ENGINEERING TRIPOS PART IB

Tuesday 3 June 2003 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.

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) The exit flow from an industrial gas turbine flows steadily through a long constant area exhaust pipe. From the inlet of the pipe to the exit the velocity rises from 150 m/s to 175 m/s and the temperature drops from 600 K to 580 K. The pressure at the inlet of the pipe is 130 kPa. Calculate the pressure at the exit of the pipe and the rate of heat loss from the pipe per kilogram of fluid flowing.

[7]

(b) Calculate the rise in specific entropy of the gas as it passes through the exhaust pipe. Suggest the causes of the specific entropy change of the gas in the exhaust pipe. The heat from the pipe is lost to an environment of constant temperature. Suggest the possible physical causes of any irreversibility in the system containing the exhaust pipe and the environment.

[5]

(c) At the end of the exhaust pipe the flow is mixed with the exhaust from a second gas turbine. The temperature of the second flow is 450 K. The mass flow rate of the second flow is three times that of the first. The pipe work is designed so that the two flows meet at the same velocity and pressure. The diameters of the pipes are arranged so that downstream of the mixing the velocity and pressure are unchanged from the inlet values. There is no heat transfer to the surroundings during the mixing process. Calculate the temperature of the gas after mixing and the rise of specific entropy due to irreversibility of the flow. Suggest physical causes of the irreversibility.

[8]

The exhaust gas can be assumed to be an ideal gas with a constant specific heat capacity c_p equal to 1.13 kJkg^{-1}K^{-1}. The gas constant R of the exhaust gas is equal to 287 Jkg^{-1}K^{-1}.

2 (a) A superheated steam Rankine cycle, as shown in Fig. 1, is used to generate power. The fluid leaves the boiler at a pressure of 20 bar. The condenser pressure is 0.04 bar. Sketch the cycle on an *h*-*s* diagram. The feed water pump may be assumed to be reversible and adiabatic. The fluid at the exit of the condenser is saturated water. Calculate the work required by the feed water pump per kilogram of fluid flowing.

[7]

(b) The heat addition in the boiler is 3500 $\mathrm{kJkg^{-1}}$. The turbine has an isentropic efficiency of 0.9. Calculate the thermal efficiency of the cycle and the dryness fraction of the fluid at turbine exit.

[7]

(c) It is discovered that the steam at exit from the turbine is unacceptably wet. It is proposed that dry saturated steam be achieved at the exit of the turbine by throttling the inlet steam to the turbine. Find the maximum acceptable turbine inlet pressure. Illustrate the cycle with and without the throttle on an *h*-*s* diagram.

[6]

Chart accuracy is acceptable for all parts of the cycle, except the feed pump.

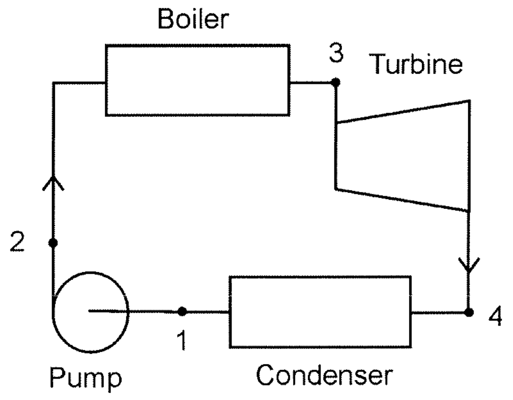

Fig. 1

3 (a) State the *Clausius Inequality.* A refrigeration cycle operates between two constant temperature reservoirs. Use the Clausius Inequality to derive a relationship between the coefficient of performance of the refrigeration cycle and the temperatures of the reservoirs.

[5]

(b) A refrigeration cycle is used to keep a cabinet at a constant −223°C. Heat leaks slowly into the cabinet at a rate of 2 kJ per hour. The cycle rejects heat to the environment at 25°C. Calculate the minimum power input required by the refrigerator.

[5]

(c) The refrigeration cycle is switched off once per year for maintenance and the temperature of the cabinet rises to 25°C. After the maintenance is completed the refrigeration cycle is switched back on and the cabinet drops in temperature. The temperature of the cabinet drops by 0.5°C for each Joule of energy removed. Calculate the minimum work input to the refrigeration cycle required to restore the temperature of the cabinet to −223°C. Explain why there is a limit to the heat rejected to the environment from the refrigerator.

[10]

SECTION B

4 (a) For an adiabatic steady flow process involving an incompressible fluid and no work output, show that the rate of loss of "mechanical" energy is given by the expression

$$\dot{m}\left(\frac{p_{01}-p_{02}}{\rho}\right)=\dot{m}\int T\,\mathrm{d}s$$

Where ρ is the density, T is the temperature, $\dot{m}$ is the mass flow rate of fluid, s is the specific entropy, and p_{01} and p_{02} are the stagnation pressures at the beginning and end of the process. [3]

(b) The jet pump shown in Fig. 2 injects water at $U_1 = 20$ m/s through a 0.1 m diameter pipe and entrains a secondary flow of water $U_2 = 1$ m/s in the annular region around the smaller pipe. The larger pipe has a diameter of 0.5 m. The two flows become fully mixed downstream, where U_3 is approximately constant.

It may be assumed that the jet pump is horizontal and that there is no circumferential component of velocity about the pipe axis.

(i) For steady incompressible flow, calculate the velocity U_3. [4]

(ii) Explain why the pressures p_1 and p_2 will be equal. [2]

(iii) If the pressure downstream p_3 is 1 bar, determine the upstream pressures, p_1 and p_2, assuming that frictional effects at the pipe walls are negligible. [5]

(iv) Determine the stagnation pressure p_{03} and the rate of change of "mechanical" energy due to the mixing process. [4]

(v) What is the rate of change of internal energy due to the mixing process? [2]

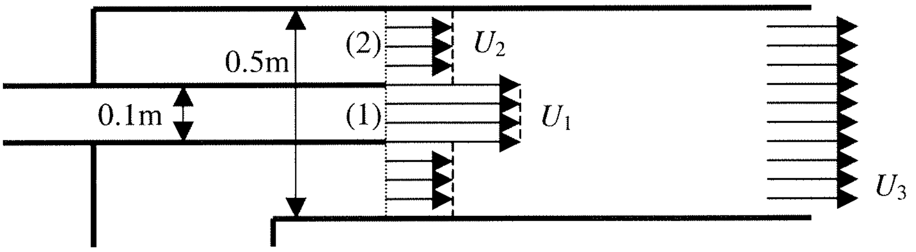

Fig. 2

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5 The performance of a pump designed for pumping liquid is dependent on the volumetric flow rate Q, the rotational speed N, the diameter of the pump D and the density of the fluid ρ.

(a) Measurements show that the effects of viscosity and hence the effects of the Reynolds number are small. Explain why this is the case. [2]

(b) Find an expression for the independent dimensionless group ϕ upon which all other pump operating parameters depend. [3]

(c) The pressure rise across the pump Δp_{pump} depends on the same parameters. Determine a dependent dimensionless group ψ involving the pressure rise. [3]

(d) A water pump of diameter 0.08 m has its performance measured when the rotational speed is 3000 rpm. It is found that the pressure rise measured in N/m^2 is related to the flow rate by the expression

$$\Delta p_{pump} = a - b\,Q^2$$

where a and b are constants equal to 82.1 kN/m^2 and 1.342×10^{10} kg m^{-7} respectively. Find the relationship between the parameters ϕ and ψ. [2]

(e) A geometrically similar pump of 0.2 m diameter rotates at 1500 rpm in a liquid of density 1200 kg/m^3. The 0.2 m pump moves liquid around a pipe work system. The pipes have diameter 0.1 m, length 570 m and a skin friction coefficient c_f of 0.005.

(i) Using the relationship for pressure drop along pipes given in the data book, or otherwise, obtain an expression relating the pressure drop to the volumetric flow rate through the pipe. [3]

(ii) Using the performance relationship developed for the pump and the pipe work pressure drop, determine the volumetric flow rate through the 0.2 m pump and the pressure rise across the pump. [5]

(cont.

(f) The shape of the pump is shown in Fig. 3. Sketch a diagram showing streamlines through the pump. Explain why the pressure is high or low in certain regions of the pump, and mark these regions on your diagram. [2]

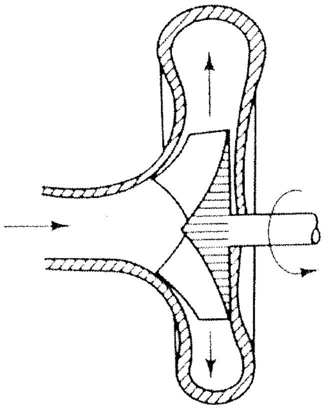

Fig. 3

6 A shock absorber containing oil of density ρ, viscosity μ, and a piston of radius R moving at a velocity V is shown in Fig. 4. The clearance between the piston and the cylinder is h.

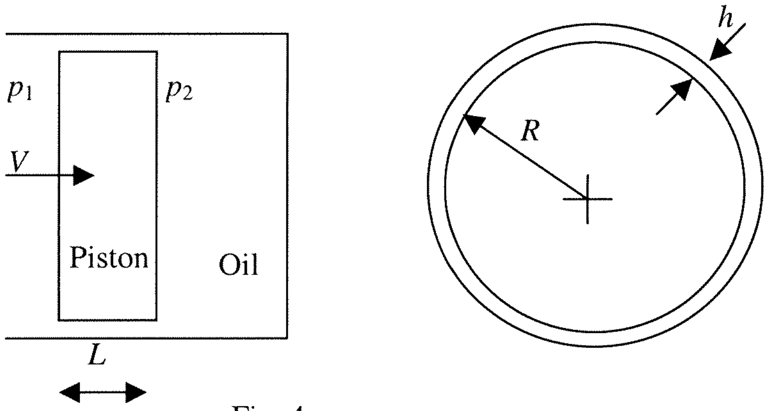

Fig. 4

(a) Obtain an expression for the mass flow rate of the oil through the clearance. [2]

(b) For the analysis of the flow through the clearance the shock absorber is idealised. The geometry is represented as two parallel plates of length L, width $2\pi R$ where the top plate moves at V, the velocity of the piston as shown in Fig. 5. It may be assumed that $R >> h$. End effects and the effects of gravity may be ignored.

By assuming that the flow is laminar, develop from first principles an expression for the velocity distribution between the plates. [8]

(c) Using the expression for the velocity variation in the clearance, determine the mass flow rate through the clearance. [6]

(d) Using the mass flow rates obtained in (a) and (c) above, determine an expression for the pressure difference across the piston $(p_1 - p_2)$ in terms of V, R, h, L and μ. [4]

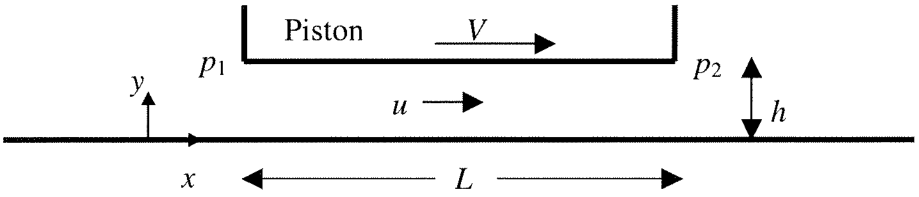

Fig. 5

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