Heat Exchanger 3

Preliminary Design of Shell-and-Tube Exchangers

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- The following procedure is commonly used to obtain the heat-transfer area for the purpose of making a preliminary cost estimate of the exchanger.
- Tabulations of overall heat-transfer coefficients such as the one presented in next slides are used for this purpose.
- One simply estimates a value for the overall coefficient based on the tabulated values and then computes the required heat-transfer area from heat transfer equation.
- A somewhat better procedure is to estimate the individual film coefficients, h_i and h_o, and use them to compute the overall coefficient by the Equation as given before.

Typical Values of Overall Heat-Transfer Coefficients in Tubular Heat Exchangers. U = Btu /h · ft^2 ·°F

Shell side	Tube side	Design *U*	Includes total dirt
Liquid–liquid media			
Aroclor 1248	Jet fuels	100–150	0.0015
Cutback asphalt	Water	10–20	0.01
Demineralized water	Water	300–500	0.001
Ethanol amine (MEA or DEA) 10–25% solutions	Water or DEA, or MEA solutions	140–200	0.003
Fuel oil	Water	15–25	0.007
Fuel oil	Oil	10–15	0.008
Gasoline	Water	60–100	0.003
Heavy oils	Heavy oils	10–40	0.004
Heavy oils	Water	15–50	0.005
Hydrogen-rich reformer stream	Hydrogen-rich reformer stream	90–120	0.002
Kerosene or gas oil	Water	25–50	0.005
Kerosene or gas oil	Oil	20–35	0.005
Kerosene or jet fuels	Trichloroethylene	40–50	0.0015
Jacket water	Water	230–300	0.002
Lube oil (low viscosity)	Water	25–50	0.002
Lube oil (high viscosity)	Water	40–80	0.003
Lube oil	Oil	11–20	0.006
Naphtha	Water	50–70	0.005
Naphtha	Oil	25–35	0.005
Organic solvents	Water	50–150	0.003
Organic solvents	Brine	35–90	0.003
Organic solvents	Organic solvents	20–60	0.002
Tall oil derivatives, vegetable oil, etc.	Water	20–50	0.004
Water	Caustic soda solutions (10–30%)	100–250	0.003
Water	Water	200–250	0.003
Wax distillate	Water	15–25	0.005
Wax distillate	Oil	13–23	0.005

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Condensing vapor–liquid media			
Alcohol vapor	Water	100–200	0.002
Asphalt (450°F.)	Dowtherm vapor	40–60	0.006
Dowtherm vapor	Tall oil and derivatives	60–80	0.004
Dowtherm vapor	Dowtherm liquid	80–120	0.0015
Gas-plant tar	Steam	40–50	0.0055
High-boiling hydrocarbons V	Water	20–50	0.003
Low-boiling hydrocarbons A	Water	80–200	0.003
Hydrocarbon vapors (partial condenser)	Oil	25–40	0.004
Organic solvents A	Water	100–200	0.003
Organic solvents high NC, A	Water or brine	20–60	0.003
Organic solvents low NC, V	Water or brine	50–120	0.003
Kerosene	Water	30–65	0.004
Kerosene	Oil	20–30	0.005
Naphtha	Water	50–75	0.005
Naphtha	Oil	20–30	0.005
Stabilizer reflux vapors	Water	80–120	0.003
Steam	Feed water	400–1000	0.0005
Steam	No. 6 fuel oil	15–25	0.0055
Steam	No. 2 fuel oil	60–90	0.0025
Sulfur dioxide	Water	150–200	0.003
Tall-oil derivatives, vegetable oils (vapor)	Water	20–50	0.004
Water	Aromatic vapor-stream azeotrope	40–80	0.005

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Gas–liquid media			
Air, N_2, etc. (compressed)	Water or brine	40–80	0.005
Air, N_2, etc., A	Water or brine	10–50	0.005
Water or brine	Air, N_2 (compressed)	20–40	0.005
Water or brine	Air, N_2, etc., A	5–20	0.005
Water	Hydrogen containing natural–gas mixtures	80–125	0.003
Vaporizers			
Anhydrous ammonia	Steam condensing	150–300	0.0015
Chlorine	Steam condensing	150–300	0.0015
Chlorine	Light heat-transfer oil	40–60	0.0015
Propane, butane, etc.	Steam condensing	200–300	0.0015
Water	Steam condensing	250–400	0.0015

NC: non-condensable gas present; V: vacuum; A: atmospheric pressure.
Dirt (or fouling factor) units are (h) (ft^2) (°F) / Btu

Example 1

In a petroleum refinery, it is required to cool 30,000 lb/h of kerosene from 400 °F to 250 °F by heat exchange with 75,000 lb/h of gas oil, which is at 110 °F A shell-and-tube exchanger will be used, and the following data are available:

Fluid property	Kerosene	Gas oil
C_P (Btu/lbm · °F)	0.6	0.5
μ (cp)	0.45	3.5
k (Btu/h · ft · °F)	0.077	0.08

For the purpose of making a preliminary cost estimate, determine the required heat-transfer area of the exchanger.

Solution

(a) Calculate the heat load and outlet oil temperature by energy balances on the two streams.

$$q = (\dot{m}\, C_P \Delta T)_K = 30{,}000 \times 0.6 \times (400 - 250)$$

$$q = 2.7 \times 10^6 \text{ Btu/h}$$

$$q = 2.7 \times 10^6 = (\dot{m}\, C_P \Delta T)_{oil} = 75{,}000 \times 0.05 \times (T - 110)$$

$$T = 182°\text{F}$$

(b) Calculate the LMTD. Assume pure counter current

$$\Delta T =$$

$$(\Delta T_{1n})_{cf} =$$

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(c) Calculate the LMTD correction factor.

For the purpose of this calculation, assume that the kerosene will flow in the shell. This assumption will not affect the result since the value of F is the same, regardless of which fluid is in the shell.

$R =$

$P =$

From suitable chart obtain F for 1-2 exchanger F =

(d) Estimate U_D from previous table. a kerosene-oil exchanger should have an overall coefficient in the range ______ Btu/h· ft^2 ·°F

Therefore, take ______ *Btu/h · ft^2 · °F*

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e) Calculate the required area.

Rating a Shell-and-Tube Exchanger

- The thermal analysis of a shell-and-tube heat exchanger is similar to the analysis of a double-pipe exchanger.
- Since the flow patterns in a shell-and-tube exchanger differ from those in a double-pipe exchanger, the procedures for calculating the film coefficients also differ.
- In computing the tube-side coefficient, h_i, it is assumed that all tubes in the exchanger are exposed to the same thermal and hydraulic conditions. The value of h_i is then the same for all tubes, and the calculation can be made for a single tube.

- In computing the Reynolds number, however, the mass flow rate per tube must be used, where

$$\dot{m}_{per\ tube} = \frac{\dot{m}_t n_p}{n_t}$$

$$\dot{m}_{\text{per tube}} = \frac{\dot{m}_t}{n_t / n_p}$$

where

$\dot{m}_t$ = total mass flow rate of tube-side fluid

n_p = number of tube-side passes

n_t = number of tubes

- Then, the calculation of h_i is similar to a double-pipe exchanger.

Note: In computing the tube-side coefficient, h_i, it is assumed that all tubes in the exchanger are exposed to the same thermal and hydraulic conditions. The value of h_i is then the same for all tubes, and the calculation can be made for a single tube.

Methods of Shell-side coefficient, h_o *calculations*

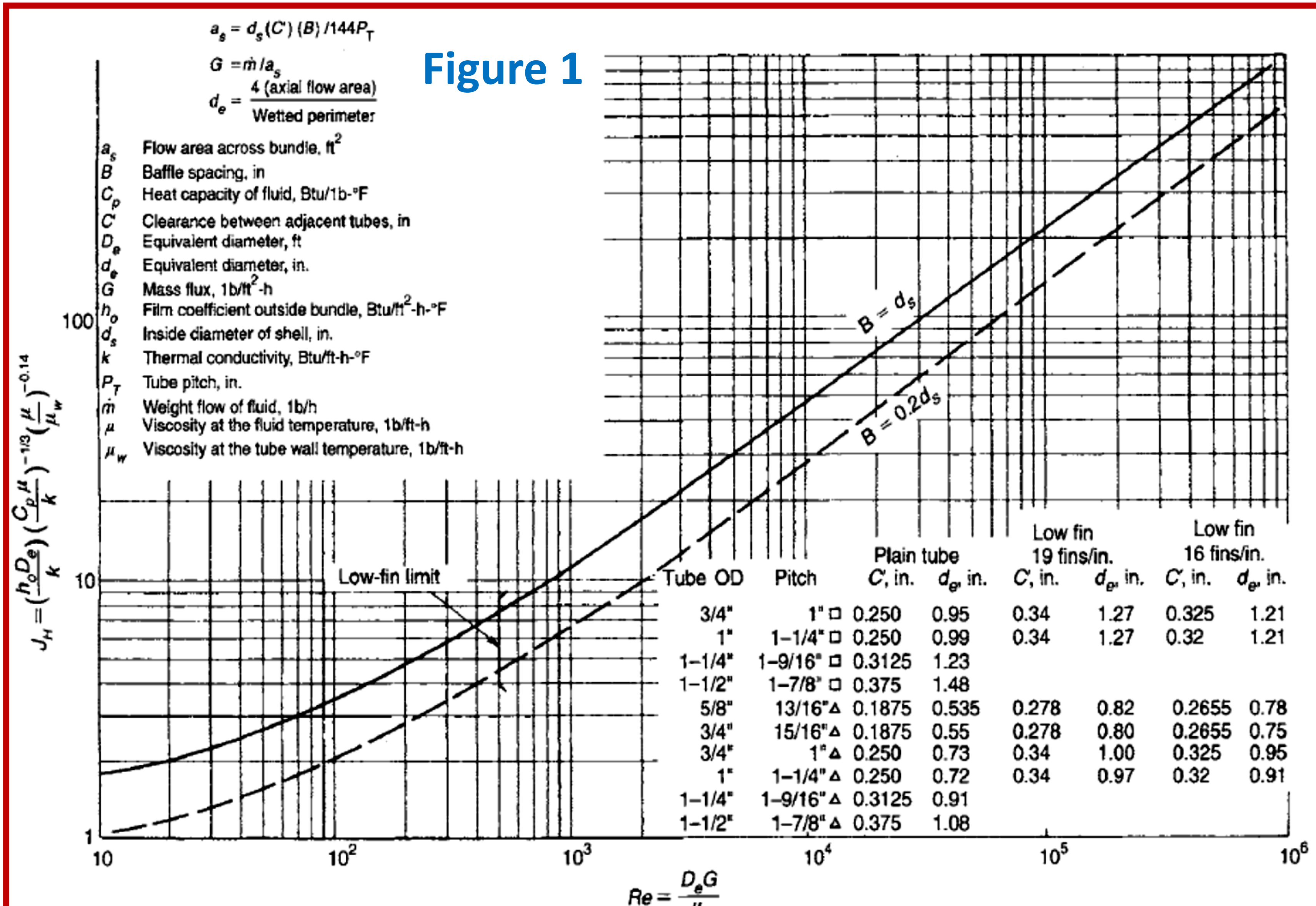
I. **Heat Transfer Research, Inc. (HTRI) method.** The method utilizes an iterative procedure to compute the various leakage streams in the shell, and therefore must be implemented on a computer.

II. **Delaware method.** The method is simple, accurate but it lengthy. We are going to use a simplified version of the Delaware. The method is very straightforward and allows us to present the overall rating procedure without considering the details.

Delaware Method

- The method utilizes the graph of modified Colburn factor, J_H, versus shell-side Reynolds number shown in Figure in the next slide.
- The graph is valid for segmental baffles with a 20% cut. It is also based on TEMA standards for tube-to-baffle and baffle-to-shell clearances.

Figure 1



Tube OD	Pitch	Plain tube C', in.	Plain tube d_e, in.	Low fin 19 fins/in. C', in.	Low fin 19 fins/in. d_e, in.	Low fin 16 fins/in. C', in.	Low fin 16 fins/in. d_e, in.
3/4"	1" □	0.250	0.95	0.34	1.27	0.325	1.21
1"	1-1/4" □	0.250	0.99	0.34	1.27	0.32	1.21
1-1/4"	1-9/16" □	0.3125	1.23				
1-1/2"	1-7/8" □	0.375	1.48				
5/8"	13/16" △	0.1875	0.535	0.278	0.82	0.2655	0.78
3/4"	15/16" △	0.1875	0.55	0.278	0.80	0.2655	0.75
3/4"	1" △	0.250	0.73	0.34	1.00	0.325	0.95
1"	1-1/4" △	0.250	0.72	0.34	0.97	0.32	0.91
1-1/4"	1-9/16" △	0.3125	0.91				
1-1/2"	1-7/8" △	0.375	1.08				

Correlation for shell-side heat-transfer coefficient. For rotated square tube layouts, use the parameter values for square pitch and replace P_T with $P_T/\sqrt{2}$ in the equation for a_s

- Read j_H from the graph and then compute ho from

$$h_o = j_H \left(\frac{k}{D_e}\right) Pr^{1/3} \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

- Appropriate fit for the curve is

$$j_H = 0.5(1 + B/d_s)(0.08Re^{0.6821} + 0.7Re^{0.1772})$$

- Flow area across the shell

$$a_s = d_s\, C\, B/144\, P_T$$

where d_s *: shell inside diameter, in ; C : clearance, in*
B : baffle spacing, in; P_T*: Pitch, in*
a_s *: shell flow area, ft*

Shell Mass flux

$$G = \dot{m} / a_s \quad lb/ft^2.h$$

Reynolds number for shell side fluid

$$Re = G\, D_e / \mu$$

Thermal rating procedure for a shell-and-tube heat exchanger

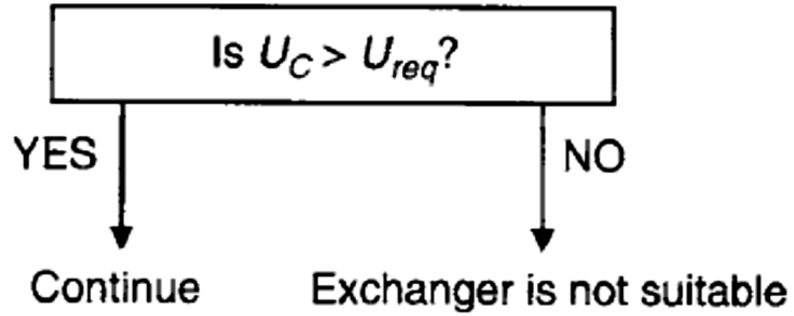
(1) Calculate the required overall coefficient.

$$U_{req} = \frac{q}{AF(\Delta T_{\ln})_{cf}}$$

(2) Calculate the clean overall coefficient.

$$U_C = \left[\frac{D_o}{h_i D_i} + \frac{D_o \ln(D_o/D_i)}{2k} + \frac{1}{h_o}\right]^{-1}$$

(3)



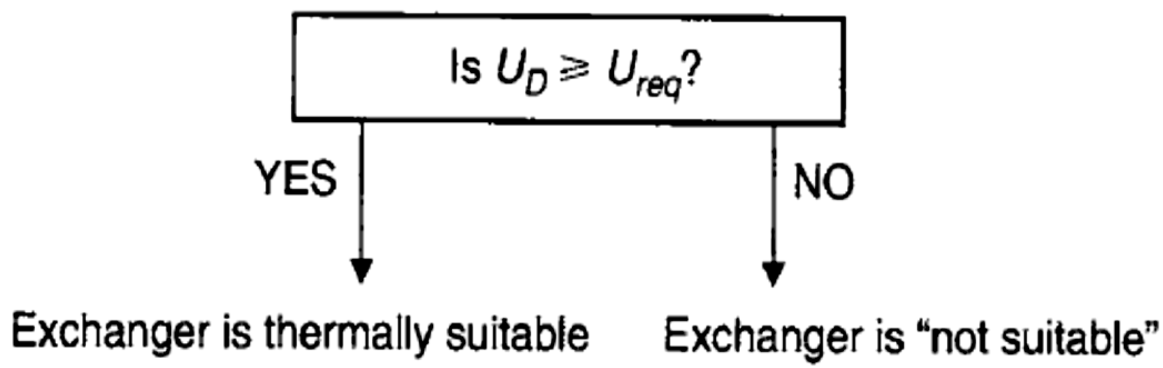
(4) Obtain required fouling factors, R_{Di} and R_{do} then calculate R_D

$$R_D = R_{Di}(D_o/D_i) + R_{Do}$$

(5) Calculate the design overall coefficient.

$$U_D = (1/U_C + R_D)^{-1}$$

(6)



The thermal rating procedure for a shell-and-tube heat exchanger is illustrated in the following example.

π OD

Table B.1 *Dimensions of Heat Exchanger and Condenser Tubing*
(b) Tubing Dimensions

Tube OD (in.)	BWG	Tube ID[a] (in.)	Internal area[b] ($in.^2$)	External surface per foot length[c] (ft^2/ft)	$\frac{OD}{ID}$
1/2	16	0.370	0.1075	0.1309	1.351
	18	0.402	0.1269	0.1309	1.244
	20	0.430	0.1452	0.1309	1.163
	22	0.444	0.1548	0.1309	1.126
5/8	12	0.407	0.1301	0.1636	1.536
	13	0.435	0.1486	0.1636	1.437
	14	0.459	0.1655	0.1636	1.362
	15	0.481	0.1817	0.1636	1.299
	16	0.495	0.1924	0.1636	1.263
	17	0.509	0.2035	0.1636	1.228
	18	0.527	0.2181	0.1636	1.186
	19	0.541	0.2299	0.1636	1.155
	20	0.555	0.2419	0.1636	1.126
3/4	10	0.482	0.1825	0.1963	1.556
	11	0.510	0.2043	0.1963	1.471
	12	0.532	0.2223	0.1963	1.410
	13	0.560	0.2463	0.1963	1.339
	14	0.584	0.2679	0.1963	1.284
	15	0.606	0.2884	0.1963	1.238
	16	0.620	0.3019	0.1963	1.210
	17	0.634	0.3157	0.1963	1.183
	18	0.652	0.3339	0.1963	1.150
	20	0.680	0.3632	0.1963	1.103
7/8	10	0.607	0.2894	0.2291	1.442
	11	0.635	0.3167	0.2291	1.378
	12	0.657	0.3390	0.2291	1.332
	13	0.685	0.3685	0.2291	1.277
	14	0.709	0.3948	0.2291	1.234
	15	0.731	0.4197	0.2291	1.197
	16	0.745	0.4359	0.2291	1.174
	17	0.759	0.4525	0.2291	1.153
	18	0.777	0.4742	0.2291	1.126
	20	0.805	0.5090	0.2291	1.087
1.0	8	0.670	0.3526	0.2618	1.493
	10	0.732	0.4208	0.2618	1.366
	11	0.760	0.4536	0.2618	1.316
	12	0.782	0.4803	0.2618	1.279
	13	0.810	0.5153	0.2618	1.235
	14	0.834	0.5463	0.2618	1.199
	15	0.856	0.5755	0.2618	1.168
	16	0.870	0.5945	0.2618	1.149
	18	0.902	0.6390	0.2618	1.109
	20	0.930	0.6793	0.2618	1.075

(Continued)

Table B.1 *(Continued)*

Tube OD (in.)	BWG	Tube ID[a] (in.)	Internal area[b] (in.^{2})	External surface per foot length[c] (ft^2/ft)	$\frac{OD}{ID}$
1.25	7	0.890	0.6221	0.3272	1.404
	8	0.920	0.6648	0.3272	1.359
	10	0.982	0.7574	0.3272	1.273
	11	1.010	0.8012	0.3272	1.238
	12	1.032	0.8365	0.3272	1.211
	13	1.060	0.8825	0.3272	1.179
	14	1.084	0.9229	0.3272	1.153
	16	1.120	0.9852	0.3272	1.116
	18	1.152	1.0423	0.3272	1.085
	20	1.180	1.0936	0.3272	1.059
1.5	10	1.232	1.1921	0.3927	1.218
	12	1.282	1.2908	0.3927	1.170
	14	1.334	1.3977	0.3927	1.124
	16	1.370	1.4741	0.3927	1.095
2.0	11	1.760	2.4328	0.5236	1.136
	12	1.782	2.4941	0.5236	1.122
	13	1.810	2.5730	0.5236	1.105
	14	1.834	2.6417	0.5236	1.091

[a] ID = OD − 2 × wall thickness from part (a) of table
[b] Internal area = $(\pi/4)(\text{ID})^2$
[c] External surface per foot length = $\pi(\text{OD}/12)$

Example 2

30,000 lb/h of kerosene are to be cooled from 400°F to 250°F by heat exchange with 75,000 lb/h of gas oil which is at ll0 °F Available for this duty is a shell-and-tube exchanger having 156 tubes in a 21 1/4-in. ID shell. The tubes are 1-in. OD, 14 BWG, 16 ft long on a $1\frac{1}{4}$-in. square pitch. There is one pass on the shell side and six passes on the tube side. The baffles are 20% cut segmental type and are spaced at 5-in. intervals. Both the shell and tubes are carbon steel having k- 26 Btu/h · ft^2 ·°F. Fluid properties are given in the previous example. Will the exchanger be thermally suitable for this service?

Fluid property	Kerosene	Gas oil
C_P (Btu/lbm · °F)	0.6	0.5
μ (cp)	0.45	3.5
k (Btu/h · ft · °F)	0.077	0.08

Solution

- Neither fluid is corrosive, but the oil stream may cause fouling problems so it should be placed in the tubes for ease of cleaning. Also, the kerosene should be placed in the shell due to its large ΔT.
- *Step 1:* Calculate $U_{req.}$

  From previous Example, we have:

$$q = 2.7 \times 10^6 \text{ Btu/h}$$

$$F = 0.93$$

$$(\Delta T_{\text{ln}})_{cf} = 176°\text{F}$$

- The surface area is obtained from the dimensions of the exchanger:

$$A = 156 \text{ tubes} \times 16\,\text{ft} \times 0.2618 \frac{\text{ft}^2}{\text{ft of tube}} = 653\,\text{ft}^2$$

- Thus

$$U_{req} = \frac{q}{AF(\Delta T_{\ln})_{cf}} = \frac{2.7 \times 10^6}{653 \times 0.93 \times 176}$$

$$U_{req} = 25.3\,\text{Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$$

- *Step 2:* Calculate the clean overall coefficient, U_c.

(a) Calculate the tube-side Reynolds number.

$$\dot{m}_{\text{per tube}} = \frac{75{,}000 \times 6}{156} = 2885\,\text{lb/h}$$

$$Re = \frac{4\dot{m}}{\pi D_i \mu} = \frac{4 \times 2885}{\pi \times \dfrac{0.834}{12} \times 3.5 \times 2.419} = 6243 \Rightarrow \text{transition region}$$

(b) Calculate h_i.

$$Nu = \frac{h_i D_i}{k} = 0.116\,[Re^{2/3} - 125]Pr^{1/3}(\mu/\mu w)^{0.14}[1 + (D_i/L)^{2/3}]$$

$$h_i = \frac{0.08}{(0.834/12)} \times 0.116\,[(6243)^{2/3} - 125]\left(\frac{0.5 \times 3.5 \times 2.419}{0.08}\right)^{1/3}(1)\left[1 + \left(\frac{0.834}{12 \times 16}\right)^{2/3}\right]$$

$$h_i = 110\,\text{Btu/h}\cdot\text{ft}^2\cdot{}^\circ\text{F}$$

Note: In this calculation, the viscosity correction factor was assumed to be unity since no data were given for the temperature dependence of the oil viscosity.

(c) Calculate the shell-side Reynolds number.

From Figure 1 {see slide 14}, *de* = 0.99 in. and C' = 0.250 in.

$$D_e = d_e/12 = 0.99/12 = 0.0825\,\text{ft}$$

$$a_s = \frac{d_s\,C'\,B}{144\,P_T} = \frac{21.25 \times 0.250 \times 5}{144 \times 1.25} = 0.1476\,\text{ft}^2$$

$$G = \frac{\dot{m}}{a_s} = \frac{30{,}000}{0.1476} = 203{,}294\,\text{lbm/h}\cdot\text{ft}^2$$

$$Re = \frac{D_e G}{\mu} = \frac{0.0825 \times 203{,}294}{0.45 \times 2.419} = 15{,}407$$

(d) Calculate h_o.

$$B/d_s = 5/21.25 = 0.235$$

From Figure 1, $j_H = 40$.

$$h_o = j_H \frac{k}{D_e} Pr^{1/3} (\mu/\mu_w)^{0.14} = \frac{40 \times 0.077}{0.0825} \left(\frac{0.60 \times 0.45 \times 2.419}{0.077}\right)^{1/3} \quad (1)$$

$$h_o = 76\,\text{Btu/h}\cdot\text{ft}^2\cdot{}^{\circ}\text{F}$$

(e) Calculate Uc.

$$U_C = \left[\frac{D_o}{h_i D_i} + \frac{D_o \ln(D_o/D_i)}{2k} + \frac{1}{h_o}\right]^{-1} = \left[\frac{1.0}{110 \times 0.834} + \frac{(1.0/12)\ln(1.0/0.834)}{2 \times 26} + \frac{1}{76}\right]^{-1}$$

$$U_C = 41.1\,\text{Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$$

Since $U_C > U_{req}$, proceed to Step 3.

Step 3: Obtain the required fouling factors. Taking 0.0025 for kerosene and 0.0035 for gas oil (check the given table), hence

$$R_D = \frac{R_{Di} D_o}{D_i} + R_{Do} = \frac{0.0035 \times 1.0}{0.834} + 0.0025 = 0.0067\,\text{h} \cdot \text{ft}^2 \cdot {}^\circ\text{F/Btu}$$

Step 4: Calculate U_D.

$$U_D = (1/U_C + R_D)^{-1} = (1/41.1 + 0.0067)^{-1} \cong 32\,\text{Btu/h}\cdot\text{ft}^2\cdot{}^\circ\text{F}$$

Final decision

Since this value, U_D, is greater than the required value of 25.3 Btu/h· ft^2· °F the exchanger is thermally suitable. A smaller exchanger would be adequate.

Note: Viscosity corrections can be done similar to the procedures that be given in the double pipe calculations.