National Exams May 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 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.
7. Useful tables and figures are appended at pp. 4-9.

Section A: Mechanical Operations

A1. **[20 marks]** A pump takes water from a reservoir and delivers it to a water tower. The water in the tower is at atmospheric pressure and is 120 ft. above the reservoir. The pipeline consists of 1000 ft. of straight 2-in sch. 40 commercial steel pipe (2.067-in ID, roughness ε = 0.0018-in), 32 fully open gate valves, 2 fully open bevel seat globe valves, and 14 standard 90° elbows. If the water were to be pumped at a rate of 100 USgpm using a pump that is 70% efficient, what horsepower motor would be required to drive the pump?

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

A2. **[20 marks]** Air is in a reservoir at a pressure of 710 kPa(abs) and a temperature of 45°C. It leaves the reservoir through a convergent nozzle with an exit area of 0.00051 m^2. If the air enters the nozzle at a pressure of 525 kPa(abs), determine the pressure at the nozzle exit, the temperature at the nozzle exit, and the mass flow rate.

The heat capacity for air is 1005 J/kg·K; the specific gas constant is 287.1 J/kg·K; and γ may be taken as 1.4.

A3. **[20 marks overall]** Spherical catalyst particles of d_p = 50 μm and ρ_s = 1.65 g/cm^3 are to be used to contact a hydrocarbon vapor in a fluidized bed reactor at 900°F and a pressure of 1.0 atm. At these operating conditions the fluid viscosity is 0.02 cP and its density is 0.21 lb_m/ft^3. Determine the following:

(a) **[15 marks]** The minimum fluidization velocity for ε_{mf} = 0.42; and

(b) **[5 marks]** The particle terminal velocity.

Fig. A2 appended to the end of the paper may be useful.

Section B: Thermal Operations

B1. **[20 marks overall]** A large curing oven in a processing plant has a high-temperature glass door that is 1.2 m high and 2.5 m wide. If the ambient air temperature is 24°C and the surface temperature of the door is 230°C calculate the rate of convective heat transfer from the oven to the room.

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

B2. **[20 marks]** Hot water at 80°C enters the tubes of a two-shell-pass, eight-tube-pass heat exchanger at the rate of 0.375 kg/s heating helium from 20°C. The overall heat transfer coefficient is 155 $W/m^2 \cdot °C$ and the exchanger area is 10 m^2. If water exits at 44°C, determine both the exit temperature and mass flow rate of helium. For water C_P may be taken as 4.158 kJ/kg·K and for helium $C_P = 5.2$ kJ/kg·K.

Useful charts are appended as Fig. B1.

B3. **[20 marks overall]** A 1-m diameter platinum sphere is removed from a heat treatment furnace at 800°C and placed in a circular holder. The holder covers 5% of the surface area of the sphere, which is allowed to cool in a quiescent environment at a temperature of $T_\infty = 27°C$. Over the temperature range of interest, the density and specific heat of platinum are 21,450 kg/m^3 and 130 J/kg·K, respectively. Platinum may be considered gray with an emissivity of 0.9. You may assume negligible heat loss by conduction through the holder. Assuming radiative heat loss is much greater than heat loss by natural convection calculate the time for the sphere to cool to 600°C.

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,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,k]	1.0	60
used as ell, entering branch[b,d,k]	1.0	60
branch flowing[f,h,i]	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
$\frac{3}{4}$ 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,i]	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,i]	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.

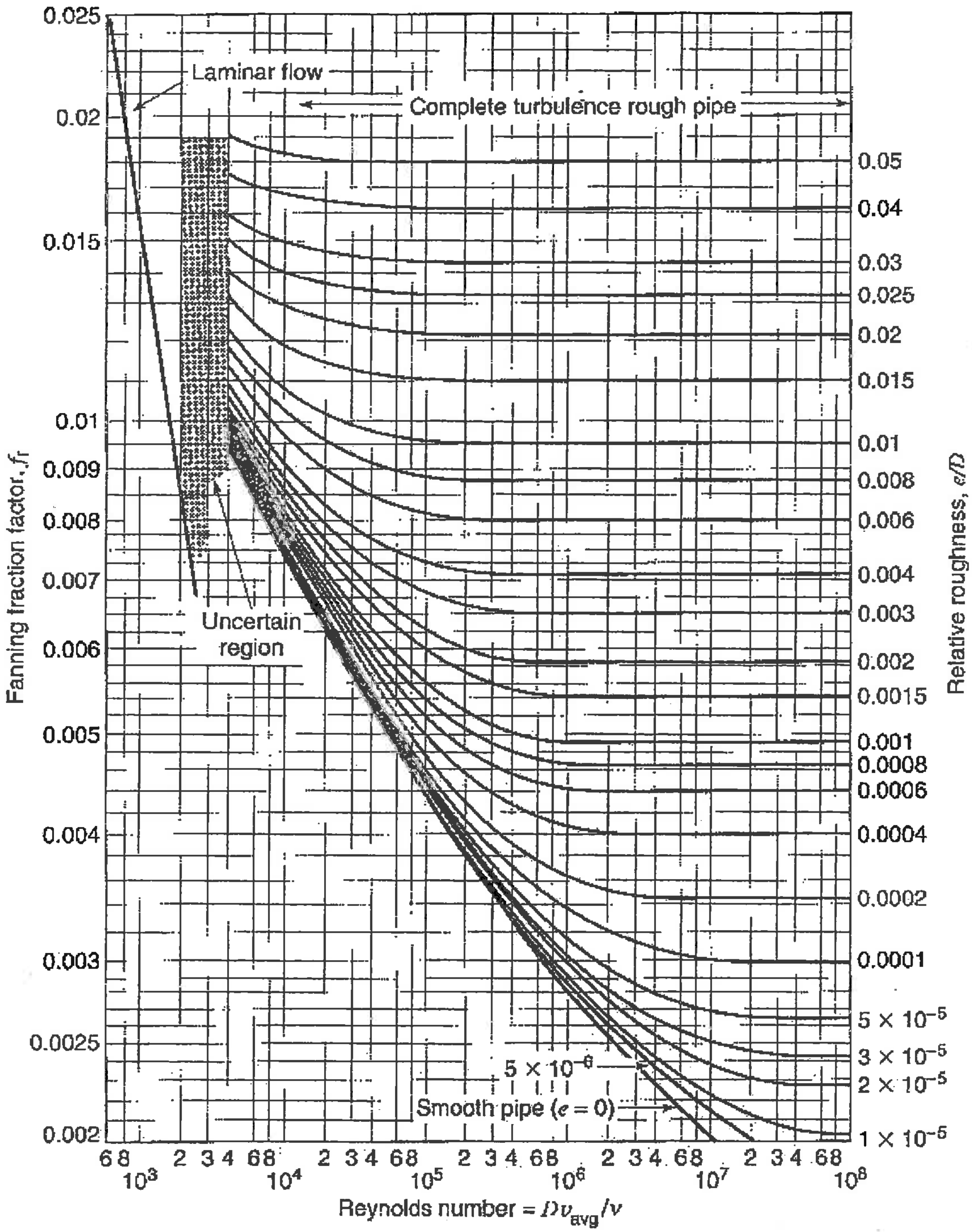
[b] Freeman: *Experiments upon the Flow of Water in Pipes and Pipe Fittings*, American Society of Mechanical Engineers, New York, 1941.

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

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

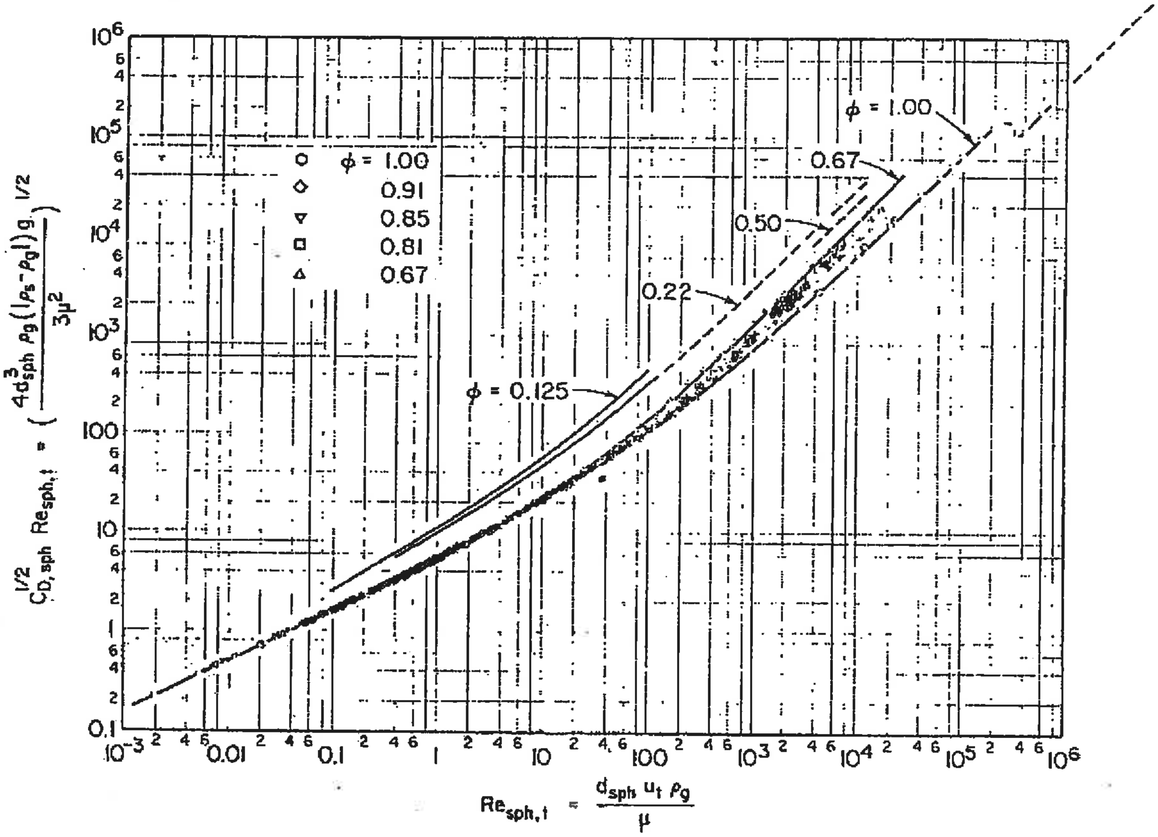
[2] From: Brodkey, R.S. and Hershey, H.C. (1988) *Transport Phenomena: A unified approach* McGraw-Hill, NY, Table 10.5, p 435.

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



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

Fig. A2: Chart for determining terminal velocity of particles falling through fluids[4]



[4] From: Levenspeil, O. (1986) "*Engineering Flow and Heat Exchange*" Plenum Press, NY, Fig. 8.2, p 152.

Table B1: Properties of air at atmospheric pressure[5]

T [K]	k [W/mK]	$10^6\ \alpha$ [m^2/s]	$10^6\ \nu$ [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
550	0.0439	66.7	45.57	0.683
600	0.0469	76.9	52.69	0.685
650	0.0497	87.3	60.21	0.690
700	0.0524	98.0	68.10	0.695
750	0.0549	109.0	76.37	0.702
800	0.0573	120.0	84.93	0.709

[5] 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.

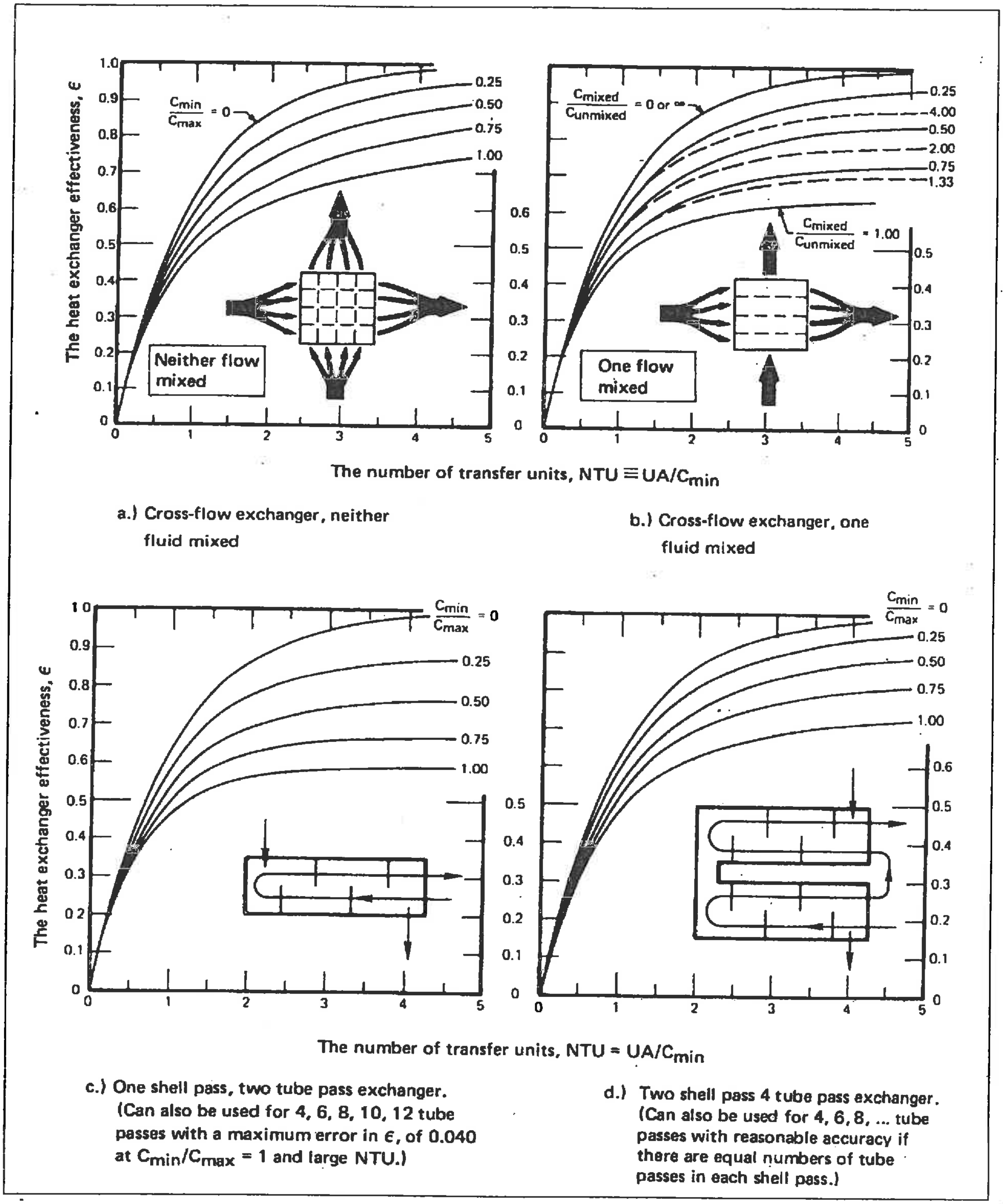


Fig. B1: The effectiveness of various heat exchanger configurations[6]

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