National Exams May 2014

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 the end of the paper.

National Exams

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Section A: Mechanical Operations

A1. **[25 marks]** The flow rate through a 10 cm ID commercial wrought iron pipe is 0.04 m^3/s. For the system shown in Fig. 1, determine the difference in elevation, h, between the two reservoirs. The fluid is water at 20°C (density of 998.2 kg/m^3 and viscosity of 0.001002 Pa s).

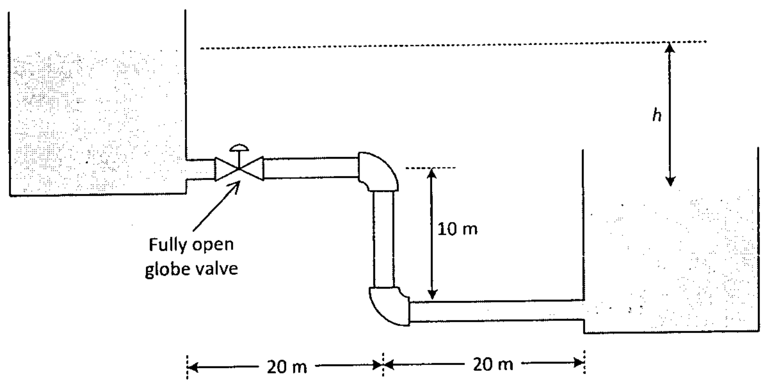


Fig. 1: Pipe system for QA1

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

A2. **[25 marks overall]** Mixing is to be carried out in a cylindrical tank that has a diameter of D_t = 2.0 m and a height of H = 2.0 m. The tank has four baffles that have a width of $J = 0.1\ D_t$. The impeller is a six-blade disk turbine with a diameter $D_a = D_t/3$, blade length $L = 0.25\ D_a$, and blade width $W = 0.2\ D_a$. The impeller speed is 85 rpm. The liquid in the mixer has the properties of water: ρ = 1000 kg/m^3 and $\mu = 1.0 \times 10^{-3}$ Pa·s. Useful information is appended as **Figure A2 and Table A3.**

(a) **[10 Marks]** Calculate the power per unit volume for the mixer.

Now you want to scale up this mixer to one having a diameter of 4.0 m.

(b) **[10 Marks]** If you carry out the scale-up on the basis of equal power per unit volume, what power is required from the motor?

(c) **[5 Marks]** What speed will the impeller have to be driven at?

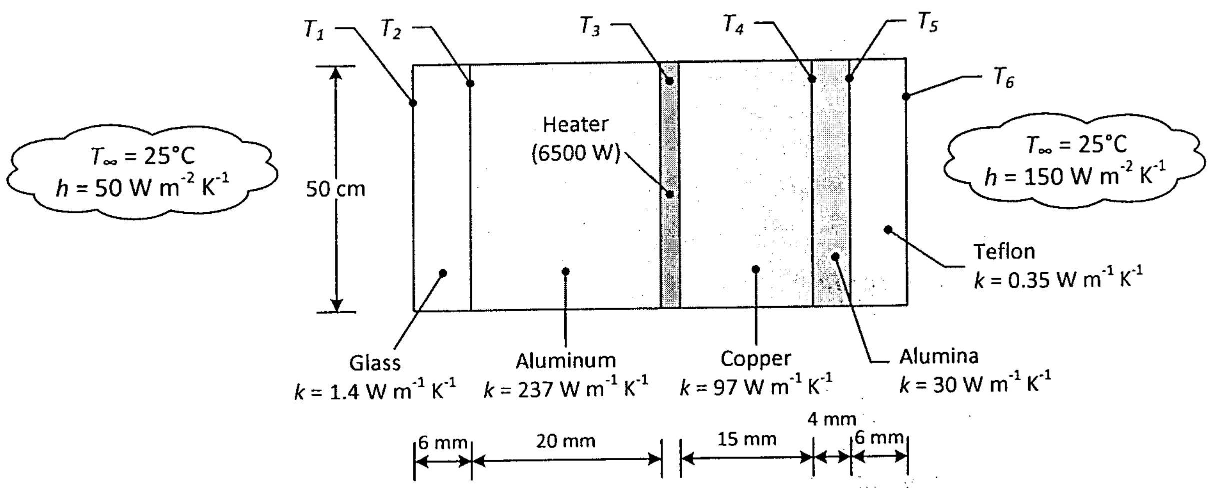
A3. **[25 marks]** A slurry with 20 wt% solids (ρ_s = 2,000 kg/m^3) is to be filtered in a rotary drum filter with an area, $A = 3\ m^2$ operating at an internal pressure of 30 kPa and with 30% of the drum surface submerged in the slurry. The density of the filtrate, ρ_f = 1,000 kg/m^3 and its viscosity, $\mu = 1 \times 10^{-3}$ Pa·s. The voidage of the cake is, $\varepsilon = 0.4$, and the specific resistance of the cake, $r = 2 \times 10^{12}/m^2$. Calculate the rate of production of filtrate when the drum rotates at 0.5 rpm if the filter cake is incompressible and the filter cloth has a resistance equal to that of 1 mm of cake, *i.e.* L = 1 mm. The rate of filtration is given by:

$$\frac{dV}{dt} = \frac{A^2(-\Delta P)}{r\mu v\left[V + (LA/v)\right]}$$

in which v is the volume of cake deposited by unit volume of filtrate

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) **[10 marks]** The heat flux through the aluminum side of the composite wall.
(b) **[3 Marks]** The heat flux through the copper side of the composite wall.
(c) **[10 Marks]** The temperatures T_1 to T_6.
(d) **[2 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]** Experimental heat transfer measurements have been made for air flows over a rough plate. For this particular plate, the convective heat transfer effects have been correlated by,

$$Nu_x = 0.04 \mathrm{Re}_x^{0.9} \mathrm{Pr}^{-1/3}$$

For air flow at 50 m/s and 300 K, determine the shear stress at 1 m from the leading edge of the plate.

Data for air at 300 K is Pr = 0.708, ρ = 1.1769 kg/m^3 and μ = 1.8464 × 10^{-5} m^2/s.

B3. **[25 marks]** A test on a cross-flow water-to-air heat exchanger in which both fluids are unmixed is conducted to determine the overall heat transfer coefficient U_i based on the inner surface area of the tubes. The exchanger has 40 tubes of internal diameter 5 mm and length 0.65 m. Hot water enters the tubes at 90°C at a rate of 36 kg/min and leaves at 65°C. Air flows across the tubes and is heated from 20°C to 40°C. Calculate U_i.

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

Table A1: 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.2: 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,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,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).

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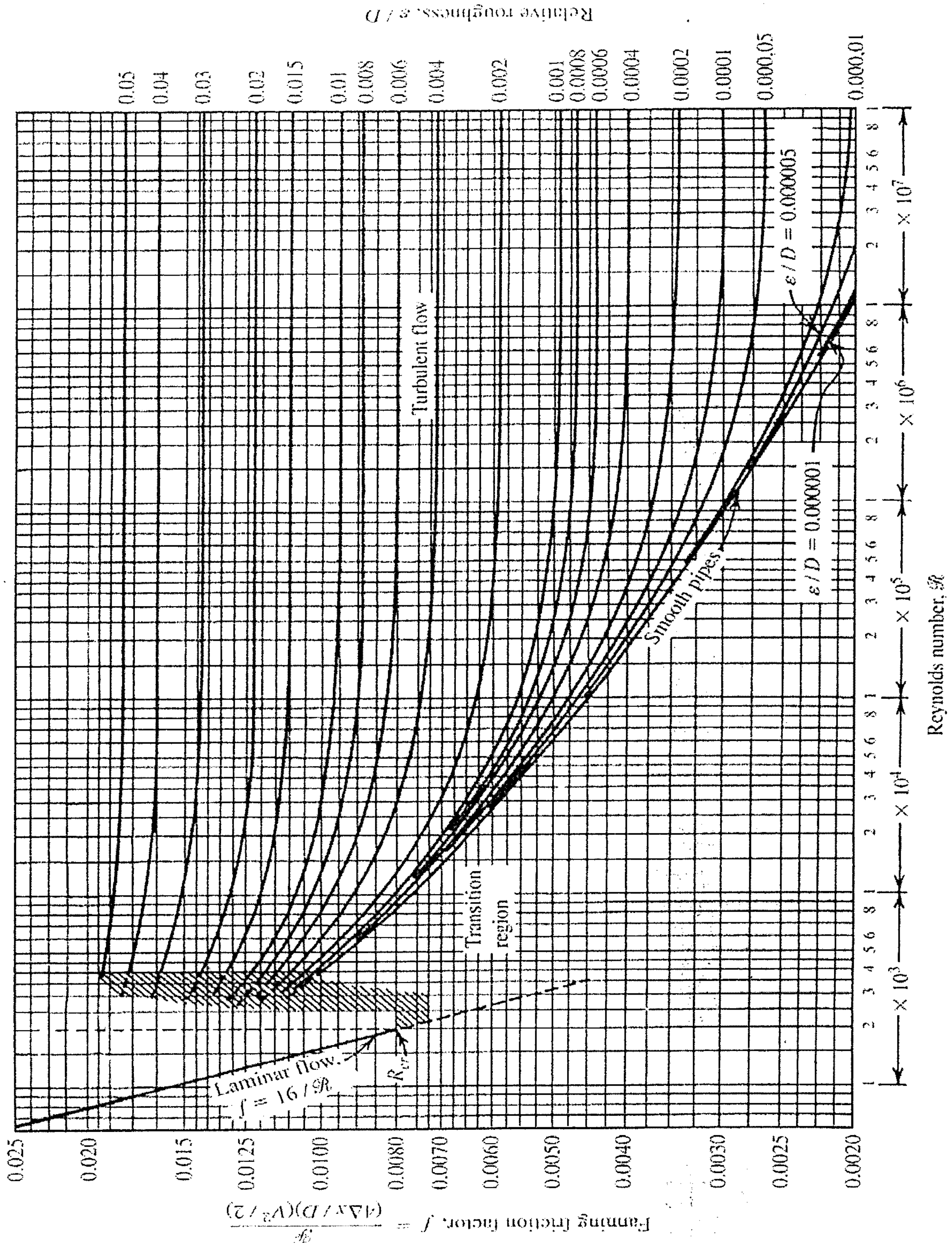
[1] From: Brodkey, R.S. and Hershey, H.C. (1988) *Transport Phenomena: A unified approach* McGraw-Hill, NY, Table 10.5, p 435.

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.

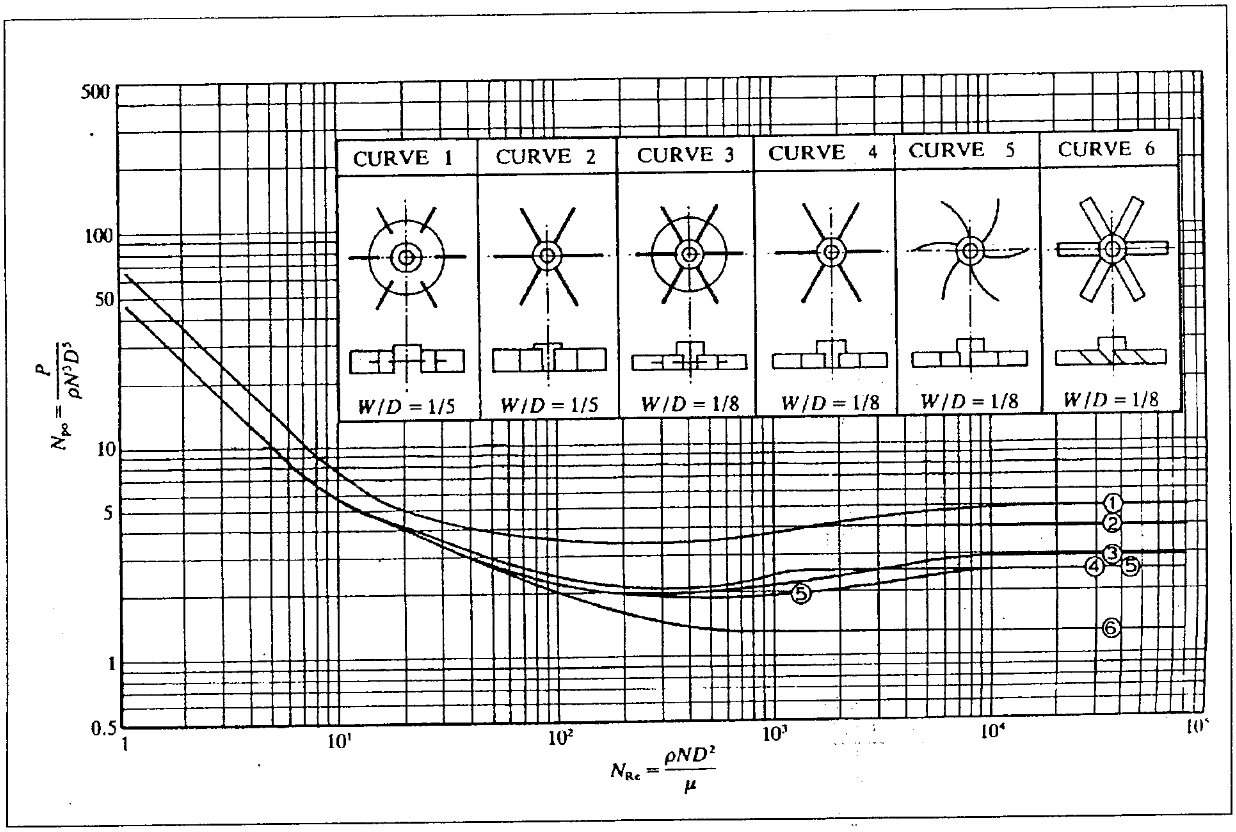


Fig. A2: Power number vs. Reynolds number for turbines and high-efficiency impellers.

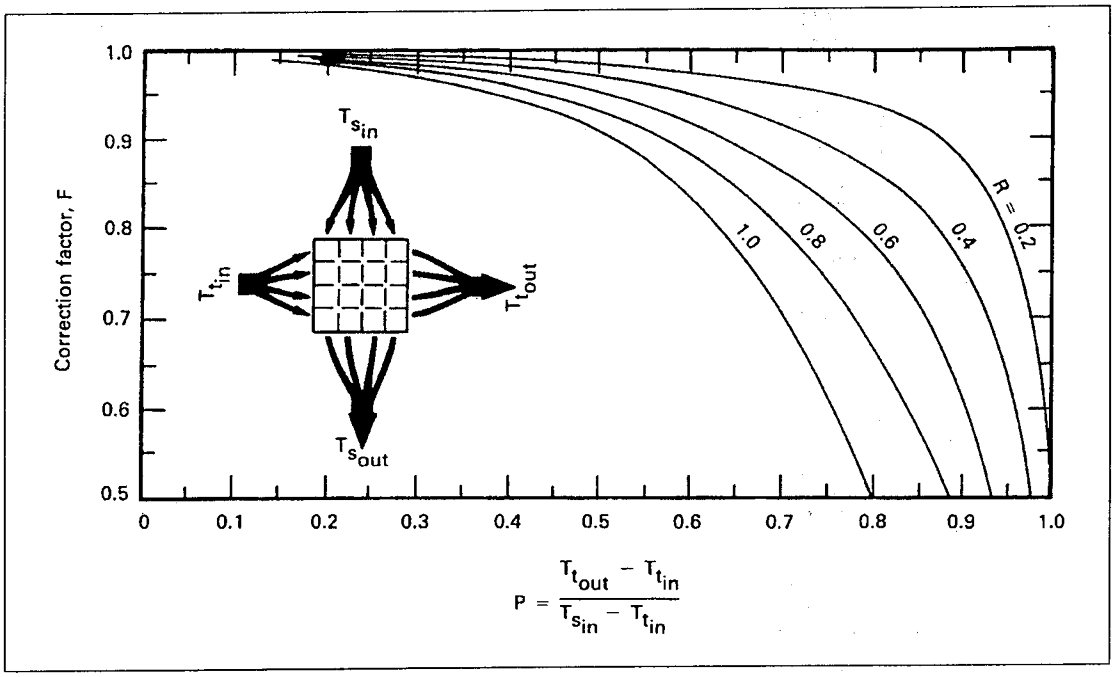
Table A3: Values of K_L and K_T for Baffled Tanks with Four Baffles Having a Width Equal to 10% of the Tank Diameter [*cf. MSH Table 9.3*]

Type of impeller	K_L	K_T
Propeller, three blades		
Pitch 1.0	41	0.32
Pitch 1.5	55	0.87
Turbine		
Six-blade disk	65	5.75
Six curved blades	70	4.80
Six pitched blades	-	1.63
Four pitched blades	44.5	1.27
Flat paddle, two blades	36.5	1.70
Anchor	300	0.35

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[3]



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

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