ENGINEERING TRIPOS PART IB

Tuesday 6 June 2006 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.

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS
Thermofluids Data Book
CUED approved calculator allowed

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

SECTION A

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

1 (a) A gas turbine for power generation consists of a compressor, a combustor and a turbine. Air from the atmosphere enters the compressor with a mass flow-rate of 45 kg s^{-1} at a pressure of 1 bar and a temperature of 290 K. It is compressed to a pressure of 20 bar with an isentropic efficiency of 85 %. The air then enters the combustor where its temperature is raised to 1450 K. The expansion in the turbine occurs with an isentropic efficiency of 85 % and the gas is then exhausted to atmosphere.

The pressure loss in the combustor and the added mass of fuel may be neglected. The air in the compressor and the gas in the combustor and turbine may be treated as the same perfect gas with $c_p = 1.10$ kJ $kg^{-1}K^{-1}$ and $\gamma = 1.35$.

Show that the turbine exit temperature is 784 K, and calculate the nett power output and thermal efficiency of the plant. [8]

(b) As shown in Fig. 1, the gas turbine is now fitted with a steam injection facility. The compressor inlet conditions and air mass flow-rate remain the same. The isentropic efficiencies of the compressor and the turbine, and the combustor outlet temperature are also unchanged. For the steam circuit, water is compressed to 20 bar by the feed pump. It then passes through the Heat Recovery Steam Generator (HRSG) where it is heated by the exhaust gas to the saturation temperature, then evaporated and superheated to a temperature of 450 °C. The "pinch-point" temperature difference in the HRSG is 5 °C. The superheated steam is then mixed with the air flow at the exit of the compressor and the mixture passes through the combustor, turbine and HRSG.

The feed pump work and the pressure losses in the HRSG (both sides) may be neglected. It may be assumed that the values of c_p and γ for the gas-steam mixture in the combustor, turbine and hot side of the HRSG are the same as for the gas in Part (a).

On a $(T - s)$ diagram, sketch the processes undergone by the exhaust gas and the steam in the HRSG. Show that the mass flow-rate of steam is 6.8 kg s^{-1}, and calculate the nett power output. [12]

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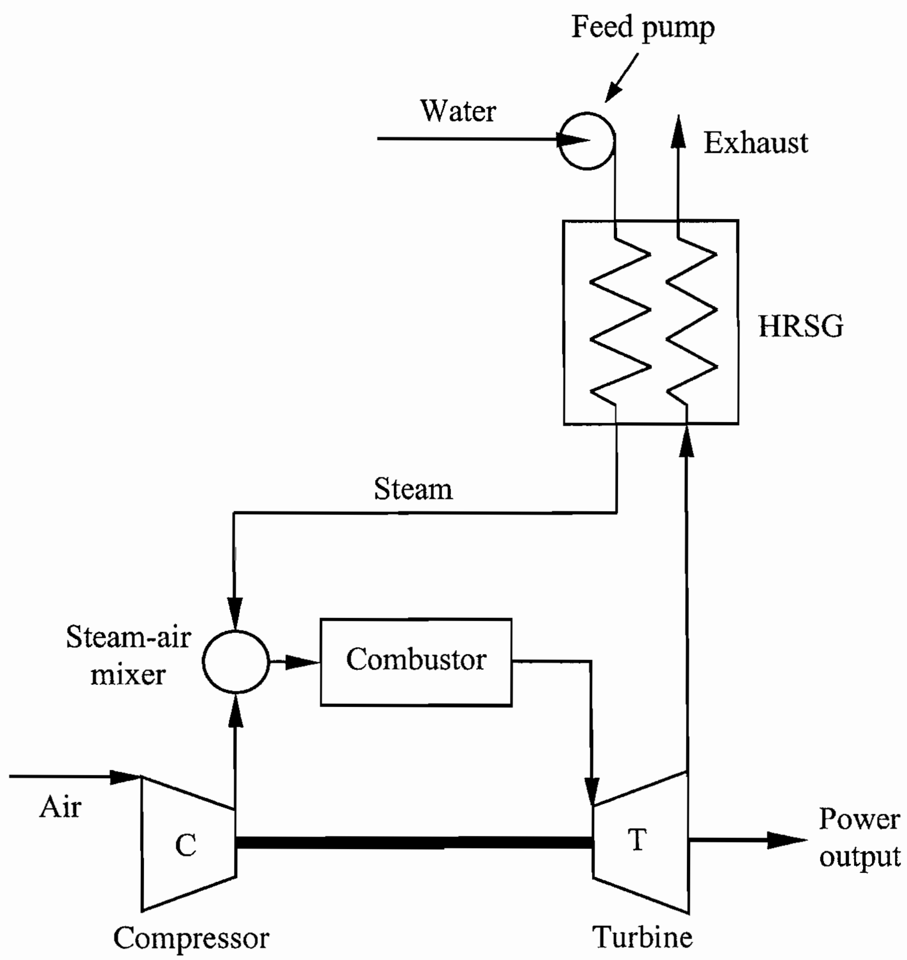

Fig. 1

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2 (a) In what follows, a *closed system* is defined as a thermodynamic system closed to mass transfer but open to work and heat transfers. State, giving a *very* brief reason, whether each of the following propositions is true or false :

(i) The entropy of a closed system at equilibrium is an intensive property. [2]

(ii) When a closed system undergoes a reversible process causing the temperature and entropy to change from (T_1, S_1) to (T_2, S_2) such that $T_2 > T_1$, the heat transferred to the system is given by ($T_2 S_2 - T_1 S_1$). [2]

(iii) The entropy of a closed system can only stay constant or increase. [2]

(iv) The entropy of a closed system increases when it undergoes a reversible, adiabatic process in which work is done on the system. [2]

(b) A heat pump is to be used to heat a house in winter and then, in a reversed mode, to cool the house in summer. Heat transfer through the walls and roof of the house is estimated to be 2400 kJ per hour per °C of temperature difference between the inside and the outside.

(i) If the outside winter temperature is 0 °C , what is the minimum possible power required to maintain the interior temperature at 20 °C ? [6]

(ii) If the maximum power input is 1.2 kW, what is the maximum possible outside summer temperature for which the interior can be maintained at 20 °C ? [6]

3 (a) A steam plant with power output of 500 MW is based on the superheated Rankine cycle. The steam enters the turbine at a pressure of 100 bar and a temperature of 550 °C and the condenser pressure is 0.06 bar. The flow in the turbine is adiabatic and reversible. Pressure losses in the boiler and condenser are negligible and the feed pump work may be neglected.

(i) Using either the steam tables or the steam chart, calculate the specific enthalpy of the steam at the turbine outlet. [4]

(ii) Calculate the mass flow-rate of steam circulating in the plant. [2]

(b) In the same plant, the cooling water enters the condenser tubes at a temperature of 15 °C and leaves at 25 °C . Based on a tube diameter of 30 mm, the overall heat transfer coefficient between the cooling water and the condensing steam is 12.0 kW $m^{-2}K^{-1}$. Assume that c_p for water is constant at c_p = 4.18 kJ $kg^{-1}K^{-1}$. Neglect pressure losses in the condenser tubes and neglect heat loss from the condenser casing to the environment. Assume that the steam leaves the condenser as saturated liquid.

(i) Calculate the mass flow-rate of cooling water. [4]

(ii) Calculate the total length of condenser tubing required. [5]

(iii) By considering the changes in entropy flow-rate of the steam and of the cooling water, calculate the nett rate of entropy creation due to irreversibility in the condenser. [5]

SECTION B

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

4 A 1/8th scale model of an aircraft is to be tested in a wind-tunnel in which the temperature and pressure of the working-section can be varied across a wide range. The real aircraft flies at a speed of 275 m s^{-1} in the upper atmosphere where the temperature T_r is 234 K and the pressure p_r is 33.7 kN m^{-2}. The flow depends on both the compressibility of the air and its viscosity. In all calculations air may be treated as a perfect gas for which the dynamic viscosity varies only with the temperature T in kelvin as $\mu \propto T^{3/2}/(T+117)$. The speed of sound in air may be taken as $\sqrt{\gamma RT}$ where γ and R are both constant.

(a) The model is to be tested at a temperature T_m and a pressure p_m . By applying the conditions for complete dynamic similarity, derive an expression for the ratio p_m/p_r in terms of the ratio T_m/T_r , the length scale ratio L_r/L_m of the real aircraft to the model and of T_r . [6]

(b) The temperature of the working-section is initially maintained at $T_m = 288$ K. In order to achieve complete dynamic similarity between the real aircraft and the model what values of pressure and velocity should be used in the working-section with the scale model? [3]

(c) Under these conditions of complete dynamic similarity what is the ratio of the lift of the model to the lift of the real aircraft? [3]

(d) Instead of changing the pressure p_m in the working-section, it is maintained at 101.1 kN m^{-2} (which is exactly $3p_r$) and the temperature T_m is varied so as to achieve complete dynamic similarity. What temperature and velocity should be used in the working-section for complete dynamic similarity at this fixed pressure? [8]

5 A device in a circular pipe is shown in cross-section in Fig. **??**. It consists of a smooth contraction from the internal diameter D_1 at station (1) to a smaller diameter D_2 at (2) immediately followed by a sudden expansion back to the initial diameter D_1 just after (2). Station (3) is far downstream of (2). The flow is steady and from left to right. The velocity is uniform across the pipe at stations (1) and (3), and at (2) it is uniform within the diameter D_2 and zero outside this diameter. The pressure is uniform across the whole pipe diameter at all three stations. The flow is incompressible and the fluid has a constant density ρ . Ignore any changes in gravitational potential energy.

(a) If the velocity at (1) is U_1 what is the velocity U_2 at (2), just upstream of the sudden expansion, in terms of U_1 , D_1 and D_2 ? [2]

(b) Ignoring frictional losses in the contraction between (1) and (2) calculate the pressure p_2 at (2) in terms of the pressure p_1 at (1), the velocity U_1 , the diameters D_1 and D_2 and the density ρ . [4]

(c) Consider a cylindrical control volume between positions (2) and (3) (as shown by the dotted line). Ignoring the friction due to the pipe walls, find the pressure p_3 at (3) in terms of p_1 , U_1 , D_1 , D_2 and ρ . [8]

(d) The flux of mechanical energy may be defined as the stagnation pressure multiplied by the volumetric flow-rate of the fluid. Find an expression for the difference between the flux of mechanical energy at (1) and the flux of mechanical energy at (3) in terms of U_1 , D_1 , D_2 and ρ . What happens to this lost energy? [6]

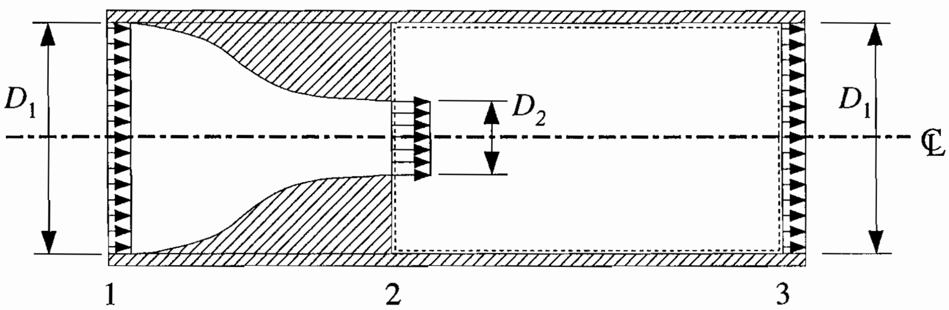

Fig. 2

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6 Two different liquids flow down a plane of inclination θ under the influence of gravity, as shown in Fig. **??**. They form two separate thin layers which do not mix. The liquids are both Newtonian and have the same viscosity μ but different densities: ρ_1 for the lower layer and ρ_2 for the upper layer. The lower layer has a thickness of h_1 as shown and the upper layer has a thickness of $h_2 - h_1$. The flow is laminar and fully-developed in the sense that the layer thicknesses and the flow rates of the liquids do not vary with the distance x along the plane or with time. The pressure is atmospheric throughout the layers and the air above the upper layer offers no resistance to the flow.

(a) By considering the forces on a small fluid element show that

$$\frac{d\tau}{dy} = -\rho g \sin\theta$$

where τ is the shear stress at distance y from the plane in the normal direction and ρ is the density of the layer under consideration. [4]

(b) Find an expression for the shear stress in the upper layer in terms of y , ρ_2 , h_2 , g and θ and hence find an expression for the shear stress at the bottom of the upper layer ($y = h_1$). Explain why this does not depend on the viscosity of the liquids. [4]

(c) The shear stress on the top of the lower layer must match the shear stress at the bottom of the upper layer. Find an expression for the shear stress in the lower layer in terms of y , h_1 , h_2 , ρ_1 , ρ_2 , g and θ . [4]

(d) Find an expression for the velocity in the lower layer in terms of μ , h_1 , h_2 , y , ρ_1 , ρ_2 , g and θ and hence find the velocity at the interface between the two fluids. [8]

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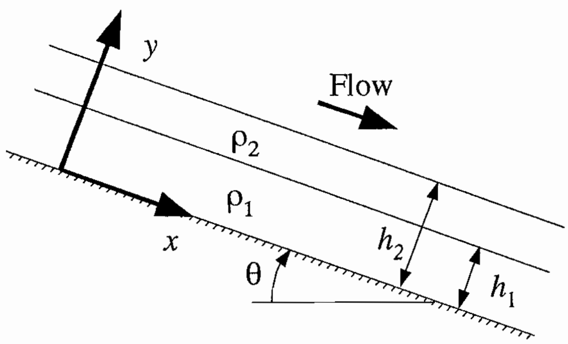

Fig. 3

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