National Exams December 2011

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 20 marks. **Two problems** from **each** of sections A and B must be attempted. A **fifth** problem from **either section** must also be attempted.
5. **Only the first five** questions as they appear in the answer book will be marked.
6. State all assumptions clearly.

Section A: Mechanical Operations

A1. **[20 marks]** Two tanks are connected with 3-in sch. 40 commercial steel pipe 625 ft long. The pipeline contains six standard 90° elbows, four open gate valves and one open globe valve. The system fluid can range from 800 to 850 kg/m^3 in density and from 1.6 to 4.25 cP in viscosity. Tank A's pressure has minimum and maximum values of 159 and 241 kPa. The corresponding values for tank B are 428 and 660 kPa. The highest and lowest liquid levels in tank A are 13 and 2.4 m whereas values for tank B are 39 and 30 m. If the flow rate range is 101.4 to 158.5 USgpm, what size of pump is required?

Tables A1, A2, and Fig A1 appended to the end of the paper may be useful.

A2. **[20 marks overall]** Nitrogen is to be vented to the atmosphere from a closed tank at a pressure of 202.65 kPa(abs) and a temperature of 20°C through a convergent nozzle with an exit diameter of 15 mm.

(a) **[5 marks]** Explain why a shock wave will occur at the nozzle exit.

(b) **[5 marks]** Calculate the initial mass flow rate of nitrogen from the tank.

(c) **[5 marks]** To what value must the pressure in the tank fall before the shock wave disappears?

(d) **[5 marks]** Calculate the mass flow rate of nitrogen from the tank when the shock wave disappears.

The Molecular Weight of nitrogen is 28 kg/kg-mol and γ may be taken as 1.4.

A3. **[20 marks overall]** A 65 mm diameter horizontal pipeline has a 24 wt% aqueous sodium hydroxide solution (density = 1266 kg/m^3) flowing through it at a rate of 16.5 L/s.

(a) **[15 marks]** Determine the diameter of a sharp-edged orifice to obtain a 200 mm difference in mercury levels (density of mercury = 13,560 kg/m^3) in a manometer when the leads are filled the sodium hydroxide solution.

(b) **[5 marks]** Determine the ratio of the pressure drop readings to be expected when measuring the same flow rate of a liquid, firstly using an orifice meter and secondly a venturi meter if the diameter of the hole in the orifice plate is the same as the throat diameter in the venturi meter. Assume the orifice meter has a discharge coefficient of 0.61 and the venturi meter has a discharge coefficient of 0.98.

Section B: Thermal Operations

B1. **[20 marks overall]** A long, cylindrical, electrical heating element with a diameter $D = 10$ mm, thermal conductivity $k = 240$ W/mK, density $\rho = 2700$ kg/m^3, and specific heat $c_p = 900$ J/kgK is installed in a duct for which air at a temperature of 300 K and velocity 10 m/s moves in cross flow over the heater.

(a) **[15 marks]** Neglecting radiation, estimate the steady-state surface temperature when electrical energy is being dissipated at i.0 kW/m.

(b) **[5 marks]** If the heater is activated from an initial temperature of 300 K, estimate the time required for the surface temperature to come within 10°C of its steady-state value.

Useful thermo-physical properties of air at atmospheric pressure are given in Table B1 appended to this paper.

B2. **[20 marks]** Consider an experiment to investigate the transition to turbulent flow in a free convection boundary layer that develops along a vertical plate suspended in a large room. The plate is constructed of a thin heater that is sandwiched between two aluminum plates and can therefore be considered isothermal. The heated plate is 1.0 m high by 2.0 m wide. The surrounding air is quiescent at 25°C. The exposed surfaces of the aluminum plate are painted with a very thin coating of high emissivity paint ($\varepsilon = 0.95$). Determine the electrical power required to maintain the plate at a temperature T_s =35°C. How much of the plate is exposed to turbulent conditions in the free convection boundary layer?

Useful thermo-physical properties of air at atmospheric pressure are given in Table B1 appended to this paper.

B3. **[20 marks overall]** Consider a concentric tube heat exchanger characterized by a uniform overall heat transfer coefficient and operating under the following conditions.

	$\dot{m}$ [kg/s]	c_P [J/kgK]	T_i [°C]	T_o [°C]
Cold fluid	0.125	4200	40	95
Hot fluid	0.125	2100	210	-

(a) **[5 marks]** What is the maximum possible heat transfer rate?

(b) **[5 marks]** What is the heat exchanger effectiveness?

(c) **[5 marks]** Should the heat exchanger be operated in parallel flow or counterflow?

(d) **[5 marks]** What is the required area for these two flow conditions?

Useful charts are appended as Figs. B1 and B2.

Table A.1: 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.2: 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,c,g,l]	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,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	—
$\frac{1}{4}$ 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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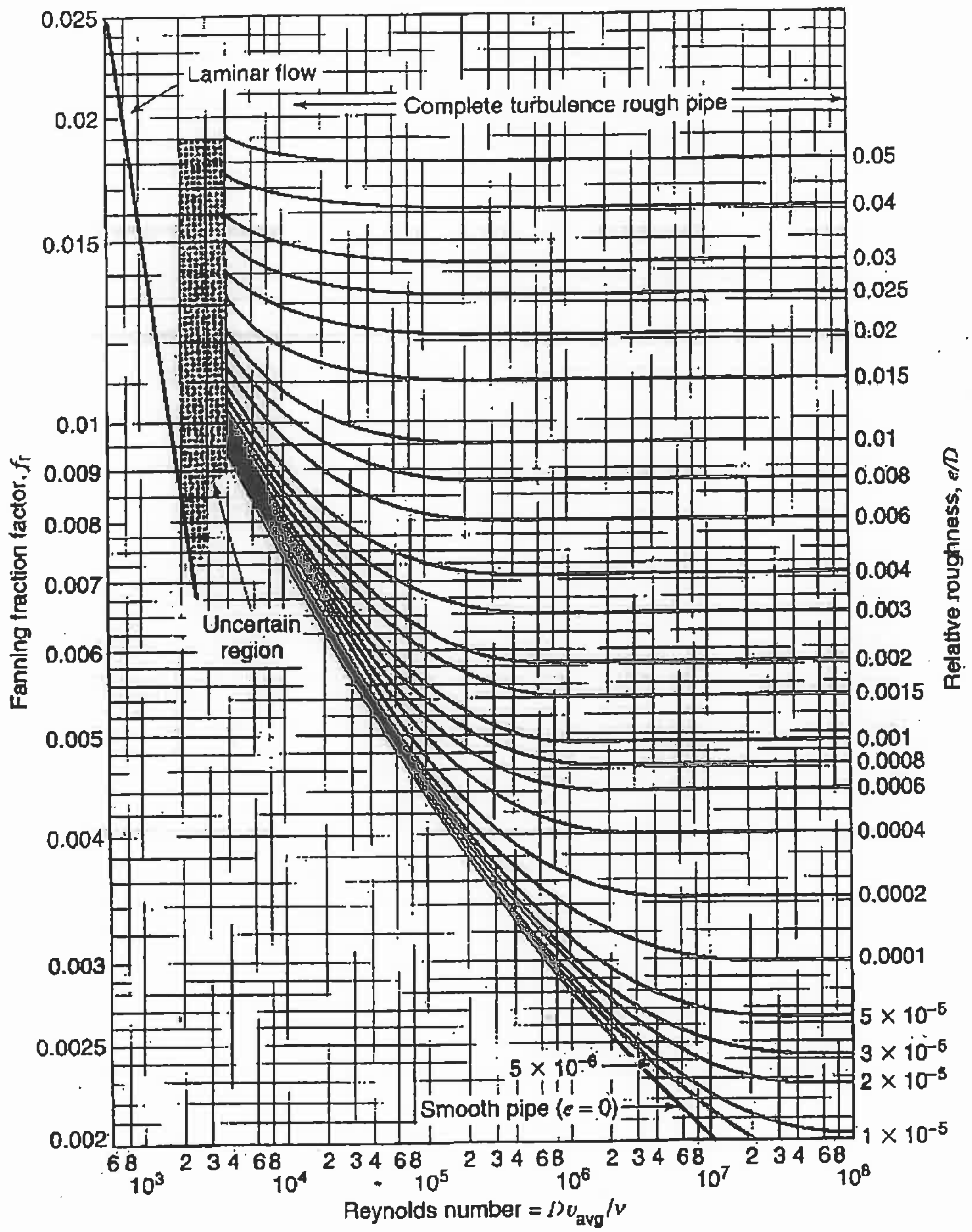
[2] From: Brodkey, R.S. and Hershey, H.C. (1988) *Transport Phenomena: A unified approach* McGraw-Hill, NY, Table 10.5, p 435.

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



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[3] From: Levenspeil, O. (1986) "*Engineering Flow and Heat Exchange*" Plenum Press, NY, Fig. 2.4, p 20.

Table B1: Properties of air at atmospheric pressure[4]

T [K]	k [W/mK]	10^6 α [m^2/s]	10^6 ν [m^2/s]	Pr [-]
300	0.0263	22.5	15.89	0.707
350	0.0300	29.9	20.92	0.700
400	0.0338	38.3	26.41	0.690
450	0.0373	47.2	32.39	0.686
500	0.0407	56.7	38.79	0.684

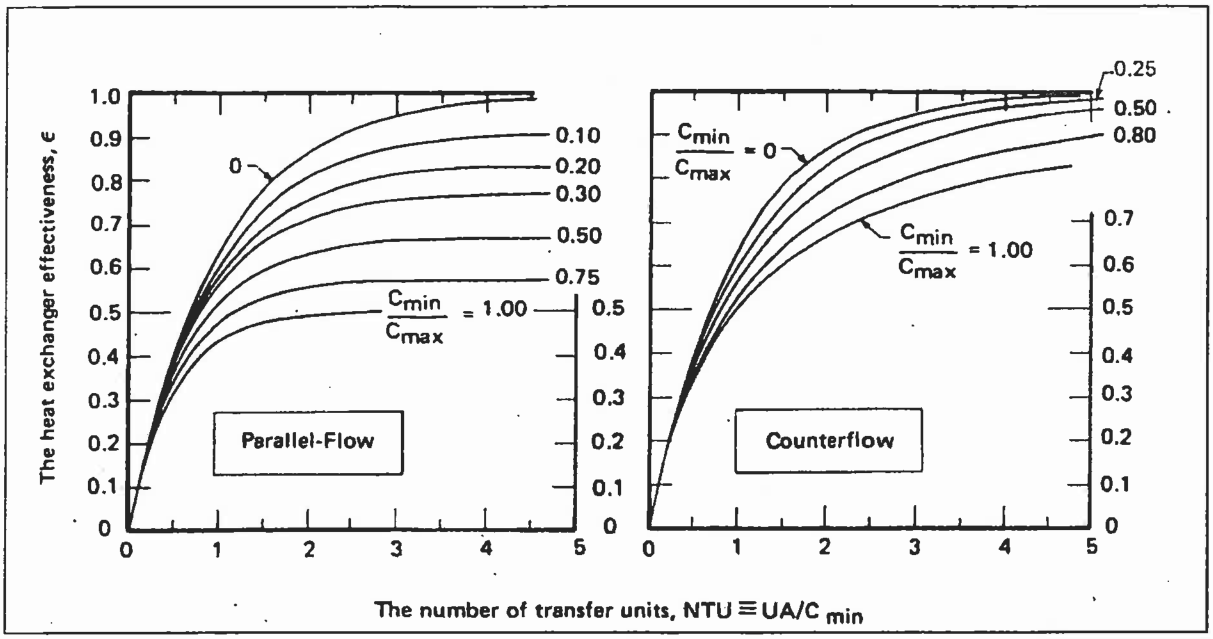

Fig. B1: The effectiveness of parallel and counterflow heat exchangers[5]

[4] Taken from Incropera, FP, Dewitt, DP, Bergman, TL and Lavine, AS *et al.* (2007) *Fundamentals of Heat and Mass Transfer* 6th. Ed. John Wiley & Sons, Table A.4, p 941.

[5] From: Lienhard, JH (1987) *A Heat Transfer Textbook* 2nd. Ed. Prentice-Hall Inc., NJ, Fig.3.16, p 99.

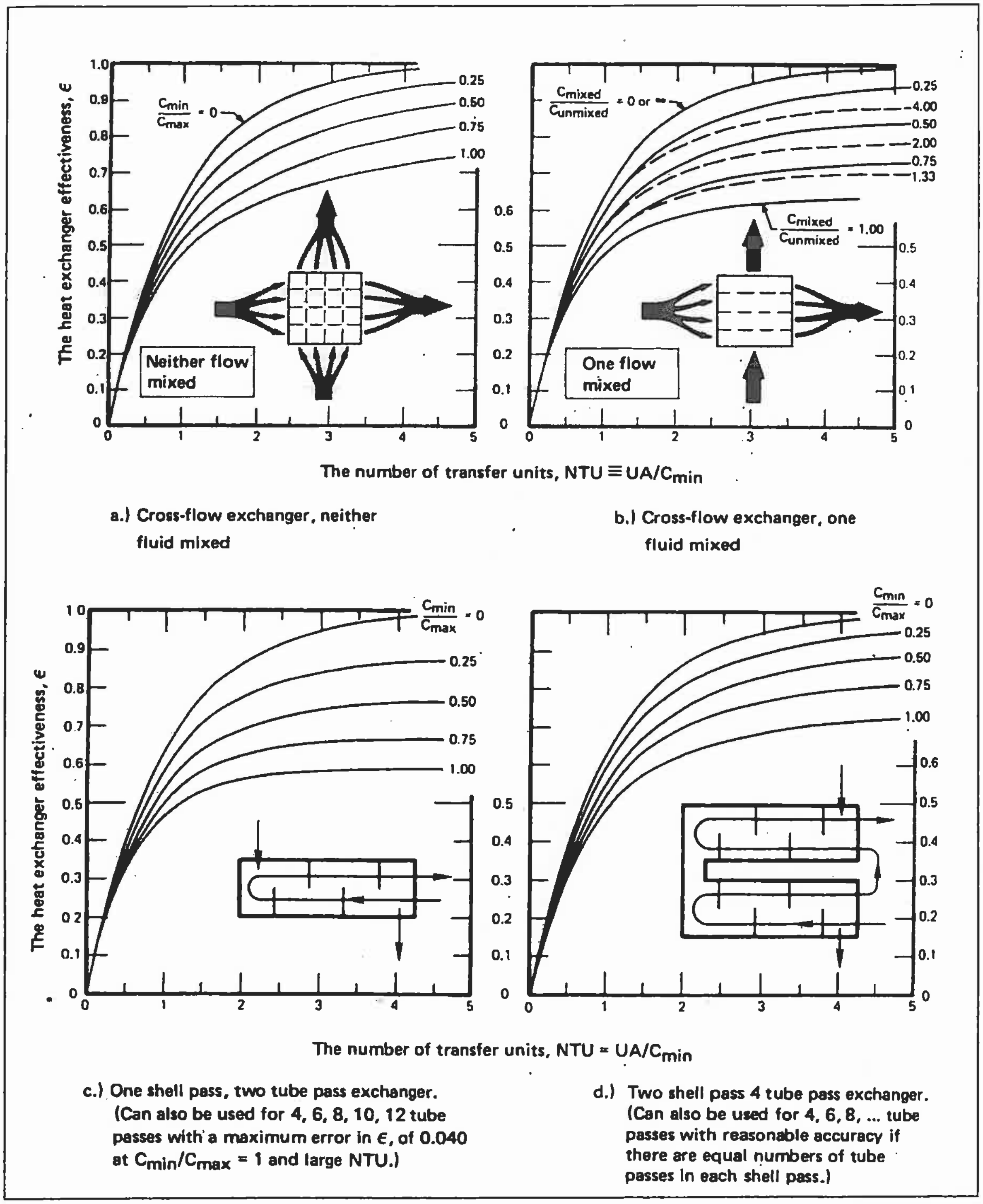

Fig. B2: The effectiveness of various heat exchanger configurations[6]

[6] From: Lienhard, JH *ibid*, Fig.3.17, p 100.