National Exams May 2013

04-CHEM-A2, Mechanical and Thermal Operations

3 hours duration

NOTES

1. If doubt exists as to the interpretation of any question, the candidate is urged to submit with the answer paper, a clear statement of any assumptions made.
2. The examination is an OPEN BOOK EXAM.
3. Candidates may use any **non-communicating** calculator.
4. All problems are worth 25 marks. **Two problems** from **each** of sections A and B must be attempted.
5. **Only the first two** questions as they appear in the answer book from each section will be marked.
6. State all assumptions clearly.
7. Useful tables and figures are appended at pp. 6-12.

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Section A: Mechanical Operations

A1. **[25 marks]** An elevated storage tank contains water at 180°F as shown in Fig. 1. It is desired to have a discharge rate at point 2 of 100 Gal (US)/min. What must be the height H in feet of the surface of the water in the tank relative to the discharge point? All pipe work is schedule 40 commercial steel.

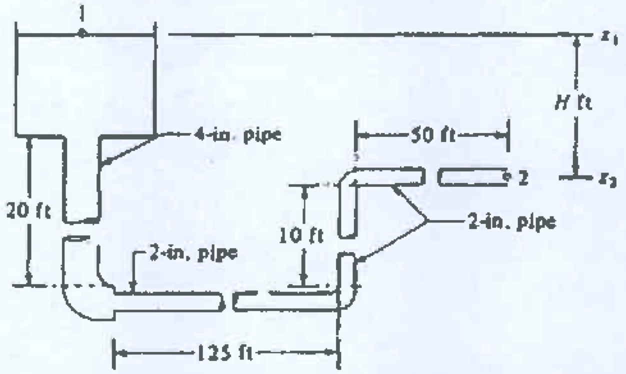

Fig. 1: Tank discharge system for QA1

Useful information is appended as **Tables A1, A2, A3** and **Figs A1 and A2.**

A2. **[25 marks overall]** Ethylene oxide is stored in a tank and for safety reasons the vapour space above the liquid ethylene oxide is purged of oxygen then padded with nitrogen. The nitrogen is supplied from a 1.4 MPa(g) source and is delivered to the vessel through 10 m of 1-in schedule 40 commercial steel pipe regulated to a pressure of 600 kPa(g). If the nitrogen regulator were to fail, the storage tank would be exposed to the full supply pressure of 1.4 MPa(g) which would exceed the pressure rating of the tank. Therefore, to prevent rupture of the tank a relief device must be installed to vent the nitrogen.

Determine the mass flow rate of nitrogen, assuming adiabatic choked flow through the delivery pipe, required to prevent the pressure from rising within the tank in the event of a regulator failure. Assume the ambient temperature and pressure are 26°C and 101 kPa, respectively. The universal gas constant, R, has a value of 8.314 kPa·m^3/kg-mol·K and for N_2, the molecular weight is 28 kg/kg-mol and $\gamma = 1.4$.

Useful pipe information is appended as **Table A1**.

A3. **[25 marks overall]** A catalytic packed bed reactor uses cylindrical-shaped catalyst pellets. The pellets (assumed to be non-porous) have a height to diameter ratio of unity (*i.e.* $h = d$) and are 4-mm in diameter. The density of the catalyst pellets is 1800 kg/m^3 and the bulk density of the overall packed bed is 1170 kg/m^3. The bed cross-sectional area is 0.15 m^2 and it is 2.5 m in length. The superficial velocity of the vapour flowing through the bed is 1.5 m/s. Calculate the following:

(a) **[5 marks]** The porosity of the bed.

(b) **[5 marks]** The effective diameter, D_p of the pellets.

(c) **[5 marks]** The ratio of the total surface area in the bed to the total volume of the bed (*i.e.* the void volume plus the particle volume) in m^{-1}.

(d) **[10 marks]** The pressure drop through the bed given that the density of vapour is 0.62 kg/m^3 and the viscosity of the vapour is 1.75×10^{-5} kg/m·s.

Useful information is appended as **Table A4.**

Section B: Thermal Operations

B1. **[25 marks overall]** A composite wall of height H and of unit length normal to the page is insulated at its ends and is comprised of four different materials, arranged as shown below in Fig. 2.

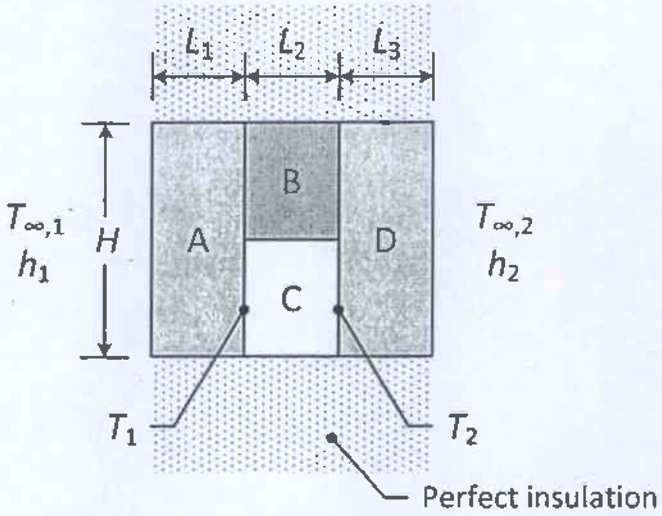

Fig. 2: Composite wall for QB1

(a) **[5 marks]** Sketch the thermal circuit of the system.

(b) **[10 marks]** Consider a wall for which $H = 3$ m, $H_B = H_C = 1.5$ m, $L_1 = L_3 = 0.05$ m, $L_2 = 0.10$ m, $k_A = k_D = 50$ W m^{-1} K^{-1}, $k_B = 10$ W m^{-1} K^{-1}, and $k_C = 1$ W m^{-1} K^{-1}. In addition, $T_{\infty,1} = 200$°C, $h_1 = 50$ W m^{-2} K^{-1}, $T_{\infty,2} = 25$°C, and $h_2 = 10$ W m^{-2} K^{-1}. Assuming that surfaces normal to the general heat flow direction are isothermal, what is the rate of heat transfer through the wall? What are the interface temperatures, T_1 and T_2?

(c) **[10 marks]** If instead of materials B and C, there was only C sandwiched between A and D, what should be its thickness for the rate of heat transfer to be the same as that calculated in b)?

B2. **[25 marks]** A cross-flow heat exchanger with both fluids unmixed has an overall heat transfer coefficient of $U = 2270$ W/m$^2\cdot$°C. Both streams are water and have equal flow rates of 75.6 kg/min. It one stream is cooled from 94°C to 72°C whilst the other fluid is initially at 38°C calculate the heat transfer surface area.

Useful information is appended as **Table B1 and Fig B1**.

B3. **[25 marks overall]**

(a) **[10 marks]** By equating the rate of decrease of enthalpy of a solid body of volume V to the rate of heat loss from its surface of area A by radiation alone, show that the governing differential equation is:

$$(\rho V C_p)\frac{dT}{dt} + A\varepsilon\sigma T^4 = 0$$

(b) **[15 marks]** A brass rod, 2-m long and 1-m in diameter is removed from a heat treatment furnace at 400°C, placed on a trestle, and allowed to cool in a quiescent environment. Assuming it cools by radiation alone (*i.e.* conduction through the trestle supports and heat loss by convection are negligible), calculate the time it takes to cool by 100°C. The density and specific heat of brass are 8526 kg/m^3 and 382 J/kg·K. The trestle support only covers 5% of the surface and the brass is oxidized on being heat-treated.

The Stefan-Boltzmann constant, $\sigma = 56.7\text{x}10^{-12}\text{kW/m}^2\cdot\text{K}^4$. Other useful data relating to emissivity is appended as **Fig. B2.**

Table A1: Dimensions of Standard Pipe

Nominal Pipe Size (in)	Outside Diameter (in)	Schedule	Wall Thickness (in)	Inside Diameter (in)	Cross-sectional Flow Area (in^2)	Cross-sectional Flow Area (m^2)
1	1.315	10	0.109	1.097	0.945	0.0006098
		40	0.133	1.049	0.864	0.0005576
		80	0.179	0.957	0.719	0.0004641
2	2.375	10	0.109	2.157	3.654	0.002358
		40	0.154	2.067	3.356	0.002165
		80	0.218	1.939	2.953	0.001905
3	3.500	10	0.12	3.260	8.347	0.005385
		40	0.216	3.068	7.393	0.004770
		80	0.3	2.900	6.605	0.004262
4	4.500	10	0.120	4.260	14.253	0.009196
		40	0.237	4.026	12.730	0.008213
		80	0.337	3.826	11.497	0.007418
5	5.563	10	0.134	5.295	22.020	0.014207
		40	0.258	5.047	20.006	0.012907
		80	0.375	4.813	18.194	0.011738
6	6.625	10	0.134	6.357	31.739	0.020477
		40	0.280	6.065	28.890	0.018639
		80	0.432	5.761	26.067	0.016818

Table A2: Surface Roughness for Common Pipe materials

Material	Surface Roughness		
	ε (ft)	ε (in)	ε (mm)
Drawn Tubing (brass, lead, glass, plastic etc.)	0.000005	0.00006	0.00152
Commercial Steel or Wrought Iron	0.00015	0.0018	0.0457
Asphalted Cast Iron	0.0004	0.0048	0.122
Galvanized Iron	0.0005	0.006	0.152
Cast Iron	0.00085	0.0102	0.259

Table A.3: Equivalent lengths $(L/D)_{eq}$ and loss coefficients (k) for turbulent flow through valves and fittings[1]

Type of fitting or valve	Loss coefficient, k	Equivalent length, L/d_o
45° ell, standard[a,b,e,g,l]	0.35	16
45° ell, long radius[b]	0.2	—
90° ell, standard[a,b,d,g,l,m]	0.75	30
long radius[a,b,e,g]	0.45	20
square or miter[m]	1.3	57
180° bend, close return[a,b,g]	1.5	50
Tee, std, along run, branch blanked off[g]	0.4	20
used as ell, entering run[d,h]	1.0	60
used as ell, entering branch[b,d,h]	1.0	60
branch flowing[f,h,l]	1.0	—
Coupling[b,g]	0.04	0.1
Union[g]	0.04	0.1
Ball valve, orifice to d_o ratio 0.9, fully open	0.17	13
Gate valve, open[a,g,l]	0.17	13
$\frac{3}{4}$ open[p]	0.9	35
$\frac{1}{2}$ open[p]	4.5	160
$\frac{1}{4}$ open[p]	24.0	900
Diaphragm valve, open[n]	2.3	—
$\frac{3}{4}$ open[p]	2.6	—
$\frac{1}{2}$ open[p]	4.3	—
$\frac{1}{4}$ open[p]	21.0	—
Globe valve, bevel seat, open[g,l]	6.0	340
$\frac{1}{2}$ open[p]	9.5	—
Globe valve, composition seat, open	6.0	340
$\frac{1}{2}$ open[p]	8.5	—
Globe valve, plug disk, open	9.0	450
$\frac{3}{4}$ open[p]	13.0	—
$\frac{1}{2}$ open[p]	36.0	—
$\frac{1}{4}$ open[p]	112.0	—
Angle valve, open[a,g]	2.0	145
Y or blowoff valve, open[a,l]	3.0	175
Check valve, swing[a,g,l]	2.0[q]	135
disk check valve	10.0[q]	—
ball check valve	70.0[q]	—
Foot valve[g]	15.0	420

*This table was compiled from Lapple [L1]; *Chemical Engineers' Handbook* [P2]; and the Crane Co. [C3]. Excerpted by special permission from *Chemical Engineering* (May, 1949), copyright © 1968 by McGraw-Hill, New York; from *Perry's Chemical Engineers' Handbook*, 6th ed., Perry and Green (eds.), McGraw-Hill, New York, 1984; reproduced from *Tech. Paper* 410, *Flow of Fluids*, courtesy Crane Co.

[a] *Flow of Fluids through Valves, Fittings, and Pipe, Tech Paper* 410., Crane Co., 1969.

[b] Freeman: *Experiments upon the Flow of Water in Pipes and Pipe Fittings*, American Society of Mechanical Engineers, New York, 1941.

[c] Gibson: *Hydraulics and Its Applications*, 5th ed., Constable, London, 1952.

[d] Giesecke and Badgett: *Heating, Piping Air Conditioning* 4(6): 443 (1932).

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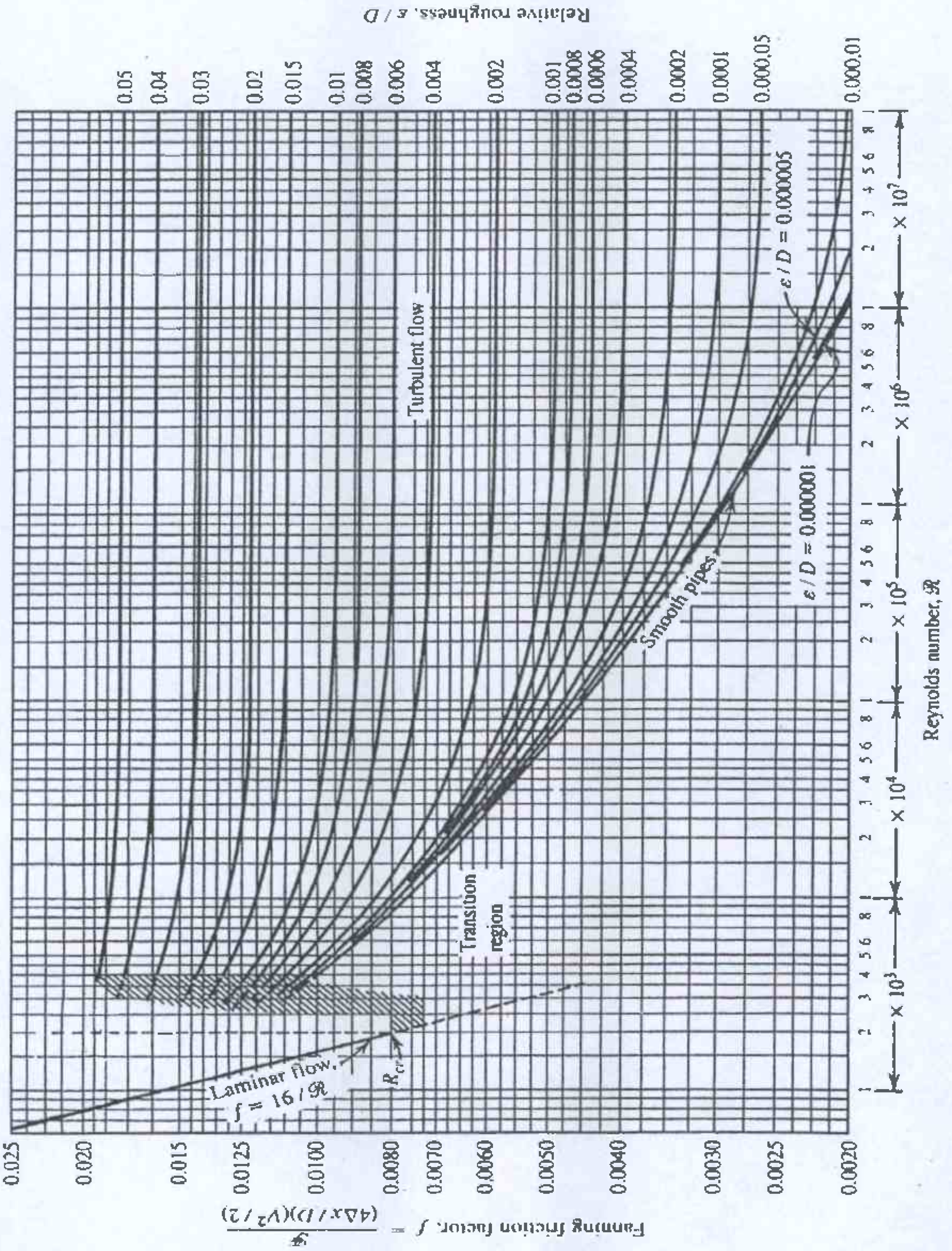
[1] From: Brodkey, R.S. and Hershey, H.C. (1988) *Transport Phenomena: A unified approach* McGraw-Hill, NY, Table 10.5, p 435.

Fig. A1: Fanning friction factor as a function of N_{Re} and ε/D[2]



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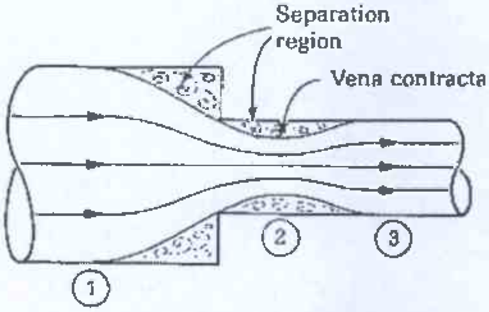
[2] From: *Fluid Mechanics for Chemical Engineers, 2nd Ed.* by Noel de Nevers (1991) The McGraw-Hill Company Inc.

For a sudden expansion, as shown below, the expansion loss coefficient can be calculated from [*MSH cf. Eq.(5.69) p122*]:

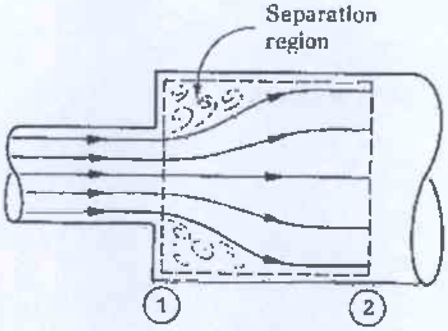
$$k_e = \left(1 - \frac{d_1^2}{d_2^2}\right)^2 = \left(1 - \beta^2\right)^2 \qquad \beta = d_1/d_2 \qquad \text{(A1)}$$

For a sudden contraction, shown below, an appropriate empirical equation for the contraction loss coefficient for turbulent flow is [*MSH cf. Eq.(5.71) p123*]:

$$k_c = 0.42 \cdot \left(1 - \frac{d_2^2}{d_1^2}\right)^2 = 0.42 \cdot \left(1 - \beta^2\right)^2 \qquad \beta = d_2/d_1 \le 0.76 \qquad \text{(A2)}$$



Sudden contraction



Sudden expansion

Figure A2 shows Eqs. (A1) and (A2) in graphical form.

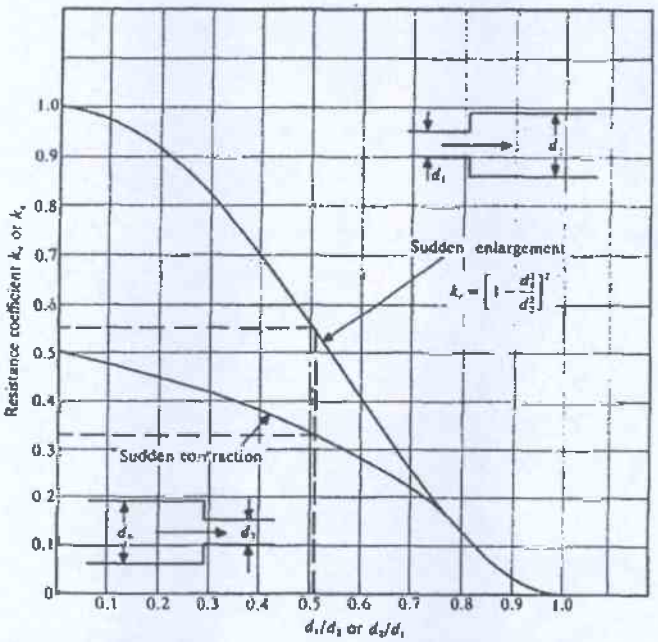


Fig. A2: Loss coefficients for sudden expansion and contraction[3]

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[3] Brodkey and Hershey (1988) *op cit.* Fig. 10.19, p 428.

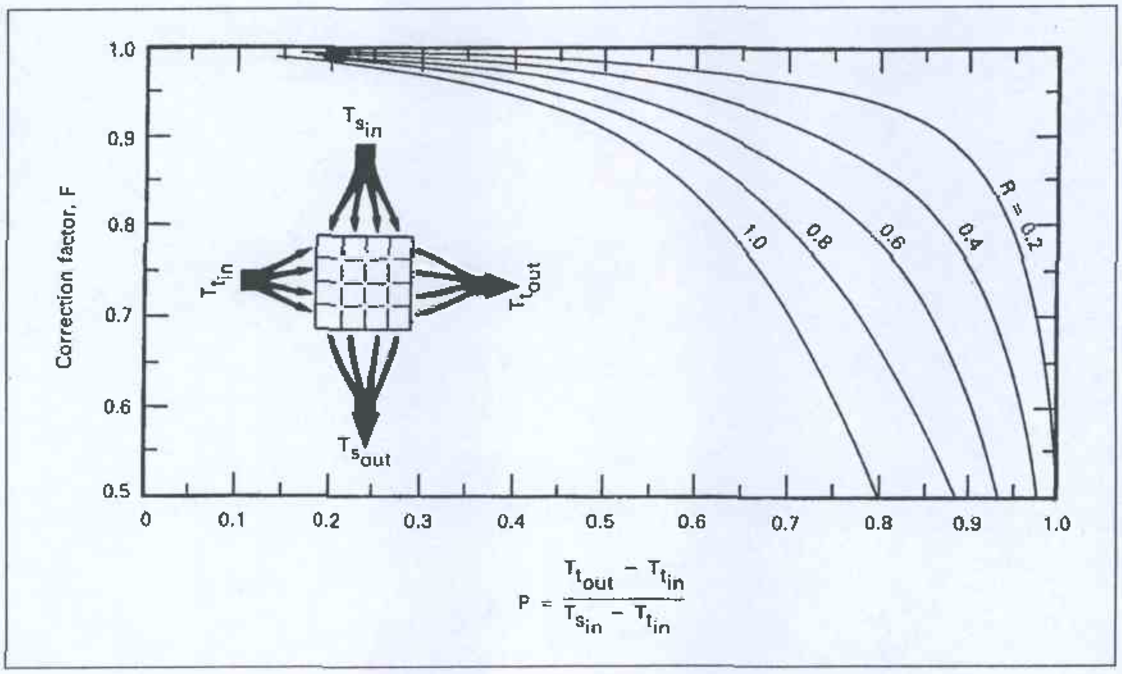
Table A4: Sphericity of particles [*cf. MSH Table 7.1, p164*]

Particle shape	ϕ_s	**Particle shape**	ϕ_s
Sphere	1.0	Old beach sand	Up to 0.86
Cube	1.0	Average for various sands	0.75
Cylinder		Discs	
$h = d$	0.87	$h = d/3$	0.76
$h = 5d$	0.70	$h = d/6$	0.60
$h = 10d$	0.58	$h = d/10$	0.47
Crushed solids	0.5-0.7	Granular particles	0.7-0.8
Mica flakes	0.28	Coal dust	0.73
Wheat	0.85	Nickel saddles	0.14
Raschig rings	0.26-0.53	Berl saddles	0.30-0.37

Table B1: Specific heat capacity of water

T [°C]	C_P [J/kg·K]	T [°C]	C_P [J/kg·K]
35	4178	70	4190
40	4179	75	4193
45	4180	80	4197
50	4181	85	4201
55	4183	90	4206
60	4185	95	4212
65	4187	100	4217

Fig. B1: LMTD correction factor, *F*, for a one-pass cross-flow exchanger with both passes unmixed [4]



NB. If $R > 1$, we can evaluate F using PR in place of P and $1/R$ in place of R.

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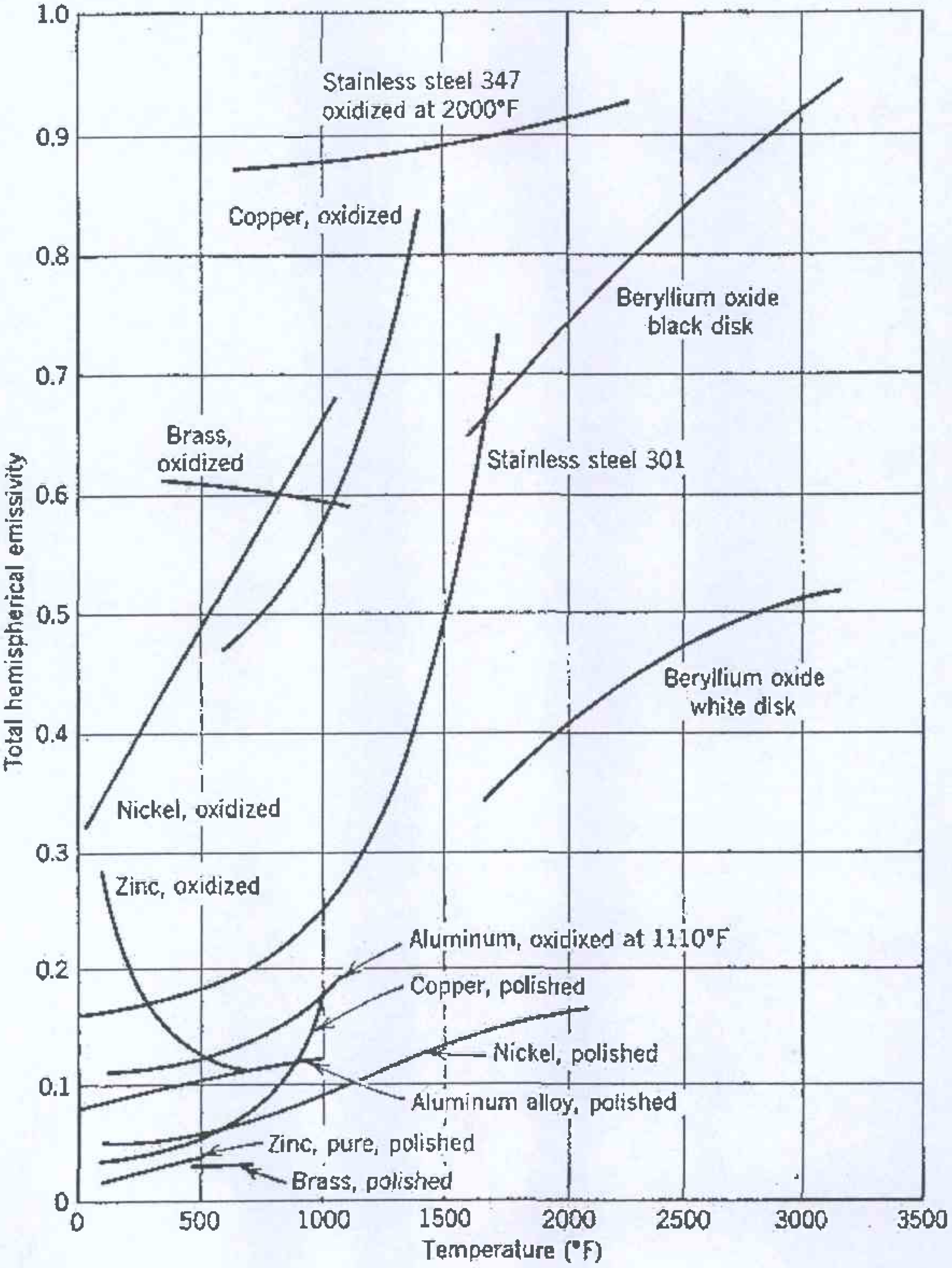
[4] From: Lienhard, JH (1987) *A Heat Transfer Textbook* 2nd. Ed. Prentice-Hall Inc., NJ, Fig.3.17, p 100.

Fig. B2: Temperature dependency on the total hemispherical emissivity of metals[5]



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[5] From: Ozisik, M.N. (1973) "*Radiative Transfer*" John Wiley & Sons, p 103.