Heat Exchangers

Design procedure for a shell and tube heat exchanger

- The initial steps in the design procedure (heat load and flow rate calculation) are similar to the calculations for double pipe heat exchangers
- In order to estimate $LMTD$ one must have an idea about the exchanger type
- The other two terms U and A in the main equation [$Q = UA(LMTD)$] are dependent on each other
- U depends on tube side Re, which depends on size and number of tubes
- U also depends on shell side coefficient, which depends on shell side Re (function of tube diameter, tube arrangement, number of tubes, tube pitch)
- As U and A are interdependent on each other, a **trial and error** method is used for heat exchanger design

The **steps involved in the design process are**:

1. Calculate the exchanger heat duty
2. Obtain the thermophysical properties of the hot and cold fluid at the mean temperatures
3. Select the tentative number of shell and tube passes, calculate the $LMTD$ and the $LMTD$ correction factor, F_T
4. Assume an overall heat transfer coefficient, U based on the outside area (Tables or Figures with U value ranges for different fluid streams are available) and calculate the heat transfer area A
5. Select the tube diameter, its thickness (BWG) and its length – this will help to determine the number of tubes. Also select the tube layout (Triangular or Square pitch)

6. Select the shell diameter that can accommodate the tubes in the selected pitch

   Also, select the type, size (% cut) and baffle spacing

7. Estimate the shell side and tube side heat transfer coefficients
8. Calculate the overall heat transfer coefficient $(U_{calculated})$ after including fouling factors
9. Calculate the heat transfer area $(A_{\ calculated})$
10. Compare the calculated U $(U_{calculated})$ and A $(A_{\ calculated})$ with the assumed U $(U_{assumed})$ and A $(A_{assumed})$
11. If $U_{calculated} > U_{assumed}$ or $A_{\ calculated} < A_{assumed}$ by around 10%, then the design is acceptable

    The area of the present configuration (area requirement) is less than the assumed area (area available with actual number of tubes)

    Hence, the design is satisfactory

12. In every case, apart from the area requirement , the estimated pressure drops on both the tube and shell side should be within limits

Design of a new exchanger

- The process followed is as given above
- The area required $(A_{\ required} = A_{calculated})$ is calculated based on the $U_{calculated}$
- This is compared to the area available $(A_{\ available} = A_{assumed})$ based on the actual number of tubes in the exchanger chosen during design
- For design to be satisfactory, $A_{\ required} < \ A_{\ available}$

Suitability of an existing exchanger for a particular duty

- For an existing exchanger, the number and size of tubes are known and hence the area available ($A_{available}$) is known
- U is again calculated based on the specifications of tubes, no of passes, shell diameter, baffle spacing, inner and outer heat transfer coefficients
- From this calculated U, the area required ($A_{required}$) is calculated
- If the area required is less than the area available ($A_{required} < A_{available}$), the exchanger is suitable for a particular duty

Suitability of a heat exchanger design based on clean and dirty heat transfer coefficient

- After estimating the inside (h_i) and outside (h_o) heat transfer coefficients, the clean overall coefficient (U_C) is estimated

$$\frac{1}{U_C} = \frac{r_o}{r_i h_i} + \frac{r_o ln\left({r_o}/{r_i}\right)}{k_w} + \frac{1}{h_o}$$

- The dirty overall heat transfer coefficient is determined as,

$$U_D = \frac{Q}{A(LMTD)}$$

- For a heat exchanger to work, U_C should be > U_D
- Dirt factor ($R_d = R_{di} + R_{do}$) is estimated as

$$R_d = \frac{1}{U_D} - \frac{1}{U_C} = \frac{U_C - U_D}{U_C U_D}$$

- This should be equal to or greater than the dirt factor required – this means that the heat exchanger is already providing for a dirt factor greater than what is required

Design procedure for a shell and tube heat exchanger

The steps in the design of a shell and tube heat exchanger can be seen by means of an example:

Design a shell and tube heat exchanger to cool 30 kg/s of butyl alcohol from 370K to 315 K using treated water as a coolant. The water enters at 300 K and leaves at 315 K.

As water is the more corrosive than butyl alcohol, water is passed through the tubes and butyl alcohol is in the shell side

Physical properties of the two fluids at their respective mean temperature:

Property	Butyl alcohol	Water
Density (kg/m^3)	780	995
Specific heat (kJ/kgK)	2.90	4.18
Thermal conductivity (W/mK)	0.16	0.59
Viscosity (Pa.s)	7.5×10^{-4}	8.0×10^{-4}

Thermal conductivity of the metal pipe is 46.52 W/mK

1. *Calculate heat duty*

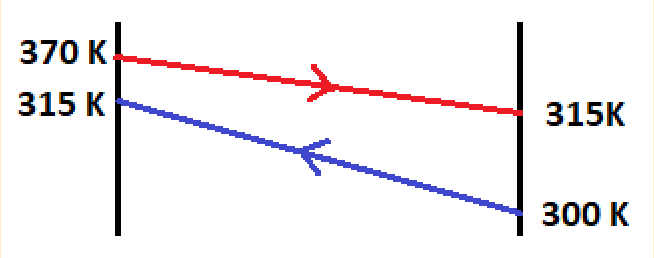
$$Q = \left(mC_p\Delta T\right)_{butyl\ alcohol} = \left(mC_p\Delta T\right)_{water}$$

$$Q = \left(mC_p\Delta T\right)_{butyl\ alcohol} = 30 \times 2.90 \times (370 - 315) = 4785\ kW$$

Flow rate of water, $m_{water} = \frac{4785}{4.18 \times (315-300)} = 76.82\ \frac{kg}{s}$

2. *Estimation of LMTD*

$$\Delta T_m = \frac{\Delta T_2 - \Delta T_1}{ln\frac{\Delta T_2}{\Delta T_1}} = \frac{(370-315)-(315-300)}{ln\frac{(370-315)}{(315-300)}} = \frac{55-15}{ln\frac{55}{15}} = 30.78\ K$$



Estimation of LMTD correction factor

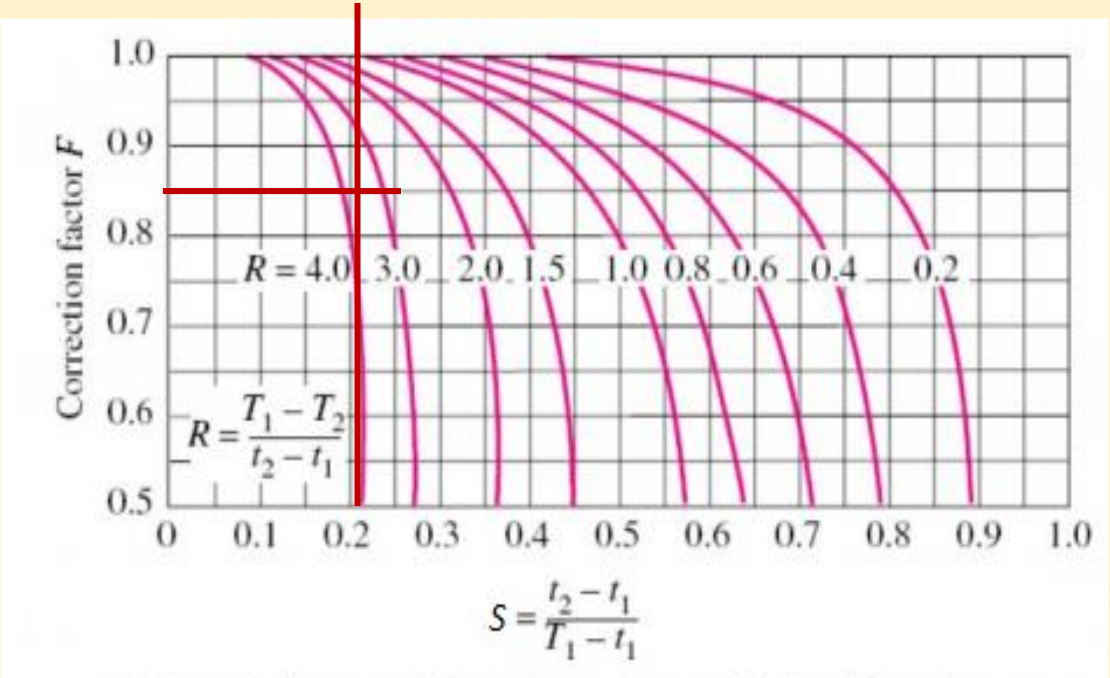
Assume 1:2 pass exchanger

$$R = \frac{(T_1 - T_2)}{(t_2 - t_1)} = \frac{(370-315)}{(315-300)} = 3.67$$

$$S = \frac{(t_2 - t_1)}{(T_1 - t_1)} = \frac{(315-300)}{(370-300)} = 0.214$$

From the figure, $F_T = 0.85$

Therefore, corrected LMTD = $30.78 \times 0.85 = 26.16\ K$



(a) One-shell pass and 2, 4, 6, etc. (any multiple of 2), tube passes

3. $Assume\ heat\ transfer\ coefficient, U$ from either Table or Figure

Table 12.1. Typical overall coefficients

Shell and tube exchangers		
Hot fluid	Cold fluid	U (W/m^2°C)
Heat exchangers		
Water	Water	800–1500
Organic solvents	Organic solvents	100–300
Light oils	Light oils	100–400
Heavy oils	Heavy oils	50–300
Gases	Gases	10–50
Coolers		
Organic solvents	Water	250–750
Light oils	Water	350–900
Heavy oils	Water	60–300
Gases	Water	20–300
Organic solvents	Brine	150–500
Water	Brine	600–1200
Gases	Brine	15–250
Heaters		
Steam	Water	1500–4000
Steam	Organic solvents	500–1000
Steam	Light oils	300–900
Steam	Heavy oils	60–450
Steam	Gases	30–300
Dowtherm	Heavy oils	50–300
Dowtherm	Gases	20–200
Flue gases	Steam	30–100
Flue	Hydrocarbon vapou	30–100
Condensers		
Aqueous vapours	Water	1000–1500
Organic vapours	Water	700–1000
Organics (some non-condensables)	Water	500–700
Vacuum condensers	Water	200–500
Vaporisers		
Steam	Aqueous solutions	1000–1500
Steam	Light organics	900–1200
Steam	Heavy organics	600–900

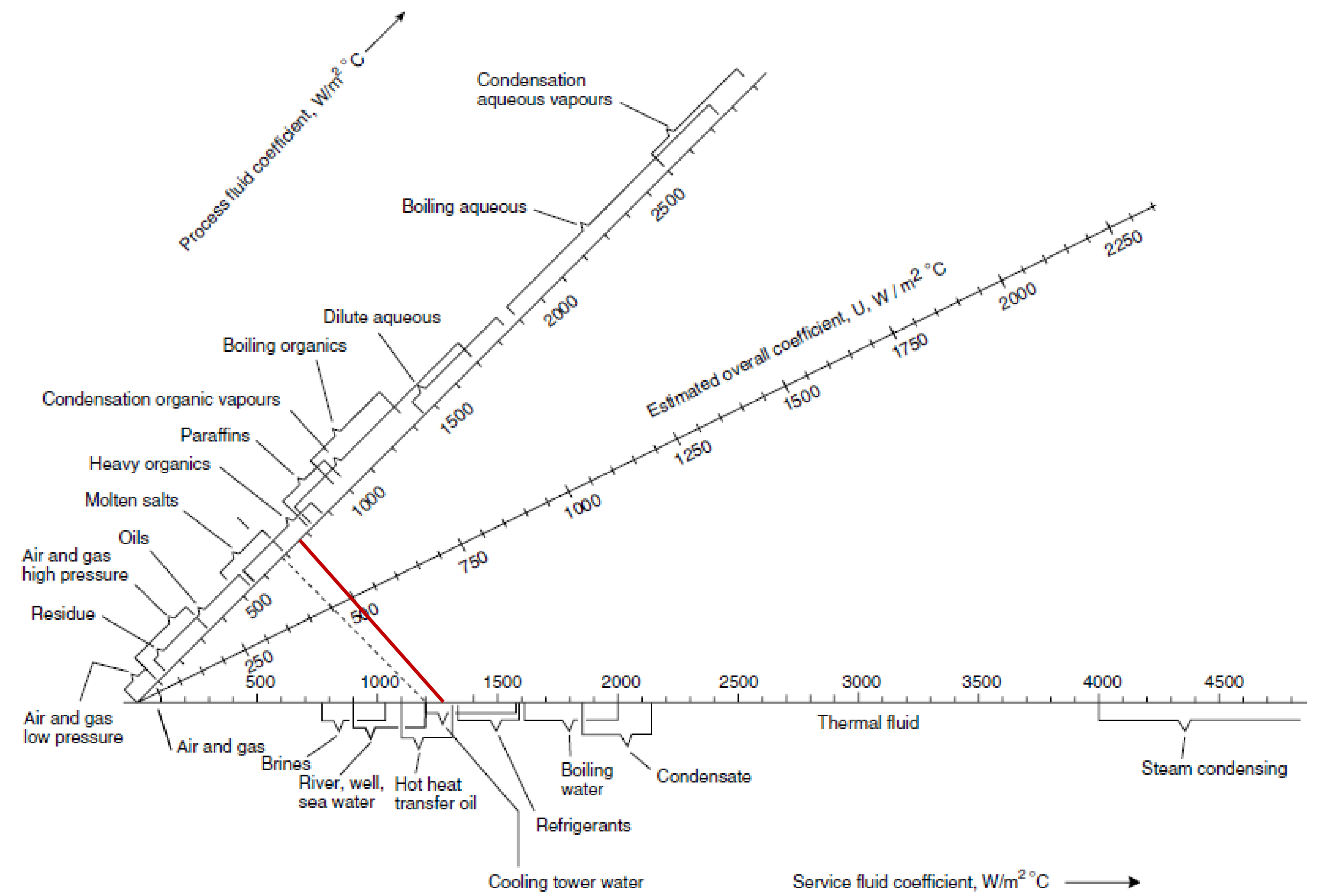


Figure 12.1. Overall coefficients (join process side duty to service side and read U from centre scale)

Assumed value of U = 500 W/m^{2}K

4. *Calculate heat transfer area,* A from $Q = UA(LMTD)$

$$A = \frac{Q}{U(LMTD)} = \frac{4785 \times 1000}{500 \times 26.16} = 365.83 \text{ m}^2$$

5. *Select tube specifications and calculate the number of tubes*

Tubes of 16 feet length and ¾ inch size are chosen

Tube specifications – (tube ID = 16 mm, tube OD = 20 mm,

tube length = 4.88 m)

Taking into account the tube sheet thickness (each 25 mm),

the tube length is = 4.88 – 0.05 = 4.83 m

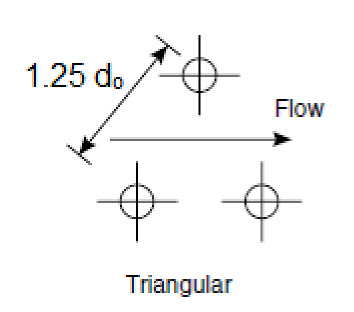
Surface area of one tube = $\pi d_o L = \pi \times 20 \times 10^{-3} \times 4.83 = 0.303$ m^2

$$No\ of\ tubes = \frac{365.83}{0.303} = 1208$$

A *1.25 triangular pitch* is chosen

Standard dimensions for steel tubes

Outside diameter (mm)	Wall thickness (mm)				
16	1.2	1.6	2.0	—	—
20	—	1.6	2.0	2.6	—
25	—	1.6	2.0	2.6	3.2
30	—	1.6	2.0	2.6	3.2
38	—	—	2.0	2.6	3.2
50	—	—	2.0	2.6	3.2



6. *Calculation of shell diameter*

Based on the tube dimensions, pitch and number of tubes, an appropriate shell diameter may be chosen using either the Tables or Bundle diameter calculations

Heat Exchanger Tubesheet Layout Tube Count Table

Note the right column for tubesheet and number of passes per configuration.

37	35	33	31	29	27	25	23 1/4	21 1/4	19 1/4	17 1/4	15 1/4	13 1/4	12	10	8	I.D. of Shell (in.)		
1,269	1,143	1,019	881	763	663	553	481	391	307	247	193	135	105	69	33	3/4 in. on 15/16 in.Δ	Fixed Tubes	One-Pass
1,127	1,007	889	765	667	577	493	423	343	277	217	157	117	91	57	33	3/4 in. on 1 in.Δ		
965	865	765	665	587	495	419	355	287	235	183	139	101	85	53	33	3/4 in. on 1 in.□		
699	633	551	481	427	361	307	247	205	163	133	103	73	57	33	15	1 in. on 1 1/4 in.Δ		
595	545	477	413	359	303	255	215	179	139	111	83	65	45	33	17	1 in. on 1 1/4 in. □		
1,242	1,088	964	846	734	626	528	452	370	300	228	166	124	94	58	32	3/4 in. on 15/16 in.Δ	Fixed Tubes	Two-Pass
1,088	972	858	746	646	556	468	398	326	264	208	154	110	90	56	28	3/4 in. on 1 in.Δ		
946	840	746	644	560	486	408	346	280	222	172	126	94	78	48	26	3/4 in. on 1 in.□		
688	608	530	462	410	346	292	244	204	162	126	92	62	52	32	16	1 in. on 1 1/4 in.Δ		
584	522	460	402	348	298	248	218	172	136	106	76	56	40	26	12	1 in. on 1 1/4 in.□		
1,126	1,008	882	768	648	558	460	398	304	234	180	134	94	64	34	8	3/4 in. on 15/16 in.Δ	U Tubes[1]	
1,000	882	772	674	566	484	406	336	270	212	158	108	72	60	26	8	3/4 in. on 1 in.Δ		
884	778	688	586	506	436	362	304	242	188	142	100	72	52	30	12	3/4 in. on 1 in.□		
610	532	466	396	340	284	234	192	154	120	84	58	42	26	8	XX	1 in. on 1 1/4 in.Δ		
526	464	406	356	304	256	214	180	134	100	76	58	38	22	12	XX	1 in. on 1 1/4 in. □		
1,072	1,024	904	788	680	576	484	412	332	266	196	154	108	84	48	XX	3/4 in. on 15/16 in.Δ	Fixed Tubes	Four-Pass
1,024	912	802	692	596	508	424	360	292	232	180	134	96	72	44	XX	3/4 in. on 1 in.Δ		
880	778	688	590	510	440	366	308	242	192	142	126	88	72	48	XX	3/4 in. on 1 in.□		
638	560	486	422	368	308	258	212	176	138	104	78	60	44	24	XX	1 in. on 1 1/4 in.Δ		
534	476	414	360	310	260	214	188	142	110	84	74	48	40	24	XX	1 in. on 1 1/4 in.□		
1,092	976	852	740	622	534	438	378	286	218	166	122	84	56	28	XX	3/4 in. on 15/16 in.Δ	U Tubes[1]	
968	852	744	648	542	462	386	318	254	198	146	98	64	52	20	XX	3/4 in. on 1 in.Δ		
852	748	660	560	482	414	342	286	226	174	130	90	64	44	24	XX	3/4 in. on 1 in.□		
584	508	444	376	322	266	218	178	142	110	74	50	36	20	XX	XX	1 in. on 1 1/4 in.Δ		
500	440	384	336	286	238	198	166	122	90	66	50	32	16	XX	XX	1 in. on 1 1/4 in.□		
1,106	964	844	732	632	532	440	372	294	230	174	116	80	XX	XX	XX	3/4 in. on 15/16 in.Δ	Fixed Tubes	Six-Pass
964	852	744	640	548	464	388	322	258	202	156	104	66	XX	XX	XX	3/4 in. on 1 in.Δ		
818	224	634	536	460	394	324	266	212	158	116	78	54	XX	XX	XX	3/4 in. on 1 in.□		
586	514	442	382	338	274	226	182	150	112	82	56	34	XX	XX	XX	1 in. on 1 1/4 in.Δ		
484	430	368	318	268	226	184	154	116	88	66	44	XX	XX	XX	XX	1 in. on 1 1/4 in.□		
1,058	944	826	716	596	510	416	358	272	206	156	110	74	XX	XX	XX	3/4 in. on 15/16 in.Δ	U Tubes[1]	
940	826	720	626	518	440	366	300	238	184	134	88	56	XX	XX	XX	3/4 in. on 1 in.Δ		
820	718	632	534	458	392	322	268	210	160	118	80	56	XX	XX	XX	3/4 in. on 1 in.□		
562	488	426	356	304	252	206	168	130	100	68	42	30	XX	XX	XX	1 in. on 1 1/4 in.Δ		
478	420	362	316	268	224	182	152	110	80	60	42	XX	XX	XX	XX	1 in. on 1 1/4 in.□		
1,040	902	790	682	576	484	398	332	258	198	140	94	XX	XX	XX	XX	3/4 in. on 15/16 in.Δ	Fixed Tubes	Eight-Pass
902	798	694	588	496	422	344	286	224	170	124	82	XX	XX	XX	XX	3/4 in. on 1 in.Δ		
760	662	576	490	414	352	286	228	174	132	94	XX	XX	XX	XX	XX	3/4 in. on 1 in.□		
542	466	400	342	298	240	190	154	120	90	66	XX	XX	XX	XX	XX	1 in. on 1 1/4 in.Δ		
438	388	334	280	230	192	150	128	94	74	XX	XX	XX	XX	XX	XX	1 in. on 1 1/4 in.□		
1,032	916	796	688	578	490	398	342	254	190	142	102	68	XX	XX	XX	3/4 in. on 15/16 in.Δ	U Tubes[1]	
908	796	692	600	498	422	350	286	226	170	122	82	52	XX	XX	XX	3/4 in. on 1 in.Δ		
792	692	608	512	438	374	306	254	194	146	106	70	48	XX	XX	XX	3/4 in. on 1 in.□		
540	464	404	340	290	238	190	154	118	90	58	38	24	XX	XX	XX	1 in. on 1 1/4 in.Δ		
456	396	344	300	254	206	170	142	98	70	50	34	XX	XX	XX	XX	1 in. on 1 1/4 in.□		
37	35	33	31	29	27	25	23 1/4	21 1/4	19 1/4	17 1/4	15 1/4	13 1/4	12	10	8	I.D. of Shell (in.)		

[1]Allowance made for tie rods.

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The bundle diameter may be estimated from the equation

$$N_t = K_1 \left(\frac{D_b}{d_o}\right)^{n_1}$$

N_t = number of tubes
D_b = bundle diameter, mm
d_o = tube OD, mm

Values of K_1 and n_1 depend on number of passes and tube pitch

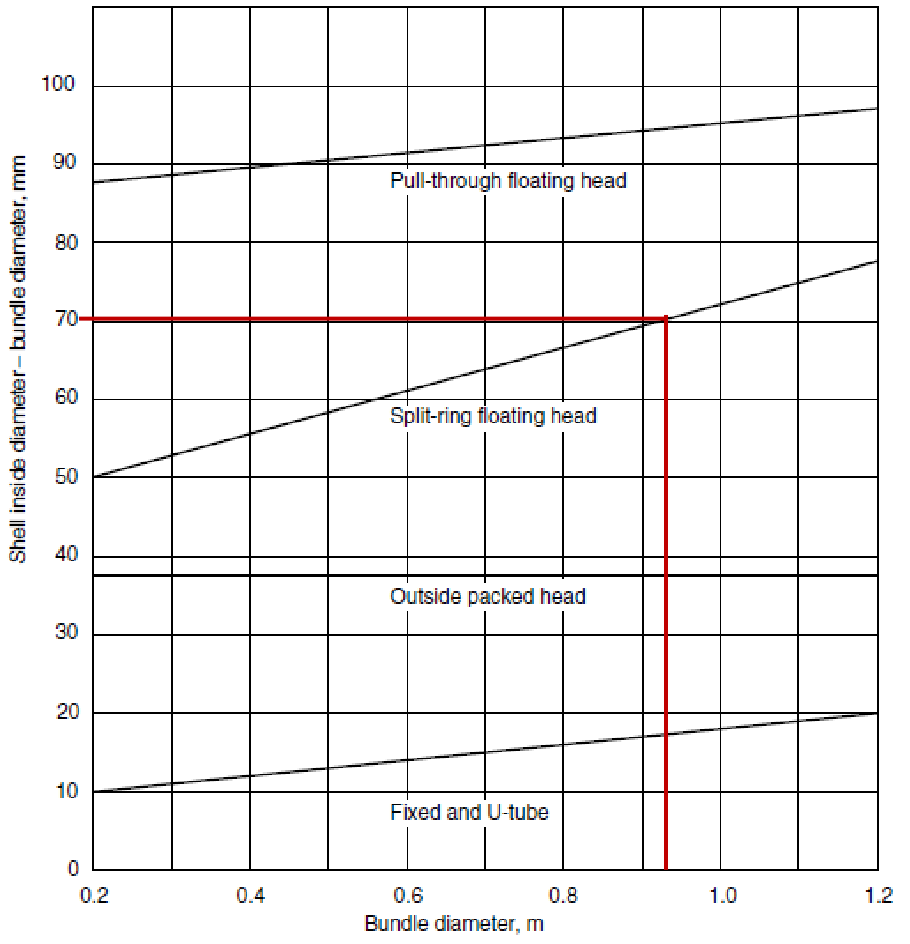
Triangular pitch, $p_t = 1.25d_o$					
No. passes	1	2	4	6	8
K_1	0.319	0.249	0.175	0.0743	0.0365
n_1	2.142	2.207	2.285	2.499	2.675
Square pitch, $p_t = 1.25d_o$					
No. passes	1	2	4	6	8
K_1	0.215	0.156	0.158	0.0402	0.0331
n_1	2.207	2.291	2.263	2.617	2.643

For a 1:2 pass, 1.25d_o triangular pitch tubes, K_1 = 0.249 and n_1= 2.207

$$1208 = 0.249 \left(\frac{D_b}{20}\right)^{2.207}$$

$$D_b = 936 \text{ mm}$$

- From the figure, for a split-ring floating head exchanger
- Clearance = 70 mm
- Therefore , inside shell diameter = 936+70 = 1006 mm
- Nearest standard pipe size is 1016 mm



Shell-bundle clearance

7. Estimation of tube side coefficient

Cross-sectional area $= \frac{\pi d_i^2}{4} = \frac{\pi \times (16 \times 10^{-3})^2}{4} = 2.01 \times 10^{-4} m^2$

Number of tubes per pass = $\frac{1208}{2} = 604$

Tube side flow area $= 604 \times 2.01 \times 10^{-4} = 0.121\ m^2$

Tube side velocity $= \frac{76.32}{995 \times 0.121} = 0.632\ \frac{m}{s}$

Reynolds No $= Re = \frac{d_i v \rho}{\mu} = \frac{16 \times 10^{-3} \times 0.632 \times 995}{8.0 \times 10^{-4}} = 12577$

Prandtl No $= Pr = \frac{\mu C_p}{k} = \frac{8.0 \times 10^{-4} \times 4.18 \times 1000}{0.59} = 5.67$

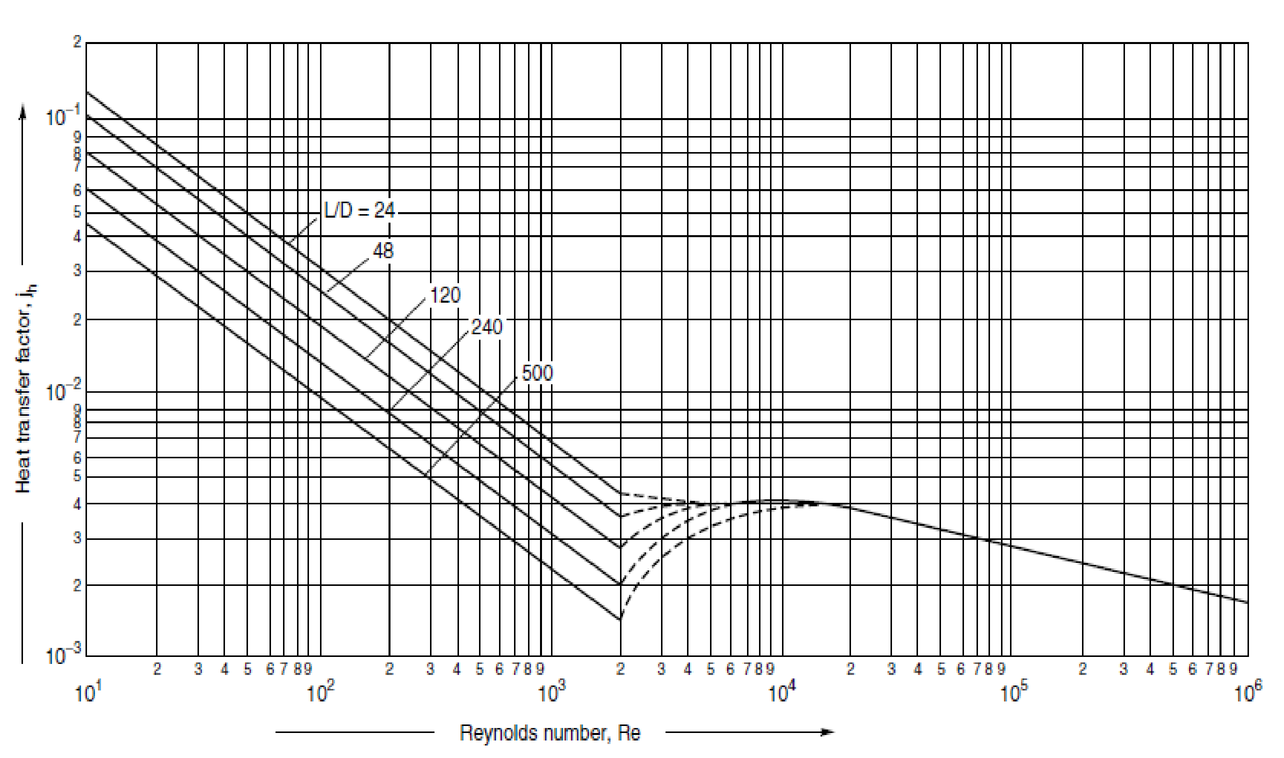
$\frac{L}{d} = \frac{4.83}{16 \times 10^{-3}} = 302$

From the figure, $j_H = 4 \times 10^{-3}$

$$j_H = \left(\frac{h_i d_i}{k}\right)\left(\frac{C_p \mu}{k}\right)^{-0.33}\left(\frac{d_i v \rho}{\mu}\right)^{-1}\left(\frac{\mu}{\mu_w}\right)^{-0.44}$$

$$\boldsymbol{h_i = \frac{4 \times 10^{-3} \times 0.59}{16 \times 10^{-3}} \times (5.67)^{0.33}(12577)}$$

$$= \mathbf{3288.9}\ W/m^2K$$



8. $Estimation\ of\ shell\ side\ coefficient$

Segmental baffles of 25% cut are selected with baffle spacing = 0.2 $\times$ $shell\ diameter$

Baffle spacing $= 0.2 \times 1016 = 203.2\ mm$

Cross-flow area, $a_s = \frac{(p-d_o)D_sB}{p} = \frac{(1.25 \times 20 - 20)1016 \times 10^{-3} \times 203.2 \times 10^{-3}}{1.25 \times 20} = 0.0413\ m^2$

Mass velocity, $G_s = \frac{W_s}{a_s} = \frac{30}{0.0413} = 726.4$ kg/m^{2}s

Equivalent diameter, $D_e = \frac{4\left(\frac{1}{2} \times p \times 0.87p - \frac{1}{2} \times \frac{\pi d_o^2}{4}\right)}{\frac{\pi d_o}{2}} = \frac{4\left(\frac{1}{2} \times 1.25 \times 20 \times 0.87 \times 1.25 \times 20 - \frac{1}{2} \times \frac{\pi (20)^2}{4}\right)}{\frac{\pi \times 20}{2}} = 14.2\ mm$

Reynolds No, $Re = \left(\frac{D_eG_s}{\mu}\right) = \frac{14.2 \times 10^{-3} \times 726.4}{7.5 \times 10^{-4}} = 13753.17$

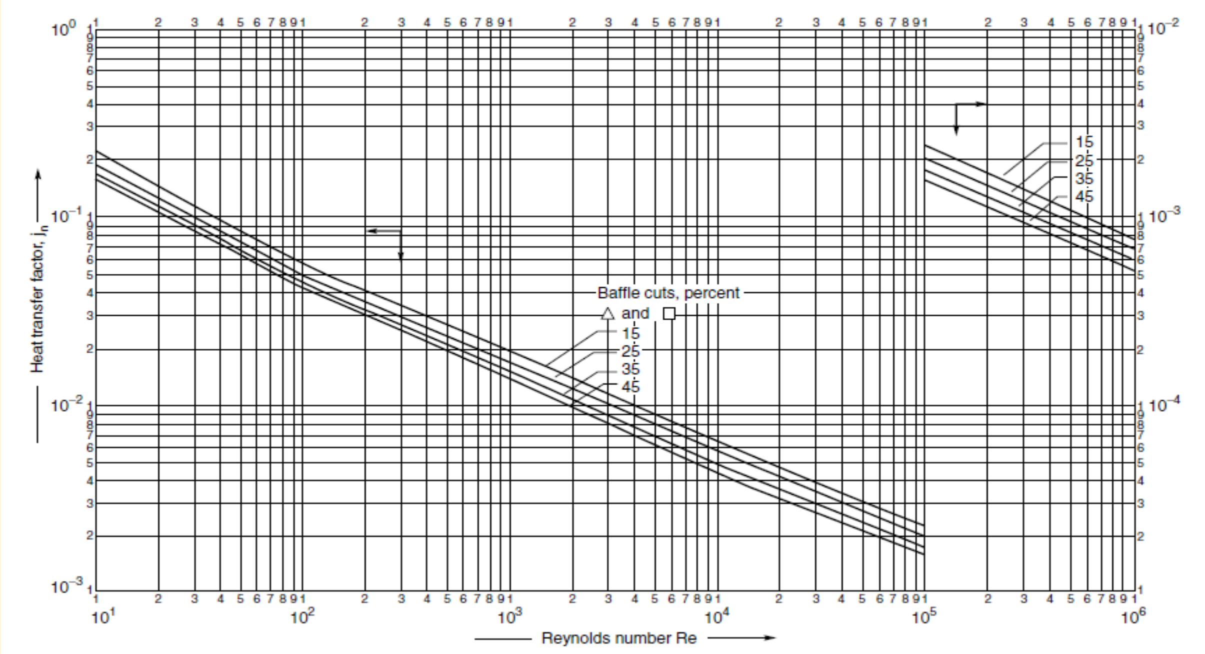
Prandtl No $= Pr = \frac{\mu C_p}{k} = \frac{7.5 \times 10^{-4} \times 2.9 \times 1000}{0.16} = 13.59$

From the figure, $j_H = 5 \times 10^{-3}$

$$j_H = \left(\frac{h_oD_e}{k}\right)\left(\frac{C_p\mu}{k}\right)^{-0.33}\left(\frac{D_eG_s}{\mu}\right)^{-1}\left(\frac{\mu}{\mu_w}\right)^{-0.44}$$

$$\boldsymbol{h_o = \frac{5 \times 10^{-3} \times 0.16}{14.2 \times 10^{-3}} \times (13.59)^{0.33}(13753)}$$

$$= \mathbf{1833}\ W/m^2K$$



8. $Calculating\ overall\ heat\ transfer\ coefficient\ (U)$

Thermal conductivity of the tube metal = 50 W/mK

Fouling factors: Treated water $h_{id} = 7750$ W/m^{2}K and Organic liquid, $h_{od} = 11{,}400$ W/m^{2}K

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{r_o ln\left({r_o}/{r_i}\right)}{k_w} + \frac{r_o}{r_i} \times \frac{1}{h_{id}} + \frac{r_o}{r_i} \times \frac{1}{h_d}$$

$$\frac{1}{U_o} = \frac{1}{1833} + \frac{1}{11400} + \frac{10 \times 10^{-3} ln\left({10}/{8}\right)}{50} + \frac{10}{8} \times \frac{1}{7750} + \frac{10}{8} \times \frac{1}{3289}$$

$$\frac{1}{U_o} = 5.455 \times 10^{-4} + 8.77 \times 10^{-5} + 4.463 \times 10^{-5} + 1.6129 \times 10^{-4} + 3.80 \times 10^{-4}$$

$$U_o = 820.264 \text{ W/m}^2\text{K}$$

The calculated value of U is well above the assumed value of 500 W/m^{2}K

9. $Calculating\ the\ required\ area$

$$A = \frac{Q}{U(LMTD)} = \frac{4785 \times 1000}{820.264 \times 26.16} = 223 \text{ m}^2$$

The area required is less than the area available (365.83 m^2)

10. *Estimation of tube side pressure drop*

For Re = 12577, $j_f = 4.5 \times 10^{-3}$

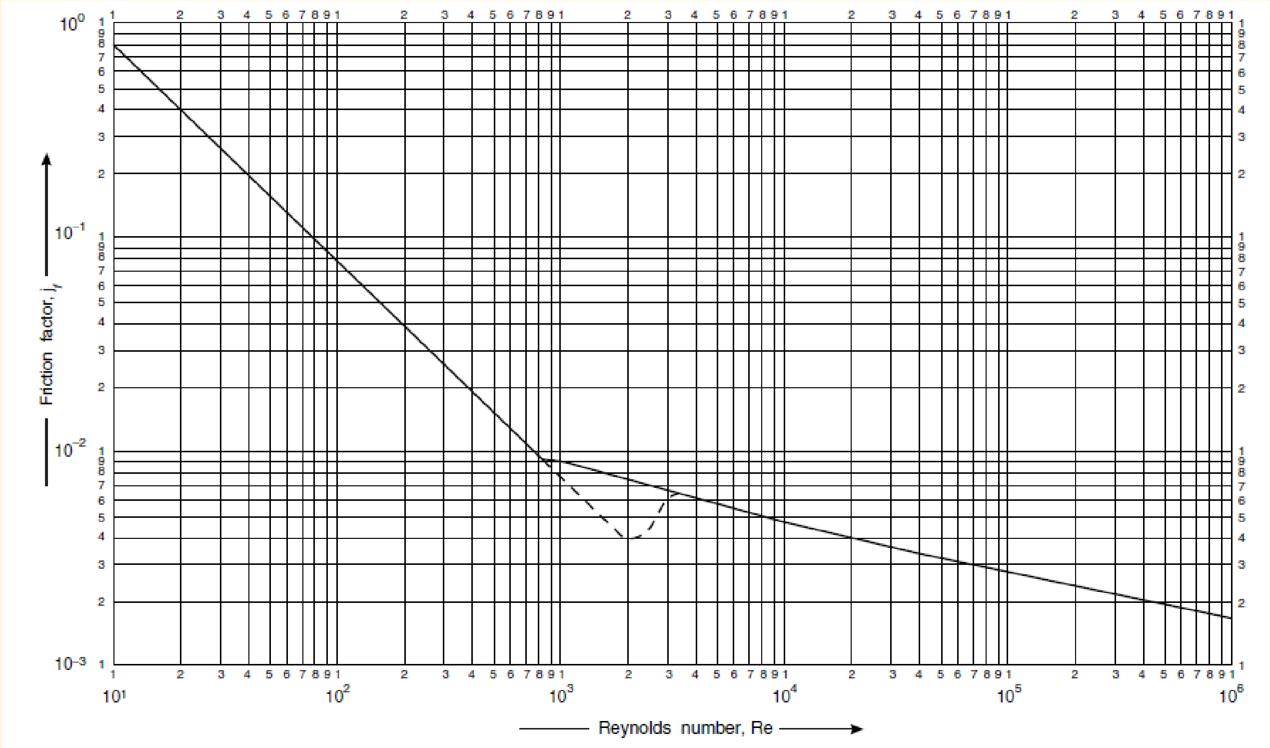
$$\Delta P_t = \frac{f G_t^2 L n}{2 g \rho_t d_i}\left(\frac{\mu}{\mu_w}\right)^{-0.14}$$

$$\Delta P_t = \frac{4.5 \times 10^{-3} \times (0.632 \times 995)^2 \times 4.83 \times 2}{2 \times 9.8 \times 995 \times 16 \times 10^{-3}}$$

ΔP_t = 55.09 kg/m^2 = 539.88 N/m^2

$$\Delta P_r = 4n\left(\frac{v^2}{2g}\right)\rho_t = 4 \times 2\left(\frac{0.632^2}{2\times 9.8}\right) \times 995$$

ΔP_r = 162 kg/m^2 = 1589.71 N/m^2



Total tube side pressure drop : $\Delta P_T = \Delta P_t + \Delta P_r = 539.88 + 1589.71 = 2129.59$ N/m^2 = 2.13 kN/m^2

Allowable pressure drop in tube side is 10 psi (= 68.93 kN/m^2)

Therefore, actual pressure drop is much lower than the allowable limit

11. *Estimation of shell side pressure drop*

For $Re = 13753$, $j_f = 4.0 \times 10^{-2}$

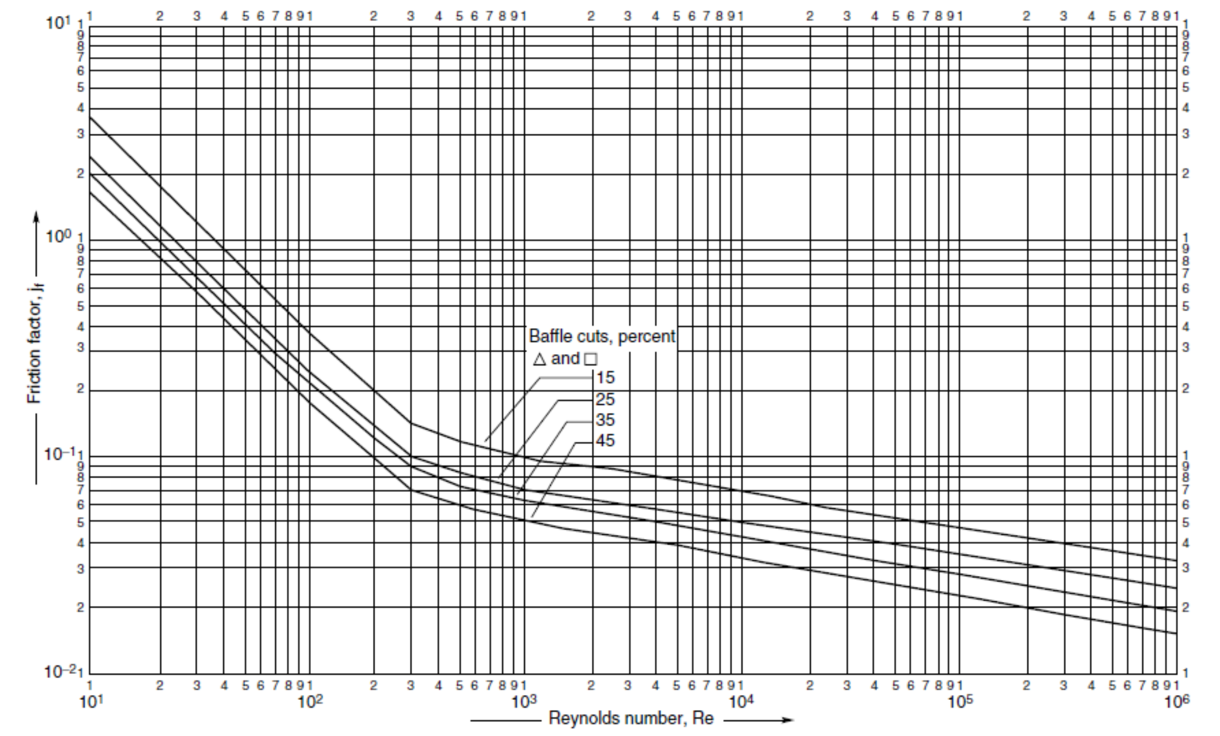
$$\Delta P_s = \frac{f_s G_s^2 D_s (N_b + 1)}{2 g \rho_s D_H} \left(\frac{\mu}{\mu_w}\right)^{-1}$$

$$N_b = \frac{4.83}{203.2 \times 10^{-3}} - 1 = 24$$

$$\Delta P_s = \frac{4.0 \times 10^{-2} \times (726.4)^2 \times 1016 \times (24 + 1)}{2 \times 9.8 \times 780 \times 14.2 \times 10^{-3}}$$

$\Delta P_s = 2469.484$ kg/m^2 = 24200 .95 N/m^2

$\Delta P_s = 24200$ .95 N/m^2 = 24.201 kN/m^2



Allowable pressure drop in tube side is 10 psi (= 68.93 kN/m^2)

Therefore, actual pressure drop is much lower than the allowable limit