ENGINEERING TRIPOS PART 1B

Tuesday 4 June 2002 2 to 4

Paper 4

THERMOFLUID MECHANICS

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

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

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

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.*

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

1 A block of iron of mass 5 kg is at 800°C. The specific heat capacity of iron is 437 Jkg^{-1} K^{-1}.

(a) A second block of iron of mass 5 kg is at 100°C. If the two blocks are placed together in thermal contact, calculate their final temperature. Determine the entropy change of each block. It may be assumed that no heat is lost to the environment. [7]

(b) The 5 kg iron block at a temperature of 800°C is placed in thermal contact with a sealed tank containing 1 kg of air. The initial temperature and pressure of the air is 500°C and 2 bar. The volume of the tank is fixed. The specific heat capacity at constant pressure of air, c_p, can be assumed to be constant and equal to 1.014 $kJkg^{-1}K^{-1}$. Calculate the final temperature and pressure of the air. Determine the entropy change of the air.

[8]

(c) A reversible heat engine is run between the iron block and an infinite thermal reservoir of temperature 500°C, as shown in Fig. 1. The block of mass 5 kg starts at 800°C and ends at 500°C. Determine the work produced by the engine.

[5]

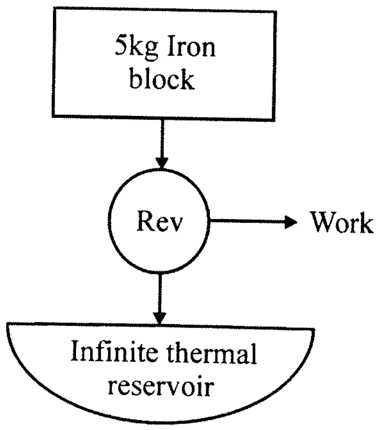

Fig. 1.

2 A new counter-flow heat exchanger is designed to cool a hot flow of oil from 100°C to 50°C. The oil flows through a central copper pipe at a flow rate of 1 kgs^{-1}. The water enters the heat exchanger at 20°C and at a flow rate of 3 kgs^{-1}. The surface heat transfer coefficients for the oil and water are 50 $Wm^{-2}K^{-1}$ and 2000 $Wm^{-2}K^{-1}$ respectively. The specific heat capacity of the oil is 2100 J $kg^{-1}K^{-1}$ and that of the water is 4180 J $kg^{-1}K^{-1}$. The thermal conductivity of copper is 390 $Wm^{-1}K^{-1}$.

(a) Show that, for a counter flow heat exchanger, the log mean temperature difference ΔT_m is given by,

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\dfrac{\Delta T_1}{\Delta T_2}\right)}$$

where ΔT_1 and ΔT_2 are the temperature differences between the two fluids at the two ends of the heat exchanger. [6]

(b) If the inner and outer radii of the copper tube are 10 mm and 11 mm respectively, calculate the overall heat transfer coefficient between the oil and water. [5]

(c) What is the exit temperature of the water? What length of tube would be required? Is this reasonable for practical purposes? [5]

(d) Which surface of the copper pipe limits the heat transfer between the oil and water? Suggest how you would improve the performance of the heat exchanger. [4]

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3 A steam plant consists of a condenser, boiler, feed pump and turbine. The cycle operates with a boiler pressure of 60 bar and a condenser pressure of 0.04 bar. Steam leaves the boiler at 600°C and water leaves the condenser wet saturated. The turbine has an isentropic efficiency of 88% and the feed pump can be assumed to be reversible and adiabatic.

(a) Sketch the cycle on a temperature-entropy (T-S) diagram. Calculate the thermal efficiency of the cycle. Determine the dryness fraction of the steam at the outlet of the turbine. [8]

(b) The cycle is altered so that the expansion in the turbine is stopped at 8 bar and the steam reheated to 600°C. The steam is then expanded through a second turbine to 0.04 bar. The efficiency of the second turbine is 88%. Calculate the thermal efficiency of the cycle. What is the condition of the steam at the outlet of the second turbine? [8]

(c) Discuss the merits of adding reheat to this cycle. How could the efficiency of the steam power plant be raised? [4]

SECTION B

4 Oil flows down an inclined surface as shown in Fig. 2. The flow is laminar and fully developed in the sense that the film thickness, h, and oil speed, u, are independent of streamwise position x and time t. The pressure throughout the oil film may be taken as atmospheric pressure and the air above the oil offers no resistance to the flow.

(a) By applying Newton's second law to a small rectangular element of fluid show that

$$\nu \frac{d^2u}{dy^2} + g\sin\theta = 0$$

where θ is the angle of inclination of the surface, g is the gravitational acceleration and ν is the kinematic viscosity of the oil, which may be considered uniform. [8]

(b) Determine the velocity distribution in the oil, sketch the velocity profile and derive expressions for the shear stress distribution and volumetric flow rate per unit depth into the page. [8]

(c) The inclined surface is now heated so that the viscosity of the oil is a function of y. Show how, given $\nu(y)$, you would calculate the velocity profile in such a case. [4]

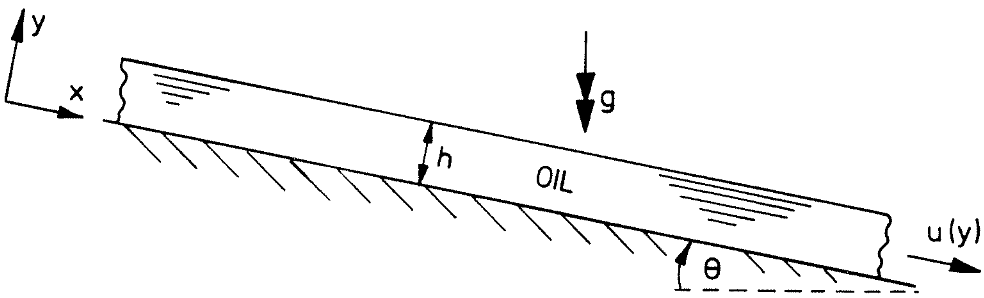

Fig. 2

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5 A hydraulic jump is triggered at the base of a spillway by a rectangular concrete block as shown in Fig. 3. The flow is steady-on-average, and uniform well upstream and downstream of the jump. The cross stream width of the channel and block are equal and much greater than the water depth, h.

(a) Explain why the pressure distribution in the water at sections 1 and 2 may be taken as hydrostatic. [3]

(b) Show that the drag force on the concrete block per unit depth into the page is

$$F = \frac{1}{2}\rho g\left(h_1^2 - h_2^2\right) + \rho h_1 V_1 (V_1 - V_2)$$

where V is the speed of the water and g is the gravitational acceleration. You may ignore friction on the channel bed. [7]

(c) The upstream depth and velocity are h_1 = 1.14 m and V_1 = 18.4 m/s, the channel width is 30 m, and the downstream depth is h_2 = 7.35 m. Calculate the force on the block and the rate of loss of mechanical energy within the jump. [10]

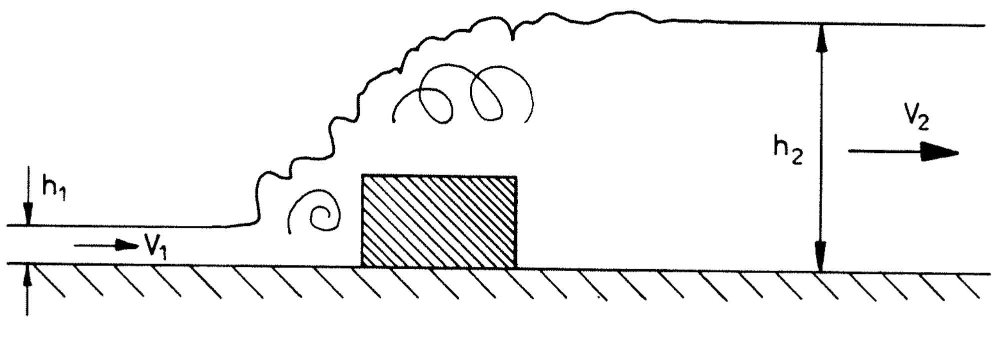

Fig. 3

6 (a) A thin flat plate sits in a flow which is uniform and steady well upstream of the plate. The plate is aligned with the oncoming flow so as to produce minimum drag. Its surfaces are smooth so that a laminar boundary layer develops on either side of the plate. The fluid has density ρ and viscosity μ, and the speed of the flow well upstream of the plate is V. The plate has length L in the direction of the flow and width W across the flow. The drag force per unit width on the plate, F/W, is a function of ρ, μ, V and L only.

A set of experiments performed for a given plate and fluid show that F/W is proportional to $V^{3/2}$. Use dimensional analysis to determine the dependence of F/W on L and μ. [10]

(b) The plate is replaced by a long cylinder whose axis is perpendicular to the flow. Show that the drag coefficient for the cylinder, as well as the flow pattern, depends only on the Reynolds number of the flow. Sketch the flow around the cylinder for Reynolds numbers, based on the diameter of the cylinder, of 0.01, 20, 100, and 10^6. [6]

(c) For a certain range of Reynolds numbers the cylinder is seen to vibrate, reflecting periodic fluctuations in the flow pattern. The period of oscillation is found to be independent of viscosity, and the amplitude of the vibration is very small. Use dimensional analysis to derive an expression for the frequency of vibration containing the relevant physical parameters and one unknown dimensionless constant. [4]

END OF PAPER