

EGT2
ENGINEERING TRIPOS PART IIA

Tuesday 26 April 2016 14:00-15:30

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 a question is indicated in the right margin.*

*Write your candidate number **not** your name on the cover sheet.*

STATIONERY REQUIREMENTS

Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM

CUED approved calculator allowed

Engineering Data Book

10 minutes reading time is allowed for this paper.

You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.

1 A substance has an equation of state of the form

$$P_r = \frac{\beta T_r}{\alpha v_r - 1} - \frac{\alpha}{v_r^2}$$

where $P_r = P/P_c$, $v_r = v/v_c$, $T_r = T/T_c$. P is the pressure, v the specific volume, T the absolute temperature, and the subscript "c" denotes the value at the critical point. α and β are constants.

(a) Starting from $df = -sdT - Pdv$, explain why the following "Maxwell" relationship holds

$$\left(\frac{\partial s}{\partial v}\right)_T = \left(\frac{\partial P}{\partial T}\right)_v.$$

Here, f and s are the specific Helmholtz energy and entropy, respectively. [10%]

(b) Explain what is meant by a critical point and show that $\alpha = 3$, $\beta = 8$. [25%]

(c) Show that the specific heat capacity at constant volume, c_v , is only a function of the temperature. [25%]

(d) Derive an expression for the change in internal energy Δu , when the specific volume is varied from v_o to v at a constant temperature. [25%]

(e) For the case where c_v does not vary with temperature, derive an expression for the characteristic equation of state $u(T, v)$, as a function of u_o, T_o and v_o . Here, the subscript "o" denotes the value of a quantity at the standard state. [15%]

- 2 (a) (i) Starting from $Td\bar{s} = d\bar{h} - \bar{v}dP$ show that

$$\left(\frac{\partial \bar{g}}{\partial T}\right)_P = -\bar{s},$$

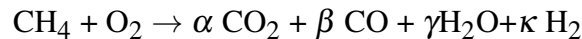
where $\bar{g}, \bar{s}, \bar{h}$ and \bar{v} are the molar Gibbs free energy, entropy, enthalpy and volume, respectively. T is the absolute temperature and P is the pressure. [10%]

- (ii) For a chemical reaction which has reached equilibrium, show that the equilibrium constant K_p varies with temperature as

$$\left(\frac{\partial \ln(K_p)}{\partial T}\right)_P = \frac{\Delta H_T^o}{RT^2},$$

where ΔH_T^o is the standard enthalpy of reaction and \bar{R} is the ideal gas constant [25%]

- (b) 1 kmol s⁻¹ of methane is fed to a burner, mixed with 1 kmol s⁻¹ of oxygen and then ignited. The system operates at 1 bar. The overall equation for this process is



At the exit of the burner the water-gas shift reaction is at equilibrium



- (i) Explain why the composition of the gas leaving the burner is independent of pressure. [10%]
- (ii) The burner operates at a temperature such that the equilibrium constant for Reaction (1) is unity. What are the values of $\alpha, \beta, \gamma, \kappa$? [25%]
- (iii) Derive an expression for the rate of change of β with temperature at constant pressure, and hence determine the sign of $\frac{\partial \beta}{\partial T}$. Comment on how the products from the burner can be converted to a mixture which is largely free of CO using Reaction (1). [30%]

3 (a) Discuss, briefly, why multiple steam pressures are beneficial in the design of the heat recovery steam generator (HRSG) of a combined-cycle power plant. [10%]

(b) A steam cycle for a combined-cycle power plant operates with a dual pressure HRSG, Fig. 1(a). The mass flow rate of steam in the condenser (at 0.04 bar) is \dot{m}_s . After the condenser, a feed pump raises the pressure of the feed water to 40 bar and heat is added in the HRSG until the steam is wet-saturated (at 40 bar). A fraction of steam α is further heated until it is dry-saturated (at 40 bar). The remainder of the feed water enters a second feed pump where the pressure is raised to 150 bar before being heated, in the HRSG, until it is super-heated to a temperature of 550 °C (at 150 bar). The super-heated steam then enters a turbine from which it exits at 40 bar with an enthalpy $h_r = 3095 \text{ kJ kg}^{-1}$. The two streams are then mixed, at constant pressure, before the flow enters a second turbine. At exit from the second turbine, the steam is wet with enthalpy $h_t = 2140 \text{ kJ kg}^{-1}$ at the condenser pressure (0.04 bar). Feed pump work may be neglected in the analysis of the cycle. You may assume c_p for the gas turbine exhaust is constant at $1.10 \text{ kJ kg}^{-1} \text{ K}^{-1}$.

(i) The HRSG has two pinch points, labelled ΔT_p in Fig. 1(b), both of which have a temperature difference between the gas turbine exhaust and the steam, of 25 °C. The temperature of the gas turbine exhaust at entry to the HRSG is $T_1 = 650 \text{ °C}$. Evaluate α and the ratio $\frac{\dot{m}_s}{\dot{m}_g}$ where \dot{m}_g is the mass flow rate of the gas turbine exhaust. [40%]

(ii) Stating any assumptions, evaluate the enthalpy h_{mix} of the steam entering the second turbine. [10%]

(iii) Calculate the cycle efficiency. [15%]

(c) Explain why feed heating is not employed in steam cycles for combined-cycle power plants. Describe the function of the “preheating loop” that is often part of the HRSG. [25%]

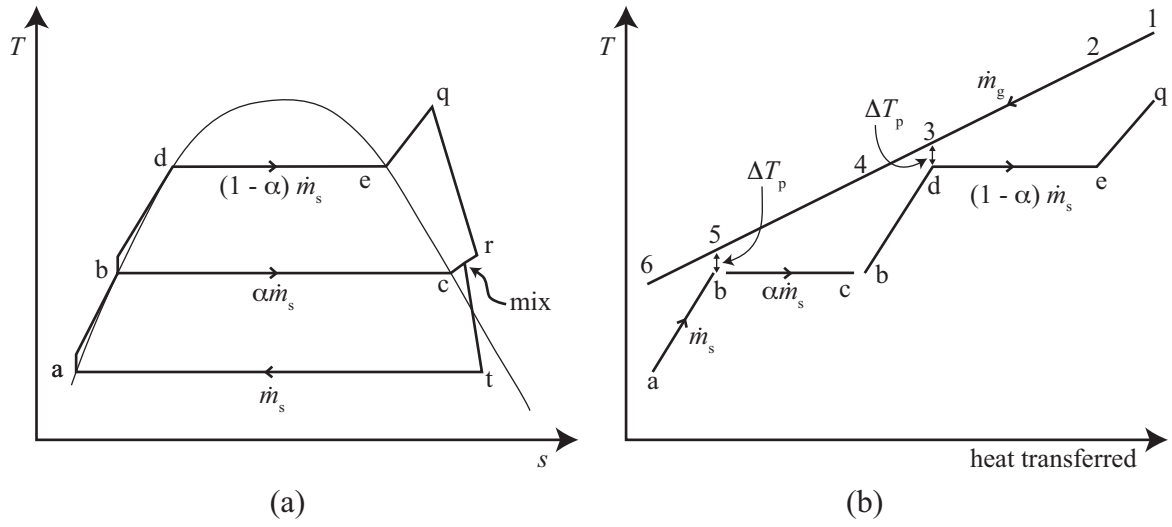


Fig. 1

4 (a) Explain the objectives in adding recuperation to a gas turbine cycle. Why is recuperation rarely used on large “grid-scale” gas turbines? [15%]

(b) A gas turbine cycle has an overall isentropic temperature ratio r_t and a ratio of turbine inlet temperature to compressor inlet temperature of θ . The compressor and turbine both have polytropic efficiency η and it may be assumed that there is no pressure drop in the combustor. An ideal recuperator, with negligible pressure drop, is added downstream of the turbine (and upstream of the combustor). Stating any assumptions, show that, for recuperation to be possible,

$$\theta > r_t^{\frac{\eta^2+1}{\eta}} .$$

[20%]

(c) The idealised recuperator of part (b) is replaced with one that has a pressure drop such that, on each side of the heat exchanger, $\frac{P_{out}}{P_{in}} = \alpha$ where $0 < \alpha \leq 1$. The isentropic temperature ratio *of the compressor* remains at r_t and there is no pressure drop in the combustor. Derive an expression for the reduction in turbine specific work output Δw_t due to the pressure drop in the recuperator, as compared to the idealised zero pressure drop case. For the case when $r_t = 2$, $\eta = 0.9$ and $\alpha = 0.9$ calculate Δw_t as a fraction of the turbine specific work output in the idealised case. (You may take the ratio of specific heat capacities to be $\gamma = 1.4$). [40%]

(d) Discuss the effect of intercooling in gas turbine cycles with and without recuperation. Describe, briefly, two methods of intercooling. [25%]

END OF PAPER

- 1) –
- 2) –
- 3) a) –
b) i) 0.0421, 0.177
ii) 3083 kJ/kg
iii) 39 %
- 4) e) 0.064