Version NS/4

EGT2
ENGINEERING TRIPOS PART IIA

Friday 9 May 2025   9.30 to 11.10

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 at the start of the exam.

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

You may not remove any stationery from the Examination Room.

1 (a) Using $dg = vdp - sdT$ and $df = -pdv - sdT$, obtain the following Maxwell relations

$$\left(\frac{\partial v}{\partial T}\right)_p = -\left(\frac{\partial s}{\partial p}\right)_T \qquad \text{and} \qquad \left(\frac{\partial s}{\partial v}\right)_T = \left(\frac{\partial p}{\partial T}\right)_v$$

where g and f are specific Gibbs and Helmholtz energies. The specific entropy and volume are s and v. The pressure and temperature are denoted using p and T. [20%]

(b) An equation of state for a substance is

$$p_r = \frac{\beta T_r}{(\alpha v_r - 1)} - \frac{\alpha}{v_r^2}$$

where $p_r = p/p_c$, $v_r = v/v_c$, and $T_r = T/T_c$ denote the reduced pressure, specific volume and temperature respectively. The subscript c denotes the value at the critical point. The symbols α and β are constants.

(i) Explain what is meant by the critical point and show that α and β are 3 and 8, respectively, at the critical point. [25%]

(ii) Show that the specific heat capacity at constant pressure, c_p, depends only on temperature. [35%]

(iii) Find an expression for the change in internal energy, Δu, when the specific volume is changed from v_0 to v. [20%]

2 Hydrogen is produced through partial oxidation of bio-butanol ($C_4H_{10}O$) with atmospheric air. The chemical reaction occurs at 1400 K with the fuel and O_2 in the air in molar proportions of 1 : 2.

(a) Write down the chemical equation for the stoichiometric condition. [10%]

(b) Calculate the mole fractions in the partially oxidised mixture, assuming that only CO_2, CO, H_2O, H_2 and N_2 are present. [60%]

(c) How will the mixture composition change if the pressure is altered? [10%]

(d) Explain how you would increase the hydrogen yield. [20%]

3 (a) A mixture with composition (by mass) of 97% carbon dioxide and 3% water enters a turbine at a pressure and temperature of 300 bar and 1100 °C and leaves the turbine at a pressure and temperature of 30 bar and 732 °C . The turbine is adiabatic and has a power output of 360 MW. The ambient temperature is 25 °C. The mixture properties at inlet and exit to the turbine are shown in Table 1.

(i) Determine the mass flow rate entering the turbine. [10%]

(ii) Determine the exergetic loss due to irreversibilities in the turbine. [10%]

(iii) Using a sketch of an enthalpy-entropy diagram, compare the real expansion across the turbine with a reversible expansion. Hence explain why the exergetic loss is smaller than the additional power output that would be achieved if the turbine was reversible. [10%]

(iv) Determine the volumetric flow rate at inlet and exit of the turbine and comment on how this affects the turbine design. Hence comment on any differences for this turbine compared with the turbine design for conventional land-based gas turbines and steam turbines. [10%]

(b) After passing through the turbine the mixture is cooled down and the water is extracted. The remaining pure carbon dioxide is then compressed isothermally at 30 °C from 30 bar to 300 bar. Carbon dioxide is bled from the compressor at a pressure of 75 bar. The bleed mass flow rate is 3.7% of the compressor inlet mass flow rate. The power input to the compressor is 56 MW. The fluid properties in the compressor are shown in Table 2.

(i) Explain why the enthalpy drops across the compressor despite the compression being isothermal. [10%]

(ii) Determine the heat transfer from the compressor. [10%]

(iii) Determine the power required if the compressor were reversible. Hence determine the power required to overcome irreversibilities. [20%]

(c) The components described above form part of an oxy-fuel power plant, where fuel is burnt in pure oxygen. Describe how such a plant provides one means of reducing the carbon dioxide emissions of power generation. Discuss any advantages and disadvantages of this approach compared to more conventional power plants with post-combustion carbon-capture. [20%]

	Pressure bar	Temperature °C	Density kg m^{-3}	Enthalpy kJ kg^{-1}	Entropy kJ $kg^{-1}K^{-1}$
Turbine inlet	300	1100	104	1839	3.494
Turbine exit	30	732	15.1	1353	3.549

Table 1

	Pressure bar	Temperature °C	Enthalpy kJ kg^{-1}	Entropy kJ $kg^{-1}K^{-1}$
Compressor inlet	30	30	480	2.039
Compressor bleed	75	30	290	1.296
Compressor exit	300	30	250	1.077

Table 2

(TURN OVER

4 A combined-cycle gas turbine (CCGT) power plant consists of a hydroden-fired gas turbine and single pressure level steam bottoming cycle without feed-heating or reheat.

(a) Discuss the use of hydrogen as a replacement fuel for natural gas in CCGT power plants, as a means to reduce the climate impact of power generation. [15%]

(b) The exhaust gases leave the gas turbine at a temperature of 570 °C. The exhaust gas should be treated as a perfect gas with specific heat capacity at constant pressure $c_p = 1.1$ kJ kg^{-1} K^{-1}. The steam turbine entry pressure and temperature are 60 bar and 550 °C. The condenser pressure and temperature are 0.04 bar and 28.96 °C. The pinch-point temperature difference is 15 °C. Pressure losses in the HRSG and feed pump work should be neglected. Use the databook steam tables for properties of water and steam. The environment temperature is equal to the condenser temperature of 28.96 °C.

(i) Sketch the temperature-heat-transfer ($T-Q$) diagram for the HRSG and identify the pinch-point. Determine the gas temperature at the pinch-point. [10%]

(ii) Determine the ratio of the mass flow rate of steam to the mass flow rate of exhaust gas. [10%]

(iii) Determine the temperature of the exhaust gas leaving the HRSG and hence the HRSG efficiency. Comment on the value you obtain. [15%]

(c) The steam turbine's isentropic efficiency is 90% and the exhaust gas mass flow rate is 300 kg s^{-1}. Determine the power output from the steam cycle. Compare this value to the maximum possible work output from the steam cycle. Discuss the sources of loss. You should use either the databook steam chart or tables for properties of steam. [40%]

(d) Comment briefly on the effect on the stack temperature and overall efficiency of adding feedheating to the CCGT power plant. [10%]

END OF PAPER