steady state time is obtained.

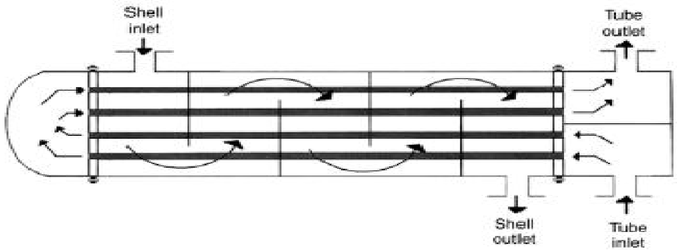

Fig. 1: A Typical shell and tube heat exchanger with one shell pass and two tube passes.

2. Nomenclature

ρ Density [kg/m3]	T Temperature [K]
ΔT Change in Temperature [K]	D Diameter [m]
V Volume [m3]	v Velocity of stream [m/s]
A Area [m2]	□ Mass Flow Rate [kg/s]
q Heat Transfer Rate [W]	CP Heat Capacity [J/kg K]
r Radius [m]	Re Reynolds Number
di Inner diameter of tube [m]	x Spatial Coordinate [m]
do Outer diameter of tube [m]	Pr Prandtl number
k Thermal conductivity	µ Dynamic viscosity [Ns/m2]
hi Heat transfer coefficient on tube side	µs Dynamic viscosity on shell side
ho Heat transfer coefficient on shell side	kw Thermal conductivity of material

3. Design of Shell and Tube Heat Exchanger

The design procedure starts with providing the standard dimensions of length and diameter of the tube which are proposed by tubular exchange manufactures association (TEMA) to the MATLAB code written. Program is run by iterating with possible combinations of the standard dimensions and the overall heat transfer coefficient (U) is obtained in each case. The obtained values of the U are compared and the corresponding dimensions for the maximum value of the same is obtained as the output. The design procedure is as follows

Assume the tube length and outer diameter according to TEMA specifications

$$0.0666 < (\text{Shell diameter/Tube length}) < 0.2 \quad (1)$$

$$1.25 < \text{Pitch/Outer diameter of tube} < 1.5 \quad (2)$$

$$\text{Number of tubes} = \frac{\pi.CTP.D_s^2}{4.CL.P^2} \quad (3)$$

After this Reynolds number and then heat transfer coefficient for the tube side is calculated, which is followed by the calculation of these parameter for the shell side.

Tube side

$$\text{Cross flow area} = \frac{(diameter\ of\ tube^2)(number\ of\ tubes)}{4(number\ of\ passes)} \quad (4)$$

$$R_e = \frac{(mass\ flow\ rate)(diameter\ of\ tube)}{(cross\ flow\ area)(viscosity)} \quad (5)$$

$$\text{Nusselt number} = \frac{h.d_0}{k} = (1.86)(viscosity^{(\frac{1}{4})})\ (\frac{(R_e.P_r.)(diameter\ of\ tube)}{2})\text{^}(1/3) \quad (6)$$

Laminar flow

$$\text{Nusselt number} = \frac{h.d_0}{k} = 0.023(R_e^{0.8})(P_r^{0.33})(\mu^{1.25}) \quad (7)$$

Turbulent flow

From the equation for Nusselt number, heat transfer coefficient is obtained. Similarly heat transfer coefficient for the shell side is obtained. Since the tubes are present inside the shell equivalent diameter (D_e) for the shell is calculated depending on the configuration of the arrangement of tube inside the shell. Main configurations which are extensively used are triangular and square, depending on which the CTP and CL values vary. Equations for equivalent diameter corresponding to each configuration is obtained from Perry H Greens hand book.

Shell side

$$\text{Nusselt number} = \frac{h.D_e}{k_s} = 0.36(R_e^{0.55})(P_r^{0.33})(\frac{\mu}{\mu_s})\text{^}0.14 \quad (9)$$

Baffle spacing = 74(outer diameter of tube)^0.75 (10) [A]

After obtaining these values overall heat transfer coefficient is calculated using the below given equation

$$Uo = \frac{\frac{1}{A_0}}{\frac{1}{h_i A_i} + \frac{ln\frac{d_0}{d_i}}{2.k_W.L} + \frac{1}{h_o A_0}} \quad (11)$$

The above given equations are coded in MATLAB in such a way that design parameters corresponding to the maximum overall heat transfer coefficient is obtained.

3.1 Steady state time

Analysis of heat exchanger is done best by considering the energy balance differential equation for shell and tube side differently

$$\frac{\delta T}{\delta t} = -v\frac{\delta T}{\delta x} - \frac{U2\pi(T_{in} - T_{out})}{\rho C_p r} \tag{12}$$

$$\frac{\delta T}{\delta t} = -v\frac{\delta T}{\delta x} + \frac{U2\pi r_{tube}(T_{in} - T_{out})}{\rho C_p(r_{shell}^2 - r_{tube}^2)} \tag{13}$$

Solving the above energy balance equation using second order Runge-Kutta method by modelling the shell and tube heat exchanger in MATLAB it is done using a finer spatial grid. The result obtained is used to plot a graph in such a way that it appears to be an animated figure. The technique used in order to obtain an animated version of graph is by holding the initial point and using the same axis for the plot of coming points. The steady state time is obtained by monitoring the graph continuously to find the time at which the plot appears to be stationary. The time is easily obtained because a provision is provided on the graph to show the time. Maximum time up to which the calculation is process is to be continued is initially provided in the program.

4. Results and Discussions

Hot engine oil is allowed to flow through the tube and water is passed through shell in order to cool the oil. Mass flow rate in this case is assumed to be unity. Thermal conductivity, Prandtl number and other required values are supplied. The design parameters proposed by the MATLAB code, tube length is 2.4, shell diameter is 0.1652, diameter of tube is 0.0065, baffle spacing in order to obtain maximum overall heat transfer coefficient is 0.463. baffle cut is 20, triangular pattern for tube layout is considered because it can accommodate more tubes than a square or rotated square pattern. Furthermore, a triangular pattern produces high turbulence and therefore a high heat transfer coefficient. Baffles spacing is the centerline to centerline distance between adjacent baffles here the obtained value satisfies the TEMA standard specification that is one-fifth of shell inside diameter. Closer spacing results in poor bundle penetration. Pressure considerations on shell and tube side are also considered such that no harm occurs. The inlet temperature of the tube is given to be 498.15 k and at the shell side is 298.15 k. Fig. 2,3,4,5 are those obtained with time 90s, 160s, 300s, and 500s respectively. Fig.4 and Fig.5 are similar in appearance which shows that after time 300s the graph appears to be stationary which comes to a conclusion that steady state time for the given STHX is 300s.

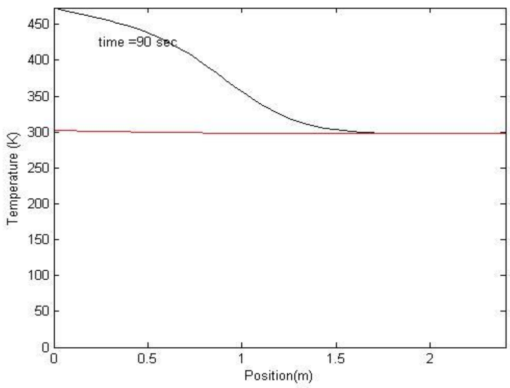

Fig. 2

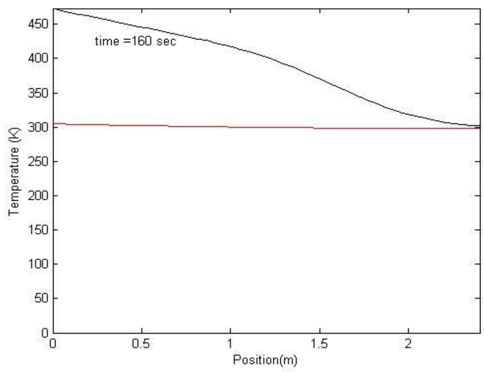

Fig. 3

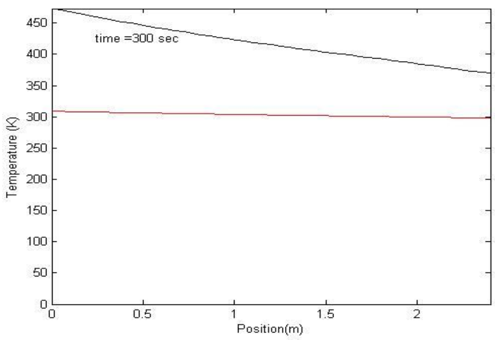

Fig. 4

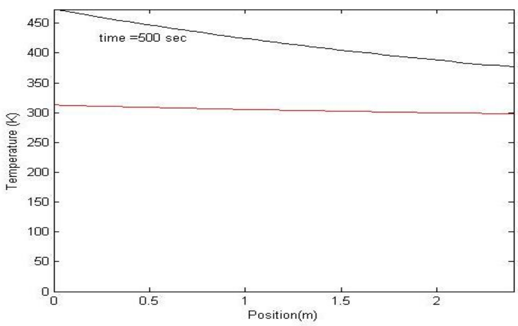

Fig. 5

5. Conclusion

A MATLAB code is written to find the design parameters by considering the standard TEMA specification and with an objective of maximum overall heat transfer coefficient. A procedure for finding out the steady state time for a shell and tube heat exchanger by modelling it in MATLAB and solving the energy balance equation by analyzing the animated graph plotted with temperature on y-axis and tube length on x-axis. Steady state is the time at which graph appears to be stationary.

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