ENGINEERING TRIPOS PART IIA

Monday 7 May 2012 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) Starting from the steady-flow energy and entropy equations, and neglecting changes in kinetic and potential energy, derive the steady-flow exergy equation

$$\dot{m}(e_2 - e_1) = \int_{\mathrm{CS}} \left(1 - \frac{T_0}{T}\right) d\dot{Q}_S - \dot{W}_X - \int_{\mathrm{CS}} \left(1 - \frac{T_0}{T}\right) d\dot{Q}_0 - T_0 \dot{S}_{irrev}$$

for the control volume shown in Fig. 1. Note that $e = h - T_0 s$ and that $d\dot{Q}_S$ and $d\dot{Q}_0$ are defined as positive in the directions of the arrows. [20%]

(b) A steam power plant is based on the superheated Rankine cycle and control at part load is obtained by throttling the steam before it enters the turbine. Saturated liquid water enters the feed pump at state 1 and is compressed adiabatically and reversibly to state 2. The pressurised water enters the boiler where it is heated at constant pressure to state 3. The steam is then throttled adiabatically before entering the turbine at state 4. In the turbine the steam is expanded adiabatically but irreversibly to state 5. Had the turbine expansion been adiabatic and reversible the exit condition would have been state 5S. After the turbine the steam enters the condenser where it is condensed at constant pressure to state 1. It may be assumed that the heat is transferred to cooling water at temperature T_0 = 25 °C. The mass flow rate of steam around the cycle is 200 kg s^{-1}. The property values at all the states are given in Table 1.

(i) Sketch the steam cycle on an enthalpy-entropy diagram. Include the hypothetical isentropic turbine expansion in your sketch. [5%]

(ii) For the turbine calculate the actual power output and the 'lost power'. Calculate also the power output from the hypothetical isentropic turbine expansion. Explain clearly why the actual turbine power and the 'lost power' do not sum to the isentropic turbine power. [25%]

(iii) Prove analytically that the entropy creation due to irreversibilities within the condenser is zero. Explain this result in physical terms. Calculate the 'lost power' associated with heat transfer to the cooling water. [25%]

(iv) Calculate the exergy supply rate to the cycle and any other power and '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 cycle. [25%]

(cont.

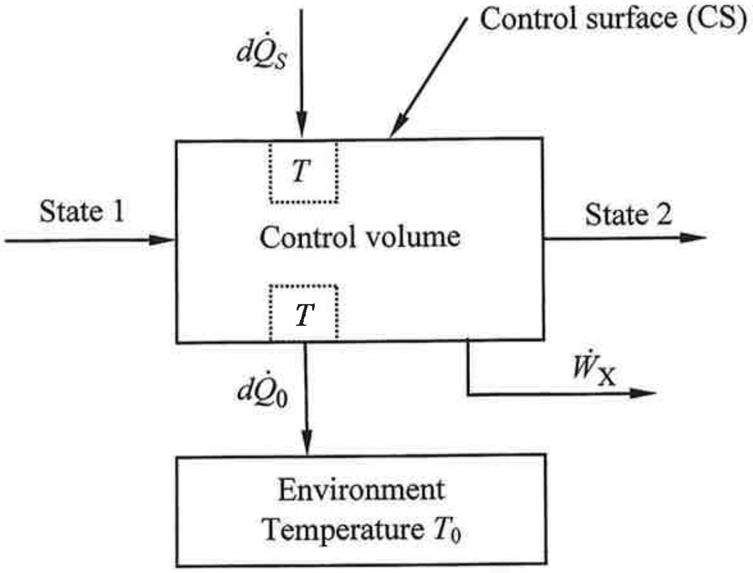

Fig. 1

		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	0.5210
State 2	Boiler inlet	100.00	36.69	162.6	0.5210
State 3	Throttle inlet	100.00	550.00	3502.0	6.7585
State 4	Turbine inlet	40.00	524.50	3502.0	7.1624
State 5	Condenser inlet	0.06	36.16	2400.2	7.7910
State 5S	Condenser inlet for isentropic turbine	0.06	36.16	2205.8	7.1624

Table 1 Property values for Question 1.

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

(a) The characteristic equation of state for a certain pure substance in the Gibbs function form $g(T, p)$ is

$$g = A(T - T\ln T) - \frac{BT^2}{2} + RT\ln p - \frac{Kp}{T^3} + h_0 - Ts_0$$

where A, B, R, K, h_0 and s_0 are constants. Proving any thermodynamic relationships you use, derive expressions for the specific volume v, specific entropy s, specific enthalpy h and constant pressure specific heat capacity c_p in terms of T, p and the appropriate constants. [40%]

(b) 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 1.5 moles of O_2 is confined in a rigid container at a temperature and pressure of 25 °C and 1 bar. The mixture is ignited and the reaction proceeds at constant volume. When chemical equilibrium has been established the temperature is found to be 2600 K. It may be assumed that the only species present are CO_2, CO and O_2, all of which behave as ideal gases.

Write down the chemical equation for the reaction in terms of the degree of dissociation α. Verify that $\alpha = 0.0313$. [60%]

3 A simple-cycle cooled gas turbine has a compressor inlet temperature T_1, a compressor inlet pressure p_1 and an overall pressure ratio r. A small mass fraction m of the compressor delivery air is bled off before the combustion chamber and is used to cool the turbine blades. This air is adiabatically throttled and then mixed with the main turbine flow at a constant pressure given by $p_{mix} = p_1\sqrt{r}$. The compressor and turbine polytropic efficiencies are both η_p and this efficiency is unaffected by the addition of the cooling air in the turbine. At exit from the turbine the pressure is p_1. The pressure loss in the combustor and the additional mass flow rate due to the fuel may both be neglected. In addition it may be assumed that air and the products of combustion behave as perfect gases with the same values of c_p and γ.

(a) Sketch the temperature-entropy diagram for the gas turbine and show that the temperature of the turbine flow, just after it has been mixed with the cooling air, is given by

$$\frac{T_{mix}}{T_1} = m\, r_t^{1/\eta_p} + (1-m)\,\theta\, r_t^{-\eta_p/2}$$

where θ is the ratio of the combustor outlet temperature to the compressor inlet temperature and r_t is the overall isentropic temperature ratio. [40%]

(b) Calculate the overall efficiency of the gas turbine using the following set of values: $\gamma = 1.37$, $r = 40$, $\theta = 5$, $\eta_p = 0.9$ and $m = 0.1$. Also, by setting $m = 0$, calculate the effect on the overall efficiency of the throttling and mixing of the cooling air. [40%]

(c) Explain why, despite the associated irreversibilities, the use of turbine blade cooling is essential for the development of high performance gas turbines. [20%]

4 *Table 2 provides properties of water and steam for various conditions within the steam cycle described in part (a). Use the steam chart in the Thermofluids Data Book for any other properties required.*

(a) The steam cycle in a combined cycle gas turbine power station includes a single stage of reheat between the high-pressure turbine and the low-pressure turbine. Wet saturated water leaves the condenser and enters a feed pump where it is compressed to 120 bar before entering the Heat Recovery Steam Generator (HRSG). Once the steam reaches a temperature of 450 °C it is passed through the high-pressure turbine. The steam is then returned to the HRSG for reheating at a pressure of 30 bar and the entry temperature to the low-pressure turbine is also 450 °C. In the condenser, the steam is condensed at a constant pressure of 0.06 bar. Pressure losses in the HRSG, and the feed pump work, can be neglected. The high-pressure turbine isentropic efficiency is 0.9 and the low-pressure turbine has an isentropic efficiency given by

$$\eta_{\mathrm{LPT}} = 0.9 - y$$

where y is the wetness fraction of the steam at exit from the low-pressure turbine.

(i) Determine the specific enthalpy of the steam at exit from the low-pressure turbine. [40%]

(ii) Find the net work output from the cycle per kg of steam and calculate the cycle efficiency. [25%]

(b) Exhaust gas that may be treated as perfect with $c_p = 1.10$ kJ kg^{-1} K^{-1} enters the HRSG from a gas turbine at a temperature of 540 °C. If the mass flow rate of exhaust gas is eight times the mass flow rate of steam, determine the temperature at which the exhaust gas leaves the HRSG. Also, calculate the HRSG efficiency when the ambient temperature is 20 °C. [15%]

(c) With the aid of a suitable sketch, briefly describe how the water vapour in the exhaust gas can be prevented from condensing on the outside of the tubes in the final section of the HRSG when the temperature of the feed water entering the tubes is close to the condenser temperature. [20%]

(cont.

	Specific enthalpy kJ kg^{-1}	Specific entropy kJ kg^{-1} K^{-1}	Temperature °C
Saturated Liquid at 0.06 bar	151.5	0.521	36.16
Saturated Vapour at 0.06 bar	2566.6	8.329	36.16
30 bar, 450 °C	3344.8	7.086	
120 bar, 450 °C	3209.8	6.303	

Table 2 Properties of water and steam for Question 4.

END OF PAPER

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MODULE 3A5 – THERMODYNAMICS AND POWER GENERATION

ANSWERS

1. (b) (ii) 220.4 MW, 37.5 MW, 259.2 MW (isentropic turbine)
   (iv) 295.9 MW, –2.2 MW (feed pump), 24.1 MW (throttle), 0.737

2. (a) $c_p = A + BT + 12KpT^{-4}$

3. (b) 0.421, 0.474

4. (a) (i) 2385.5 kJ/kg
   (ii) 1275.7 kJ/kg, 0.363
   (b) 141 °C, 0.770

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Draft Version 8 – for read-through meeting