ENGINEERING TRIPOS PART IIA

Monday 9 May 2011 2.30 – 4.00

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	SPECIAL REQUIREMENTS
Single-sided script paper.	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

Final version

1 A steam power plant is based on a superheated Rankine cycle. Saturated liquid water enters the feed pump at a pressure of 0.06 bar (state 1) and is compressed reversibly and adiabatically to a pressure of 60 bar (state 2). The pressurised water then enters the boiler where it is heated at constant pressure, leaving as superheated steam at a temperature of 500 °C (state 3). After the boiler the steam enters the turbine where it is expanded adiabatically but irreversibly to a pressure of 0.06 bar in the wet state (state 4). Finally, the wet steam enters the condenser where it transfers heat to a steady flow of cooling water and is completely condensed at constant pressure to state 1. The mass flow rate of steam around the cycle is 200 kg s^{-1}. The specific enthalpies and entropies of all the states are given in Table 1 on the next page.

The cooling water enters the condenser tubes at a temperature of 10 °C and a pressure of 1 bar. It leaves at 30 °C and the pressure drop in the tubes may be neglected. It may be assumed that the isobaric specific heat capacity of the cooling water is constant at 4.18 kJ kg^{-1} K^{-1}. Take the dead state temperature and pressure as 10 °C and 1 bar respectively.

(a) Initially, consider the steam cycle on its own. For the cycle, calculate the net power output and the thermal efficiency. [15%]

(b) For the steam cycle on its own, calculate the exergy supply rate to the cycle and all the lost power terms. Draw up a balance showing how the exergy supply rate is related to the net power output and the lost power terms. Calculate the rational efficiency of the steam cycle. [40%]

(c) Now consider the power plant comprising the steam cycle and the cooling water. Treating the condenser as a single adiabatic heat exchanger, calculate all the lost power terms associated with the plant. Draw up a balance showing how the exergy supply rate is related to the net power output and the lost power terms. Calculate the rational efficiency of the power plant. [45%]

(cont.

		p (bar)	T (°C)	h (kJ kg^{-1})	s (kJ kg^{-1} K^{-1})
State 1	Feed pump inlet	0.06	36.16	151.5	0.521
State 2	Boiler inlet	60.00	36.57	158.6	0.521
State 3	Turbine inlet	60.00	500.00	3423.1	6.883
State 4	Condenser inlet	0.06	36.16	2325.2	7.548

Table 1   Steam property values for Question 1.

2 *Note that parts (a) and (b) of this question are unrelated to each other.*

(a) A reaction chamber operating in steady-flow is supplied with separate streams of gaseous ammonia, hydrogen and nitrogen in molar proportions $NH_3 : H_2 : N_2$ of $2 : 3 : 1$. The gases are well-mixed in the chamber and the gas mixture leaving is at a temperature of 600 K, a pressure of 10 bar and can be assumed to be at chemical equilibrium subject to the reaction:

$$-\frac{1}{2}N_2 - \frac{3}{2}H_2 + NH_3 = 0$$

(i) Assuming that the only species present are NH_3, H_2 and N_2 and that they all behave as ideal gases, calculate the mole fractions of each species in the mixture leaving the chamber. [50%]

(ii) Explain qualitatively how the mole fraction of hydrogen is affected by an increase in temperature. [10%]

(b) (i) Given Maxwell's relation for a pure substance $(\partial s/\partial p)_T = -(\partial v/\partial T)_p$ prove that:

$$\left(\frac{\partial h}{\partial p}\right)_T = v - T\left(\frac{\partial v}{\partial T}\right)_p$$

[10%]

(ii) The p-v-T equation of state of an imperfect gas is given by:

$$v = \frac{RT}{p}(1 + Bp)$$

where $B = B(T)$ is a function of temperature only. Using the equations above and the definition of the constant pressure specific heat capacity $c_p = (\partial h/\partial T)_p$ prove that the only thermodynamically acceptable form for c_p is:

$$c_p = c_{p0} - p\frac{d}{dT}\left(RT^2\frac{dB}{dT}\right)$$

where $c_{p0} = c_{p0}(T)$ is a function of temperature only. [30%]

3 A gas turbine in a combined cycle power plant has a turbine inlet temperature of 1660 K and turbine cooling may be neglected. Both the compressor and turbine are adiabatic and there is no pressure loss in the combustion chamber. The turbine has a polytropic efficiency of 0.9 and the compressor has a polytropic efficiency of 0.85 . The ambient pressure and temperature are 1 bar and 25 °C . At exit from the turbine the pressure is 1 bar . The exhaust gas then enters the heat recovery steam generator (HRSG) where it is cooled at constant pressure as it transfers heat to the steam cycle.

Assume that air behaves as a perfect gas with $c_p = 1.01\ \mathrm{kJ\ kg^{-1}\ K^{-1}}$ and $\gamma = 1.40$, and that the combustion products also behave as a perfect gas with $c_p = 1.15\ \mathrm{kJ\ kg^{-1}\ K^{-1}}$ and $\gamma = 1.33$.

(a) Sketch a temperature-entropy diagram for the flow through the gas turbine and the gas side of the HRSG. [10%]

(b) The exhaust gas temperature at entry to the HRSG is 550 °C . In the gas turbine combustion chamber, gaseous fuel with a lower calorific value of 50.0 MJ kg^{-1} enters at 25 °C . Calculate:

(i) the compressor pressure ratio; [10%]

(ii) the temperature of the air entering the combustion chamber; [5%]

(iii) the air-to-fuel ratio; [30%]

(iv) the gas turbine overall efficiency. [10%]

(c) The exhaust gas leaves the HRSG at a temperature of 140 °C . If the steam cycle efficiency is 0.38 , determine the overall efficiency of the combined cycle power plant. [20%]

(d) Explain why aero-derivative gas turbines are not suitable for use in combined cycle gas turbine power plants. Describe an alternative way the efficiency of an aero-derivative gas turbine can be improved for use in power generation. [15%]

4 *Refer to the steam tables and steam chart in the Thermofluids Data Book for all the properties required in this question.*

A solar thermal power plant generates 11 MW of electricity using a conventional steam cycle with a boiler pressure of 40 bar and no reheater. The steam at turbine entry is dry saturated and the turbine isentropic efficiency is 0.86 . The condenser pressure is 0.06 bar and the water leaving the condenser is saturated liquid. The pressure losses in the boiler and condenser can be neglected. The feed pump work can also be neglected.

(a) Calculate the cycle efficiency without feed heating. [20%]

(b) A single direct contact feed heater is included in the cycle using steam bled from the turbine at 16 bar . There are no pressure losses in the feed heater and it produces saturated water. Assuming that the expansion through the turbine can be represented by a straight line on the enthalpy-entropy chart:

(i) Find the ratio of the mass flow rate of bled steam to the mass flow rate through the boiler. [15%]

(ii) Determine the cycle efficiency and the rate of solar heat input to the cycle. [15%]

(iii) Calculate the lost power due to the irreversibility in the feed heater and comment on the value obtained. Assume that the ambient temperature is equal to the condenser temperature. [25%]

(c) Explain carefully how the inclusion of the feed heater leads to an increase in cycle efficiency. Describe two ways the efficiency could be further increased without changing the maximum cycle temperature or the condenser pressure. [25%]

END OF PAPER