National Exams December 2008

04-CHEM-B1, Transport Phenomena

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. **One problem** from **each** of sections A, B, and C must be attempted. A **fourth** problem from **any section** must also. be attempted.
5. **Only the first four** questions as they appear in the answer book will be marked.
6. State all assumptions clearly.

Section A: Fluid Mechanics

A1 [25 marks overall] Figure A1 shows the flow of a viscous isothermal liquid film (viscosity μ, and density ρ) along an inclined flat surface under the influence of gravity (g).

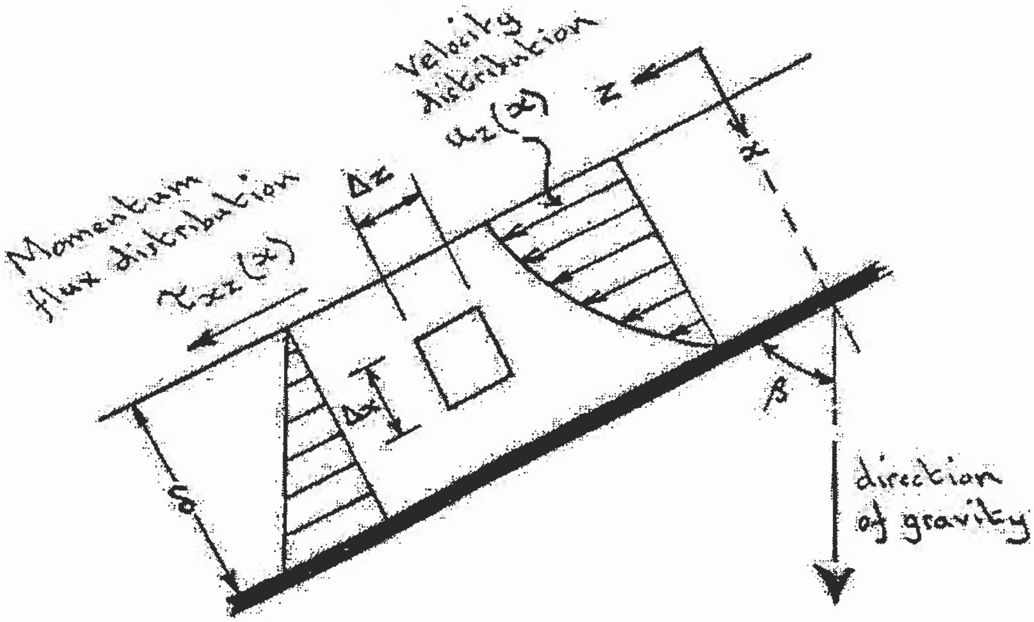

Fig. A1: Inclined flat plate with a flowing liquid film

(a) **[15 marks]** By writing a momentum balance for a volume element $\Delta x \Delta y \Delta z$ in the Cartesian coordinate system oriented as shown in Fig. A1, show that the steady-state momentum flux distribution is given by:

$$\tau_{xz} = \rho g x \cos\beta$$

(b) **[10 marks]** If the fluid is Newtonian, show that the steady-state velocity distribution is given by:

$$u_x = \rho g \delta^2 \cos\beta \cdot \left[\frac{1-(x/\delta)^2}{2\mu}\right]$$

A2 [25 marks overall]

My wife loves tomatoes. So much so, that when we wanted to go away for a few days during the growing season she said. "*You're an engineer; surely you can rig up something to give my tomato plant sufficient water each day we are away.*" She tells me the plant needs 2.5 L of cold water per day. My proposed plan is shown in Fig. A2. The water pressure at the outlet of the faucet is 150kPa(g). I need you to calculate the length of 0.3 mm diameter plastic tube I need to connect to the wide-open faucet to deliver 2.5 L/day of cold water. Everything, of course, is on the level.

The cold water is delivered at 40°F. At 40°F, the density of water is 62.43 lb_m/ft^3 and the viscosity is1.546 cP.

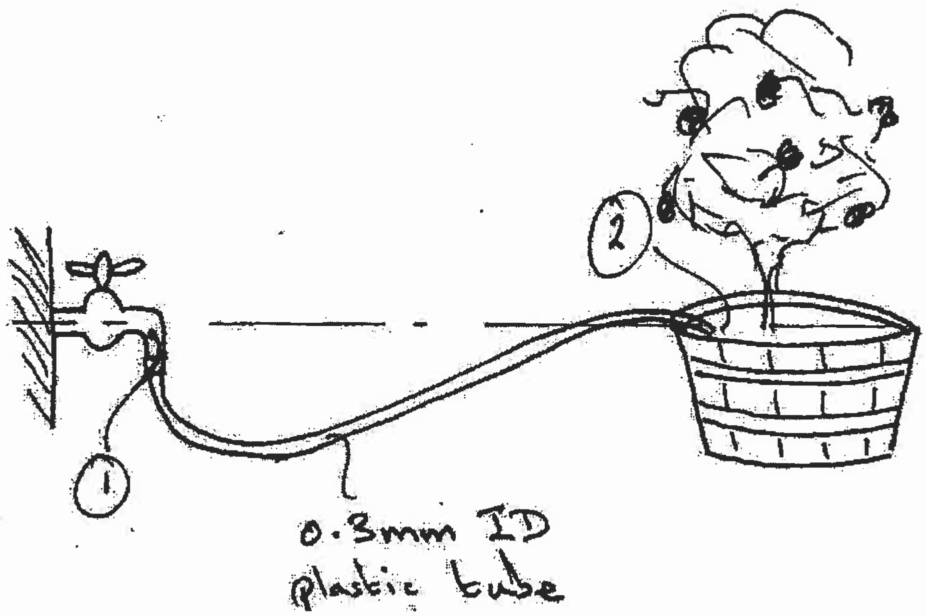

Fig. A2: Tomato growing in absentia

Section B: Heat Transfer

B1 [25 marks overall] Consider unidirectional conduction of heat in a conically shaped conductor, the surfaces of which are thermally insulated, as shown in Fig. B1. The cross-sectional area of the cone normal to the direction of heat flow at any location $x_1 < x < x_2$ is given by $A_x = ax^2$.

(a) [20 marks] For a particular geometry in which $a = 0.1131$, $T_1 = 1000\text{K}$ at $x_1 = 0.1$ m, and $T_2 = 500$ K at $x_2 = 0.5$ m, calculate the heat flow ($\dot{Q}_x$) if the thermal conductivity (k) of the material is 5.0 W/mK.

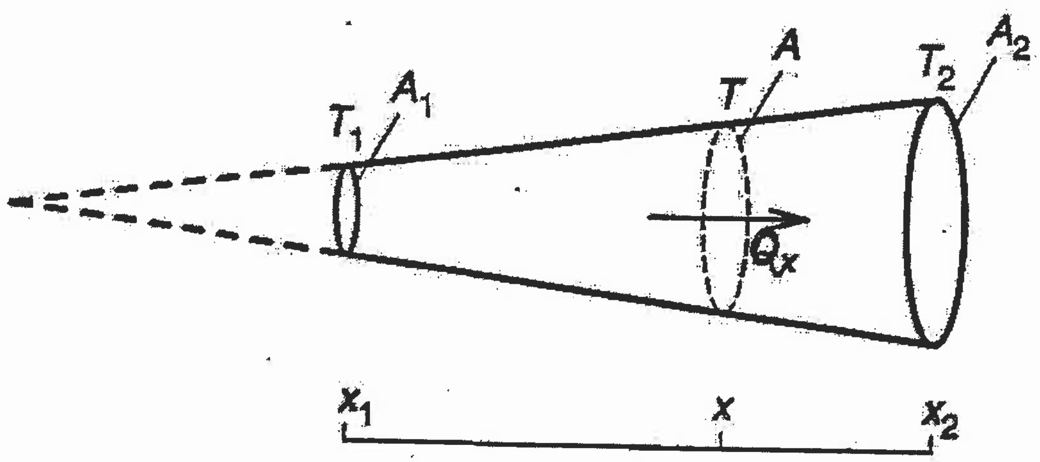

Fig. B1: Unidirectional conduction of heat in a conically shaped conductor

(b) [5 marks] Furthermore, show that the variation of temperature with distance x is given by:

$$T = T_1 - \left\{ (T_1 - T_2) \cdot \frac{(x_1 - x)}{(x_1 - x_2)} \cdot \frac{x_2}{x} \right\}$$

B2 [25 marks overall]

Atmospheric nitrogen at 150°C flows across a long 50-mm diameter circular cylinder at a velocity of 20 m/s. The surface temperature of the cylinder is 550°C. On a per-unit-length basis, find:

(a) [10 marks] The drag force exerted on the cylinder. The drag coefficient as a function of Reynolds number for cylinders is shown in Fig. B2

(b) [15 marks] The convective heat transfer coefficient from the cylinder.

The thermophysical properties of nitrogen are given in Table B1.

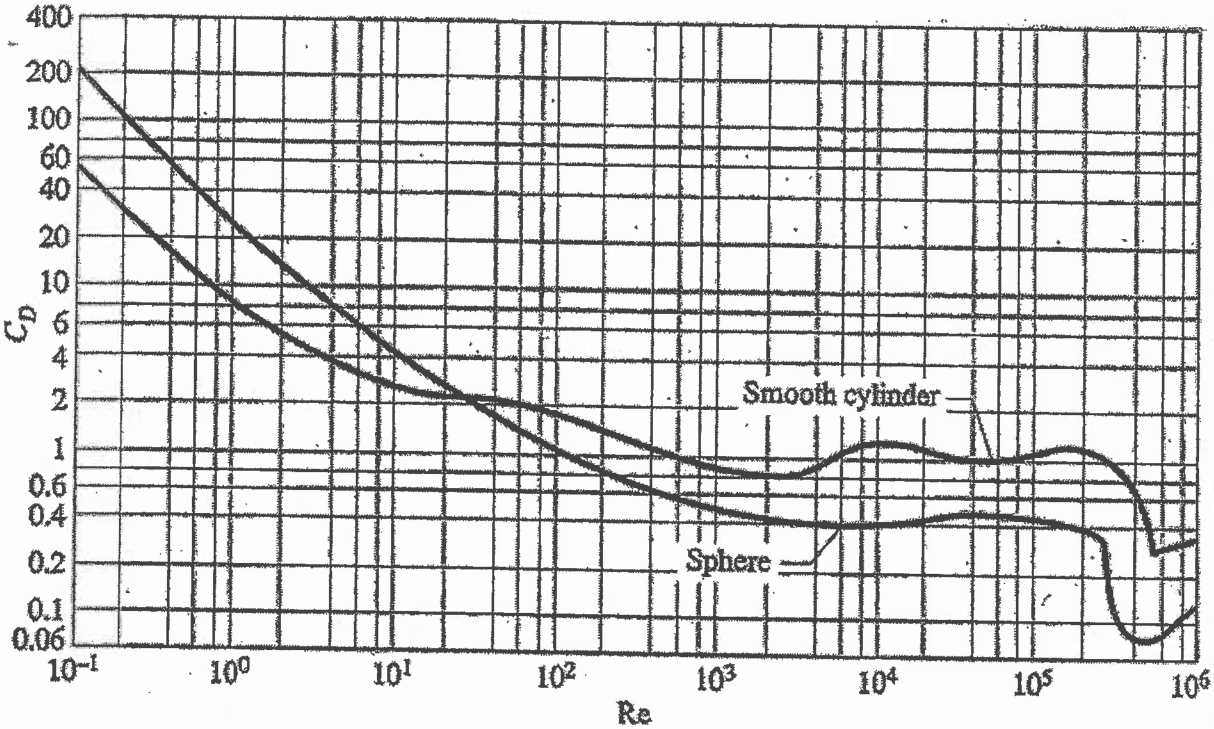

Fig. B2.: Average drag coefficient for cross flow over a smooth cylinder

Table B1: Thermophysical properties of nitrogen

T [K]	ρ [kg/m³]	C_p [J/kgK]	k [W/mK]	10^5 α [m²/s]	10^5 μ [kg/ms]	10^5 ν [m²/s]	Pr [-]
300	1.136	1040	0.0260	2.16	1.79	1.57	0.715
350	0.967	1041	0.0294	2.92	2.01	2.08	0.711
400	0.854	1045	0.0235	3.64	2.21	2.59	0.710
450	0.759	1050	0.0356	4.47	2.41	3.17	0.709
500	0.683	1057	0.0387	5.36	2.59	3.79	0.708
550	0.621	1065	0.0414	6.26	2.76	4.45	0.711

Section C: Mass Transfer

C1 [25 marks overall] The formulae given for mass transfer from a long cylinder in a cross-flow of air are:

$$j_m = 0.60(\mathrm{Re}_D)^{-0.487} \qquad \text{and} \qquad j_m = \frac{k_c}{u_\infty}(Sc)^{2/3}$$

in which j_m is Colburn's j-factor for mass transfer and the Reynolds number is based on the outside diameter (D) of the cylinder and the approach air flow velocity (u_∞).

(a) **[10 marks]** Transform these such that it is of the form:

$$Sh = (const)\,\mathrm{Re}^m\, Sc^n$$

(b) **[15 marks]** Benzene is evaporating at a rate of 20 kg/h from the surface of a long porous cylinder 100-mm in diameter. Dry air at 52°C and atmospheric pressure flows orthogonal to the cylinder at a velocity of 2m/s. The liquid benzene is at 42°C and exerts a vapour pressure of 26.7 kPa. The kinematic viscosity of air at 52°C is $17.91\text{x}10^{-6}$ m^2/s and the diffusivity of benzene in air at 52°C and atmospheric pressure is $1.0\text{x}10^{-5}$ m^2/s. Ignoring evaporation from the ends, calculate the length of the cylinder.

C2 [25 marks overall] The mass transfer coefficient for the laminar boundary formed over a flat plate has been correlated in terms of a local Sherwood number by:

$$Sh_x = 0.332\,\mathrm{Re}_x^{1/2}\, Sc^{1/3}$$

Likewise, mass transfer coefficient for the turbulent boundary is correlated by:

$$Sh_x = 0.0292\,\mathrm{Re}_x^{4/5}\, Sc^{1/3}$$

in which x is the distance along the plate from the leading edge.

(a) **[10 marks]** Show that the mean mass transfer coefficient for a flat plate of length L is:

$$\bar{k}_c = \frac{0.664 D_{AB}\left(\frac{u}{\nu}\right)^{1/2} Sc^{1/3} L_t^{1/2} + 0.0365 D_{AB}\left(\frac{u}{\nu}\right)^{1/2} Sc^{1/3}\left[L^{4/5} - L_t^{4/5}\right]}{L}$$

in which u is the fluid velocity, ν is the kinematic viscosity and L_t is the distance from the leading edge of the plate to where the transition to from laminar to turbulent flow occurs.

(b) **[10 marks]** A container of acetone was accidentally spilled on a clean, smooth, laboratory bench in a semi-conductor fabrication building. The exhaust fan in the building produced a 6 m/s air flow parallel to the 1-m wide bench surface. The air was maintained at 298 K and atmospheric pressure. The vapour pressure of acetone at 298 K is 3.066 x 10^4 Pa. Also at 298 K the kinematic viscosity of air is 1.55 x 10^{-5} m^2/s and the diffusivity of acetone in air is 0.93 x 10^{-5} m^2/s. Calculate the mass transfer coefficient at 0.5 m downstream from the leading edge of the bench. The critical Reynolds number for the onset of turbulence over a flat plate is 2 x 10^5.

(c) **[5 marks]** Calculate the amount of acetone (mol/s) evaporating from one square meter of the surface at that location.

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Marking Scheme

A1: 25 marks

- (a) 15 marks
- (b) 10 marks

A2: 25 marks

- (a) 20 marks
- (b) 5 marks

B1: 25 marks

- (a) 20 marks
- (b) 5 marks

B2: 25 marks

- (a) 20 marks
- (b) 5 marks

C1: 25 marks

- (a) 10 marks
- (b) 15 marks

C2: 25 marks

- (a) 10 marks
- (b) 10 marks
- (c) 5 marks