Design of Shell and Tube Heat Exchanger

Semester 5 PBL

Heat and Mass Transfer

DHA Suffa University

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Problem Statement

Following are the input physical parameters:

	Fluid	T_i (ºC)	T_o (ºC)	Mass Flow Rates (kg/s)
Shell Side	Kerosene	200	94	5.52
Tube Side	Crude Oil	38	77	18.8

Shell diameter = 1.5 m

Tube diameter = 0.05 m

Baffle Spacing = 0.5 m

In the design problem you are expected to:

1. Calculate the heat transfer
2. Calculate overall heat coefficient
3. Calculate the area
4. Incorporate the fouling factor of a typical STHX with the given conditions
5. Find out appropriate number of tubes, length and thickness of the tubes
6. Calculate the pressure drop
7. Comment on the results
8. Propose improvement measures
9. Prepare a small report with all the design considerations, calculations and results.

Note: Use appropriate values of the missing or required parameters in the problem.

Properties of Fluids

Physical properties of 42° API Kerosene:

Kerosene	Inlet	Mean	Outlet	Units
Temperature	200	147	94	ºC
Specific Heat	2.72	2.47	2.26	kJ/kgºC
Thermal Conductivity	0.130	0.132	0.135	W/mºC
Density	690	730	770	kg/m^3
Viscosity	0.22	0.43	0.8	mNs/m^2

Physical Properties of 34° API Light Crude Oil

Crude Oil	Inlet	Mean	Outlet	Units
Temperature	38	57.5	77	ºC
Specific Heat	1.93	1.97	2.01	kJ/kgºC
Thermal Conductivity	0.133	0.134	0.135	W/mºC
Density	800	820	840	kg/m^3
Viscosity	2.4	3.2	4.3	mNs/m^2

Assumptions

- 1 Shell and 2, 4, 6 etc (any multiple of 2), tube passes
    - Number of tubes assumed = 6
- Tube Outer Diameter = 10% of Tube Inner Diameter

Fluid Properties

- Thermal Conductivity of Copper Tubes (K) = 385 W/mºC
- R_{fi} = 0.00035
- R_{fo} = 0.00020
- Specific Gravity of Kerosene (Sk) = 0.785
- Specific Gravity of Crude Oil (Sc) = 0.850

Calculations

$$\dot{Q}_s = \dot{m}_s C_p (T_i - T_o)$$
$$= 5.52 \times 2.47 \times (200 - 94)$$
$$= 1445.25 \text{ kW}$$

$$\Delta T_1 = T_{h,in} - T_{c,out}$$
$$= 200 - 77 = 123^{\circ}C$$

$$\Delta T_2 = T_{h,out} - T_{c,in}$$
$$= 94 - 38 = 56^{\circ}C$$

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1 / \Delta T_2)}$$
$$= \frac{123 - 56}{\ln(123/56)} = 85.15^{\circ}C$$

$$\Delta T_m = F \Delta T_{lm}$$
$$= 0.94 \times 85.15$$
$$= 80.04^{\circ}C$$

$$P = \frac{t_2 - t_1}{T_1 - t_1}$$
$$= \frac{94 - 200}{38 - 200} = 0.654$$

$$R = \frac{t_1 - t_2}{T_2 - T_1}$$
$$= \frac{38 - 77}{94 - 200} = 0.368$$

$$F = 0.94$$

(from Table)

1 shell and 2, 4, 6 etc tube passes
hence,

$n_t = 6$ tubes

Tube:

$\dot{m} = \rho A v n_t \rightarrow v = \dfrac{\dot{m}}{\rho A n_t} = \dfrac{18.8}{820 \times \frac{\pi}{4} \times 0.05^2 \times 6}$

$= 1.946 \ ms^{-1}$

$Re = \dfrac{v D \rho}{\mu} = \dfrac{1.946 \times 0.05 \times 820}{3.2 \times 10^{-3}}$

$= 24933.125 = 0.24933 \times 10^5$

($Re > 10000$, hence Turbulent Flow)

$Pr = \dfrac{\mu C_p}{k} = \dfrac{3.2 \times 10^{-3} \times 1.97 \times 10^3}{0.134}$

$= 47.04$

$Nu = \dfrac{hD}{k} = 0.023 \, Re^{0.8} \, Pr^{0.4}$

$\dfrac{h(0.05)}{0.134} = 0.023 (0.249 \times 10^5)^{0.8} (47.04)^{0.4}$

$h = 946.5 \ W/m^2 \cdot K$

Shell:

$h = 1000 \ W/m^2 \cdot K$

based on type of fluids.

$D_{ti} = 0.05m$

$D_{to} = D_{ti} + (0.1 D_{ti} \times 2)$

$= 0.05 + (0.1(0.05) \times 2) = 0.06m$

$$\frac{1}{U_i} = D_{ti}\left(\frac{1}{h_i D_{ti}} + \frac{R_{fi}}{h_i D_{ti}} + \frac{\ln(D_{to}/D_{ti})}{2K} + \frac{R_{fo}}{h_o D_{to}} + \frac{1}{h_o D_{to}}\right)$$

$$\frac{1}{U_i} = 0.05\left(\frac{1}{946.5 \times 0.05} + \frac{0.00035}{946.5 \times 0.05} + \frac{\ln(0.06/0.05)}{2(385)} + \frac{0.0002}{1000 \times 0.06} + \frac{1}{1000 \times 0.06}\right)$$

$U_i = 525.70$

$$\frac{1}{U_o} = D_{to}\left(\frac{1}{h_i D_{to}} + \frac{R_{fi}}{h_i D_{ti}} + \frac{\ln(D_{to}/D_{ti})}{2K} + \frac{R_{fo}}{h_o D_{to}} + \frac{1}{h_o D_{to}}\right)$$

$$\frac{1}{U_o} = 0.06\left(\frac{1}{946.5 \times 0.06} + \frac{0.00035}{946.5 \times 0.05} + \frac{\ln(0.06/0.05)}{2(385)} + \frac{0.0002}{1000 \times 0.06} + \frac{1}{1000 \times 0.06}\right)$$

$U_o = 482.77$

$\dot{Q} = A_i U_i \Delta T_m$

$1445.25 \times 10^3 = A_i \times 525.70 \times 80.04$

$A_i = 34.34\ m^2$

$\dot{Q} = A_o U_o \Delta T_m$

$1445.25 \times 10^3 = A_o \times 482.77 \times 80.04$

$A_o = 37.40\ m^2$

∵ Taking A_o as it is highest area.

$A_o = n \pi D_o L$

$37.40 = 6\pi \times 0.06 \times L$

$L = 198.42\,m$ (length of all tubes)

$\frac{198.42}{n_t} = \frac{198.42}{6} = 33.07\ m$ (length of 1 tube)

Thickness of tube $= D_{to} - D_{ti}$

$= 0.06 - 0.05$

$= 0.01\,m = 10\,mm$

Tube Pressure:

$f = 0.4137\, Re^{-0.2585}$

$= 0.4137\,(24988.125)^{-0.2585}$

$= 0.03021$

$$Re = \frac{4\dot{m}\,(np/nt)}{\pi D_{ti}\mu}$$

$$24988.125 = \frac{4(18.8)(np/6)}{\pi(0.05)(8.2\times10^{-3})}$$

$np = 1 \approx 2$ (even)

$$G = \frac{\dot{m}\,(np/nt)}{\pi D_{ti}^2/4} = \frac{18.8\,(2/6)}{\pi(0.05)^2/4}$$

$= 3191.59$

$$\Delta P_f = \frac{f\,np\,L G^2}{7.5\times10^{12}\, D_i\, s_c\, \phi} \qquad \because \phi = 1$$

$$= \frac{0.03021 \times 2 \times 198.42 \times 3191.59^2}{7.5\times10^{12} \times 0.05 \times 0.850 \times 1} = 3.8\times10^{-3}\ Pa$$

$\Delta P_r = 1.334\times10^{-13}\,(2np - 1.5)\,G^2 / s_c$

$= 1.334\times10^{-13}\,(2(2) - 1.5)\,(3191.59)^2 / 0.850$

$= 3.996\times10^{-5}\ Pa$

$\Delta P = \Delta P_f + \Delta P_r$

$= (3.8\times10^{-3}) + (3.996\times10^{-5})$

$= 3.84\times10^{-3}\ Pa$

Shell Pressure:

$$P = \frac{\text{Shell Diameter}}{\#\ \text{Tubes}} = \frac{1.5}{6} = 0.25$$

$$A_e = D_s \times B_s \times (p - D_{to}) / p$$
$$= 1.5 \times 0.5 \times (0.25 - 0.06) / 0.25$$
$$= 0.57\ m^2$$

$$V = \frac{\dot{m}}{\rho A} = \frac{5.52}{730 \times 0.57} = 0.0133\ m s^{-1}$$

$$D_e = 4 \times \frac{p^2 - \pi D_{to}^2 / 4}{\pi D_{to}}$$
$$= 4 \times \frac{0.25^2 - \pi (0.06)^2 / 4}{\pi (0.06)} = 1.27\ m$$

$$f_k = 1.79 \times (\rho \times v \times D_e / \mu)^{-1.9}$$
$$= 1.79 \left[\frac{0.0133 \times 730 \times 1.27}{043 \times 10^{-3}} \right]^{-1.9} = 6.075 \times 10^{-9}$$

∴ Assuming length of shell = 40 m

$$N = \frac{\text{Length of shell}}{\text{Baffle spacing}} = \frac{40}{0.5} = 80$$

$$\Delta P = \frac{(N+1) \times f_k \times D_s \times \rho v^2}{2 \times D_e}$$
$$= \frac{(80+1) \times 6.075 \times 10^{-9} \times 1.5 \times 730 \times 0.0133^2}{2 \times 1.27}$$
$$= 37.5 \times 10^{-9}\ Pa$$

References

$$\dot{Q} = \dot{m}_c C_{pc}(T_{c,\text{out}} - T_{c,\text{in}}) \quad \textbf{(13-9)}$$

and

$$\dot{Q} = \dot{m}_h C_{ph}(T_{h,\text{in}} - T_{h,\text{out}}) \quad \textbf{(13-10)}$$

where the subscripts c and h stand for *cold* and *hot* fluids, respectively, and

$$\begin{aligned} \dot{m}_c, \dot{m}_h &= \text{mass flow rates} \\ C_{pc}, C_{ph} &= \text{specific heats} \\ T_{c,\text{out}}, T_{h,\text{out}} &= \text{outlet temperatures} \\ T_{c,\text{in}}, T_{h,\text{in}} &= \text{inlet temperatures} \end{aligned}$$

$$\dot{Q} = UA_s\,\Delta T_{\text{lm}} \quad \textbf{(13-24)}$$

where

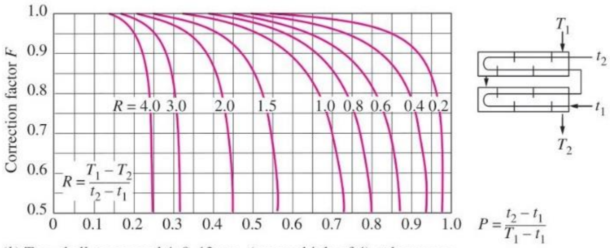
$$\Delta T_{\text{lm}} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)} \quad \textbf{(13-25)}$$

$$\Delta T_{\text{lm}} = F\,\Delta T_{\text{lm},\,CF} \quad \textbf{(13-26)}$$

$$P = \frac{t_2 - t_1}{T_1 - t_1} \quad \textbf{(13-27)}$$

and

$$R = \frac{T_1 - T_2}{t_2 - t_1} = \frac{(\dot{m}C_p)_{\text{tube side}}}{(\dot{m}C_p)_{\text{shell side}}} \quad \textbf{(13-28)}$$



(*b*) Two-shell passes and 4, 8, 12, etc. (any multiple of 4), tube passes

$$\frac{1}{UA_s} = \frac{1}{U_iA_i} = \frac{1}{U_oA_o} = R = \frac{1}{h_iA_i} + \frac{R_{f,i}}{A_i} + \frac{\ln(D_o/D_i)}{2\pi kL} + \frac{R_{f,o}}{A_o} + \frac{1}{h_oA_o} \quad \textbf{(13-8)}$$

Tube Pressure Formulae

Process Heat Transfer Principles and Applications Book • 2007

https://www.sciencedirect.com/book/9780123735881/process-heat-transfer

$$\Delta P_f = \frac{f\, n_p L G^2}{7.50 \times 10^{12} D_i s \phi} \tag{5.1}$$

where

f = Darcy friction factor (dimensionless)
L = tube length (ft)
G = mass flux ($\mathrm{lbm/h \cdot ft^2}$)
D_i = tube ID (ft)
s = fluid specific gravity (dimensionless)
ϕ = viscosity correction factor (dimensionless)
$= (\mu/\mu_w)^{0.14}$ for turbulent flow
$= (\mu/\mu_w)^{0.25}$ for laminar flow

$$f = 0.4137\, Re^{-0.2585} \tag{5.2}$$

$$\Delta P_r = 1.334 \times 10^{-13} \alpha_r G^2 / s \tag{5.3}$$

Table 5.1 *Number of Velocity Heads Allocated for Minor Losses on Tube Side*

Flow regime	Regular tubes	U-tubes
Turbulent	$2n_p - 1.5$	$1.6\, n_p - 1.5$
Laminar, $Re \geq 500$	$3.25\, n_p - 1.5$	$2.38\, n_p - 1.5$

Shell Pressure Formulae

https://www.enggcyclopedia.com/2019/05/shell-tube-heat-exchanger-pressure-drop/#pressure_drop_calculation

Effective Area = $Ae = Ds \times Bs \times (P-Dt) / P$

where, Ds = shell diameter
Bs = Baffle spacing
P = pitch (distance between center axes of two adjacent tubes)
Dt = Tube diameter

$V = \text{Mass flow}/(\rho \times Ae \times 3600)$

$f_k = 1.79 \times (\rho \times V \times D/\mu)^{-1.9}$

$De = 4 \times (P^2 - (\pi Dt^2/4)) / \pi Dt$

$\Delta P = ((N+1) \times f_k \times Ds \times \rho V^2) / (2 \times De)$

where, N = number of baffles