UNIVERSITI TEKNOLOGI PETRONAS

FINAL EXAMINATION
JANUARY 2025 SEMESTER

COURSE : CFB1063 - PROCESS HEAT TRANSFER

DATE : 14 APRIL 2025 (MONDAY)

TIME : 9.00 AM - 12.00 NOON (3 HOURS)

INSTRUCTIONS TO CANDIDATES

1. Answer **ALL** questions in the Answer Booklet.
2. Begin **EACH** answer on a new page in the Answer Booklet.
3. Indicate clearly answers that are cancelled, if any.
4. Where applicable, show clearly steps taken in arriving at the solutions and indicate **ALL** assumptions, if any.
5. **DO NOT** open this Question Booklet until instructed.

Note :

i. There are **SEVENTEEN (17)** pages in this Question Booklet including the cover page and appendix.

ii. **DOUBLE-SIDED** Question Booklet.

1. a. A spherical tank is insulated to reduce heat loss from it. However, measurements indicate that the rate of heat loss has increased instead of decreasing. Can the measurements be right? Discuss your answer.

[5 marks]

b. Steam at 300°C is flowing inside a steel pipe (k = 56 W/m·°C) whose inner and outer diameters are 8 cm and 10 cm, respectively, in an environment at 30°C. A layer of insulation (k = 0.043 W/m·°C) with the thickness of 12 cm is installed at the outer surface of the pipe. The heat transfer coefficients, inside and outside the pipe are 110 W/m^2·°C and 20 W/m^2·°C, respectively. Determine the annual cost (365 days) of this energy lost if steam is generated in a natural gas furnace that has an efficiency of 80%. Given the price of natural gas is RM 0.48/therm (1 therm = 105,500 kJ) and the length of the pipe is 5 m.

[10 marks]

c. A square opaque surface with 50 cm x 50 cm has an absorptivity of 0.4 between 0-5 μm, 0.3 between 5-10 μm and 0.2 above 10 μm. Determine the reflected energy of the opaque surface at 4000 K.

[9 marks]

2. a. Air at velocity of 1.5 km/min and temperature of 25°C is flowing across a cylindrical pipe with diameter of 20 cm and length of 10 m.

i. Explain the physical significant of Prandtl number (Pr) in convection heat transfer process.

[3 marks]

ii. Determine the rate of heat transfer if the surface temperature of the pipe is 75°C.

[8 marks]

b. Water at 20°C is heated by passing it through 1.5 cm internal diameter thin-walled tube. Heat is supplied to water by steam that condenses outside the tube at 140°C.

i. If the water is to be heated to 70°C at a rate of 0.33 kg/s, calculate the length of the tube that needs to be used.

[11 marks]

ii. Define **TWO (2)** types of entrance regions in internal forced convection heat transfer.

[4 marks]

3. a. A 15 m long and 8 cm outer diameter copper-scored pipe is submerged in water at 475.8 kPa pressure. Estimate the maximum rate of evaporation of this boiling process.

[10 marks]

b. Saturated propane at a pressure of 1215 kPa is condensed over horizontal tubes arranged in 20 tubes high and 6 tubes wide, each with a diameter of 5 cm and length of 0.8 m. The tube surfaces are maintained at a uniform temperature of 5°C.

i. Evaluate the rate of condensation.

[10 marks]

ii. For film and dropwise condensation, which one is a more effective mechanism of heat transfer? Justify your answer.

[4 marks]

4. In a chemical processing plant, an alcohol (c_p = 2.23 kJ/kg·°C) is heated from 20°C to 65°C by geothermal water (c_p = 4.32 kJ/kg·°C) using 2-shell passes and 12-tube passes heat exchanger. The geothermal water enters the 0.8 cm-diameter thin-walled tubes at 90°C and leaves at 38°C. The total length of the tube is 45 m. The convection heat transfer coefficient is 22 W/m^2·°C on the alcohol side and 115 W/m^2·°C on the geothermal water side.

a. Explain the heat transfer mechanisms involved during heat transfer from the hot fluid to the cold fluid in the heat exchanger.

[5 marks]

b. Compare the rate of heat transfer in the heat exchanger before and after fouling occurs if the fouling factor is 0.0096 m^2·°C/W on the inner surface of the tube.

[15 marks]

c. Estimate the effectiveness of the heat exchanger before fouling.

[6 marks]

– END OF PAPER –

APPENDIX

Equations:

$$R_{conv} = \frac{1}{hA}, \; R_{cond} = \frac{L}{kA}, \; R_{cond,cyl} = \frac{\ln(r_2/r_1)}{2\pi k_1 L}, \; R_{cond,sph} = \frac{r_2 - r_1}{4\pi r_1 r_2 k}$$

$$\dot{Q} = \frac{\Delta T}{R_{Total}}$$

$$\dot{Q} = hA_s(T_s - T_\infty)$$

$$\dot{Q} = hA_s \Delta T_{lm}$$

$$\dot{Q} = \dot{m} c_p (T_e - T_i)$$

$$\dot{q}_s = h(T_s - T_m)$$

$$\Delta T_{lm} = \frac{(T_s - T_e) - (T_s - T_i)}{\ln[(T_s - T_e)/(T_s - T_i)]}$$

Radiation Heat Trasnfer

$$E = \frac{Q}{A} = \varepsilon \sigma T^4, \sigma = 5.67 \times 10^{-8}\, \mathrm{W/m^2 \cdot K^4}$$

Forced convection correlation

$$\mathrm{Re} = \frac{\rho V L_c}{\mu} = \frac{V L_c}{\nu}, \quad Nu = \frac{h L_c}{k}$$

$L_c = L$ for flat plate, $L_c = D$ for cylinder and sphere

$$V = \text{velocity} = \frac{\dot{m}}{\rho A_c}, \quad A_c = \text{cross-sectional area}$$

Geometry	Condition	Nu relation
Flow inside duct	Laminar (Re< 2,300) Constant heat flux	Nu = 4.36 (fully developed laminar region)
	Laminar (Re< 2,300) Constant surface temperature	Nu = 3.66 (fully developed laminar region) $Nu = 3.66 + \frac{0.065(D/L)\mathrm{Re}\,\mathrm{Pr}}{1+0.04[(D/L)\mathrm{Re}\,\mathrm{Pr}]^{2/3}}$ (for entry region)
	Turbulent Re>10,000	$Nu = 0.023\mathrm{Re}^{0.8}\,\mathrm{Pr}^{n}$ (fully developed turbulent region, n = 0.3 for cooling, n = 0.4 for heating)
	Entry length	$L_h = L_t = 10D$ (turbulent) $L_t = 0.05\,\mathrm{Re}\,\mathrm{Pr}\,D$ (laminar)
Flow over flat plate	Laminar $\mathrm{Re_L} < 5\times 10^5$	$Nu = 0.664\,\mathrm{Re}_L^{\;0.5}\,\mathrm{Pr}^{1/3}$
	Turbulent $5\times 10^5 < \mathrm{Re_L} < 10^7$	$Nu = 0.037\,\mathrm{Re}_L^{\;0.8}\,\mathrm{Pr}^{1/3}$
Flow over circular cylinder	Re.Pr >0.2	$Nu = 0.3 + \frac{0.62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}}{\left(1+(0.4/\mathrm{Pr})^{2/3}\right)^{1/4}}\left\{1+\left(\frac{\mathrm{Re}}{282{,}000}\right)^{5/8}\right\}^{4/5}$

Boiling and condensation correlation

Condition	Correlation
Boiling	$\dot{q}_{boiling} = hA_s(T_s - T_{sat}) = hA_s \Delta T_{excess}$
	$\dot{q}_{nucleate} = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left[\frac{c_{pl}(T_s - T_{sat})}{C_{sf} h_{fg} \Pr_l^n} \right]^3$ g = 9.81 m/s²
	$\dot{q}_{\max} = C_{cr} h_{fg} \left[\sigma\, g\, \rho_v^2 (\rho_l - \rho_v) \right]^{1/4}$
	$\dot{q}_{film} = C_{film} \left[\frac{g\, k_v^3 \rho_v (\rho_l - \rho_v) \left[h_{fg} + 0.4 c_{pv}(T_s - T_{sat}) \right]}{\mu_v D (T_s - T_{sat})} \right]^{1/4} (T_s - T_{sat})$ C_{film} = 0.62 (horizontal cylinders) = 0.67 for spheres
Condensation	Modified latent heat of evaporation $h^*_{fg} = h_{fg} + 0.68 c_{pl} (T_{sat} - T_s)$
	$\dot{Q}_{conden} = hA_s(T_{sat} - T_s) = \dot{m} h^*_{fg}$
	Laminar Flow on Vertical Plate (0 < Re < 30) $h_{vert} = 0.943 \left[\frac{g\, \rho_l (\rho_l - \rho_v) \left[h^*_{fg} k_l^3 \right]}{\mu_l (T_{sat} - T_s) L} \right]^{1/4}$
	Wavy Laminar Flow on Vertical Plates (30<Re<1800) $h_{vert,wavy} = \frac{\mathrm{Re}\, k_l}{1.08\, \mathrm{Re}^{1.22} - 5.2} \left(\frac{g}{\nu_l^2} \right)^{1/3}$ $\mathrm{Re}_{vert,wavy} = \left[4.81 + \frac{3.70 L k_l (T_{sat} - T_s)}{\mu_l h^*_{fg}} \left(\frac{g}{\nu_l^2} \right)^{1/3} \right]^{0.82}$

Condensation	Turbulent Flow on Vertical Plates (Re>1800) $h_{vert,turbulent} = \frac{\text{Re}\, k_l}{8750 + 58\,\text{Pr}^{-0.5}(\text{Re}^{0.75} - 253)}\left(\frac{g}{\nu_l^2}\right)^{1/3}$ $\text{Re}_{vert,turbulent} = \left[\frac{0.0690\, L k_l\, \text{Pr}_l^{0.5}(T_{sat} - T_s)}{\mu_l h^*_{fg}}\left(\frac{g}{\nu_l^2}\right)^{1/3} - 151\,\text{Pr}_l^{0.5} + 253\right]^{4/3}$ Laminar and Wavy Laminar on Tilted Vertical Plates $h_{titled} = h_{vert}(\cos\theta)^{1/4}$
	Horizontal Tubes and Spheres $h_{horiz} = 0.729\left(\frac{g\,\rho_l(\rho_l - \rho_v)\,h^*_{fg}\,k_l^3}{\mu_l(T_{sat} - T_s)D}\right)^{1/4}$ $\frac{h_{vert}}{h_{horiz}} = 1.29\left(\frac{D}{L}\right)^{1/4}$
	Horizontal Tube Banks $h_{horiz,\,N\,tubes} = 0.729\left(\frac{g\,\rho_l(\rho_l - \rho_v)\,h^*_{fg}\,k_l^3}{\mu_l(T_{sat} - T_s)ND}\right)^{1/4} = \frac{1}{N^{1/4}}h_{horiz,\,1\,tube}$

Heat exchanger correlation

Condition	Correlation
Overall heat transfer coefficient	$\frac{1}{UA_s} = \frac{1}{U_i A_i} = \frac{1}{U_o A_o}$ $= R = \frac{1}{h_i A_i} + \frac{R_{f,i}}{A_i} + \frac{\ln(D_o/D_i)}{2\pi kL} + \frac{R_{f,o}}{A_o} + \frac{1}{h_o A_o}$ For thin-walled tube, $1/U = 1/h_i + 1/h_o$
Heat transfer	$\dot{Q} = \dot{m}_c c_{pc}(T_{c,out} - T_{c,in})$, $\dot{Q} = \dot{m}_h c_{ph}(T_{h,in} - T_{h,out})$ $\dot{Q}_{max} = C_{min}(T_{h,in} - T_{c,in})$ $\dot{Q} = UA_s F \Delta T_{lm,CF}$ $\Delta T_{lm,CF} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)}$
Parallel flow	$\Delta T_1 = T_{h,in} - T_{c,in}$ $\Delta T_2 = T_{h,out} - T_{c,out}$
Counter flow	$\Delta T_1 = T_{h,in} - T_{c,out}$ $\Delta T_2 = T_{h,out} - T_{c,in}$
Cross flow and multipass	$\Delta T_1 = T_{h,in} - T_{c,out}$ $\Delta T_2 = T_{h,out} - T_{c,in}$
Effectiveness relation	$c = C_{min}/C_{max}$ $\mathrm{NTU} = UA_s/C_{min}$ $C_h = \dot{m}_h C_{ph}$, $C_c = \dot{m}_c C_{pc}$

Properties of air at 1 atm pressure

Temp. T, °C	Density ρ, kg/m^3	Specific Heat c_p, J/kg·K	Thermal Conductivity k, W/m·K	Thermal Diffusivity α, m^2/s	Dynamic Viscosity μ, kg/m·s	Kinematic Viscosity ν, m^2/s	Prandtl Number Pr
−150	2.866	983	0.01171	4.158×10^{-6}	8.636×10^{-6}	3.013×10^{-6}	0.7246
−100	2.038	966	0.01582	8.036×10^{-6}	1.189×10^{-5}	5.837×10^{-6}	0.7263
−50	1.582	999	0.01979	1.252×10^{-5}	1.474×10^{-5}	9.319×10^{-6}	0.7440
−40	1.514	1002	0.02057	1.356×10^{-5}	1.527×10^{-5}	1.008×10^{-5}	0.7436
−30	1.451	1004	0.02134	1.465×10^{-5}	1.579×10^{-5}	1.087×10^{-5}	0.7425
−20	1.394	1005	0.02211	1.578×10^{-5}	1.630×10^{-5}	1.169×10^{-5}	0.7408
−10	1.341	1006	0.02288	1.696×10^{-5}	1.680×10^{-5}	1.252×10^{-5}	0.7387
0	1.292	1006	0.02364	1.818×10^{-5}	1.729×10^{-5}	1.338×10^{-5}	0.7362
5	1.269	1006	0.02401	1.880×10^{-5}	1.754×10^{-5}	1.382×10^{-5}	0.7350
10	1.246	1006	0.02439	1.944×10^{-5}	1.778×10^{-5}	1.426×10^{-5}	0.7336
15	1.225	1007	0.02476	2.009×10^{-5}	1.802×10^{-5}	1.470×10^{-5}	0.7323
20	1.204	1007	0.02514	2.074×10^{-5}	1.825×10^{-5}	1.516×10^{-5}	0.7309
25	1.184	1007	0.02551	2.141×10^{-5}	1.849×10^{-5}	1.562×10^{-5}	0.7296
30	1.164	1007	0.02588	2.208×10^{-5}	1.872×10^{-5}	1.608×10^{-5}	0.7282
35	1.145	1007	0.02625	2.277×10^{-5}	1.895×10^{-5}	1.655×10^{-5}	0.7268
40	1.127	1007	0.02662	2.346×10^{-5}	1.918×10^{-5}	1.702×10^{-5}	0.7255
45	1.109	1007	0.02699	2.416×10^{-5}	1.941×10^{-5}	1.750×10^{-5}	0.7241
50	1.092	1007	0.02735	2.487×10^{-5}	1.963×10^{-5}	1.798×10^{-5}	0.7228
60	1.059	1007	0.02808	2.632×10^{-5}	2.008×10^{-5}	1.896×10^{-5}	0.7202
70	1.028	1007	0.02881	2.780×10^{-5}	2.052×10^{-5}	1.995×10^{-5}	0.7177
80	0.9994	1008	0.02953	2.931×10^{-5}	2.096×10^{-5}	2.097×10^{-5}	0.7154
90	0.9718	1008	0.03024	3.086×10^{-5}	2.139×10^{-5}	2.201×10^{-5}	0.7132
100	0.9458	1009	0.03095	3.243×10^{-5}	2.181×10^{-5}	2.306×10^{-5}	0.7111
120	0.8977	1011	0.03235	3.565×10^{-5}	2.264×10^{-5}	2.522×10^{-5}	0.7073
140	0.8542	1013	0.03374	3.898×10^{-5}	2.345×10^{-5}	2.745×10^{-5}	0.7041
160	0.8148	1016	0.03511	4.241×10^{-5}	2.420×10^{-5}	2.975×10^{-5}	0.7014
180	0.7788	1019	0.03646	4.593×10^{-5}	2.504×10^{-5}	3.212×10^{-5}	0.6992
200	0.7459	1023	0.03779	4.954×10^{-5}	2.577×10^{-5}	3.455×10^{-5}	0.6974
250	0.6746	1033	0.04104	5.890×10^{-5}	2.760×10^{-5}	4.091×10^{-5}	0.6946
300	0.6158	1044	0.04418	6.871×10^{-5}	2.934×10^{-5}	4.765×10^{-5}	0.6935
350	0.5664	1056	0.04721	7.892×10^{-5}	3.101×10^{-5}	5.475×10^{-5}	0.6937
400	0.5243	1069	0.05015	8.951×10^{-5}	3.261×10^{-5}	6.219×10^{-5}	0.6948
450	0.4880	1081	0.05298	1.004×10^{-4}	3.415×10^{-5}	6.997×10^{-5}	0.6965
500	0.4565	1093	0.05572	1.117×10^{-4}	3.563×10^{-5}	7.806×10^{-5}	0.6986
600	0.4042	1115	0.06093	1.352×10^{-4}	3.846×10^{-5}	9.515×10^{-5}	0.7037
700	0.3627	1135	0.06581	1.598×10^{-4}	4.111×10^{-5}	1.133×10^{-4}	0.7092
800	0.3289	1153	0.07037	1.855×10^{-4}	4.362×10^{-5}	1.326×10^{-4}	0.7149
900	0.3008	1169	0.07465	2.122×10^{-4}	4.600×10^{-5}	1.529×10^{-4}	0.7206
1000	0.2772	1184	0.07868	2.398×10^{-4}	4.826×10^{-5}	1.741×10^{-4}	0.7260
1500	0.1990	1234	0.09599	3.908×10^{-4}	5.817×10^{-5}	2.922×10^{-4}	0.7478
2000	0.1553	1264	0.11113	5.664×10^{-4}	6.630×10^{-5}	4.270×10^{-4}	0.7539

Properties of saturated water

Temp. T, °C	Saturation Pressure P_{sat}, kPa	Density ρ, kg/m³ Liquid	Density Vapor	Enthalpy of Vaporization h_{fg}, kJ/kg	Specific Heat c_p, J/kg·K Liquid	Specific Heat Vapor	Thermal Conductivity k, W/m·K Liquid	Thermal Conductivity Vapor	Dynamic Viscosity μ, kg/m·s Liquid	Dynamic Viscosity Vapor	Prandtl Number Pr Liquid	Prandtl Number Vapor	Volume Expansion Coefficient β, 1/K Liquid
0.01	0.6113	999.8	0.0048	2501	4217	1854	0.561	0.0171	1.792×10^{-3}	0.922×10^{-5}	13.5	1.00	-0.068×10^{-3}
5	0.8721	999.9	0.0068	2490	4205	1857	0.571	0.0173	1.519×10^{-3}	0.934×10^{-5}	11.2	1.00	0.015×10^{-3}
10	1.2276	999.7	0.0094	2478	4194	1862	0.580	0.0176	1.307×10^{-3}	0.946×10^{-5}	9.45	1.00	0.733×10^{-3}
15	1.7051	999.1	0.0128	2466	4185	1863	0.589	0.0179	1.138×10^{-3}	0.959×10^{-5}	8.09	1.00	0.138×10^{-3}
20	2.339	998.0	0.0173	2454	4182	1867	0.598	0.0182	1.002×10^{-3}	0.973×10^{-5}	7.01	1.00	0.195×10^{-3}
25	3.169	997.0	0.0231	2442	4180	1870	0.607	0.0186	0.891×10^{-3}	0.987×10^{-5}	6.14	1.00	0.247×10^{-3}
30	4.246	996.0	0.0304	2431	4178	1875	0.615	0.0189	0.798×10^{-3}	1.001×10^{-5}	5.42	1.00	0.294×10^{-3}
35	5.628	994.0	0.0397	2419	4178	1880	0.623	0.0192	0.720×10^{-3}	1.016×10^{-5}	4.83	1.00	0.337×10^{-3}
40	7.384	992.1	0.0512	2407	4179	1885	0.631	0.0196	0.653×10^{-3}	1.031×10^{-5}	4.32	1.00	0.377×10^{-3}
45	9.593	990.1	0.0655	2395	4180	1892	0.637	0.0200	0.596×10^{-3}	1.046×10^{-5}	3.91	1.00	0.415×10^{-3}
50	12.35	988.1	0.0831	2383	4181	1900	0.644	0.0204	0.547×10^{-3}	1.062×10^{-5}	3.55	1.00	0.451×10^{-3}
55	15.76	985.2	0.1045	2371	4183	1908	0.649	0.0208	0.504×10^{-3}	1.077×10^{-5}	3.25	1.00	0.484×10^{-3}
60	19.94	983.3	0.1304	2359	4185	1916	0.654	0.0212	0.467×10^{-3}	1.093×10^{-5}	2.99	1.00	0.517×10^{-3}
65	25.03	980.4	0.1614	2346	4187	1926	0.659	0.0216	0.433×10^{-3}	1.110×10^{-5}	2.75	1.00	0.548×10^{-3}
70	31.19	977.5	0.1983	2334	4190	1936	0.663	0.0221	0.404×10^{-3}	1.126×10^{-5}	2.55	1.00	0.578×10^{-3}
75	38.58	974.7	0.2421	2321	4193	1948	0.667	0.0225	0.378×10^{-3}	1.142×10^{-5}	2.38	1.00	0.607×10^{-3}
80	47.39	971.8	0.2935	2309	4197	1962	0.670	0.0230	0.355×10^{-3}	1.159×10^{-5}	2.22	1.00	0.653×10^{-3}
85	57.83	968.1	0.3536	2296	4201	1977	0.673	0.0235	0.333×10^{-3}	1.176×10^{-5}	2.08	1.00	0.670×10^{-3}
90	70.14	965.3	0.4235	2283	4206	1993	0.675	0.0240	0.315×10^{-3}	1.193×10^{-5}	1.96	1.00	0.702×10^{-3}
95	84.55	961.5	0.5045	2270	4212	2010	0.677	0.0246	0.297×10^{-3}	1.210×10^{-5}	1.85	1.00	0.716×10^{-3}
100	101.33	957.9	0.5978	2257	4217	2029	0.679	0.0251	0.282×10^{-3}	1.227×10^{-5}	1.75	1.00	0.750×10^{-3}
110	143.27	950.6	0.8263	2230	4229	2071	0.682	0.0262	0.255×10^{-3}	1.261×10^{-5}	1.58	1.00	0.798×10^{-3}
120	198.53	943.4	1.121	2203	4244	2120	0.683	0.0275	0.232×10^{-3}	1.296×10^{-5}	1.44	1.00	0.858×10^{-3}
130	270.1	934.6	1.496	2174	4263	2177	0.684	0.0288	0.213×10^{-3}	1.330×10^{-5}	1.33	1.01	0.913×10^{-3}
140	361.3	921.7	1.965	2145	4286	2244	0.683	0.0301	0.197×10^{-3}	1.365×10^{-5}	1.24	1.02	0.970×10^{-3}
150	475.8	916.6	2.546	2114	4311	2314	0.682	0.0316	0.183×10^{-3}	1.399×10^{-5}	1.16	1.02	1.025×10^{-3}
160	617.8	907.4	3.256	2083	4340	2420	0.680	0.0331	0.170×10^{-3}	1.434×10^{-5}	1.09	1.05	1.145×10^{-3}
170	791.7	897.7	4.119	2050	4370	2490	0.677	0.0347	0.160×10^{-3}	1.468×10^{-5}	1.03	1.05	1.178×10^{-3}
180	1,002.1	887.3	5.153	2015	4410	2590	0.673	0.0364	0.150×10^{-3}	1.502×10^{-5}	0.983	1.07	1.210×10^{-3}
190	1,254.4	876.4	6.388	1979	4460	2710	0.669	0.0382	0.142×10^{-3}	1.537×10^{-5}	0.947	1.09	1.280×10^{-3}
200	1,553.8	864.3	7.852	1941	4500	2840	0.663	0.0401	0.134×10^{-3}	1.571×10^{-5}	0.910	1.11	1.350×10^{-3}
220	2,318	840.3	11.60	1859	4610	3110	0.650	0.0442	0.122×10^{-3}	1.641×10^{-5}	0.865	1.15	1.520×10^{-3}
240	3,344	813.7	16.73	1767	4760	3520	0.632	0.0487	0.111×10^{-3}	1.712×10^{-5}	0.836	1.24	1.720×10^{-3}
260	4,688	783.7	23.69	1663	4970	4070	0.609	0.0540	0.102×10^{-3}	1.788×10^{-5}	0.832	1.35	2.000×10^{-3}
280	6,412	750.8	33.15	1544	5280	4835	0.581	0.0605	0.094×10^{-3}	1.870×10^{-5}	0.854	1.49	2.380×10^{-3}
300	8,581	713.8	46.15	1405	5750	5980	0.548	0.0695	0.086×10^{-3}	1.965×10^{-5}	0.902	1.69	2.950×10^{-3}
320	11,274	667.1	64.57	1239	6540	7900	0.509	0.0836	0.078×10^{-3}	2.084×10^{-5}	1.00	1.97	
340	14,586	610.5	92.62	1028	8240	11,870	0.469	0.110	0.070×10^{-3}	2.255×10^{-5}	1.23	2.43	
360	18,651	528.3	144.0	720	14,690	25,800	0.427	0.178	0.060×10^{-3}	2.571×10^{-5}	2.06	3.73	
374.14	22,090	317.0	317.0	0	—	—	—	—	0.043×10^{-3}	4.313×10^{-5}			

Properties of propane

Temp.	Saturation Pressure	Density ρ, kg/m³		Enthalpy of Vaporization	Specific Heat c_p, J/kg·K		Thermal Conductivity k, W/m·K		Dynamic Viscosity μ, kg/m·s		Prandtl Number Pr		Volume Expansion Coefficient β, 1/K	Surface Tension,
T, °C	P, kPa	Liquid	Vapor	h_{fg}, kJ/kg	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	N/m
−120	0.4053	664.7	0.01408	498.3	2003	1115	0.1802	0.00589	6.136×10^{-4}	4.372×10^{-6}	6.820	0.827	0.00153	0.02630
−110	1.157	654.5	0.03776	489.3	2021	1148	0.1738	0.00645	5.054×10^{-4}	4.625×10^{-6}	5.878	0.822	0.00157	0.02486
−100	2.881	644.2	0.08872	480.4	2044	1183	0.1672	0.00705	4.252×10^{-4}	4.881×10^{-6}	5.195	0.819	0.00161	0.02344
−90	6.406	633.8	0.1870	471.5	2070	1221	0.1606	0.00769	3.635×10^{-4}	5.143×10^{-6}	4.686	0.817	0.00166	0.02202
−80	12.97	623.2	0.3602	462.4	2100	1263	0.1539	0.00836	3.149×10^{-4}	5.409×10^{-6}	4.297	0.817	0.00171	0.02062
−70	24.26	612.5	0.6439	453.1	2134	1308	0.1472	0.00908	2.755×10^{-4}	5.680×10^{-6}	3.994	0.818	0.00177	0.01923
−60	42.46	601.5	1.081	443.5	2173	1358	0.1407	0.00985	2.430×10^{-4}	5.956×10^{-6}	3.755	0.821	0.00184	0.01785
−50	70.24	590.3	1.724	433.6	2217	1412	0.1343	0.01067	2.158×10^{-4}	6.239×10^{-6}	3.563	0.825	0.00192	0.01649
−40	110.7	578.8	2.629	423.1	2258	1471	0.1281	0.01155	1.926×10^{-4}	6.529×10^{-6}	3.395	0.831	0.00201	0.01515
−30	167.3	567.0	3.864	412.1	2310	1535	0.1221	0.01250	1.726×10^{-4}	6.827×10^{-6}	3.266	0.839	0.00213	0.01382
−20	243.8	554.7	5.503	400.3	2368	1605	0.1163	0.01351	1.551×10^{-4}	7.136×10^{-6}	3.158	0.848	0.00226	0.01251
−10	344.4	542.0	7.635	387.8	2433	1682	0.1107	0.01459	1.397×10^{-4}	7.457×10^{-6}	3.069	0.860	0.00242	0.01122
0	473.3	528.7	10.36	374.2	2507	1768	0.1054	0.01576	1.259×10^{-4}	7.794×10^{-6}	2.996	0.875	0.00262	0.00996
5	549.8	521.8	11.99	367.0	2547	1814	0.1028	0.01637	1.195×10^{-4}	7.970×10^{-6}	2.964	0.883	0.00273	0.00934
10	635.1	514.7	13.81	359.5	2590	1864	0.1002	0.01701	1.135×10^{-4}	8.151×10^{-6}	2.935	0.893	0.00286	0.00872
15	729.8	507.5	15.85	351.7	2637	1917	0.0977	0.01767	1.077×10^{-4}	8.339×10^{-6}	2.909	0.905	0.00301	0.00811
20	834.4	500.0	18.13	343.4	2688	1974	0.0952	0.01836	1.022×10^{-4}	8.534×10^{-6}	2.886	0.918	0.00318	0.00751
25	949.7	492.2	20.68	334.8	2742	2036	0.0928	0.01908	9.702×10^{-5}	8.738×10^{-6}	2.866	0.933	0.00337	0.00691
30	1076	484.2	23.53	325.8	2802	2104	0.0904	0.01982	9.197×10^{-5}	8.952×10^{-6}	2.850	0.950	0.00358	0.00633
35	1215	475.8	26.72	316.2	2869	2179	0.0881	0.02061	8.710×10^{-5}	9.178×10^{-6}	2.837	0.971	0.00384	0.00575
40	1366	467.1	30.29	306.1	2943	2264	0.0857	0.02142	8.240×10^{-5}	9.417×10^{-6}	2.828	0.995	0.00413	0.00518
45	1530	458.0	34.29	295.3	3026	2361	0.0834	0.02228	7.785×10^{-5}	9.674×10^{-6}	2.824	1.025	0.00448	0.00463
50	1708	448.5	38.79	283.9	3122	2473	0.0811	0.02319	7.343×10^{-5}	9.950×10^{-5}	2.826	1.061	0.00491	0.00408
60	2110	427.5	49.66	258.4	3283	2769	0.0765	0.02517	6.487×10^{-5}	1.058×10^{-5}	2.784	1.164	0.00609	0.00303
70	2580	403.2	64.02	228.0	3595	3241	0.0717	0.02746	5.649×10^{-5}	1.138×10^{-5}	2.834	1.343	0.00811	0.00204
80	3127	373.0	84.28	189.7	4501	4173	0.0663	0.03029	4.790×10^{-5}	1.249×10^{-5}	3.251	1.722	0.01248	0.00114
90	3769	329.1	118.6	133.2	6977	7239	0.0595	0.03441	3.807×10^{-5}	1.448×10^{-5}	4.465	3.047	0.02847	0.00037

Blackbody radiation functions, f_λ

$$f_\lambda(T) = \frac{\int_0^\lambda E_{b\lambda}(\lambda, T)\,d\lambda}{\sigma T^4}$$

λT, μm · K	f_λ	λT, μm · K	f_λ
200	0.000000	6200	0.754140
400	0.000000	6400	0.769234
600	0.000000	6600	0.783199
800	0.000016	6800	0.796129
1000	0.000321	7000	0.808109
1200	0.002134	7200	0.819217
1400	0.007790	7400	0.829527
1600	0.019718	7600	0.839102
1800	0.039341	7800	0.848005
2000	0.066728	8000	0.856288
2200	0.100888	8500	0.874608
2400	0.140256	9000	0.890029
2600	0.183120	9500	0.903085
2800	0.227897	10,000	0.914199
3000	0.273232	10,500	0.923710
3200	0.318102	11,000	0.931890
3400	0.361735	11,500	0.939959
3600	0.403607	12,000	0.945098
3800	0.443382	13,000	0.955139
4000	0.480877	14,000	0.962898
4200	0.516014	15,000	0.969981
4400	0.548796	16,000	0.973814
4600	0.579280	18,000	0.980860
4800	0.607559	20,000	0.985602
5000	0.633747	25,000	0.992215
5200	0.658970	30,000	0.995340
5400	0.680360	40,000	0.997967
5600	0.701046	50,000	0.998953
5800	0.720158	75,000	0.999713
6000	0.737818	100,000	0.999905

Surface tension of liquid-vapor interface for water

T, °C	σ, N/m*
0	0.0757
20	0.0727
40	0.0696
60	0.0662
80	0.0627
100	0.0589
120	0.0550
140	0.0509
160	0.0466
180	0.0422
200	0.0377
220	0.0331
240	0.0284
260	0.0237
280	0.0190
300	0.0144
320	0.0099
340	0.0056
360	0.0019
374	0.0

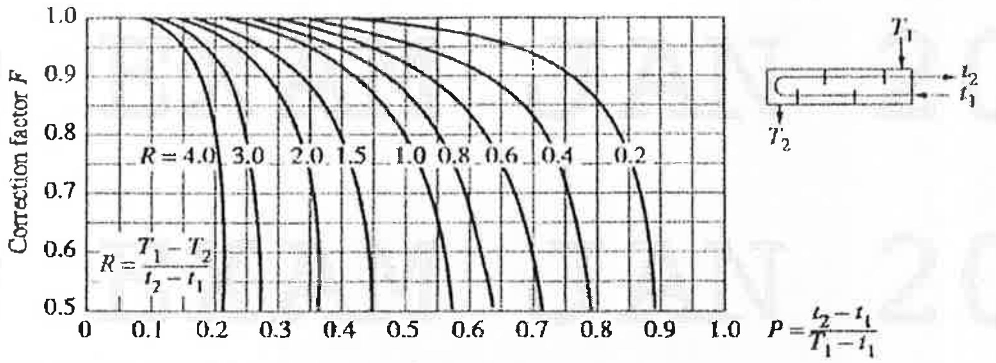
Values of the coefficient C_{sf} and n for various fluid-surface combination

Fluid–Heating Surface Combination	C_{sf}	n
Water–copper (polished)	0.0130	1.0
Water–copper (scored)	0.0068	1.0
Water–stainless steel (mechanically polished)	0.0130	1.0
Water–stainless steel (ground and polished)	0.0060	1.0
Water–stainless steel (teflon pitted)	0.0058	1.0
Water–stainless steel (chemically etched)	0.0130	1.0
Water–brass	0.0060	1.0
Water–nickel	0.0060	1.0
Water–platinum	0.0130	1.0
n-Pentane–copper (polished)	0.0154	1.7
n-Pentane–chromium	0.0150	1.7
Benzene–chromium	0.1010	1.7
Ethyl alcohol–chromium	0.0027	1.7
Carbon tetrachloride–copper	0.0130	1.7
Isopropanol–copper	0.0025	1.7

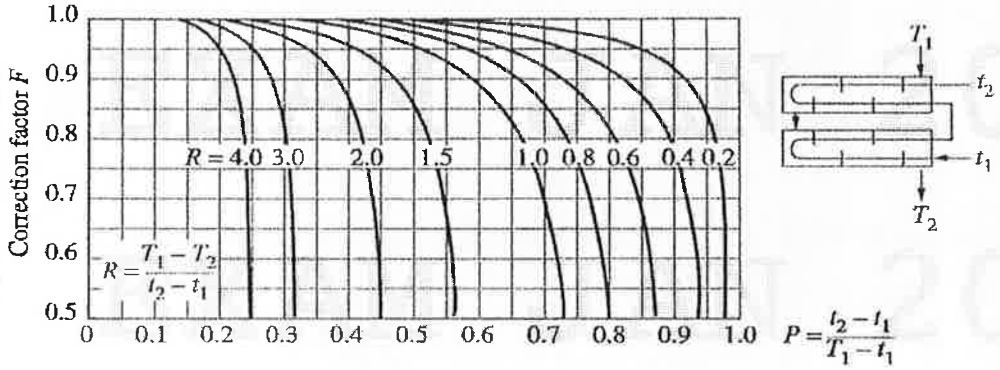
C_{cr} for maximum heat flux , $L^* = L\left[\dfrac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/2}$

Heater Geometry	C_{cr}	Charac. Dimension of Heater, L	Range of L^*
Large horizontal flat heater	0.149	Width or diameter	$L^* > 27$
Small horizontal flat heater[1]	$18.9K_1$	Width or diameter	$9 < L^* < 20$
Large horizontal cylinder	0.12	Radius	$L^* > 1.2$
Small horizontal cylinder	$0.12L^{*-0.25}$	Radius	$0.15 < L^* < 1.2$
Large sphere	0.11	Radius	$L^* > 4.26$
Small sphere	$0.227L^{*-0.5}$	Radius	$0.15 < L^* < 4.26$

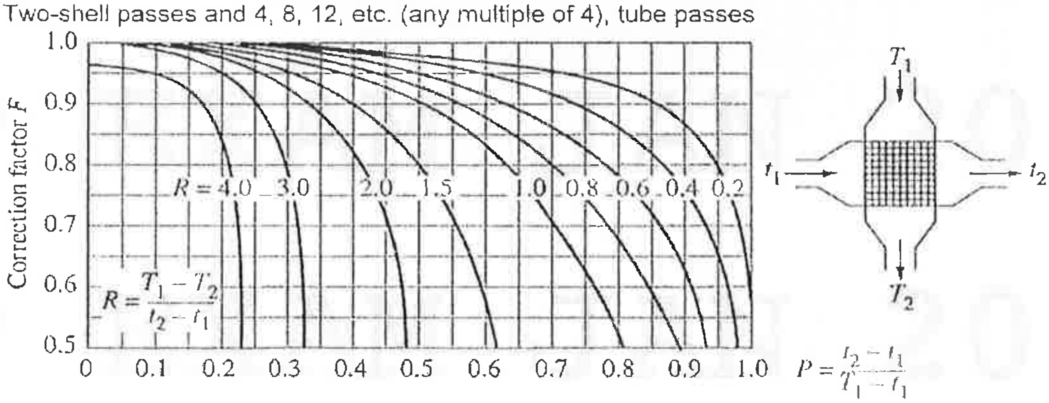
Correction factor F chart for common shell-and tube and cross flow heat exchangers



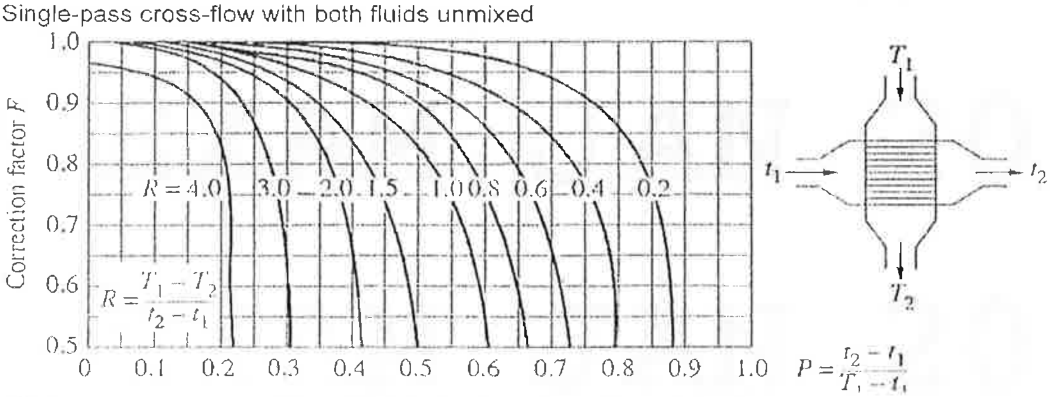
One-shell pass and 2, 4, 6, etc. (any multiple of 2), tube passes



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

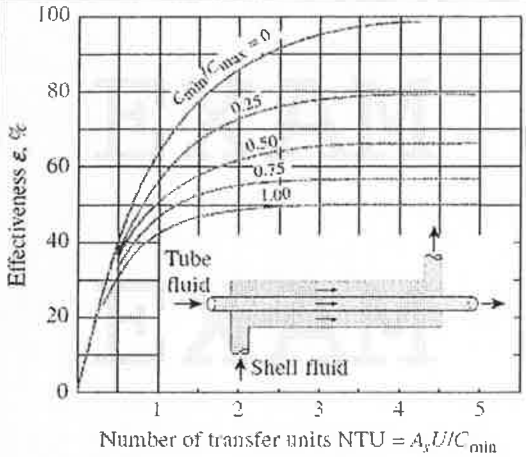


Single-pass cross-flow with both fluids unmixed

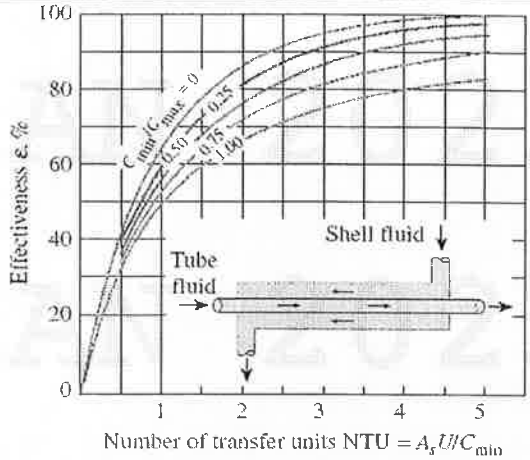


Single-pass cross-flow with one fluid mixed and the other unmixed

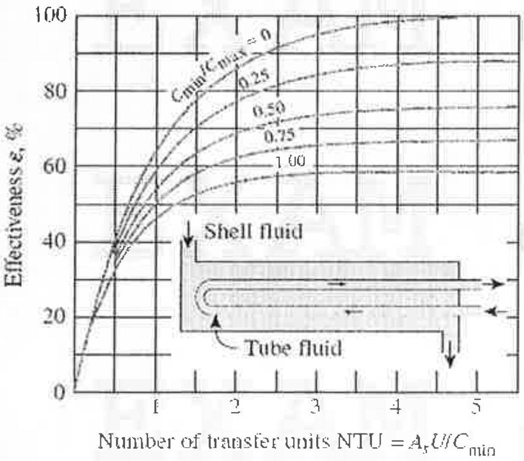
Effectivenes for heat exchangers



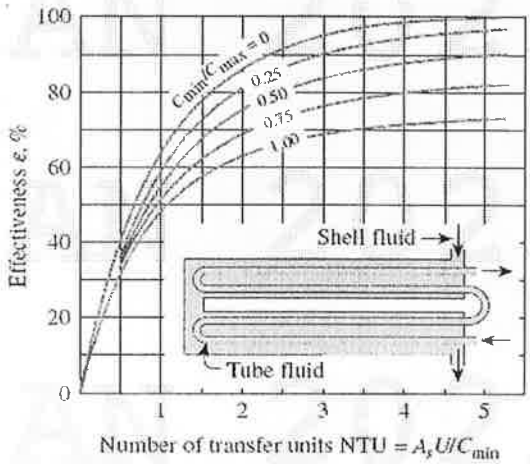
(a) Parallel-flow



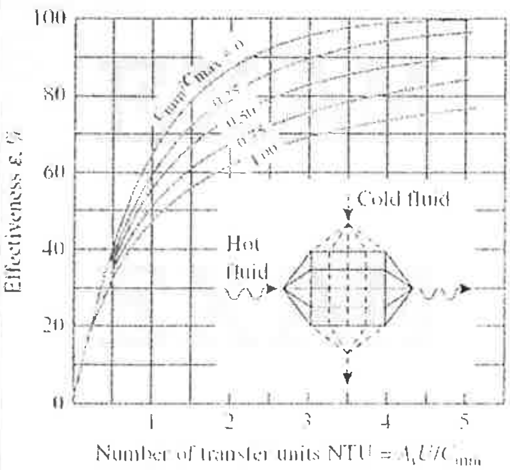
(b) Counter-flow



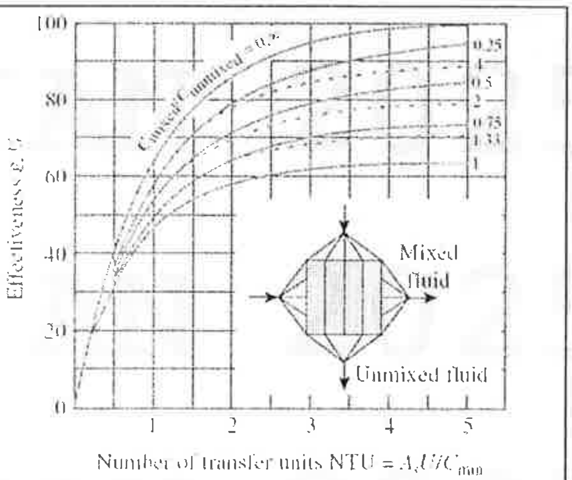
(c) One-shell pass and 2, 4, 6, … tube passes



(d) Two-shell passes and 4, 8, 12, … tube passes



(e) Cross-flow with both fluids unmixed



(f) Cross-flow with one fluid mixed and the other unmixed