

National Exams December 2013  
**04-CHEM-A2, Mechanical and Thermal Operations**  
3 hours duration

**NOTES**

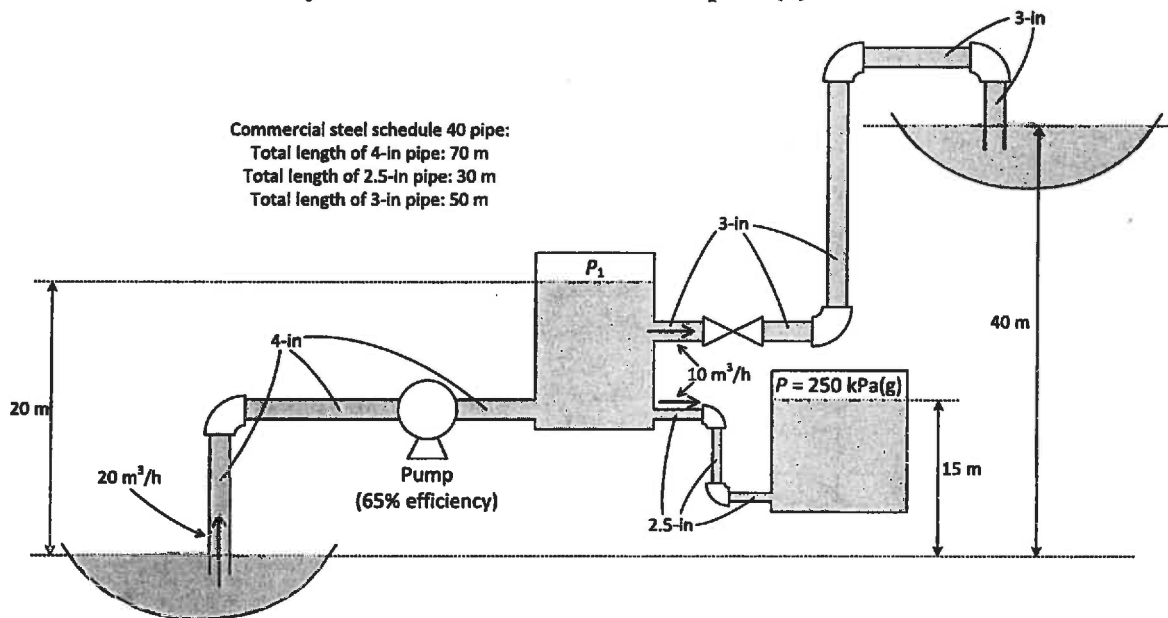
1. If doubt exists as to the interpretation of any question, the candidate is urged to submit with the answer paper, a clear statement of any assumptions made.
2. The examination is an OPEN BOOK EXAM.
3. Candidates may use any **non-communicating** calculator.
4. All problems are worth 25 marks. **Two 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. 5-8.

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**Section A: Mechanical Operations**

**A1. [25 marks overall]** Consider the water delivery system shown below. Water is pumped from a reservoir to an intermediate pressurized tank through a commercial steel pipe with an internal diameter of 4-in at  $20 \text{ m}^3/\text{h}$ . The pump operates with an efficiency of 65%. Leaving the pressurized tank are two lines. A 2.5-in internal diameter commercial steel pipe is connected to another pressurized tank. The flow rate through this pipe is  $10 \text{ m}^3/\text{h}$ . The other pipe leaving the intermediate tank has a flow rate of  $10 \text{ m}^3/\text{h}$  and is commercial steel with an internal diameter of 3-in. Total pipe lengths are listed on the diagram. All elbows are  $90^\circ$  standard, for which the equivalent length is 30 and the loss coefficient is 0.75 (i.e.  $L/D$  for the elbows is 30 or  $k$  for the elbows is 0.75). For water, assume a density of  $998.2 \text{ kg/m}^3$  and a viscosity of  $0.001002 \text{ Pa}\cdot\text{s}$ . The roughness ( $\epsilon$ ) of commercial steel pipe is  $0.0457 \text{ mm}$  ( $0.0018 \text{ in}$ ).

**Friction effects associated with all entrances, exits, expansions and contractions should be neglected. Note that the loss coefficient,  $k$ , for the valve on the 3-in line is unknown and you are asked to solve for it in part (d).**



- (a) Fill in the missing information in the following table (show calculations and state assumptions on the following pages).
- (b) Estimate the pressure in the intermediate tank in kPa (gauge). Use either the equivalent length or loss coefficient method to account for friction losses through the elbows.
- (c) Estimate the required pump power in kW. Use either the equivalent length or loss coefficient method to account for friction losses through the elbows.
- (d) Determine the loss coefficient,  $k$ , for the valve on the 3-in line. Use either the equivalent length or loss coefficient method to account for friction losses through the elbows.

Useful information is appended as **Table A1** and **Fig. A1**.

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Hand in this completed table with your answers

	4-in ID Pipe	3-in ID Pipe	2.5-in ID Pipe
Length (m)	70	50	30
Diameter (in)	4	3	2.5
Diameter (m)	0.101601	0.076201	
Volumetric flow rate (m <sup>3</sup> /h)	20	10	10
Cross-sectional area (m <sup>2</sup> )	0.0081075	0.0045605	0.0031670
Velocity (m/s)	0.6852	0.6091	
Reynolds number	69357	46238	
$\epsilon/D$	0.00045	0.0006	
Friction factor, $f$			
$(L/D)_{eq}$			
$F_{pipe} + F_{fittings}$ (m <sup>2</sup> /s <sup>2</sup> ) OR $h_{pipe} + h_{fittings}$ (m)			(without valve)
Mass flow rate (kg/s)		Not Required	Not Required

**A2. [25 marks overall]**

Air at 27°C and 107.5 kPa is continuously fed to a packed bed consisting of spherical particles 5-mm in diameter. If the bed height is 5.0 m and the voidage is 33%, what is the bed Reynolds number? The viscosity of air under these conditions may be taken as  $1.5 \times 10^{-5}$  Pa·s and  $R = 8.314 \text{ m}^3 \cdot \text{Pa} / \text{mol} \cdot \text{K}$ .

**A3. [25 marks overall]** In a vegetable refining process, the aqueous phase is being separated from the oil phase in a centrifuge. The radius for the overflow of the light liquid is set at 10.160 mm and the heavy liquid outlet is set at 10.414 mm.

You decide to measure the density of both the aqueous and oil phases using an uncalibrated hydrometer. The hydrometer consists of a composite glass rod 150 mm long and 15 mm in diameter. You place the hydrometer on a balance and find it weighs 20.800 g. The hydrometer has markings along its length going from 0.0000 to 1.0000. When you place the hydrometer in the oil phase, it settles in the liquid and reads 0.8533. When placed in the aqueous phase it reads 0.8004.

- (a) [20 marks] Determine the density of the two phases; and  
 (b) [5 marks] Calculate the location of the interface in the centrifuge.

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**Section B: Thermal Operations**

- B1. [25 marks overall]** A chemical reaction produces heat uniformly throughout a 25 cm diameter sphere at a rate of  $2 \text{ kW/m}^3$ . If the sphere is made of a material with a thermal conductivity of  $0.1 \text{ W/m}\cdot\text{K}$  and the outer surface temperature is maintained at  $40^\circ\text{C}$ :
- (a) [20 marks] Derive an expression for the temperature profile in the sphere.
  - (b) [5 marks] What is the maximum temperature in the sphere?
- B2. [25 marks overall]** Steam flows through a finned pipe heat exchanger. The outer pipe diameter is 30 mm and the pipe walls are maintained at  $130^\circ\text{C}$ . The ambient air temperature is  $20^\circ\text{C}$  and the combined heat transfer coefficient is  $60 \text{ W/m}^2\cdot\text{C}$ .
- (a) [10 marks] What is the rate of heat transfer per meter of the unfinned pipe?
  - (b) [15 marks] Circular fins of thickness 2 mm and an outer diameter of 60 mm are attached to the pipe spaced 3 mm apart. If the fins are made from aluminum ( $k = 200 \text{ W/m}\cdot\text{C}$ ), what is the increase in the rate of heat transfer per meter of finned tube?

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

- B3. [25 marks overall]** A shell-and-tube exchanger is to heat  $6,800 \text{ kg/h}$  of benzene from  $22^\circ\text{C}$  to  $70^\circ\text{C}$  by having  $4,500 \text{ kg/h}$  of hot water flow through the single pass shell of the exchanger entering at  $100^\circ\text{C}$ . Pressure-drop considerations limit the maximum velocity of the benzene in the tubes to  $1.2 \text{ m/s}$ . Furthermore, space limitations limit the length of the exchanger to 6 m. Tubes of 13-mm internal diameter are to be used and the overall heat transfer coefficient based on the internal diameter of the tubes has been estimated at  $284 \text{ W/m}^2\cdot\text{K}$ . Determine the following: (i) the number of tubes passes; (ii) the number of tubes per pass; and (iii) the length of the tubes.

The properties of benzene are:  $c_p = 1.88 \text{ J/kg}\cdot\text{K}$ ,  $\rho = 857 \text{ kg/m}^3$ ). Useful information is appended as **Table B1 and Fig. B2**.

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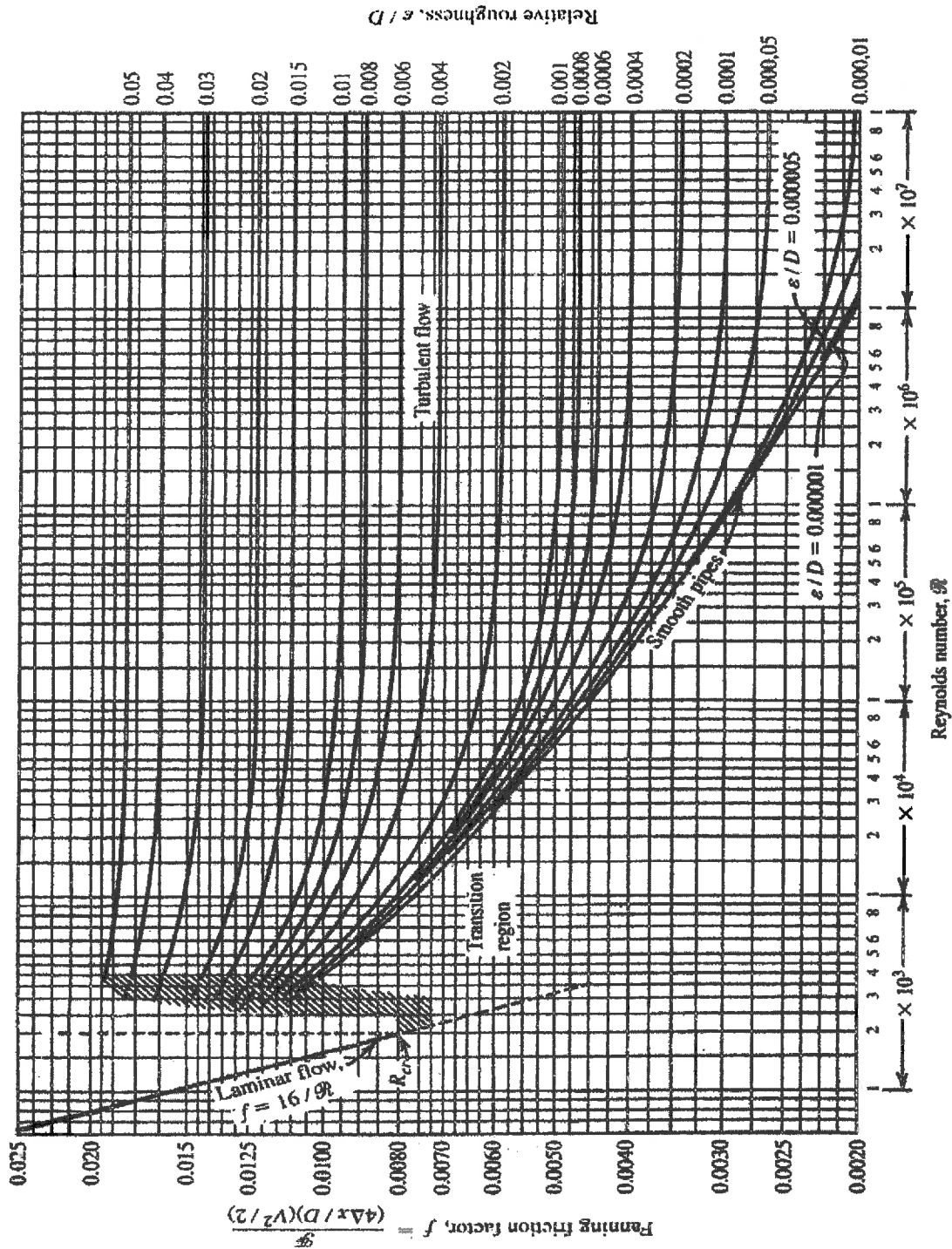
**Table A1: Equivalent Lengths  $(L/D)_{eq}$  and Loss Coefficients  $(k)$  for Turbulent Flow Through Valves and Fittings<sup>1</sup>**

Fitting or Valve type			Loss Coefficient $k$	Equivalent Length $(L/D)$	
Elbows	180°	Bend, close return	1.50	50	
		Standard	0.75	30	
	90°	Long radius	0.45	20	
		Square or mitre	1.30	57	
		45°	Standard	0.35	16
			Long radius	0.2	-
Tees	used as elbow	Entering run	1.0	60	
		Entering branch	1.0	60	
	run-through	Branch blanked off	0.4	20	
Coupling			0.04	0.1	
Union			0.04	0.1	
Ball		Fully open	0.17	13	
Gate		Fully open	0.17	13	
		75% open	0.9	35	
		50% open	4.5	160	
		25% open	24	900	
	Diaphragm	Fully open	2.3	-	
	75% open	2.6	-		
	50% open	4.3	-		
	25% open	21	-		
Globe	Bevel seat	Fully open	6.0	340	
		50% open	9.5	-	
Globe	Composition seat	Fully open	6.0	340	
		50% open	8.5	-	
Globe	Plug disk	Fully open	9.0	450	
		75% open	13.0	-	
		50% open	36.0	-	
		25% open	112.0	-	

<sup>1</sup> From *Transport Phenomena: A Unified Approach*, by Brodkey and Hershey, copyright © 1988 By Brodkey and Hershey. Reprinted by permission of the McGraw-Hill Companies, Inc.

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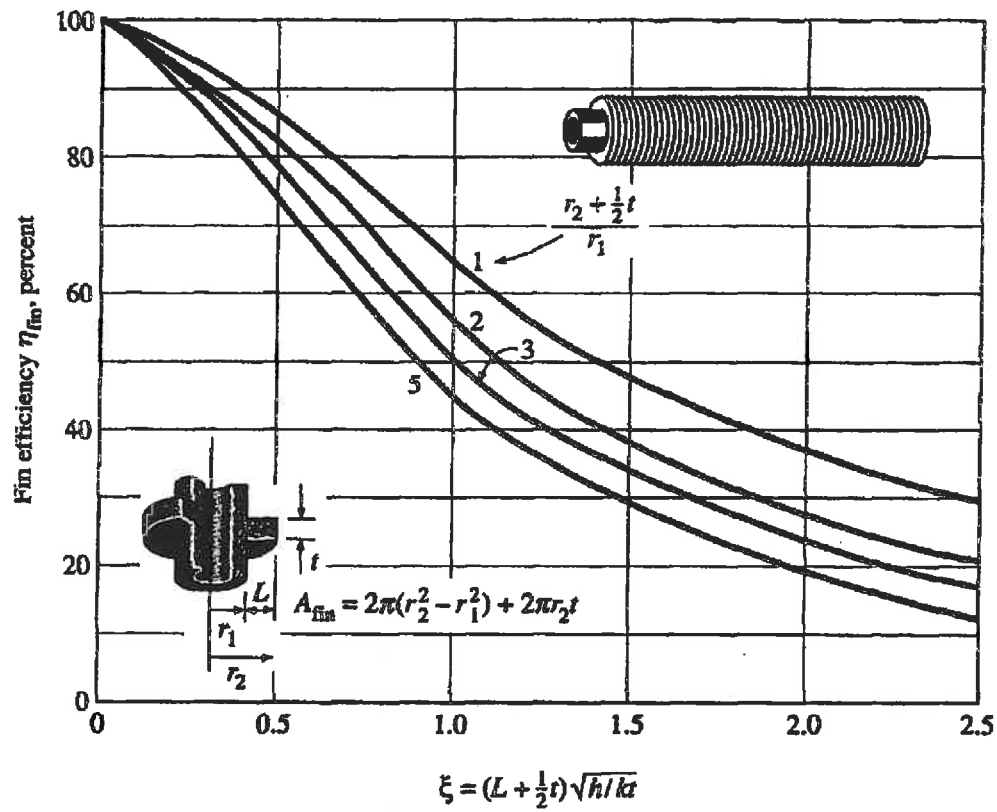
Fig. A1: Fanning friction factor as a function of  $N_{Re}$  and  $\epsilon/D^2$



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

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Fig. B1: Efficiency of circular fins of length  $L$  and constant thickness  $t$ .<sup>3</sup>



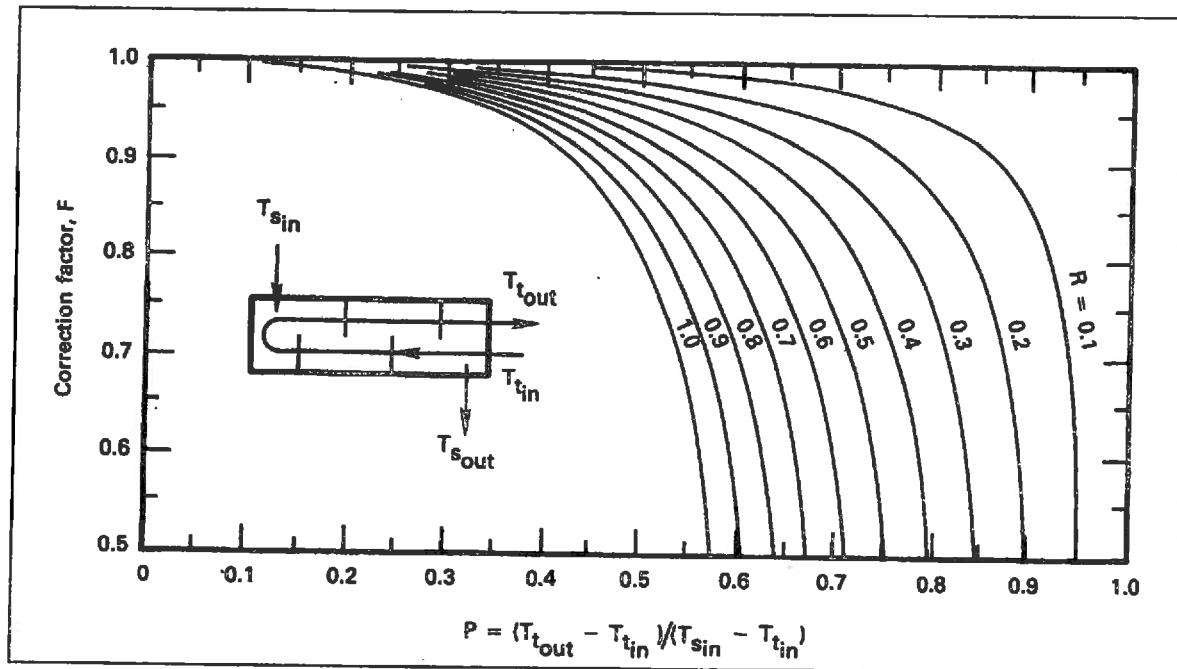
<sup>3</sup> From Çengel, Y.A. (1998) *ibid.* p 185. Also see Fig. 3.19 p 150.

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**Table B1: Specific heat capacity of water**

T [°C]	c <sub>p</sub> [J/kg·K]	T [°C]	c <sub>p</sub> [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. B2: LMTD correction factor, *F*, for a one-shell-pass, two-, four-, six-... or more tube-pass exchanger<sup>4</sup>**



<sup>4</sup> *Standards of Tubular Exchanger Manufacturer's Association*, 4<sup>th</sup> and 6<sup>th</sup> eds. Tubular Exchanger Manufacturer's Association (TEMA), Inc. NY (1959 and 1978).