ENGINEERING TRIPOS PART IB

Tuesday 7 June 2005 2 to 4

Paper 4

THERMOFLUID MECHANICS

Answer not more than ***four*** *questions.*

Answer ***two*** *questions from each section.*

All questions carry the same number of marks.

The ***approximate*** *number of marks allocated to each part of a question is indicated in the right margin.*

Answers to questions in each section should be tied together and handed in separately.

There are no attachments to this paper.

You may not start to read the questions printed on the subsequent pages of this question paper until instructed that you may do so by the Invigilator

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SECTION A

*Answer **two** questions from this section.*

1 (a) The specific heat capacity at constant pressure c_p of a certain liquid is constant. When the temperature of unit mass of this liquid changes from T_1 to T_2 at constant pressure, show that its change in entropy Δs is given by

$$\Delta s = c_p \ln\left(\frac{T_2}{T_1}\right)$$

Explain why this result does not depend on how the temperature change takes place. [4]

(b) The same liquid flows steadily and reversibly through a pipe with mass flow rate of $\dot{m}$. The temperature of the liquid falls from T_1 to T_2 and the heat transferred is used to supply a cyclic power plant which rejects heat to a thermal reservoir at constant temperature T_0 (which is less than T_2).

(i) What is the change in enthalpy flowrate of the liquid?

(ii) What is the change in entropy flowrate of the liquid?

(iii) Show that the maximum possible thermal efficiency of the plant is

$$1 - \frac{T_0 \ln(T_2/T_1)}{(T_2 - T_1)}$$

(iv) Explain whether the liquid flow rate should be as high or as low as possible in order to maximise the efficiency? [8]

(c) Water/steam in a horizontal pipe flows steadily and isothermally at 300 °C with a mass flow rate of 10 kgs^{-1}. At two positions along the pipe, A and B, the pressures are 80 bar and 100 bar respectively. Kinetic and potential energy changes may be neglected.

(i) Explain whether B is upstream or downstream of A.

(ii) Calculate the heat transfer across the pipe wall between A and B.

(iii) Calculate the rate of entropy increase due to irreversibility. Suggest a physical cause for this increase. [8]

2 (a) Starting from the differential form of the 1st Law of Thermodynamics

$$\mathrm{d}q - \mathrm{d}w = \mathrm{d}u$$

and an appropriate statement of the 2nd Law of Thermodynamics, show that for a reversible process

$$T\,\mathrm{d}s = \mathrm{d}u + p\,\mathrm{d}v = \mathrm{d}h - v\,\mathrm{d}p$$

Explain why the above is also valid for an irreversible process. [6]

(b) When an incompressible fluid undergoes an isentropic process, show that the change in specific enthalpy is given by

$$\Delta h = v\Delta p$$

where Δp is the change in pressure and v is the specific volume. [4]

(c) The exhaust gas from the gas turbine of a combined-cycle power plant enters the heat recovery steam generator (HRSG) at a temperature of 530 °C as a steady flow. The exhaust gas can be assumed to behave as a perfect gas with the same properties as ambient air and its pressure in the HRSG is constant. The steam in the steam generator is at a uniform pressure of 40 bar. It leaves as superheated steam at a temperature of 400 °C. The pinch-point temperature difference in the HRSG is 10 K.

(i) Determine the ratio of the mass flow rate of the exhaust gas to the mass flow rate of the steam.

(ii) The condenser temperature is 30 °C. The feed pump is isentropic. Determine the enthalpy of the steam after the feed pump. Hence determine the temperature of the exhaust gas after it leaves the HRSG.

(iii) Calculate the change of the entropy of the steam and of the gas in the HRSG per kg of the gas. Comment on the cause of the difference between the two values.

(iv) If the environment is at 30 °C, how much work is lost in the HRSG per kg of the gas? [10]

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3 The refrigeration plant shown in Fig. 1 uses R-134a as the working fluid. The compressor is not isentropic. Saturated vapour enters the compressor. Saturated liquid enters the throttle. The temperature in the evaporator is –10 °C. The pressure in the condenser is 10.17 bar. There is 30 K of superheat at entry to the condenser.

(a) Sketch the cycle on *T-s* and *p-h* diagrams, labelling the thermodynamic states at entry to each component. [2]

(b) What is the dryness fraction at the exit from the throttle? [2]

(c) The rate of heat exchange in the evaporator is 10 kW. What is the mass flow rate of the refrigerant? [2]

(d) What is the isentropic efficiency of the compressor? [4]

(e) Calculate the power input to the compressor and the coefficient of performance of the refrigerator. [4]

(f) What is the highest coefficient of performance that could be achieved for a refrigerator operating between the exit temperatures of the condenser and the evaporator? Why is the actual figure much less than this value? Suggest how you could modify the refrigeration plant to achieve this value? Sketch the new cycle on the *T-s* diagram. [6]

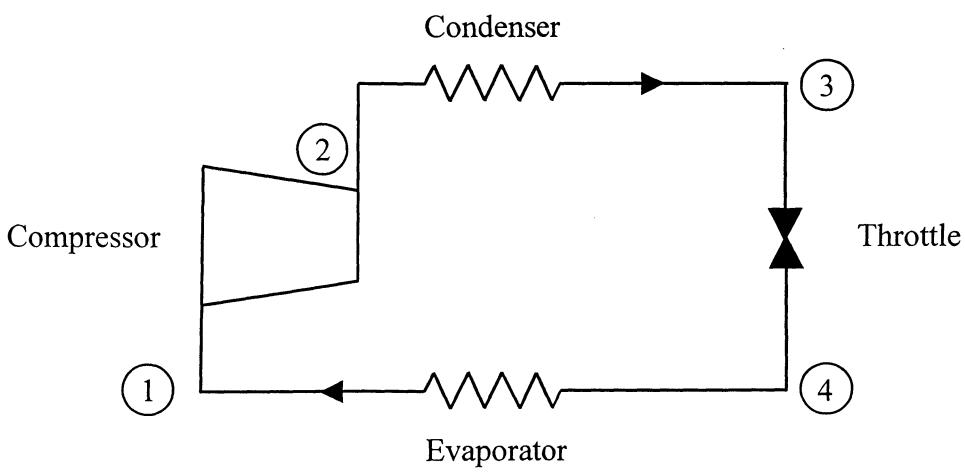

Fig. 1

SECTION B

*Answer **two** questions from this section.*

4 A semi-cylindrical body of height H is suspended in a duct of height $3H$, as shown in Fig. 2. Both the body and the duct are of unit width. The velocity u_1 and pressure p_1 at (1) are both uniform and the flow is incompressible with a density ρ. Flow separates from the downstream edges of the body at (2) and the flow mixes with the wake such that the velocity and pressure are also uniform far downstream at (3). All boundary layer effects may be neglected.

(a) Assume that the velocity is uniform between the edge of the body and the duct wall at (2). The pressure is uniform across the whole duct at (2). Estimate the static pressure at (2) in terms of p_1, u_1 and ρ. [4]

(b) Consider the control volume ABCD as shown. Calculate the static pressure at (3) in terms of p_1, u_1 and ρ. [6]

(c) Calculate the difference in the flux of mechanical energy crossing stations (2) and (3). Explain what happens to the lost mechanical energy. [6]

(d) Calculate the drag on the body and express this as a non-dimensional drag coefficient, C_D. [4]

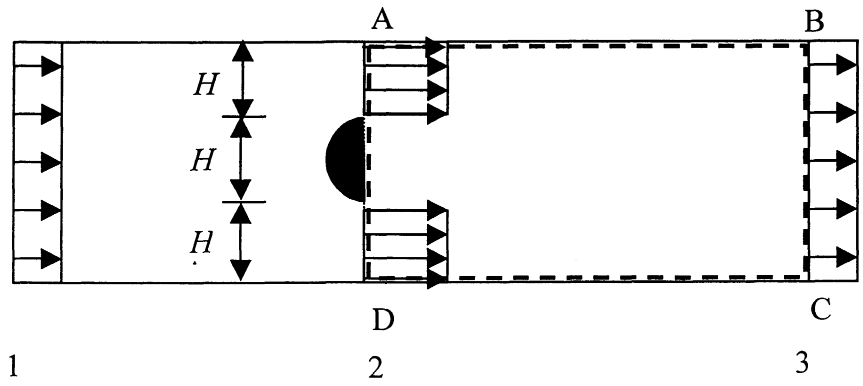

Fig. 2

5 A viscometer is used to measure the dynamic viscosity μ of a Newtonian fluid of density ρ. The viscometer, shown in cross-section in Fig. 3a, consists of a slowly turning rotor of radius R which makes contact at its apex with a flat disk. The axis of rotation of the rotor is vertical and it rotates with constant angular velocity Ω. The angle θ between the conical face and the disk is small so that the gap size scales with the radius r according to $h = r\theta$. The fluid fills the gap and the cone is rotated by applying a torque Γ to the rotor.
In parts (a), (b) and (c) you may assume that Ω is sufficiently small that centripetal forces may be neglected.

(a) A typical annular fluid element is shown in Figs. 3a and 3b. The element at radius r has a cross-section of dimensions $\mathrm{d}r \times \mathrm{d}y$. Assume that **only** circumferential shear stresses τ and $\tau + (\partial\tau/\partial y)\mathrm{d}y$ act on the lower and upper faces of the element respectively. Derive an expression for the net torque acting **on this element** about the axis. [2]

(b) The annular element has no angular acceleration. Derive an expression for the circumferential velocity of the fluid as a function of y and radius r. [10]

(c) Obtain an expression for the overall applied torque Γ in terms of μ, Ω, θ and R. [4]

(d) Explain why centrifugal forces on the fluid become important at high values of Ω and write down a non-dimensional parameter that shows the relative importance of centrifugal forces to viscous shear forces. [4]

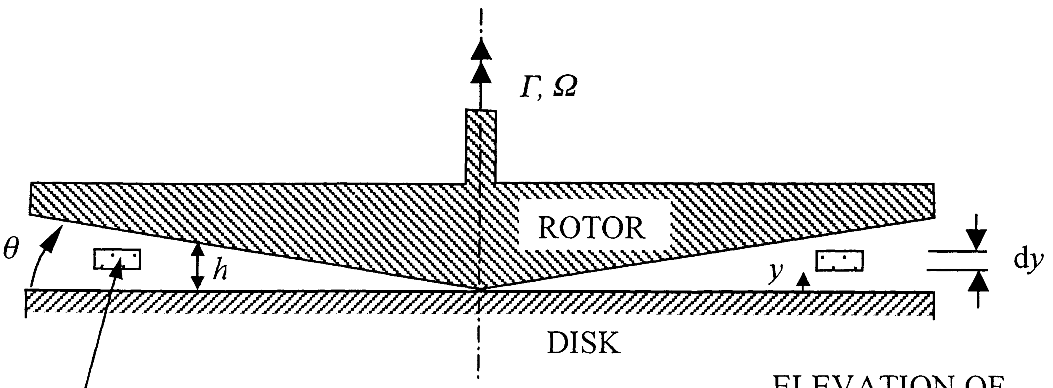

Fig. 3a

ELEVATION OF VISCOMETER (Cross-section)

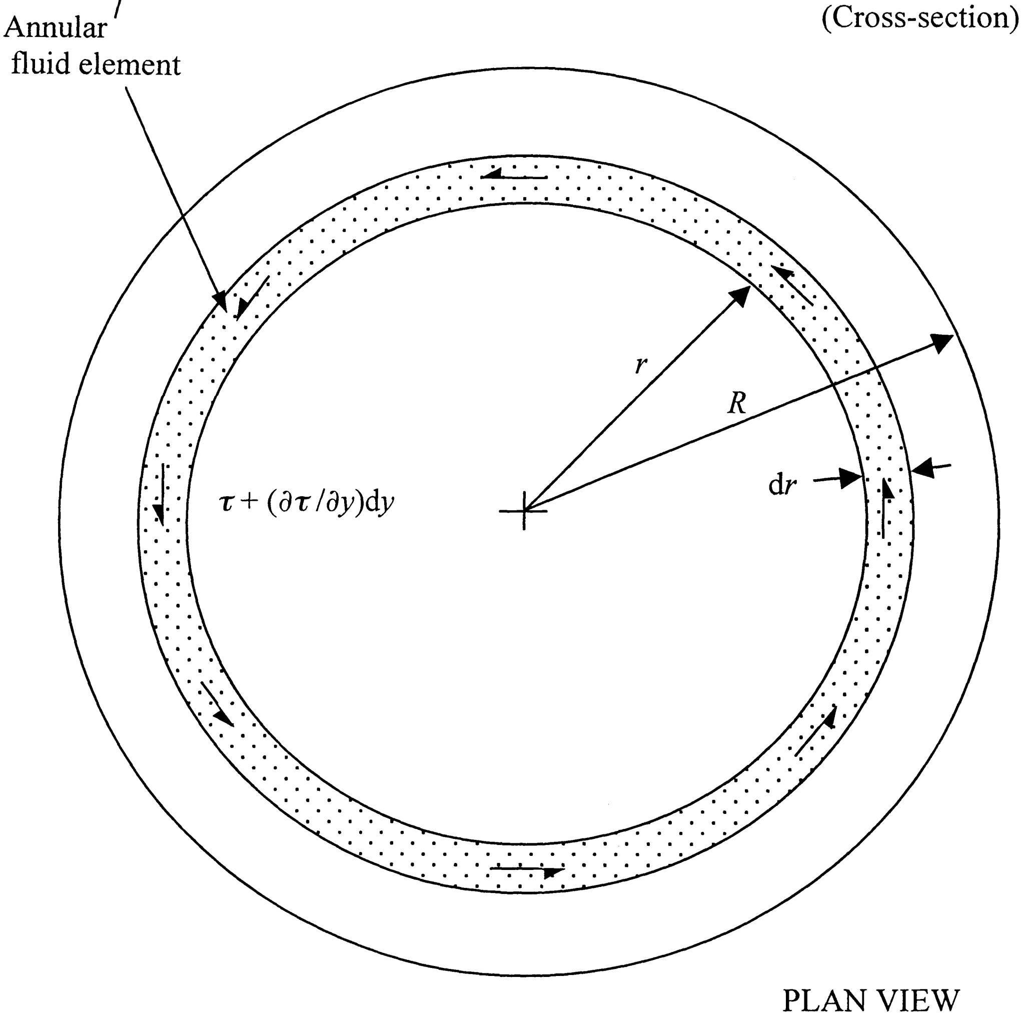

Fig. 3b

PLAN VIEW OF TOP OF FLUID ELEMENT

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6 A large chemical mixing tank has been designed consisting of an impeller immersed in a cylindrical tank of fluid as shown in Fig. 4.

(a) Assume that the torque Γ required to drive the impeller depends only on the diameter of the tank D, the height of the tank h, the angular velocity of the impeller ω, and the dynamic viscosity and density of the fluid, μ and ρ, respectively. Write down a dimensionless group that includes Γ, ρ and D (and other variables) and then find the other dimensionless groups on which it must depend. [6]

(b) In order to assess the potential performance of the mixing tank, a half-sized model of the tank is constructed and is tested using the same fluid. Find an expression for the angular velocity ω_m at which the model should be operated in order to achieve dynamic similarity. [4]

(c) What is the relationship between the torque required to drive the impeller of the model at this angular speed and the torque required to drive the impeller of the real mixer at the corresponding speed ω? [4]

(d) Assume that all of the energy used to drive the impeller is converted into a change in internal energy of the fluid and there is no heat loss from the tank. The temperature in the model tank increases by 2 °C in a time t_o. Calculate the temperature increase that would occur in the large tank in the same time period. The specific heat capacity of the fluid C may be assumed to be constant. [6]

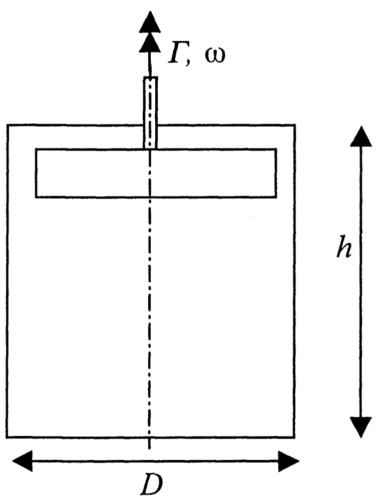

Fig. 4

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