SOE3211

UNIVERSITY OF EXETER

SCHOOL OF ENGINEERING, COMPUTER SCIENCE AND MATHEMATICS

DEPARTMENT OF ENGINEERING

Thermofluids and Energy Conversion A

Time allowed : TWO HOURS

January 2006

The marks for this module are calculated from 70% of the percentage mark for this paper plus 30% of the percentage mark for associated coursework.

Full marks may be obtained from full answers to three questions. Candidates are required to answer **at least one question from section A** and **at least one question from section B**.

This is a **closed book** examination. Candidates are permitted to use approved portable calculators. Separate formula and data sheets have been provided. Also provided : C.F.G. Rogers and Y.R. Mayhew, 'Thermodynamic and Transport Properties of Fluids', 5th edition. Graph paper is available on request.

SECTION A

Question 1 (20 marks)

1(a) (6 marks) The support tower for a commercial wind turbine consists of a cylinder 3.2 m in diameter and 45 m high. Calculate **i**. the drag force and **ii**. the bending moment about the base, if the wind speed is 40 km/hr.

1(b) (7 marks) Describe the structure of a turbulent boundary layer. Your answer should include a sketch. Discuss how the presence of a boundary layer over the ground would affect your answer to part **(a)** above.

1(c) (7 marks) By using Bernoulli's theorem, show that the efficiency of a wind turbine is given by

$$\eta = \frac{1}{2}(1 + u_r - u_r^2 - u_r^3)$$

where u_r is the ratio of the downstream and upstream wind speeds. From this show that the maximum possible efficiency for a wind turbine is 59.3% (the Betz limit).

Question 2 (20 marks)

2(a) (10 marks) A model aircraft wing, of span 1.2 m, tapers evenly from a chord of 40 cm at the root to a chord of 25 cm at the tip. The wing is placed in a wind tunnel (free stream speed 40 m/s) and the lift force measured at various angles of attack ; results are given in the table below.

α	0°	5°	10°	15°	20°	25°(A)	30°
F_L/N	76	230	380	510	610	680	460

i. Plot the lift coefficent as a function of angle of attack.

ii. Explain how the airfoil is generating lift, relating your explanation to the shape of the plotted curve, and paying particular attention to the behaviour at point (A).

2(b) (10 marks) A symmetrical airfoil is placed in a wind tunnel at zero angle of attack. The velocity in the wake of the airfoil is measured and found to fit the following profile :

$$u_x = \begin{cases} U_\infty\,(0.2 + 80y^2) & |y| < 0.1 \text{ m} \\ U_\infty & |y| \geq 0.1 \text{ m} \end{cases}$$

where $U_\infty = 40$ m/s is the free stream velocity, and y is the distance from the centreline of the airfoil. Use the von Karman integral technique to evaluate the drag on the airfoil, per unit span. If the chord length of the airfoil is 20 cm, calculate the drag coefficient for this Reynolds number.

SECTION B

Question 3 (20 marks)

3(a) (10 marks) A turboprop aircraft is flying at a steady altitude and speed. The pressure and temperature of air entering the compressor of one of the engines are 0.55 bar and −5 °C, respectively. The isentropic efficiencies of the compressor and turbine are 0.80 and 0.90, respectively, and the compressor pressure ratio is 8.5/1. There is negligible pressure drop in the combustion chambers, the maximum cycle temperature is 725 °C and the turbine discharges at 0.55 bar. Assume that the gases have a constant mass flow rate throughout the engine and that they have constant properties equal to those of air given in the formula sheet.

i. Determine the values of P and T at compressor outlet, turbine inlet and turbine outlet. **(5 marks)**

ii. Calculate the net work output of the engine and the heat supplied per kg of air. **(3 marks)**

iii. Calculate the thermal efficiency of the engine. **(2 marks)**

3(b) (10 marks) A different turboprop engine has a thermal efficiency of 27.8% and produces a power output of 11.25 MW under steady flow conditions. Kerosine fuel, of formula $C_{10}H_{20}$ (see also further data at the end of the question), is supplied to the engine.

i. At what mass flow rate (kg s^{-1}) is kerosine consumed in this engine? **(5 marks)**

ii. What mass of carbon dioxide, CO_2, is produced by this engine per second? **(5 marks)**

Data
Kerosine fuel: $C_{10}H_{20}$
net calorific value: 43.4 MJ kg^{-1} at combustion chamber conditions
Relative atomic masses: C 12.0, H 1.0, O 16.0

Question 4 (20 marks)

4(a) (4 marks) Explain why you might consider that investment in fuel cell research and development is worthwhile in the context of sustainability and environmental protection.

4(b) (6 marks) Outline briefly the basic principles of operation of *two* of the following types of fuel cell.

i. A hydrogen-air PEM cell.

ii. A direct methanol fuel cell.

iii. A solid oxide fuel cell.

4(c) (10 marks) A four-stroke spark ignition engine, at part load, is being modelled by an air-standard Otto cycle in which a fixed mass of air, 0.001 kg, in the cylinder behaves as a perfect gas (properties given in the Formula Sheet). The conditions at the start of the cycle are 0.8 bar and 310 K. The value of the compression ratio, r_{v}, is 10.5/1, and 375 J of heat is supplied during the 'combustion' part of the cycle.

i. Sketch the cycle (not to scale) on $P-V$ and $T-S$ diagrams and identify (using letters or numbers) the location of the initial conditions at BDC, the compressed gas at TDC, the conditions after heat addition, and the conditions at the end of the power stroke. **(2 marks)**

ii. Calculate the pressure, temperature and volume at the four locations identified in **(i)** above. **(4 marks)**

iii. Calculate the net work, the heat transferred from the cycle, and the cycle thermal efficiency. **(2 marks)**

iv. Calculate the mean effective pressure. **(2 marks)**

SECTION C

Question 5 (20 marks)

Water is flowing over a filter with a free stream velocity U in the x-direction. The filter is a porous surface which draws water through at a constant velocity V in the $-y$ direction. When the apparatus is set up correctly, a boundary layer forms which is time-independent and fully developed (the flow through the filter is just enough to prevent the boundary layer from expanding).

5(a) (5 marks) Write down the boundary conditions at the filter. By considering the continuity equation, show that $u_y = -V$ at all points in the flow.

5(b) (4 marks) Show that the Navier-Stokes equations reduce to the form

$$-V\frac{\partial u_x}{\partial y} = \nu\frac{\partial^2 u_x}{\partial y^2}$$

5(c) (6 marks) Solve this equation, together with the boundary conditions, to find an expression for the velocity component $u_x(y)$.

5(d) (5 marks) The displacement thickness for a boundary layer is defined as

$$\delta^* = \int_0^\infty \left(1 - \frac{u_x}{U}\right) dy$$

Evaluate δ^* for this case, and compare the results with the boundary layer thickness δ as conventionally defined.

<u>Question 6</u> (20 marks)

6(a) (9 marks) Explain the principles of Combined Heat and Power (CHP) systems and discuss the positive and negative features of large- and small-scale CHP for use in the U.K.

6(b) (11 marks) A particular small-scale CHP system for domestic use employs a Diesel engine of thermal efficiency $\eta = 37\%$, where $\eta =$ (mechanical power output)/(rate of energy input as fuel). The remaining energy is transferred from the engine as heat to the cooling system ($\dot{Q}_{\text{cs}}$) and heat to the exhaust ($\dot{Q}_{\text{exh}}$) in the proportions $\dot{Q}_{\text{exh}}/\dot{Q}_{\text{cs}} = 2/1$. The engine produces 12 kW of mechanical power which is used to generate electricity with an efficiency of 90%. Half the heat from the cooling system and two thirds of the heat from the exhaust are utilised for space heating and hot water, the remainder being lost from the system. The Diesel fuel has a net calorific value of 42.5 MJ kg^{-1}.

i. Calculate the rate of energy supplied to the engine as fuel (kW), the mass flow rate of fuel and the rate of electricity generation. **(3 marks)**

ii. Calculate the rate of heat transfer to : **(2 marks)**

- the engine cooling system, $\dot{Q}_{\text{cs}}$
- the exhaust, $\dot{Q}_{\text{exh}}$

iii. Calculate the rate of heat transfer to space heating/hot water from : **(4 marks)**

- the engine cooling system
- the exhaust

iv. Calculate the overall efficiency of the CHP system expressed in the form (total useful energy)/(energy supplied as fuel). **(2 marks)**