Reg. No.										

MANIPAL INSTITUTE OF TECHNOLOGY
MANIPAL

A Constituent Institution of Manipal University

VII SEMESTER B.TECH. END SEM (Additional OPE) EXAMINATIONS (MAR 2021)

SUBJECT: DESIGN AND DRAWING OF CHEMICAL EQUIPMENT [CHE 4102]

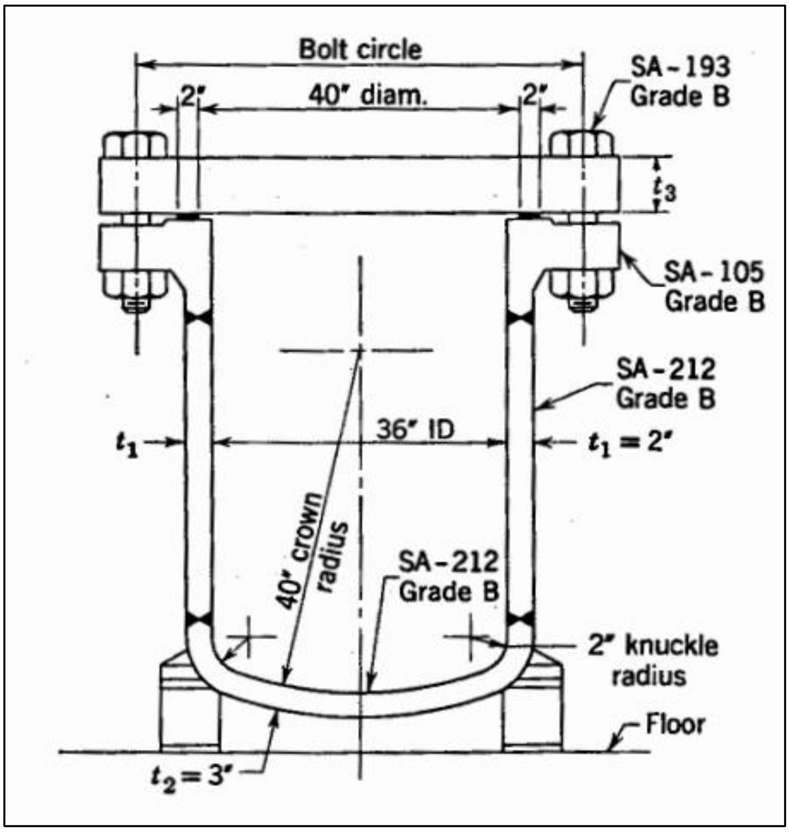
REVISED CREDIT SYSTEM

Date of Exam: 19/03/2021 **Time of Exam: 2 – 5 pm**

Time: 3 Hours **Max. Marks: 50**

Instructions to Candidates:

- Answer ALL the questions & missing data may be suitably assumed
- Use of code book/data book/formula sheet are permitted (**ATTACHED**)

1	Determine the thickness of the reaction vessel and the jacket from the following data: Vessel shell internal diameter: 2130 mm; Jacket length: 2500 mm; Width of channel jacket: 100 mm; Internal pressure (Shell): 0.35 N/mm^2; Internal pressure (Jacket): 0.55 N/mm^2; Design temperature: 150°C; Allowable stress value at design temperature: 96 N/mm^2; Spot radiography given. Dished head and bottom − Internal diameter: 2130 mm; Crown radius : 2130 mm; Knuckle radius: 128 mm	**5 + 5**
2	• Determine the maximum operating pressure for the vessel shown based on the shell dimensions and material. • For this pressure select a suitable gasket material and determine the optimum number of bolts (20 mm), minimum gasket width and flange thickness. The service temperature is 400°F.  **Hint:** For pressures above 20 bar, ring-joint gasket (m=5.5; y=124N/mm^2) can be chosen. For SA-212, Grade B : f = 1.19x10^8 N/m^2 ; For SA-193, Grade B : f = 1.36x10^9 N/m^2; For SA-105, Grade B : f = 1.19x10^9 N/m^2	**2.5 x 4**

3	80,000 kg/h distilled water (shell) has to be cooled from 34°C to 29.5°C in a 1 – 2 STHE. Raw water (tube) enters at 24°C and the exit temperature should not exceed 30°C. Use Chrome steel (1% Cr), 16 BWG, ¾” OD tube (OD =1.905cm; ID=1.575cm), 1” triangular pitch, number of tubes = 302, shell ID = 21.25”, and baffle spacing = 40% of shell ID. The fouling resistances (m^2 K/W) are 8.81×10^{-5} and 1.76×10^{-4} for distilled and raw water respectively. Assume a correction factor (F_T) of 0.85 for multi-pass. **Property** | **Raw Water** | **Distilled water** ρ (kg/m^3) | 997 | 995 μ (kg/m-sec) | 0.9×10^{-3} | 0.82×10^{-3} c_P (kJ/kg K) | 4.184 | 4.184 k (W/m K) | 0.618 | 0.623 i. the tube side heat transfer coefficient ii. the shell side heat transfer coefficient iii. the length of the tubes required. **Useful Formula:** **Tube Side:** $a_t = (\pi/4\ d_i^2)\ N/n$; $Nu = 0.027\ Re^{0.8}Pr^{0.33}$ **Shell side:** $a_s = D_s\ C\ B\ /\ P_T$; $Nu = 0.36\ Re^{0.55}Pr^{0.33}$ $D_{eq} = 4\{[0.44\ P_T^2 - (\pi d_o^2/8)]\ /\ [\pi d_o/2]\}$	**4+4+2**
4	A water-cooled, 1–1 shell-and-tube freon condenser with in-tube condensation of R-22 @37°C (c_{pL} = 1.305 kJ/kg K; $v_L = 8.3734 \times 10^{-4}$ m^3/kg; v_g = 0.01643 m^3/kg; $\mu_L = 1.86\times10^{-4}$ Pa.s; $\mu_g = 1.39\times10^{-5}$ Pa.s; k_L = 0.082 W/m K; λ= 169 kJ/kg; Pr = 2.96) has to be designed. City water (Inlet and outlet temperatures are 18°C & 26°C respectively) is used as solvent. The physical properties at the average temperature of the coolant are: c_{pL} = 4.181 kJ/kg K; $\mu_L = 959\times10^{-6}$ Pa.s; k_L = 0.606 W/m K; Pr = 6.61. Fouling resistance: 1.76×10^{-4} m^2 K/W for both inside and outside. **Design parameters:** Design cooling load: 100 kW**;** One tube pass; Pitch: 1” Square; Shell dia: 15.25”; Baffle Spacing: 35 cm; Number of Tubes: 137**;** Size of tubes: 0.75” OD & 0.68” ID; Vapor quality = 50%**.** i. Determine the shell side heat transfer coefficient. ii. By using *Cavallini and Zecchin* theory, calculate the tube side heat transfer coefficient. Take vapor quality = 50% iii. Calculate the length of the condenser.	**4+4+2**
5	A forward-feed evaporator (triple effect) is being used to evaporate a solution containing 5wt% solids to a concentrated solution of 50wt%. Saturated steam at 8.5 atm is being used. The feed rate is 2×10^5 kg/hr at 16°C. Take U_1 = 4500, U_2 = 2800 and U_3=1700 W/m^2K; ΔT_1 = 28 K, ΔT_2 = 23 K and ΔT_3 = 42 K. Calculate the surface area of the evaporator and the steam economy. Determine, i. the amount of concentrated liquor leaving each evaporator ii. the surface area of the evaporator and iii. the steam economy	**5+3+2**

FORMULA SHEET / DATA SHEET

CHE 4102 Design and Drawing of Chemical Process Equipment

1. Internal Pressure Vessels – Minimum thickness for various shapes

Cylinder: $t = \frac{PD_i}{2fJ-P} = \frac{PD_o}{2fJ+P}$	t : min thickness of the shell plates exclusive of corrosion allowance P : design pressure D_i : inside diameter of the shell D_o : outside diameter of the shell f : allowable stress value J : joint efficiency factor
Sphere: $t = \frac{PD_i}{4fJ-P} = \frac{PD_o}{4fJ+P}$	
Hemi Sphere: $t = \frac{PD_i}{4fJ}$	
Flat plate: $t = CD_e\sqrt{\frac{P}{f}}$	C : a design constant, dependent on the edge constraint D_e : nominal plate diameter
Ellipsoid: $t = \frac{PD_iC}{2fJ}$ & $C = \frac{1}{4}[2 + K^2]$	K : ratio of major to minor axis
Tori-sphere: $t = \frac{PD_iC}{2fJ}$ & $C = \frac{1}{4}\left[3 + \sqrt{\frac{R_c}{R_k}}\right]$	R_c : crown radius R_k : knuckle radius
Conical: $t = \frac{PD_i}{2fJ-P}\left(\frac{1}{\cos\alpha}\right)$	α : Half-cone angle

2. Volume of various shapes

Tori-sphere: $V = 0.0809D_i^3$	D_i : inside diameter of the shell
Ellipsoid: $V = \frac{\pi}{24}D_i^3$	
Conical: $V = \frac{\pi h}{12}\left[D_i^2 + D_i d + d^2\right]$	d: dia of the small end

3. External pressure vessels

Allowable working external pressure: $P_a = \frac{B}{14.22(D_o/t)}\ kg_f/cm^2$	t : min thickness of the shell plates exclusive of corrosion allowance D_o : outside diameter of the shell B : Factor B from Chart (Fig F. 2 – Indian Standard Code for unfired pressure vessel, BIS 2825-1969)

4. Flange and Gasket design

Actual width of gasket, $N = (G_o - G_i)/2$	G_o : outside diameter of the gasket G_i : inside diameter of the gasket
Ratio of gasket diameters, $\left(\frac{G_0}{G_i}\right) = \left(\frac{y-mP}{y-P(m+1)}\right)^{0.5}$	P : design pressure y : gasket seating stress m : gasket factor

Bolt load due to initial gasket load reaction, $W_{m1} = \pi b G y$	b_0 : Basic gasket seating width (before applying load) = N/2 b : Effective gasket seating width (after applying load) – $b = b_0$, when $b_0 \leq 6.3$mm – $b = \frac{1}{2}\sqrt{b_0}$, when $b_0 > 6.3$mm G : diameter at location of gasket load reaction = mean diameter of gasket contact face if $b_0 \leq 6.3$mm = (Inside diameter of gasket) + 2N – 2b if $b_0 > 6.3$mm
Bolt load at operating conditions, $W_{m2} = H + H_P$ H = Hydrostatic end force = $(\pi/4)\,G^2 P$ H_P = total joint contact surface compression = $\pi(2b)\,G\,m\,P$	
Minimum bolt area, $A_{m1} = (W_{m1}/f_a)$ and $A_{m2} = (W_{m2}/f_b)$	f_a & f_b : allowable stress values at atmospheric and operating conditions respectively Bolt Circle Diameter, B = OD of gasket + 2(bolt diameter) + 12mm
Minimum gasket width, $N_{min} = (A_b f_a)/2\pi y G$	
h_G = radial distance from gasket load reaction to the bolt circle = (B – G)/2	
Thickness of the flange, $t_f = G\left[\frac{P}{K f}\right]^{0.5}$ & $K = \dfrac{1}{0.3 + \dfrac{1.5(W_m)(h_G)}{(H)(G)}}$	

5. Process Design of Shell and Tube Heat Exchanger

Heat Duty, $Q = (\dot{m} C_p \Delta T)_{hot} = (\dot{m} C_p \Delta T)_{cold}$	$\dot{m}$: mass flowrate C_p : specific heat capacity ΔT : Temperature difference Hot : hot stream Cold: cold stream
Total area required, $A_o = (Q / U_{OD}\, \Delta T_{LMTD})$	U_{OD}: Overall heat transfer coefficient including dirt factor ΔT_{LMTD} : Log mean temperature difference
Number of tubes, $N = A_o / \pi d_o L$	L = length of the tubes d_o = outside diameter of the tubes
Equivalent diameter, D_{eq} Triangular Pitch: $D_{eq} = 4\{[0.44\,P_T^2 - (\pi d_o^2/8)] / [\pi d_o/2]\}$ Square Pitch: $D_{eq} = 4\{[P_T^2 - (\pi d_o^2/4)] / [\pi d_o]\}$	P_T = pitch d_o = outside diameter of the tubes
Tube side cross sectional area, $a_t = (\pi/4\, d_i^2)\, N/n$	N : number of tubes n : number of tube passes
Shell area available for flow, $a_s = D_s\, C\, B / P_T$	D_s : shell diameter B: Baffle spacing

	C : clearance, = $P_T - d_o$ P_T = pitch d_o = outside diameter of the tubes
Tube Side: $Nu = 0.027\ Re^{0.8}Pr^{0.33}$ Shell side: $Nu = 0.36\ Re^{0.55}Pr^{0.33}$	Nu = Nusselt number Re = Reynolds number Pr = Prandl number
Clean overall heat transfer Coefficient, U_{OC} $[1/U_{OC}] = [1/h_o] + [d_o/d_i][1/h_i]$	h_o = individual heat transfer coefficient (outside) h_i = individual heat transfer coefficient (inside) d_i = inside diameter of the tubes d_o = outside diameter of the tubes
Overall heat transfer coefficient including dirt factor $[1/U_{OD}] = [1/U_{OC}] + [1/h_{di}] + [1/h_{do}]$	h_{di} : heat transfer coefficient for deposit (tubes) h_{di} : heat transfer coefficient for deposit (shell)
Shell side pressure drop, ΔP_s $\Delta P_s = \dfrac{f\ G_s^2 D_s}{2\times10^6\ D_e s}\dfrac{L}{B} \qquad (kN/m^2)$	f = friction factor = $1.87\ (Re_s)^{-0.2}$ Re_s = Shell side Reynolds number G_s = mass velocity D_s = shell diameter D_e = equivalent diameter of shell in m L = length of the tube B = baffle spacing s = specific gravity
Tube side pressure drop, ΔP_t $\Delta P_t = \dfrac{f G_t^2 Ln}{2\times10^6\ d_i s} + 2.26\ nv^2 s \qquad (kN/m^2)$	f = friction factor = $0.72\ (Re_t)^{-0.33}$ Re_t = Tube side Reynolds number n = number of passes L = length of the tube G_t = mass velocity d_i = tube diameter s = specific gravity

6. Process Design of Condenser

Nusselt's Theory (Laminar Flow): $Nu = \frac{h_m d}{k_l} = 0.728 \left[\frac{\rho_l(\rho_l-\rho_g) g\ \lambda\ d^3}{\mu_l\ (T_{sat}-T_w)\ k_l}\right]^{1/4}$	h_m : mean condensation film coefficient d : diameter of tube ρ_l: condensate density k_l: thermal conductivity μ_l: condensate viscosity g : gravitational acceleration λ : latent heat of condensation x: is the vapor quality, the mass fraction of vapor G : Mass velocity
Travis theory (Turbulent): $Re_l = \dfrac{G(1-x)d}{\mu_l}$ $Nu = \frac{h_{TP} d}{k_l} = Pr_l Re_l^{0.9} \frac{F_l(X_{tt})}{F_2(Re_l, Pr_l)}$	

Non-dimensional parameter, F_1, is $$F_1 = 0.15\left[\frac{1}{X_{tt}} + \frac{2.85}{X_{tt}^{0.476}}\right]$$ X_{tt} is the Lockhart – Martinelli parameter $$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_g}\right)^{0.1}$$ $F_2 = 0.7\, Pr_l Re_l^{0.5}\ for\ Re_l \leq 50$ $F_2 = 5\, Pr_l + 5\ln\left[1 + Pr_l\left(0.09636\, Re_l^{0.585} - 1\right)\right]\ for\ 50 < Re_l \leq 1125$ $F_2 = 5\, Pr_l + 5\ln(1 + 5\, Pr_l) + 2.5\ln(0.00313\, Re_l^{0.812})\ for\ Re_l > 1125$	
Cavallini and Zecchin theory (Turbulent): $$h_{TP} = 0.05 Re_{eq}^{0.8} Pr_l^{0.33} \frac{k_l}{d}$$ $$Re_{eq} = Re_v \left[\frac{\mu_v}{\mu_l}\right]\left[\frac{\rho_l}{\rho_v}\right]^{0.5} + Re_l$$ $$Re_l = \frac{G(1-x)d}{\mu_l}$$ $$Re_v = \frac{Gxd}{\mu_v}$$	
Shaw theory (Turbulent): $$h_{TP} = h_l\left[1 + \frac{3.8}{Z^{0.95}}\right]$$ $$Z = \left[\frac{1-x}{x}\right]^{0.8} Pr^{0.4}$$ $$h_l = 0.023\left[\frac{G(1-x)d}{\mu_l}\right]^{0.8}\frac{Pr^{0.4}k}{d}$$	

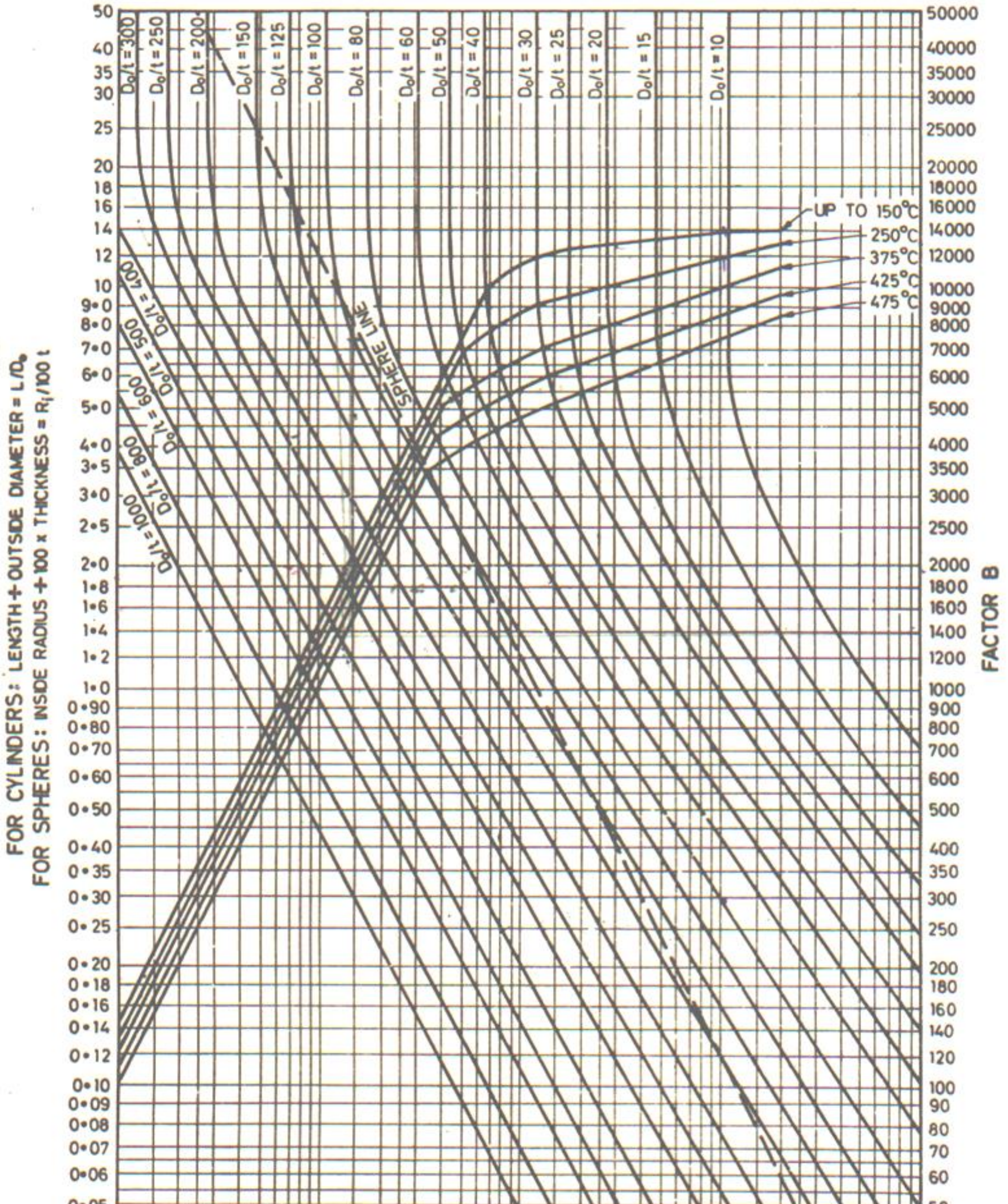


FIG. F.2 CHARTS FOR DETERMINING SHELL THICKNESSES OF CYLINDRICAL AND SPHERICAL VESSELS UNDER EXTERNAL PRESSURE, CARBON AND LOW ALLOY STEEL

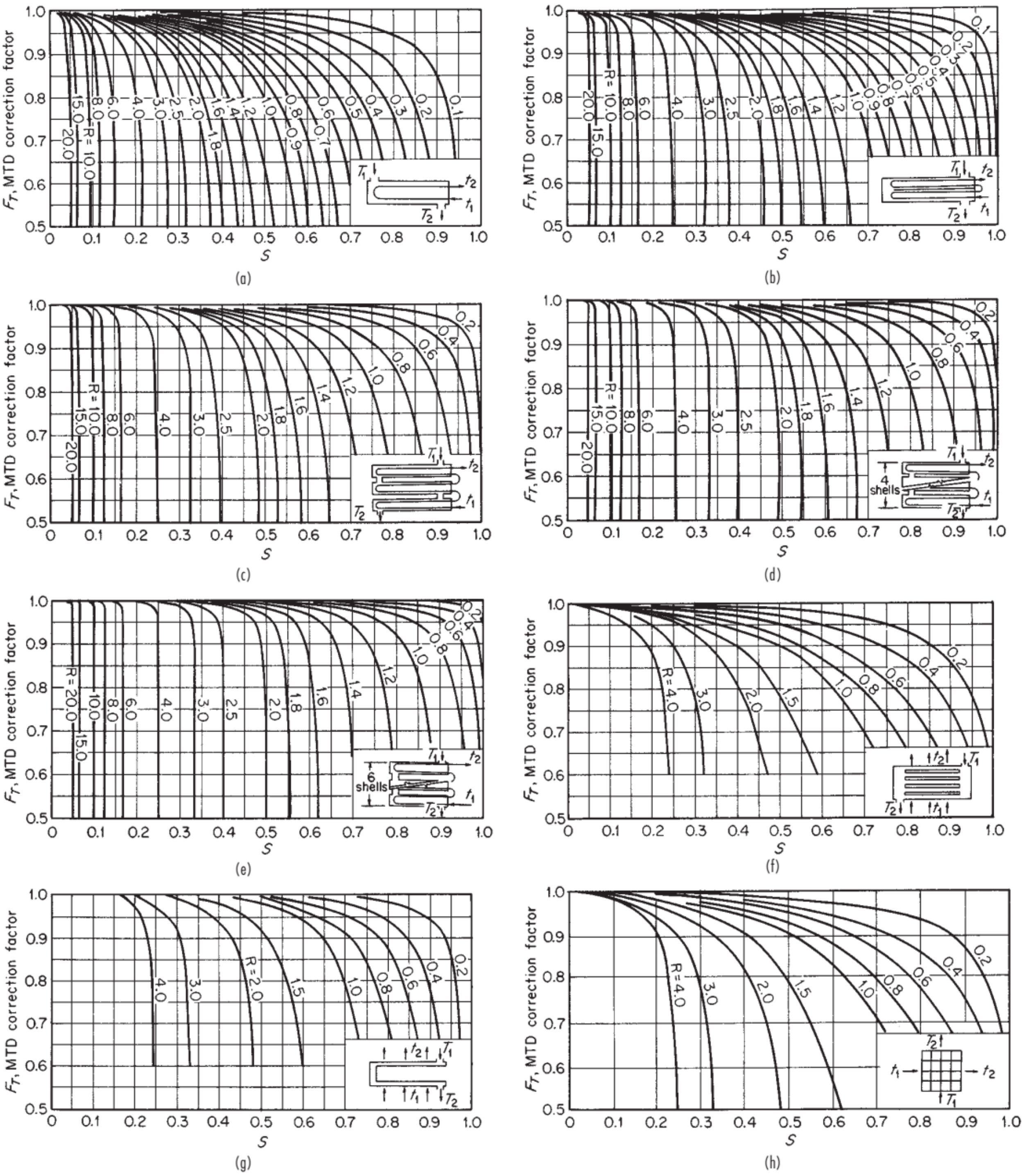


FIG. 11-4 LMTD correction factors for heat exchangers. In all charts, $R = (T_1 - T_2)/(t_2 - t_1)$ and $S = (t_2 - t_1)/(T_1 - t_1)$. (*a*) One shell pass, two or more tube passes. (*b*) Two shell passes, four or more tube passes. (*c*) Three shell passes, six or more tube passes. (*d*) Four shell passes, eight or more tube passes. (*e*) Six shell passes, twelve or more tube passes. (*f*) Cross-flow, one shell pass, one or more parallel rows of tubes. (*g*) Cross-flow, two passes, two rows of tubes; for more than two passes, use $F_T = 1.0$. (*h*) Cross-flow, one shell pass, one tube pass, both fluids unmixed

A.2-9 Properties of Saturated Steam and Water (Steam Table), SI Units

Temperature (°C)	Vapor Pressure (kPa)	Specific Volume (m^3/kg)		Enthalpy (kJ/kg)		Entropy ($kJ/kg \cdot K$)	
		Liquid	Sat'd Vapor	Liquid	Sat'd Vapor	Liquid	Sat'd Vapor
0.01	0.6113	0.0010002	206.136	0.00	2501.4	0.0000	9.1562
3	0.7577	0.0010001	168.132	12.57	2506.9	0.0457	9.0773
6	0.9349	0.0010001	137.734	25.20	2512.4	0.0912	9.0003
9	1.1477	0.0010003	113.386	37.80	2517.9	0.1362	8.9253
12	1.4022	0.0010005	93.784	50.41	2523.4	0.1806	8.8524
15	1.7051	0.0010009	77.926	62.99	2528.9	0.2245	8.7814
18	2.0640	0.0010014	65.038	75.58	2534.4	0.2679	8.7123
21	2.487	0.0010020	54.514	88.14	2539.9	0.3109	8.6450
24	2.985	0.0010027	45.883	100.70	2545.4	0.3534	8.5794
25	3.169	0.0010029	43.360	104.89	2547.2	0.3674	8.5580
27	3.567	0.0010035	38.774	113.25	2550.8	0.3954	8.5156
30	4.246	0.0010043	32.894	125.79	2556.3	0.4369	8.4533
33	5.034	0.0010053	28.011	138.33	2561.7	0.4781	8.3927
36	5.947	0.0010063	23.940	150.86	2567.1	0.5188	8.3336
40	7.384	0.0010078	19.523	167.57	2574.3	0.5725	8.2570
45	9.593	0.0010099	15.258	188.45	2583.2	0.6387	8.1648
50	12.349	0.0010121	12.032	209.33	2592.1	0.7038	8.0763
55	15.758	0.0010146	9.568	230.23	2600.9	0.7679	7.9913
60	19.940	0.0010172	7.671	251.13	2609.6	0.8312	7.9096
65	25.03	0.0010199	6.197	272.06	2618.3	0.8935	7.8310
70	31.19	0.0010228	5.042	292.98	2626.8	0.9549	7.7553
75	38.58	0.0010259	4.131	313.93	2635.3	1.0155	7.6824
80	47.39	0.0010291	3.407	334.91	2643.7	1.0753	7.6122
85	57.83	0.0010325	2.828	355.90	2651.9	1.1343	7.5445
90	70.14	0.0010360	2.361	376.92	2660.1	1.1925	7.4791
95	84.55	0.0010397	1.9819	397.96	2668.1	1.2500	7.4159
100	101.35	0.0010435	1.6729	419.04	2676.1	1.3069	7.3549

A.2-9 **SI Units,** *Continued*

Temperature (°C)	Vapor Pressure (kPa)	Specific Volume (m^3/kg)		Enthalpy (kJ/kg)		Entropy (kJ/kg · K)	
		Liquid	Sat'd Vapor	Liquid	Sat'd Vapor	Liquid	Sat'd Vapor
105	120.82	0.0010475	1.4194	440.15	2683.8	1.3630	7.2958
110	143.27	0.0010516	1.2102	461.30	2691.5	1.4185	7.2387
115	169.06	0.0010559	1.0366	482.48	2699.0	1.4734	7.1833
120	198.53	0.0010603	0.8919	503.71	2706.3	1.5276	7.1296
125	232.1	0.0010649	0.7706	524.99	2713.5	1.5813	7.0775
130	270.1	0.0010697	0.6685	546.31	2720.5	1.6344	7.0269
135	313.0	0.0010746	0.5822	567.69	2727.3	1.6870	6.9777
140	316.3	0.0010797	0.5089	589.13	2733.9	1.7391	6.9299
145	415.4	0.0010850	0.4463	610.63	2740.3	1.7907	6.8833
150	475.8	0.0010905	0.3928	632.20	2746.5	1.8418	6.8379
155	543.1	0.0010961	0.3468	653.84	2752.4	1.8925	6.7935
160	617.8	0.0011020	0.3071	675.55	2758.1	1.9427	6.7502
165	700.5	0.0011080	0.2727	697.34	2763.5	1.9925	6.7078
170	791.7	0.0011143	0.2428	719.21	2768.7	2.0419	6.6663
175	892.0	0.0011207	0.2168	741.17	2773.6	2.0909	6.6256
180	1002.1	0.0011274	0.19405	763.22	2778.2	2.1396	6.5857
190	1254.4	0.0011414	0.15654	807.62	2786.4	2.2359	6.5079
200	1553.8	0.0011565	0.12736	852.45	2793.2	2.3309	6.4323
225	2548	0.0011992	0.07849	966.78	2803.3	2.5639	6.2503
250	3973	0.0012512	0.05013	1085.36	2801.5	2.7927	6.0730
275	5942	0.0013168	0.03279	1210.07	2785.0	3.0208	5.8938
300	8581	0.0010436	0.02167	1344.0	2749.0	3.2534	5.7045

Source: Abridged from J. H. Keenan, F. G. Keyes, P. G. Hill, and J. G. Moore, *Steam Tables—Metric Units.* New New York: John Wiley & Sons, Inc., 1969. Reprinted by permission of John Wiley & Sons, Inc.