ENGINEERING TRIPOS PART IB

Tuesday 4 June 2013 2 to 4

Paper 4

THERMOFLUID MECHANICS

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

Answer not more than ***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
Engineering 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

nra06

SECTION A

*Answer not more than **two** questions from this section*

1 (a) Water passes through a thin-wall cylindrical pipe of diameter d with a mass flow rate of $\dot{m}$. The water enters at a position $x = 0$ with temperature T_{in} and has constant heat capacity c. Cooling air at temperature T_∞ flows across the pipe with a direction perpendicular to its centreline. The fluid-dynamic interactions with the pipe can be approximated by average convective heat transfer coefficients h_{air} and h_{water}.

(i) Stating any assumptions, show that U, the overall heat transfer coefficient of the system, is given by [2]

$$U = \left(\frac{1}{h_{air}} + \frac{1}{h_{water}} \right)^{-1}$$

(ii) Show that the variation in temperature T with distance x along the pipe is given by [5]

$$T = T_\infty + (T_{in} - T_\infty) \exp \left\{ -\frac{xU\pi d}{\dot{m}c} \right\}$$

(iii) Deduce an expression for the overall heat transfer coefficient that gives a temperature drop which is 90% of the maximum possible with a pipe of length L. [1]

(b) Consider a case where $\dot{m} = 0.11\,\mathrm{kg\,s^{-1}}$, $c = 4.2\,\mathrm{kJ\,kg^{-1}}$, $d = 50\,\mathrm{mm}$ and $L = 30\,\mathrm{m}$. The flow of water can be considered turbulent and fully-developed.

(i) Estimate h_{water} using a correlation from the Thermofluids Data Book. You should neglect the variation in temperature along the pipe. Assume the water has density $1000\,\mathrm{kg\,m^{-3}}$, viscosity $1.14 \times 10^{-3}\,\mathrm{Pa\,s}$ and conductivity $0.620\,\mathrm{Wm^{-1}K^{-1}}$. [5]

(ii) Estimate the air velocity required to achieve 90% of the maximum temperature drop. This time you should use the correlation $\mathrm{Nu}_d = 0.027\,\mathrm{Re}_d^{0.8}$. Assume the air has density $1.25\,\mathrm{kg\,m^{-3}}$, viscosity $1.78 \times 10^{-5}\,\mathrm{Pa\,s}$ and conductivity $0.0252\,\mathrm{Wm^{-1}K^{-1}}$. [5]

(c) How could this rate of cooling be achieved with a lower air velocity? [2]

2 (a) A superheated steam cycle power plant consists of a feed pump, boiler, turbine and condenser. The condenser pressure is 0.05 bar and the boiler operates at 30 bar. The condenser exit is saturated liquid, and the turbine inlet temperature is 350 °C. The feed pump is isentropic and the turbine has an isentropic efficiency of 85%. You may find it helpful to use the enthalpy-entropy chart provided at the back of the Thermofluids Data Book.

(i) Sketch a temperature-entropy, T-s, and enthalpy-entropy, h-s, diagram for the cycle. [4]

(ii) Calculate the thermal efficiency of the cycle. You should include the feed pump work in your analysis. [5]

(iii) Comment on the dryness fraction at turbine exit. [1]

(b) A throttle is introduced between the exit of the boiler and the inlet of the turbine in order to increase the dryness fraction at turbine exit. You should assume that the turbine efficiency does not change.

(i) Calculate the pressure drop across the throttle required to bring the turbine exit dryness fraction up to 0.90. [6]

(ii) Calculate the reduction in thermal efficiency. [2]

(c) Discuss another cycle modification which would both increase the thermal efficiency of the cycle *and* increase the dryness fraction of the turbine exhaust for the same maximum turbine inlet temperature. You should explain your answer using a T-s diagram. [2]

3 The change in steady flow availability function, b, of a steady flow process can be expressed as

$$b_2 - b_1 = -\dot{w}_x + \int_1^2 \left(1 - \frac{T_0}{T}\right) \mathrm{d}\dot{q} - T_0 \Delta s_{irrev}$$

where the symbols have their usual meanings. For this question the dead state has temperature $T_0 = 300\,\mathrm{K}$ and pressure $1\,\mathrm{bar}$. The air should be treated as an ideal gas with ratio of specific heats $\gamma = 1.4$, specific heat capacity at constant pressure $c_p = 1005\,\mathrm{J kg^{-1} K^{-1}}$ and specific gas constant $R = 287\,\mathrm{J kg^{-1} K^{-1}}$.

(a) A steady flow of air at temperature $600\,\mathrm{K}$ and pressure $1\,\mathrm{bar}$ is compressed using an adiabatic and reversible compressor to a pressure of $3\,\mathrm{bar}$.

(i) Calculate the compressor exit temperature and the shaft work input per unit mass. [3]

(ii) Explain why your answer is equal to the increase in steady flow availability across the compressor. [2]

(b) The exit from the compressor enters a heat exchanger which reduces the temperature of the stream back to $600\,\mathrm{K}$. There is no pressure drop in the heat exchanger.

(i) Sketch this process on a T-s diagram. [2]

(ii) Calculate the change in steady flow availability of the stream because of heat transfer. [4]

(c) The compressor and heat exchanger of part (a) and (b) are replaced with a reversible isothermal compressor which operates over the same pressure ratio such that the exit flow is at $600\,\mathrm{K}$ and $3\,\mathrm{bar}$.

(i) Sketch this process on a T-s diagram. [2]

(ii) By considering the entropy change or otherwise, calculate the shaft work input per unit mass to the compressor. Calculate the change in steady flow availability because of heat transfer. [4]

(d) Compare the change in steady flow availability because of heat transfer in cases (b) and (c). Comment on the difference. [3]

SECTION B

*Answer not more than **two** questions from this section*

4 A viscous fluid flows down the slope of angle γ shown in Fig. 1. The flow is steady and the upper surface of the fluid is open to the atmosphere.

(a) Explain, stating any assumptions, why the pressure, velocity and fluid thickness t are independent of streamwise position x. [3]

(b) Show that the variation of shear stress τ with distance perpendicular to the slope y is given by [3]

$$\frac{\mathrm{d}\tau}{\mathrm{d}y} = -\rho g \sin\gamma$$

(c) The fluid is Newtonian with a constant dynamic viscosity μ. However, the density of the fluid is not constant and varies with y according to $\rho = \rho_0(1 - \alpha y/t)$, where α is a positive constant.

(i) Find an expression for the velocity profile $v(y)$. [6]

(ii) Find an expression for the volumetric flow rate per unit width. [3]

(iii) Sketch the velocity profile and show the effect of varying α. How does the wall shear stress change as α is varied? [5]

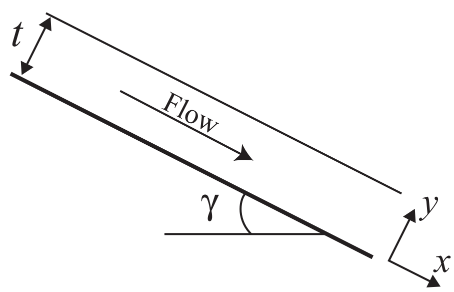

Fig. 1

5 An incompressible fluid flows through a duct in the horizontal circuit shown in Fig. 2(a). The width of the duct is $0.9\,\mathrm{m}$ apart from between the contraction and the diffuser where it reduces to $0.45\,\mathrm{m}$. The height of the duct (the distance out of the plane of the circuit) is constant at $1\,\mathrm{m}$. The stagnation pressure loss coefficient, based on inlet velocity, is the same for the bends and the diffuser and is $K = 0.5$. The stagnation pressure loss in the contraction is negligible.

(a) Explain, using sketches as appropriate, the causes of the loss in stagnation pressure in the bends and the diffuser. Why is the loss in the contraction negligible? [5]

(b) If the velocity at location 1 is V_0, show that the reduction in stagnation pressure around the circuit is given by, [2]

$$\Delta p_0^{lost} = \frac{11}{4}\rho V_0^2$$

(c) To compensate for the loss in stagnation pressure around the circuit, a jet of fluid with velocity αV_0 is added over 10% of the cross-sectional area at location 1, as shown in Fig. 2(b). The jet mixes with the main flow, so that the flow is uniform again at location 2. Downstream of location 2, some flow is removed so that the main flow returns to velocity V_0. The pressure at locations 1 and 2 is uniform at p_1 and p_2 respectively. The cross-sectional area between locations 1 and 2 is constant.

(i) Calculate the velocity V_2 of the flow at location 2. [2]

(ii) Calculate $p_2 - p_1$ in terms of V_0, ρ and α. State any assumptions made. [5]

(iii) What value of α is required for the stagnation pressure rise between locations 1 and 2 to balance the stagnation pressure drop around the circuit? State any assumptions made. [4]

(iv) Explain why it may be advantageous to introduce the jet at a different location in the circuit, rather than at location 1. [2]

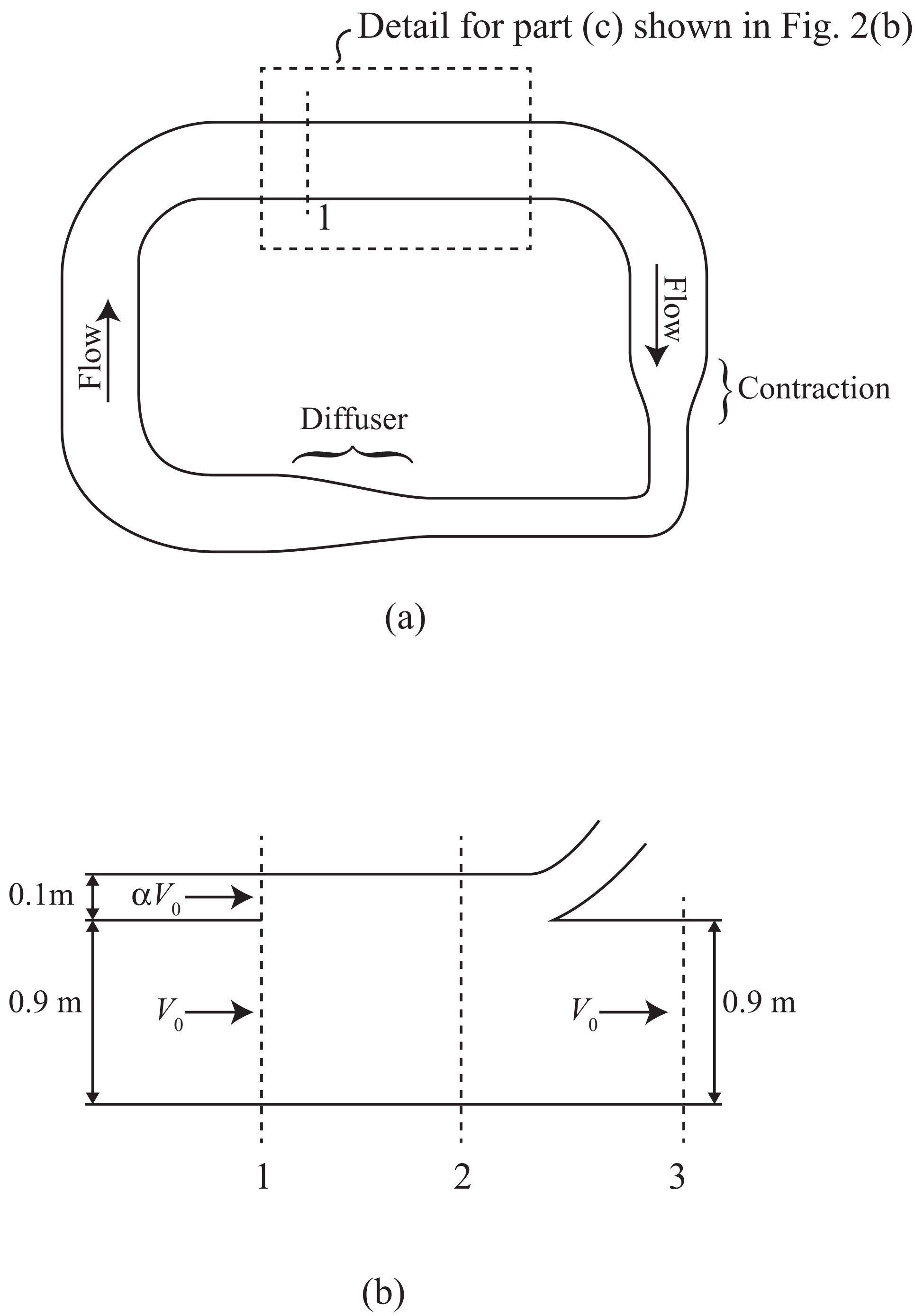
Detail for part (c) shown in Fig. 2(b)
1
Flow
Flow
Contraction
Diffuser
(a)
0.1m
αV_0
0.9 m
V_0
V_0
0.9 m
1
2
3
(b)

Fig. 2

6 (a) An incompressible viscous fluid flows over a cylinder of diameter D. Show that the dimensionless drag per unit length (the drag coefficient C_D) is a function of Reynolds number only. Explain the physical significance of the drag coefficient and Reynolds number. [3]

(b) The variation in drag coefficient with Reynolds number of a cylinder is shown in Fig. 3.

(i) Using scaling arguments, show that the drag coefficient is inversely proportional to Reynolds number at low Reynolds numbers. [4]

(ii) Explain the subsequent shape of the curve. [4]

(c) A cylindrical factory chimney of diameter $2\,\mathrm{m}$ is exposed to wind at $7\,\mathrm{m\,s^{-1}}$. A scale model of the chimney, with a diameter of $0.15\,\mathrm{m}$ is tested in a wind tunnel.

(i) What flow velocity should be used in the model test? Explain your reasoning. [2]

(ii) If the drag per unit length is measured to be $300\,\mathrm{N\,m^{-1}}$ in the model test, what will be the drag per unit length for the real chimney? [2]

(iii) As well as the drag force, an unsteady lateral force (perpendicular to the oncoming flow direction) is also measured. The frequency of the unsteadiness is $120\,\mathrm{Hz}$ in the model test. Explain how this unsteady force arises and calculate the expected frequency for the real chimney. [5]

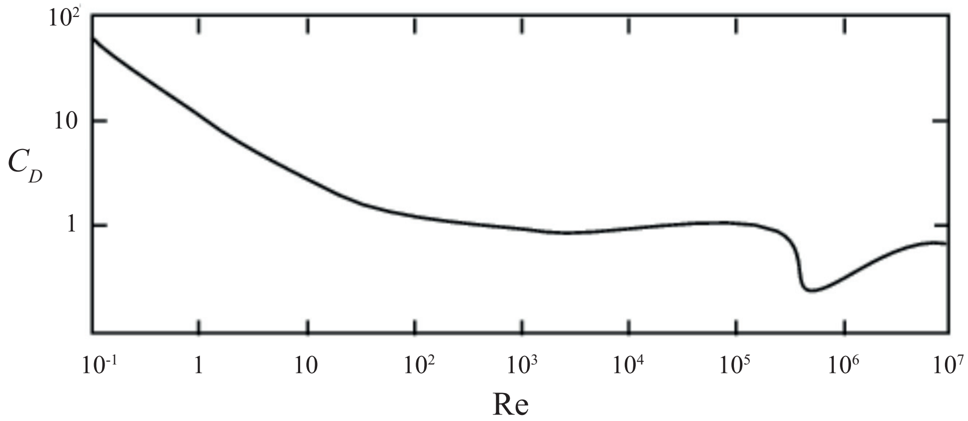

Fig. 3

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