ENGINEERING TRIPOS PART IIA

Thursday 1 May 2008 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 *Note that parts (a) and (b) of this question are unrelated to each other.*

(a) A closed, simple-cycle gas turbine uses helium as the working fluid. The helium enters the compressor at a pressure and temperature of 1.0 bar and 300 K. It is then compressed adiabatically and reversibly to a pressure of 8.0 bar whereupon it enters a heater where it is heated at constant pressure to a temperature of 1500 K. The helium then enters a turbine where it is expanded adiabatically to a pressure of 1.0 bar with an isentropic efficiency of 0.85. Finally, it is cooled at constant pressure to its initial state at compressor inlet, the heat being rejected to the environment at 300 K.

Assume that helium behaves as a perfect gas with constant c_p and c_v. Take the dead state pressure and temperature as 1.0 bar and 300 K.

(i) Calculate the exergy supplied in the heater, the net work output from the cycle, the 'lost work' in the turbine, and the 'lost work' in the cooling process, all per kg of helium circulating. [55 %]

(ii) Calculate the thermal efficiency of the cycle. [5 %]

(iii) Calculate the maximum possible thermal efficiency of a cycle which has the same heater inlet and outlet conditions. Hence calculate the rational efficiency of the actual cycle. [10 %]

(b) The characteristic equation of state of a pure substance in the form $u = u(v, s)$ is,

$$\frac{u}{u_0} = \left(\frac{v}{v_0}\right)^{-(R/c_v)} \exp\left(\frac{s - s_0}{c_v}\right) ,$$

where u, v and s are the specific internal energy, volume and entropy, and R, c_v, u_0, v_0 and s_0 are all constants ($u = u_0$ when $v = v_0$ and $s = s_0$). Find the p-v-T equation of state. [30 %]

2 (a) A gas turbine combustion chamber operating adiabatically in steady-flow is supplied with air at 800 K and methane (CH_4) at 25 °C. The products of combustion leave the chamber at 1600 K. Assuming the products comprise the chemical species CO_2, H_2O, O_2 and N_2 only, and neglecting changes of kinetic energy between inlet and outlet, show that the molar air-fuel ratio is 26.3.

Treat air as a mixture of 21 % O_2 and 79 % N_2 by volume. The lower calorific value of methane is 50 MJ/kg. Enthalpy differences of chemical species should be evaluated using the table 'Molar Enthalpies of Common Gases at Low Pressures' in the Thermofluids Data Book. [50 %]

(b) For experimental purposes, a small sample of the combustion products is heated to a temperature of 2400 K. At this temperature, it is important to consider the dissociation of CO_2 into CO and O_2 according to the reaction,

$$-\mathrm{CO} - \frac{1}{2}\mathrm{O_2} + \mathrm{CO_2} = 0 \ .$$

Assuming that the CO, O_2 and CO_2 are in chemical equilibrium subject to this reaction, and ignoring other dissociation processes, calculate the pressure at which the sample should be held in order that precisely 5 % of the CO_2 is dissociated. [50 %]

3 (a) A steam cycle power plant has a main boiler pressure of 160 bar and a single reheater at a pressure of 40 bar between the high-pressure and low-pressure turbines (both of which are adiabatic). The high-pressure turbine has an isentropic efficiency of 90 %. Within the low-pressure turbine steam is bled off at a pressure of 5 bar and delivered to a single direct contact feed heater that produces saturated water. The expansion in the low-pressure turbine can be represented by a straight line on the enthalpy-entropy chart and the dryness fraction at exit is 0.95. The entry temperature of the steam for both turbines is 550 °C and the condenser pressure is 0.04 bar. Pressure losses in the boiler, condenser and feed heater, and the work input to the feed pumps, can all be neglected in the following calculations.

(i) Sketch the temperature-entropy diagram for the cycle. [15 %]

(ii) Calculate the work output from the high-pressure turbine per kg of flow through the boiler. [15 %]

(iii) Find the ratio of the mass flow rate of bled steam from the low-pressure turbine to the mass flow rate through the boiler. [15 %]

(iv) Determine the cycle efficiency. [15 %]

Table 1 on the following page provides properties of steam for various conditions within the cycle. Use the Steam Chart in the Thermofluids Data Book for any other properties required.

(b) An existing conventional coal-fired power station uses a steam cycle with the configuration described in part (a). The company operating the power station is required to reduce the environmental impact of the plant. List four options available to the company and for each option discuss the issues associated with its implementation. [40 %]

(Continued ...

Condition	Specific Enthalpy (kJ kg^{-1})	Specific Entropy (kJ kg^{-1} K^{-1})	Temperature (°C)
Saturated Liquid at 0.04 bar	121.4	0.422	28.96
Saturated Liquid at 5 bar	640.1	1.860	151.83
160 bar, 550 °C	3439.5	6.486	
40 bar, 550 °C	3560.3	7.235	
Saturated Vapour at 0.04 bar	2553.7	8.473	28.96

Table 1 : Steam properties for Question 3

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4 An open-circuit uncooled gas turbine may be modelled as a compressor, heater and turbine with a working fluid that behaves as a perfect gas with constant c_p and γ throughout. The pressure loss in the heater can be neglected but the pressure loss in the exhaust system is significant and is represented by a parameter α which is the ratio of the turbine exit pressure to the compressor inlet pressure. The *polytropic* efficiencies of the compressor and turbine are η_c and η_t respectively, θ is the ratio of turbine inlet temperature to compressor inlet temperature, and r_t is the *isentropic* temperature ratio across the compressor.

(a) If T_4 is the turbine exit temperature and T_1 the compressor inlet temperature, show that the gas turbine thermal efficiency η_{gt} can be written,

$$\eta_{gt} = 1 - \left(\frac{T_4/T_1 - 1}{\theta - r_t^{1/\eta_c}} \right), \qquad \text{where} \quad \frac{T_4}{T_1} = \theta \left(\frac{\alpha^{(\gamma-1)/\gamma}}{r_t} \right)^{\eta_t} .$$

[40 %]

(b) A gas turbine as described above is used as the topping cycle for a combined cycle gas turbine (CCGT) power station. The turbine entry temperature is 1500 K and the compressor inlet temperature is equal to the environment temperature of 300 K. The compressor pressure ratio is 20 and the inlet is at atmospheric pressure. The compressor and turbine polytropic efficiencies are $\eta_c = \eta_t = 0.9$ and the working fluid has $c_p = 1.1$ kJ kg^{-1} K^{-1} and $\gamma = 1.35$ throughout. The gas turbine exhaust gas enters a heat recovery steam generator (HRSG) at a pressure 10 % greater than atmospheric and it leaves at atmospheric pressure with a temperature of 120 °C. The HRSG provides heat to a steam cycle that has a cycle efficiency of 40 %.

(i) Determine the HRSG efficiency η_b (the ratio of actual heat transferred to the maximum amount of heat that could be transferred). [20 %]

(ii) Calculate the overall efficiency of the CCGT power plant. [20 %]

(c) Suggest two ways in which the performance of the HRSG in a CCGT power plant can be improved. What limits the temperature at which the exhaust gas leaves the HRSG ? [20 %]

END OF PAPER