ENGINEERING TRIPOS PART IIA

Saturday 29 April 2006 9.00 to 10.30

Module 3A5

THERMODYNAMICS AND POWER GENERATION

*Answer not more than **three** questions.*

All questions carry the same number of marks.

*The **approximate** percentage of marks allocated to each part of the question is indicated in the right margin.*

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

1 (a) In a gas turbine, the combustion products enter the turbine at a pressure and temperature of 30 bar and 1600 K (state 1). The expansion is adiabatic (but not reversible) and at turbine exit the pressure and temperature are 1.2 bar and 830 K (state 2). The flow then enters a long duct before exhausting to atmosphere at a pressure and temperature of 1.0 bar and 780 K (state 3). The pressure drop in the duct is caused by flow friction and the temperature drop is caused by heat transfer to the environment at 300 K. The mass flowrate through the turbine and duct is 10 kg s^{-1}.

It may be assumed that the combustion products behave as a perfect gas with $R = 0.29$ kJ kg^{-1} K^{-1} and $c_p = 1.25$ kJ kg^{-1} K^{-1}. Changes in kinetic and potential energy between states 1, 2 and 3 may be neglected.

(i) Calculate the maximum possible power output for a steady-flow of 10 kg s^{-1} between states 1 and 3.

(ii) Calculate the actual power output from the turbine and the 'lost power' due to irreversibility in the turbine expansion.

(iii) Calculate the 'lost power' due to heat transfer from the duct.

(iv) Using the results of parts (i), (ii) and (iii), calculate the 'lost power' due to flow friction in the duct. [60 %]

(b) The characteristic equation of state of a pure substance is,

$$g = A(T-T_0) - AT\ln\left(\frac{T}{T_0}\right) + RT\ln\left(\frac{p}{p_0}\right) + b(p-p_0)$$

where g is the specific Gibbs function, p is pressure, T is temperature, R is the specific gas constant, and A, b, p_0 and T_0 are constants.

(i) Find the p-v-T equation of state.

(ii) Derive expressions for the specific entropy and specific enthalpy (as functions of p and T). What does the constant A represent?

(iii) Prove that $c_p - c_v = R$. [40 %]

2 At high temperature, CO_2 dissociates into CO and O_2, and the *degree of dissociation* α is defined by the chemical transformation,

$$CO_2 \rightarrow (1-\alpha)\, CO_2 + \alpha\, CO + \frac{\alpha}{2} O_2$$

A mixture of 1 mole of CO and 1 mole of O_2 is confined to a rigid container at a temperature and pressure of 25 °C and 1 bar. The mixture is ignited and when chemical equilibrium has been established the temperature and pressure are found by experimental measurement to be 2600 K and 6.625 bar. It may be assumed that the only species present are CO_2, CO and O_2, all of which behave as ideal gases.

(a) Write down the chemical equation for the reaction in terms of the degree of dissociation α. [10 %]

(b) For the above conditions, verify that $\alpha = 0.03884$. [30 %]

(c) Show that the measured pressure is consistent with combustion at constant volume. [20 %]

(d) Calculate the heat transferred from the container during the constant volume combustion process. [40 %]

(TURN OVER

3 An industrial gas turbine is fitted with a heat exchanger which transfers heat from the hot turbine exhaust gas to the air leaving the compressor. The ambient pressure and temperature are 1 bar and 25 °C. Both compressor and turbine are adiabatic and have *polytropic* efficiencies of 0.9. The heat exchanger effectiveness is 0.8. The products of combustion leave the combustion chamber at 1600 K and turbine cooling may be neglected. Pressure losses in the combustion chamber and heat exchanger may also be neglected.

Assume that air behaves as a perfect gas with $c_p = 1.01$ kJ kg^{-1} K^{-1} and $\gamma = 1.40$, and that the combustion products also behave as a perfect gas with $c_p = 1.10$ kJ kg^{-1} K^{-1} and $\gamma = 1.35$.

(a) Sketch a temperature-entropy diagram for the gas turbine and heat exchanger. [5 %]

(b) Sketch a graph of temperature versus heat transferred for the hot and cold flows in the heat exchanger. [10 %]

(c) What is the maximum compressor pressure ratio for which the heat exchanger can be used? [25 %]

(d) The actual compressor pressure ratio is 15.0. The air leaving the heat exchanger is supplied directly to the adiabatic combustion chamber where it is mixed with a gaseous fuel which enters the chamber at 25 °C. For the combustion of the fuel with air, $\Delta H^0_{298} = -48.0$ MJ kg^{-1} and $\Delta G^0_{298} = -50.0$ MJ kg^{-1}. Calculate :

(i) the temperature of the air entering the combustion chamber;

(ii) the air/fuel ratio;

(iii) the net work output from the gas turbine per kg of air entering the compressor;

(iv) the overall and rational efficiencies of the plant. [60 %]

4 (a) Explain why feed heating is used in conventional steam power plants but not in combined cycle power plants. [20 %]

(b) An ideal superheated Rankine cycle has a turbine entry pressure and temperature of 150 bar and 550 °C. The condenser pressure is 0.06 bar and the feed pump work may be neglected. Calculate the work output per kg of steam passing through the boiler, and the thermal efficiency of the cycle. [25 %]

(c) A direct contact feed heater is now added to the cycle, steam being bled from the turbine at a pressure of 5 bar. Find the ratio of the mass flowrate of bled steam to the mass flowrate of steam in the boiler. Calculate also the work output per kg of steam passing through the boiler, and the thermal efficiency of the modified cycle. [30 %]

(d) Consider a steam cycle that has the same boiler inlet and exit conditions, and the same condenser pressure, as the modified cycle of part (c). Calculate the maximum possible work output per kg of steam passing through the boiler, and the maximum possible thermal efficiency of the cycle. Why is the thermal efficiency as calculated in part (c) less than this? [25 %]

END OF PAPER

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ANSWERS

1	(a)	(i) 10.52 MW (ii) 9.63 MW, 0.34 MW, 0.39 MW, 0.16 MW
2	(d)	130.7 kJ
3	(c)	21.12
	(d)	(i) 821.4 K (ii) 51.5 (iii) 430.0 kJ/kg air (iv) 0.462, 0.443
4	(b)	1442.3 kJ/kg, 0.437
	(c)	0.198, 1321.1 kJ/kg, 0.470
	(d)	1368.0 kJ/kg, 0.487

J.B. Young & H.P. Hodson