EGT2
ENGINEERING TRIPOS PART IIA

Friday 7 May 2021 13.30 to 15.10

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 and at the top of each answer sheet.*

STATIONERY REQUIREMENTS
Write on single-sided paper.

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed.
You are allowed access to the electronic version of the Engineering Data Books.

10 minutes reading time is allowed for this paper at the start of the exam.

The time taken for scanning/uploading answers is 15 minutes.

Your script is to be uploaded as a single consolidated pdf containing all answers.

1 (a) Figure 1 shows a reversible cycle ABCDA for a pure substance plotted on the T-s diagram. The cycle comprises two isothermal processes (AB and CD) separated by an infinitesimal temperature interval dT, and two other processes BC and DA that follow the vapour and liquid saturation lines respectively.

(i) Sketch the same cycle on a p-v diagram, showing the saturation curve and labelling the points A to D. Explain why the area enclosed by the cycle is the same for the two diagrams. Hence or otherwise derive the Clausius-Clapeyron equation for the variation of temperature with pressure along the saturation line

$$\left(\frac{\mathrm{d}T}{\mathrm{d}p}\right)_{\mathrm{sat}} = \frac{T v_{\mathrm{fg}}}{h_{\mathrm{fg}}}$$

where v_{fg} and h_{fg} are respectively the specific volume and specific enthalpy changes during evaporation. [30%]

(ii) At 1 bar, propane (C_3H_8) boils at 230.7 K and has a specific enthalpy of evaporation of 425.9 kJ kg^{-1}. Stating clearly your assumptions, estimate its boiling temperature at 2 bar. [25%]

(b) Consider a mixture of fluids that behaves as an ideal solution in the liquid phase and an ideal gas mixture in the vapour phase. The criteria for liquid and vapour to co-exist at equilibrium at pressure p and temperature T may be written

$$\bar{\mu}_i^v(T, p_{si}) + \int_{p_{si}}^{p} \frac{\bar{R}T}{p}\mathrm{d}p + \bar{R}T \ln X_i^v = \bar{\mu}_i^l(T, p_{si}) + \int_{p_{si}}^{p} \bar{v}_i^l \mathrm{d}p + \bar{R}T \ln X_i^l$$

where $\bar{\mu}_i$, $\bar{v}_i$, and X_i are respectively the molar chemical potential, molar volume and mole fraction of component i, and $\bar{R}$ is the molar gas constant. Superscripts l and v denote liquid and vapour respectively, and p_{si} is the saturation pressure of pure component i evaluated at temperature T.

(i) Explaining clearly any approximations, show that the above criteria simplify to Raoult's law

$$X_i^v p \simeq X_i^l p_{si}$$ [20%]

(ii) A binary mixture comprising one mole of propane and one mole of butane (C_4H_{10}) is held at a constant temperature of 230.7 K, at which the saturation pressure of butane is 0.147 bar. The pressure is gradually reduced from an initial value of 1 bar. Estimate the pressure at which bubbles of gas first appear and determine their molar composition. [25%]

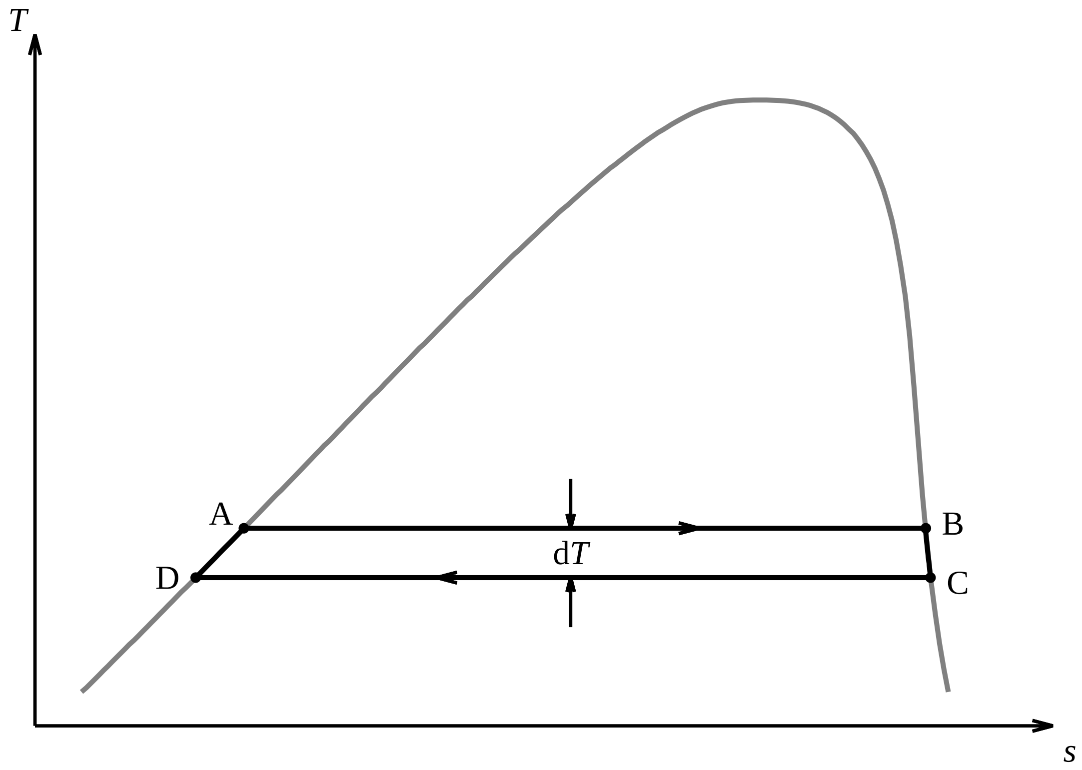

Fig. 1

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2 (a) Write down the chemical reaction for the complete combustion of carbon monoxide with a stoichiometric quantity of air and calculate the stoichiometric air-to-fuel ratio on a mass basis. [15%]

(b) 1 kg-mole of carbon monoxide and a stoichiometric quantity of air are introduced into a rigid vessel. The initial pressure and temperature in the vessel are $p_0 = 1\,\text{bar}$ and $T_0 = 298.15\,\text{K}$ respectively. Combustion is initiated by means of a spark such that the temperature and pressure rise rapidly. The products of combustion may be assumed to contain only CO_2, CO, O_2 and N_2. The vessel is not perfectly insulated and hence the temperature inside (which may be assumed uniform) falls slowly with time.

(i) Stating your assumptions, show that the number of kg-moles x of CO in the combustion products may be related to the temperature T by an expression of the form

$$\frac{1-x}{x^a} = bK_p(T)\left(\frac{T}{T_0}\right)^c$$

where $K_p(T)$ is the appropriate equilibrium constant. Determine values for the constants a, b and c. [35%]

(ii) Show that $x \simeq 0.1295$ when the temperature has fallen to 2600 K and find the corresponding pressure. [25%]

(iii) Determine to 3 significant figures the total heat released from the vessel once the temperature has returned to T_0. [25%]

3 (a) (i) A gas-turbine compressor has an isentropic efficiency of 0.80. At the inlet to the compressor the air temperature is 290 K. The pressure ratio is 16. Calculate the temperature at the compressor exit. [10%]

(ii) The same compressor is divided into two sections, each having a pressure ratio of 4. The isentropic efficiency of each section remains at 0.80. The two sections of the compressor are arranged such that the exit flow from the first is fed straight into the second. Calculate the temperature at exit from the second section. [15%]

(iii) Explain why polytropic efficiency provides a fairer measure of compressor performance and determine the value of polytropic efficiency that gives an isentropic efficiency of 0.80 for a pressure ratio of 16. [15%]

(b) A gas-turbine power plant has a compressor with a polytropic efficiency of 0.89 and a pressure ratio of 20. The air inlet pressure and temperature are 1 bar and 280 K respectively. The combustor is fuelled with natural gas (lower calorific value 49 MJ kg^{-1}) at a temperature of 298 K. There is a 5% pressure loss in the combustor. The turbine is uncooled and has a polytropic efficiency of 0.86, an inlet temperature of 1450 K and an exit pressure of 1.1 bar. Both air and the combustion products may be treated as perfect gases. For air the isobaric heat capacity c_p is 1.005 kJ kg^{-1}K^{-1} and $\gamma = 1.40$. For the combustion products $c_p = 1.100$ kJ kg^{-1}K^{-1} and $\gamma = 1.36$.
Calculate:

(i) the fuel-to-air ratio on a mass basis; [30%]

(ii) the work output per kg of air flow in the compressor; [25%]

(iii) the overall efficiency. [5%]

4 A coal-fired power station operates on a standard superheated Rankine cycle with a boiler pressure of 150 bar, a turbine inlet temperature of 550 °C, and a condenser pressure of 0.04 bar. The power output of the plant is 500 MW and the thermal efficiency of the cycle is 0.36.

(a) (i) Draw the cycle on a *T-s* diagram. [5%]

(ii) Estimate the isentropic efficiency of the turbine. [15%]

(iii) Find the dryness fraction of the steam at turbine exit. [5%]

(b) The lower calorific value of the coal is 23 MJ kg^{-1} and the air-to-fuel ratio on a mass basis is 20. The isobaric heat capacity, c_p, of the combustion products is 1.1 kJ kg^{-1}K^{-1} and the exhaust stack temperature is 130 °C. Calculate the overall efficiency of the power station and the mass of coal burnt per day during continuous operation, assuming an ambient temperature of 25 °C. Determine also the mass of carbon dioxide emitted per day if the coal contains 75% carbon by mass. [35%]

(c) The plant efficiency is to be improved by adding a single direct-contact feedheater using steam bled from the turbine at 10 bar and 250 °C. Making appropriate assumptions estimate the boiler feedwater temperature, the mass flow fraction of bled steam and the new cycle efficiency. [25%]

(d) Explain carefully what other modification needs to be made to the power station in order to realise the benefit of feedheating on the overall plant performance. Briefly describe other methods of improving the cycle efficiency, giving thermodynamic reasoning for how the improvements are achieved. [15%]

END OF PAPER

ANSWERS

Q1.	(a)	(ii) 248.3 K		
	(b)	(ii) 0.574 bar; 12.8% butane		
Q2.	(a)	AFR = 2.45 by mass		
	(b)	(i) a = 3/2; b = 0.3846; c = ½		
		(ii) 7.60 bar		
		(iii) –282 MJ		
Q3.	(a)	(i) 728.0 K	(ii) 749.4 K	(iii) 0.861
	(b)	(i) 0.0174	(ii) 319.6 kJ/kg	(iii) 37.5%
Q4.	(a)	(ii) 81%	(iii) 0.876	
	(b)	32.2%	5833 tonne/day	16041 tonne/day
	(c)	0.227	38.7%	