National Exams December 2012

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. 5-10.

Section A: Mechanical Operations

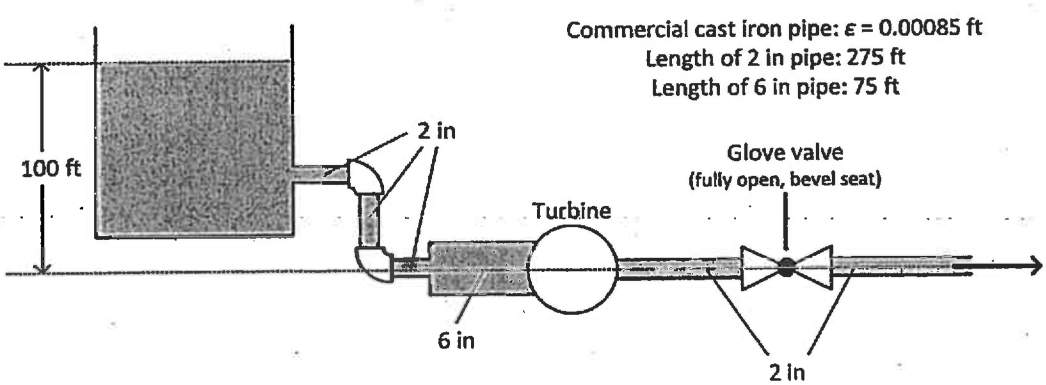
A1. **[25 marks]** You are on site with very little equipment. The problem to be resolved is determining the nitrogen pad pressure above 2.0-m of benzene in a tank. There are no pressure gauges but you do have about 10 m of tygon tubing to rig up a manometer. Unfortunately the only manometric fluid you have is of unknown density (you forgot the calibration data). After rummaging around in your equipment box you find an uncalibrated hydrometer. It consists of a hollow glass rod, 20 mm in diameter and 120 mm long with a 4 mm length of iron attached to one end. You are lucky because stamped on the glass rod is its composite density, which is 600 kg/m^3. You look up the density of iron and find it to be 7870 kg/m^3. When you place the hydrometer in the manometric fluid 80% of the glass rod is immersed. You can now use this information to calculate the density of the manometric fluid.

Having determined the density of your manometric fluid you set up the manometer in the following manner. You connect the tygon tube with the manometric fluid in it to a small drain cock near the bottom of the tank and tape the tygon tube to a steel support running up to the top of the building. When you open the drain cock benzene (specific gravity 0.876) runs into the manometer and establishes an interface with the manometric fluid 150 mm below the bottom of the tank. The height difference in the two limbs of the manometer is 6.65 m. You telephone the weather centre and they tell you that the atmospheric pressure is 101 kPa. So, what is the absolute pressure of the nitrogen in the tank?

A2. **[25 marks overall]** Water at 20°C [$\rho = 62.3\ lb_m/ft^3$; $\mu = 2.09\cdot10^{-5}\ lb_f\cdot s/ft^2$)] flows from a reservoir through a piping system and a turbine (see figure shown below). The piping is commercial cast iron schedule 40 pipe with the nominal diameters provided in the figure.

a) **[10 marks]** Neglecting frictional effects, determine the power extracted by the turbine for a water flow rate of 0.16 ft^3/s. Assume a turbine efficiency of 100%.

b) **[15 marks]** Including frictional effects, determine the power extracted by the turbine for a water flow rate of 0.16 ft^3/s. Assume a turbine efficiency of 100%.



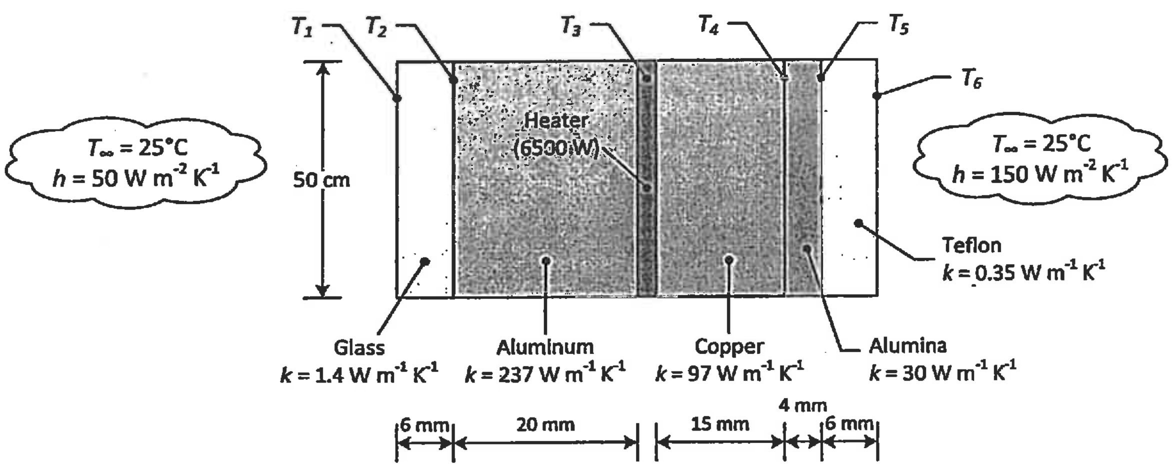
Useful information is appended as **Tables A1, A2, A3, A4** and **Fig A1.**

A3. **[25 marks]** A cyclone separator has a diameter of 0.333 m and a height of 1.28 m. The diameter of the circular inlet and outlet both equal 0.095 m. The cyclone is expected to remove spherical particles of mineral ore (density = 2655 kg/m^3) down to a particle diameter of 2 μm form an air stream. Calculate the minimum air flow rate (in m^3/s) into the cyclone.

Density of air = 1.210 kg/m^3 and viscosity of air = 1.780×10^{-5} kg/m·s

Section B: Thermal Operations

B1. **[25 marks overall]** Consider the system shown below. A thin square heater is sandwiched between two composite square walls with a width of 50 cm. The heater emits 6500 W of heat. The edges of the square wall are insulated so that all of the heat is transferred through the walls and radiation effects may be neglected.



Determine:

a) **[7 marks]** The heat flux through the aluminum side of the composite wall.
b) **[7 marks]** The heat flux through the copper side of the composite wall.
c) **[6 marks]** The temperatures T_1 to T_6.
d) **[5 marks]** What do you notice about the change of T in materials with high conductivity *vs.* materials with low conductivity? Is conductivity the only important factor?

B2. **[25 marks]** Water enters a cross-flow heat exchanger (both fluids unmixed) at 16°C and flows at a rate of 7.5 kg/s to cool 10.0 kg/s of air from 120°C. For an overall heat transfer coefficient of 225 W/m^2·K and an exchange surface area of 240 m^2, what is the exit air temperature?

For water C_P may be taken as 4.182 kJ/kg·K and for air C_P = 1.014 kJ/kg·K.

Useful charts are appended as **Fig B1.**

B3. **[20 marks overall]** Two blackbody rectangles 1.8 m by 3.6 m are parallel and directly opposed (see **Fig B2**) are 3.6 m apart. If surface 1 is at T_1 = 95°C and surface 2 is at T_2 = 315°C, determine the following:

a) **[15 marks]** The net rate of heat transfer $\dot{Q}_{1-2}$; and

b) **[10 marks]** The net rate of energy loss from surface 1 to the surroundings if they are black at T_∞ = 295 K.

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 in pipe diameters $(L/D)_{eq}$ of various valves and fittings[1]

Description	Equivalent Length in Pipe Diameters (L/D)
Globe valves	
Conventional	
With no obstruction in flat, bevel, or plug type seat—Fully open	340
With wing or pin guided disk—Fully open	450
Y-pattern	
(No obstruction in flat, bevel, or plug type seat)	
With stem 60 degrees from run of pipeline—Fully open	175
With stem 45 degrees from run of pipeline—Fully open	145
Angle valves	
Conventional	
With no obstruction in flat, bevel, or plug type seat—Fully open	145
With wing or pin-guided disk—Fully open	200
Gate valves	
Conventional wedge disk, double disk, or plug disk	
Fully open	13
Three-quarters open	35
One-half open	160
One-quarter open	900
Pulp stock	
Fully open	17
Three-quarters open	50
One-half open	260
One-quarter open	1200
Conduit pipe line—Fully open	3[a]
Check valves	
Conventional swing—0.5[b]—Fully open	135
Clearway swing—0.5[b]—Fully open	50
Globe lift or stop—2.0[b]—Fully open	Same as globe
Angle lift or stop—2.0[b]—Fully open	Same as angle
In-line ball—2.5 vertical and 0.25 horizontal[b]—Fully open	150
Foot valves with strainer	
With poppet lift-type disk—0.3[b]—Fully open	420
With leather-hinged disk—0.4[b]—Fully open	75
Butterfly valves (6-inch and larger)—Fully open	20
Cocks	
Straight-through	
Rectangular plug port area equal to 100% of pipe area—Fully open	18
Three-way	
Rectangular plug port area equal to 80% of pipe area (fully open)	
Flow straight through	44
Flow through branch	140

[a]Exact equivalent length is equal to the length between flange faces or welding ends.
[b]Minimum calculated pressure drop (psi) across valve to provide sufficient flow to lift disk fully.

[1] From From: Foust, AS, Wenzel, LA, Clump, CW, Maus, M and Andersen, LB (1980) *Principles of Unit Operations* John Wiley & Sons, NY, Appendix C-2a, p 718.

Table A.4: Equivalent lengths $(L/D)_{eq}$ and loss coefficients (k) for turbulent flow through valves and fittings[2]

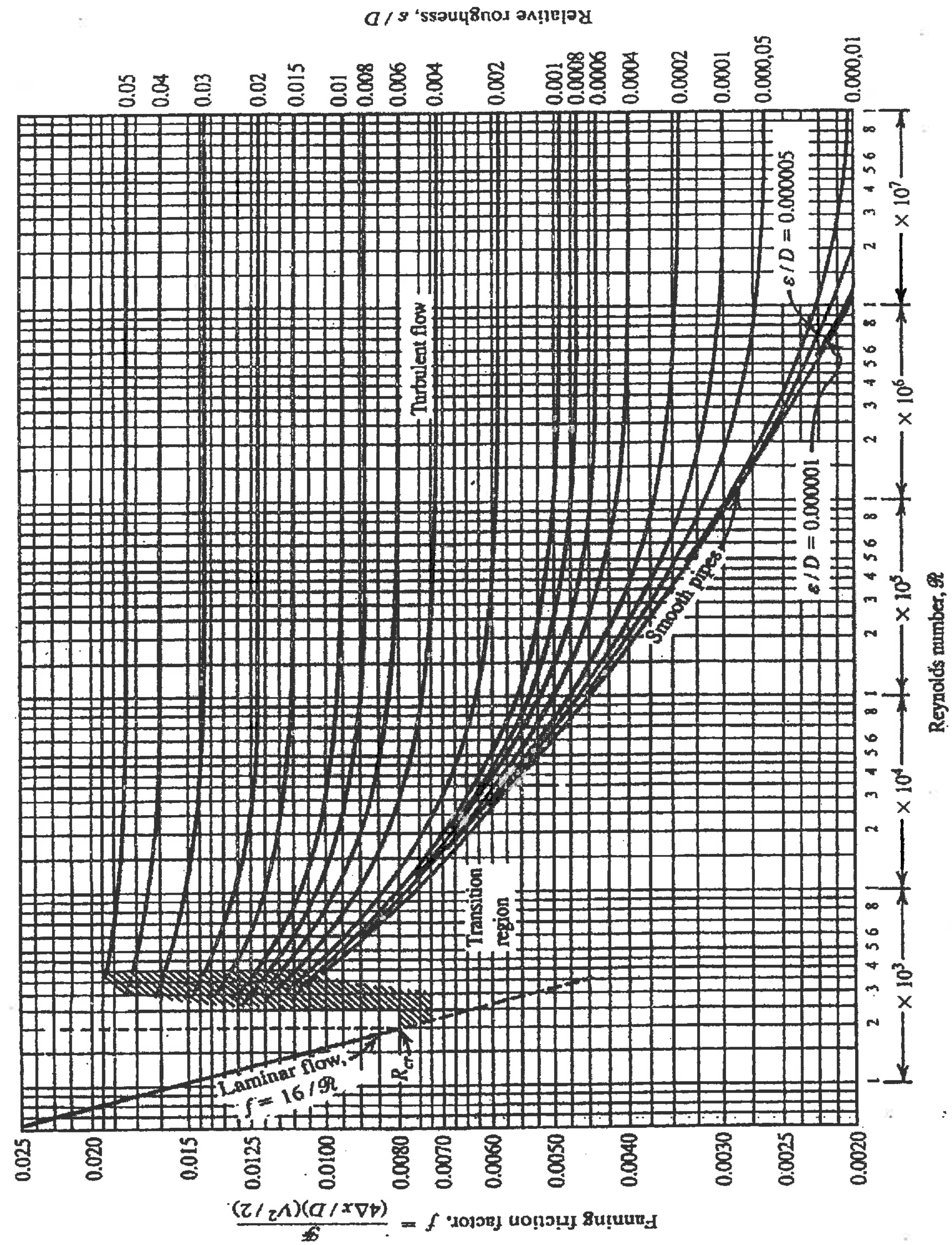
Type of fitting or valve	Loss coefficient, k	Equivalent length, L/d_o
45° ell, standard[a,b,e,g,i]	0.35	16
45° ell, long radius[b]	0.2	—
90° ell, standard[a,b,d,g,i,m]	0.75	30
long radius[a,b,e,g]	0.45	20
square or miter[m]	1.3	57
180° bend, close return[a,b,g]	1.5	50
Tee, std, along run, branch blanked 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,j]	0.17	13
¾ open[p]	0.9	35
½ open[p]	4.5	160
¼ open[p]	24.0	900
Diaphragm valve, open[n]	2.3	—
¼ open[p]	2.6	—
½ open[p]	4.3	—
¼ open[p]	21.0	—
Globe valve, bevel seat, open[g,l]	6.0	340
½ open[p]	9.5	—
Globe valve, composition seat, open	6.0	340
½ open[p]	8.5	—
Globe valve, plug disk, open	9.0	450
¾ open[p]	13.0	—
½ open[p]	36.0	—
¼ 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,j]	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).

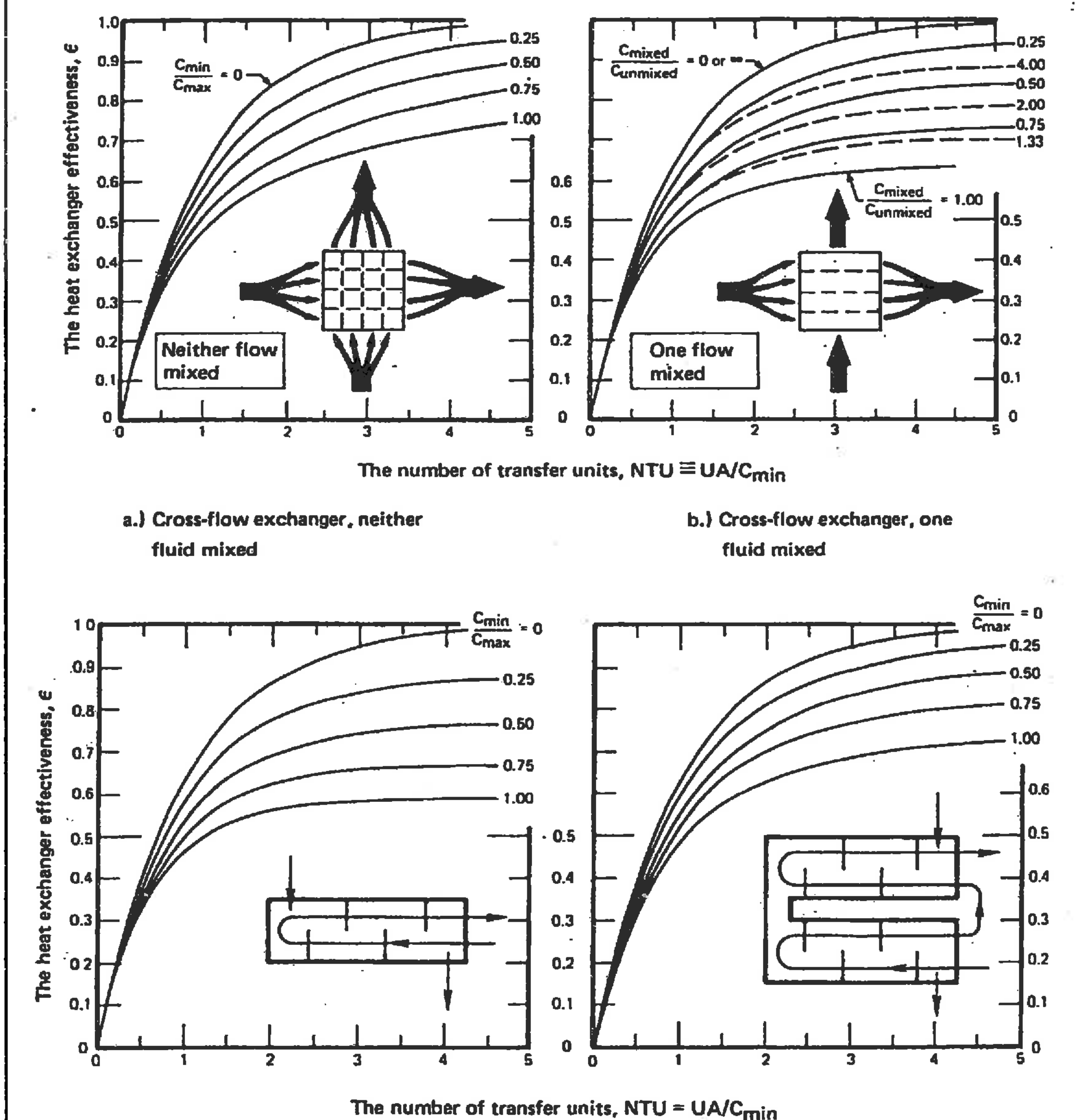
[2] From: Brodkey, R.S. and Hershey, H.C. (1988) *Transport Phenomena: A unified approach* McGraw-Hill, NY, Table 10.5, p 435.

Fig. A1: Fanning friction factor as a function of N_{Re} and ε/D[3]



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

Fig. B1: The effectiveness of various heat exchanger configurations[4]



a.) Cross-flow exchanger, neither fluid mixed

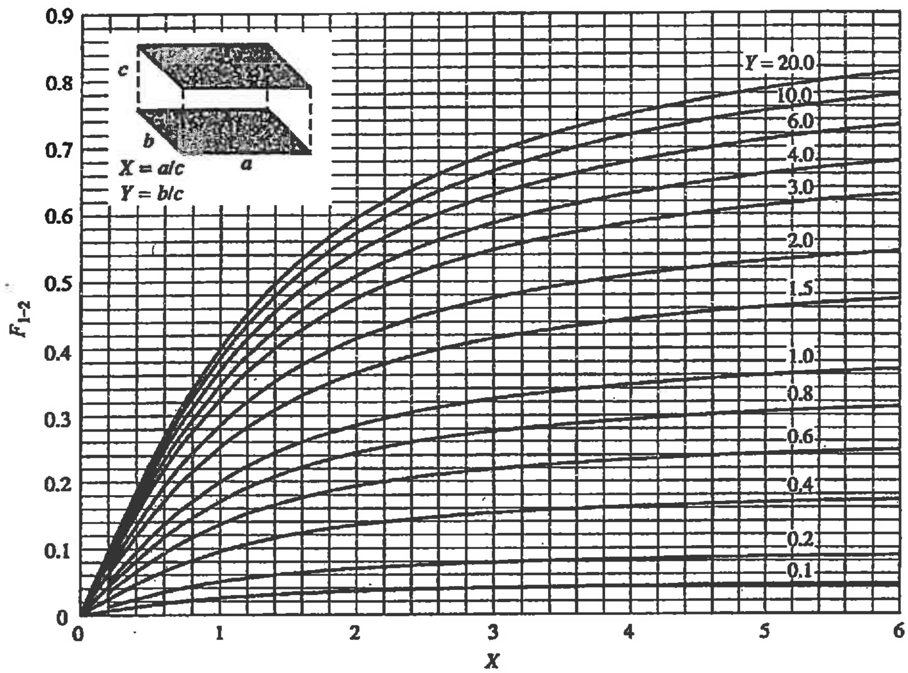
b.) Cross-flow exchanger, one fluid mixed

c.) One shell pass, two tube pass exchanger. (Can also be used for 4, 6, 8, 10, 12 tube passes with a maximum error in ϵ, of 0.040 at C_{min}/C_{max} = 1 and large NTU.)

d.) Two shell pass 4 tube pass exchanger. (Can also be used for 4, 6, 8, ... tube passes with reasonable accuracy if there are equal numbers of tube passes in each shell pass.)

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

Fig. B2: View factor between identical, parallel, directly opposed rectangles[5]



[5] From: Modest, MF (1993) *Radiative Heat Transfer*, Mc-Graw-Hill Inc., NJ, Fig. D-2, p 794.