Version AJW/3

EGT2
ENGINEERING TRIPOS PART IIA

Friday 6 May 2022   2 to 3.40

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) Figure 1 shows a section of the specific enthalpy against specific entropy (h-s) chart for H_2O. The scale on the entropy axis has been deliberately removed. Point A on the diagram is in the vapour region at a pressure of 0.1 bar and temperature of 100 °C. Points B and C lie on a single isobar in the two-phase region.

(i) Using a combination of thermodynamic and molecular arguments, explain why it is reasonable to suppose that the steam behaves approximately as an ideal gas in the vicinity of point A. [10%]

(ii) Using only information available from the figure, and showing clearly your reasoning, determine the difference in specific entropy between points B and C. [15%]

(b) Starting from the definition of the specific Gibbs function $g = h - Ts$, derive the Maxwell relation

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

where v is specific volume, T is temperature and p is pressure. [10%]

(c) A particular gas obeys the relationship

$$p(v - b) = RT$$

where b is a constant and R is the specific gas constant. The gas undergoes a steady-flow adiabatic throttling process, for which changes in kinetic energy of the flow may be neglected. By considering the enthalpy change of the gas, and making use of the Maxwell relation given in part (b), show that the temperature must increase during this process. [40%]

(d) The van der Waal's equation of state may be written

$$p = \frac{RT}{v - b} - \frac{a}{v^2}$$

where a and b are constants. For H_2O $a = 1680\,\mathrm{Pa}\,(\mathrm{m^3kg^{-1}})^2$ and $b = 0.0017\,\mathrm{m^3kg^{-1}}$. Use these values to estimate the critical temperature for H_2O. Comment on the accuracy of the result. [25%]

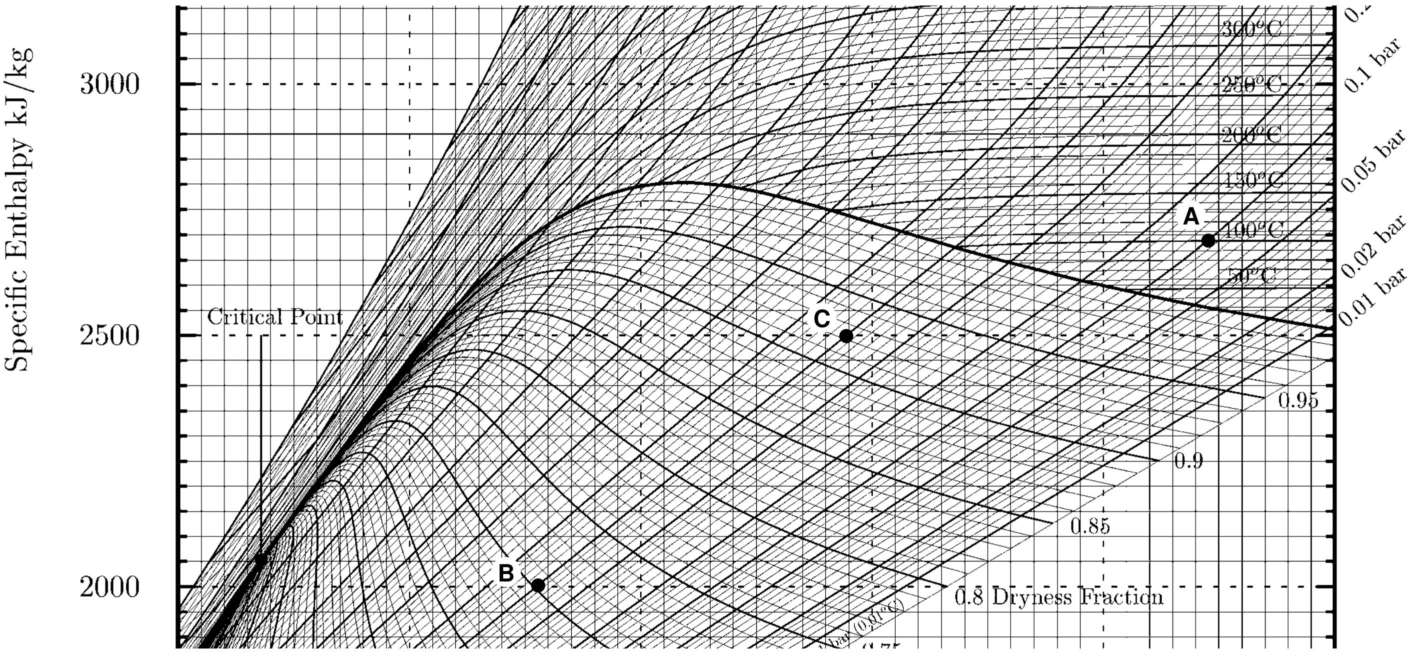

Fig. 1

(TURN OVER

2 (a) Figure 2 shows an idealised power plant that uses hydrogen gas as the fuel. All processes are reversible and the only heat exchange is with the atmosphere. All reactants and products are at $p_0 = 1$ bar and $T_0 = 298.15$ K. Starting from molar forms of the steady flow energy and entropy equations, show that the maximum work output per kmol of H_2 supplied is

$$\bar{W}_{\text{max}} = -\Delta\bar{G}^0_{T_0}$$

where $\Delta\bar{G}^0_{T_0}$ is the standard Gibbs function of reaction per kmol for the oxidation of H_2 at temperature T_0. Calculate the maximum output per *kilogram* of H_2. [30%]

(b) A power plant is being designed to use ammonia (NH_3) as the fuel.

(i) Write down the stoichiometric equation for the combustion of NH_3 in pure oxygen. Assume that the only products are water vapour and nitrogen. [5%]

(ii) By considering how this reaction relates to other reactions listed in the Databook, determine the maximum work that can be extracted per kg of ammonia. [25%]

(iii) At 298.15 K ammonia liquefies at a pressure of 10 bar and the resulting liquid has a density of $600\,\text{kg}\,\text{m}^{-3}$. Calculate and compare the exergy (available energy) densities of liquid ammonia and hydrogen gas as fuels at this temperature and pressure. [10%]

(c) The production of ammonia requires nitrogen gas, which is obtained by separation from air. Estimate the minimum work required to separate sufficient nitrogen to produce 1 kg of ammonia. Assume all streams are supplied or withdrawn at p_0 and T_0. Suggest how the separation might be achieved in practice and comment on whether this estimate is realistic. [30%]

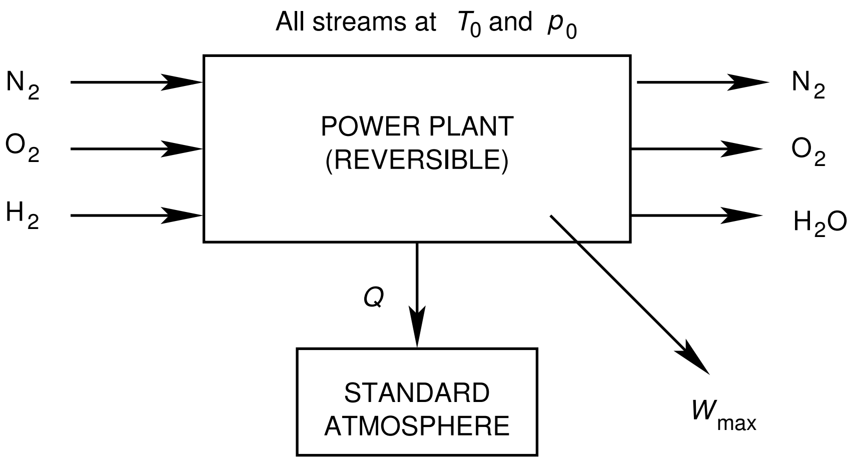
All streams at T_0 and p_0
N_2
O_2
H_2
POWER PLANT
(REVERSIBLE)
N_2
O_2
H_2O
Q
STANDARD
ATMOSPHERE
W_{max}

Fig. 2

3 *Throughout this question you may wish to make use of the steady flow availability function, defined as $b = h - T_0\, s$, where h and s are specific enthalpy and specific entropy respectively, and T_0 is the environment temperature.*

(a) In a compressed air energy storage (CAES) system, designed to support off-shore wind generation, compressed air is stored in numerous inflatable bags submerged under the sea. The bags have a total volume of $10^5\,\mathrm{m}^3$ when fully inflated and are at a depth of 700 m in water of density $1038\,\mathrm{kg\,m^{-3}}$. The air is stored at ambient temperature, $T_0 = 280\,\mathrm{K}$. Atmospheric pressure at sea level is $P_0 = 1$ bar. Determine the maximum work that could, in principle, be extracted from the fully inflated bags. [20%]

(b) Figure 3 shows the compression system used to charge the inflatable bags described in part (a). The two compressors C1 and C2 have a polytropic efficiency of 90% and have the same pressure ratio. After each compressor the air is cooled back to T_0 in the counter-flow heat exchangers HX1 and HX2, which transfer heat to a thermal storage oil, as shown. Pressure losses in the heat exchangers and pipework may be neglected.

(i) Sketch on a *T*-*s* diagram the charging process (i.e., states 0 to 4, as indicated in Fig. 3) and calculate the work input required to fully charge the system. Electrical and frictional losses may be neglected. [25%]

(ii) Assuming that the heat-exchange processes are reversible, calculate the exergy (available energy) stored in each of the hot thermal-oil tanks. Hence or otherwise determine the rational efficiency of the charging process. [25%]

(c) The CAES system described above is discharged by reversing the flows, replacing the two compressors with two turbines and replacing the motor with a generator. The turbines have a polytropic efficiency of 90% and it may again be assumed that HX1 and HX2 are reversible.

(i) Sketch the discharge process on your *T*-*s* diagram for part (b) and explain why an additional component is required to fully discharge the system. What is this component and where is it situated? [10%]

(ii) Calculate the round-trip efficiency of the storage system. Electrical and frictional losses may be neglected. [20%]

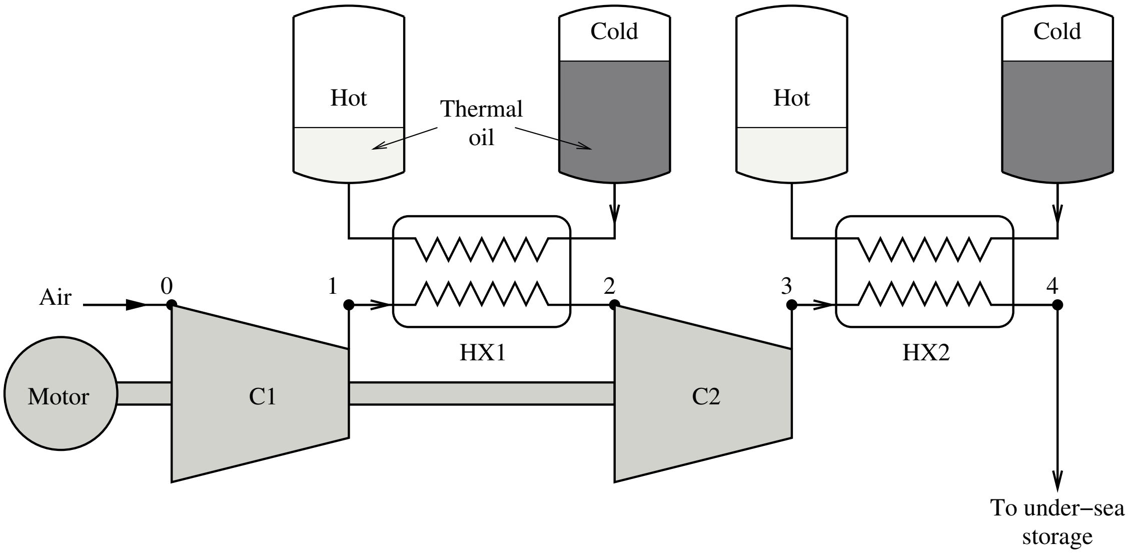

Fig. 3

 (TURN OVER

4 (a) A power station uses a superheated Rankine cycle with a boiler pressure of 160 bar and a condenser pressure of 0.04 bar. The turbine entry temperature is 560 °C and the turbine isentropic efficiency is 0.85. Assuming that the feed-pump work is negligible, calculate:

(i) the dryness fraction at the turbine exit; [20%]

(ii) the thermal efficiency of the cycle. [20%]

(b) The power station of part (a) is designed to produce 500 MW of electric power. It is fuelled with biomass having a lower calorific value of 18 MJ kg^{-1} and a composition by mass of 42% carbon, 48% oxygen, 8% hydrogen and 2% nitrogen. The mass flowrate of air is 15% greater than that required for stoichiometric combustion. The temperature of the combustion products at the boiler exit is 80 °C and the temperature of the environment is 25 °C. Assuming the flue gas has a constant isobaric specific heat capacity of 1.15 kJ kg^{-1}K^{-1}, calculate:

(i) the air-fuel ratio on a mass basis; [20%]

(ii) the rate of fuel supply in kg s^{-1}. [20%]

(c) Rather than fuelling the power station with biomass it is proposed to burn coal instead and to minimise the environmental impact by using Carbon Capture and Storage (CCS). Discuss the practical advantages and disadvantages of each approach. [20%]

END OF PAPER

ANSWERS

Q1. (a) (ii) 1.34 $kJkg^{-1}K^{-1}$

(d) 634.5 K

Q2. (a) 114.3 $MJkg^{-1}$

(b) (ii) 19.2 $MJkg^{-1}$

(iii) 11.5 GJm^{-3} (NH_3) 92.2 MJm^{-3} (H_2)

(c) 0.047 MJ per kg of NH_3

Q3. (a) 3.08×10^{12} J (859.4 MWh)

(b) (i) 4.92×10^{12} J (1.37 GWh) (ii) 0.742×10^{12} J (206 MWh) ; 92.8%

(c) (ii) 85.8%

Q4. (a) (i) $x_4 = 0.85$ (ii) 38%

(b) (i) AFR = 6.31 kg/kg (ii) 74.7 kg/s