Version AJW/2

EGT2
ENGINEERING TRIPOS PART IIA

Friday 5 May 2023 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) The exergy equation for a control volume with a single inlet (state 1) and single exit (state 2) passing a mass flow rate $\dot{m}$ may be written in the form

$$\dot{m}(b_2 - b_1) = \dot{E}_Q - \dot{W}_X - \dot{W}_{L,Q} - \dot{W}_{L,\text{irr}}$$

where b is the steady flow availability function, $\dot{E}_\text{Q}$ is the rate of exergetic input from external heat sources, $\dot{W}_\text{X}$ is the shaft power output, and $\dot{W}_{L,Q}$ and $\dot{W}_{L,\text{irr}}$ are rates of lost work due to heat exchange with the environment and irreversibility respectively.

Provide expressions for b, $\dot{E}_\text{Q}$, $\dot{W}_{L,Q}$ and $\dot{W}_{L,\text{irr}}$ that would enable these four quantities to be evaluated in practice. Ensure that all quantities in your expressions are fully defined. [20%]

(b) The charging cycle of an energy storage system comprises a compressor (C), a counter-flow heat exchanger (HX) and two expanders (E1 and E2), as shown in Fig. 1. The working fluid is pressurised nitrogen which may be treated as a perfect gas. The inlet to the compressor is at 280 K and the compression is adiabatic with a polytropic efficiency of 0.9. In the heat exchanger, heat is transferred from the working fluid to a thermal storage oil, raising its temperature from 320 K to 620 K, as shown. During this process there is a constant temperature difference $\Delta T = 10$ K between the working fluid and oil, and pressure losses are negligible. Expander E1 is adiabatic with a polytropic efficiency of 0.9, whereas expander E2 operates isothermally and has no internal irreversibility. The environment temperature is 300 K.

(i) Sketch a temperature-entropy diagram of the cycle for the working fluid, marking on the temperatures at points 1 to 4, as indicated in Fig. 1. [10%]

(ii) Given that the thermal oil has a density of 800 kg m^{-3} and a constant specific heat capacity of 2.0 kJ kg^{-1}K^{-1}, calculate the exergy density of storage (i.e., the exergy stored per m^3 of oil). How does this compare with the exergy density of a typical pumped hydro system? [20%]

(iii) Calculate the rate of lost work in the heat exchanger, expressed as a fraction of the rate at which exergy is transferred from the working fluid. What is the cause of this loss? [20%]

(iv) Calculate the charging efficiency, defined as the ratio

$$\frac{\text{rate of exergy transfer to the oil}}{\text{net rate of work input to cycle}}$$

and describe briefly the nature and cause of any other losses in the cycle. [30%]

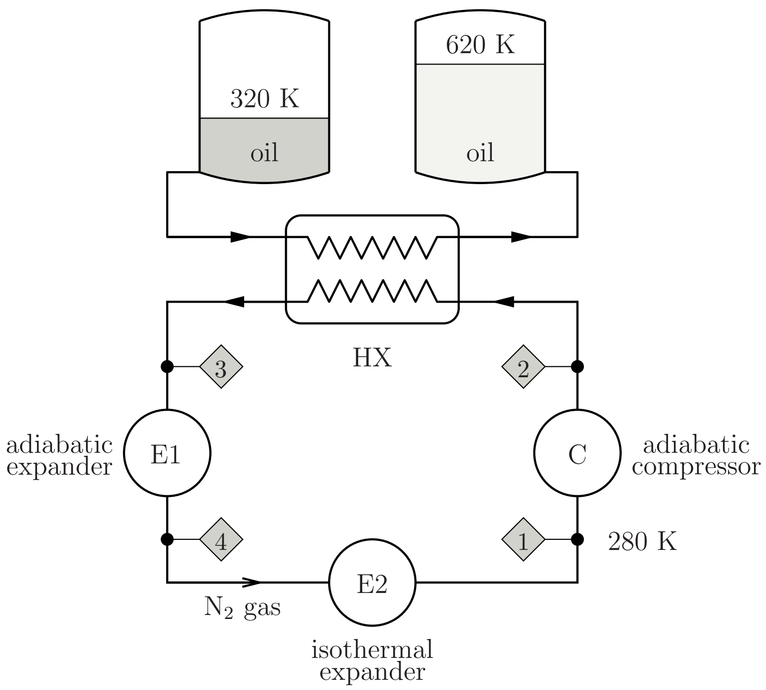
620 K
320 K
oil
oil
HX
3
2
adiabatic
expander
E1
C
adiabatic
compressor
4
1
280 K
E2
N_2 gas
isothermal
expander

Fig. 1

2 *Throughout this question all substances may be assumed to behave as semi-perfect gases. The average molar heat capacity of ammonia should be taken as* $42\,\mathrm{kJ\,kmol^{-1}}$.

(a) Ammonia (NH_3) may be produced by reacting nitrogen and hydrogen gases at high pressure and temperature in the presence of a catalyst, in accord with the following reaction (reaction 9 in the Data Book):

$$\tfrac{1}{2}N_2 + \tfrac{3}{2}H_2 \rightleftharpoons NH_3$$

Giving brief explanations, state whether the yield of ammonia is increased, decreased or remains the same in each of the following:

(i) An increase in pressure by isothermal compression of the gas mixture. [10%]

(ii) An increase in temperature at constant pressure. [10%]

(iii) An increase in pressure at constant temperature by the addition of neon gas. [10%]

(b) A gaseous mixture comprising 0.1 kmol of N_2 and 0.3 kmol H_2 is contained within a rigid vessel at 10 bar and 400 K (state 1). A catalyst is introduced and the above ammonia-producing reaction takes place. At a particular instant there is an equilibrium mixture of N_2, H_2 and NH_3 in the vessel at a temperature of 600 K (state 2).

(i) Determine the pressure and composition at state 2. Comment briefly on the semi-perfect gas assumption. [35%]

(ii) Calculate the heat transfer from the gas mixture to the surroundings in undergoing the process between states 1 and 2. [35%]

3 (a) Explain the effects of pressure ratio β on the specific work output w from the ideal Joule cycle and sketch the variation of w with β. [15%]

(b) Stating any assumptions, show that the minimum specific shaft work required for a steady-flow compression process is given by

$$-w_x = \int_1^2 \frac{1}{\rho}\, \mathrm{d}p$$

where p is pressure, ρ is the fluid density and states 1 and 2 correspond to compressor inlet and outlet respectively. Hence explain the effect of intercooling on specific work output for a gas turbine. [15%]

(c) A simple closed-cycle gas turbine comprises the usual four components, with the exception that the compressor operates isothermally (the turbine remains adiabatic). The working fluid is a perfect gas.

(i) Sketch the temperature-entropy diagram for the cycle and show that the maximum possible cycle efficiency is given by

$$\eta = \frac{\theta(1 - 1/r_t) - \ln r_t}{\theta - 1}$$

where θ is the ratio between the highest and lowest temperatures in the cycle and r_t is the isentropic temperature ratio across the turbine. [20%]

(ii) Find an expression for the pressure ratio at which the efficiency is maximised for a given θ and provide a thermodynamic interpretation for why the maximum is achieved at this pressure ratio. [20%]

(d) The isothermal compressor in the cycle of part (c) operates at temperature $T_1 = \alpha T_0$, where T_0 is the temperature of the environment. Heat rejected from this cycle is used to drive a secondary cycle which rejects heat to the environment. Derive an expression for the maximum possible efficiency of the combined cycle. Does the primary cycle need to operate at a particular pressure ratio in order to achieve this maximum efficiency? Explain your answer. [30%]

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4 The steam cycle of a concentrating solar power plant has an output of 100 MW and uses a single stage of reheat situated between the high pressure turbine (HPT) and low pressure turbine (LPT), as shown in Fig. 2. Steam for reheating is taken from the steam generator and passes via a throttle to the reheater where it mixes with the HPT exit flow, as shown. The feedpump and turbines are adiabatic. Conditions around the cycle and local saturation temperatures are given in Table 1. The environment temperature is 15 °C.

(a) Explain the advantages and disadvantages of reheat and suggest a reason for its use in this case. [10%]

(b) Calculate the mass flow of steam required for reheating per kg of flow through the steam generator. Hence determine the exergy loss per kg of flow through the steam generator. [15%]

(c) Calculate the steam generator mass flow rate and the cycle efficiency. [20%]

(d) By considering the thermodynamic relationship $dh = T\,ds + v\,dp$ and using only information from Table 1, estimate the isentropic efficiencies of the pump and the two turbines. Comment on the accuracy of your estimate in each case and explain which of these efficiencies has the greatest impact on the cycle efficiency. [25%]

(e) The hot side of the steam generator is supplied with a thermal oil which may be assumed to have constant specific heat capacity. The oil enters the steam generator at 468 °C and the minimum temperature difference between the hot and cold streams is 10 °C.

(i) Sketch the temperature-heat-transfer (T-Q) diagram for both streams in the steam generator and label the pinch point. [10%]

(ii) Find the temperature of the oil leaving the steam generator. [10%]

(iii) A new steam generator is to be designed for this application. Explain the factors affecting the choice of steam-generation pressure, assuming the maximum steam temperature is to remain unchanged. [10%]

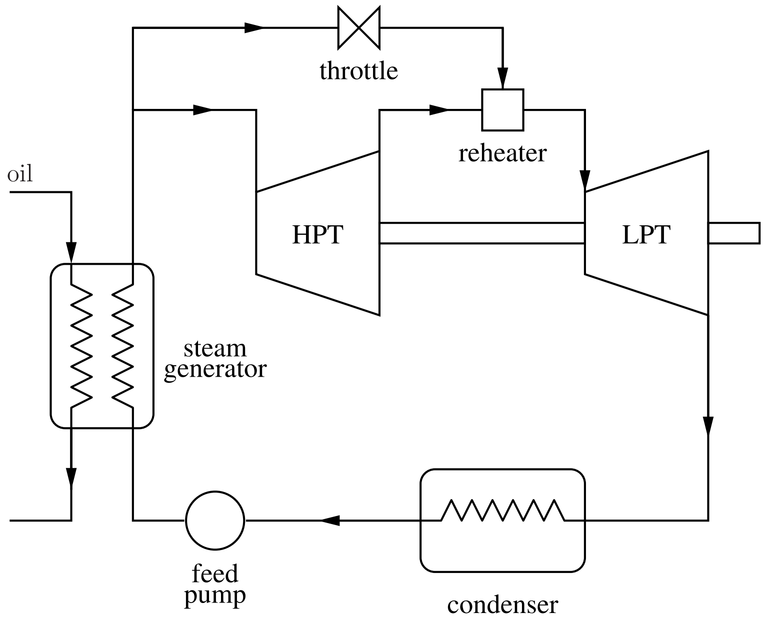

Fig. 2

Table 1

Location	T (°C)	p (bar)	h ($\mathrm{kJ\,kg^{-1}}$)	s ($\mathrm{kJ\,kg^{-1}K^{-1}}$)	$T_{sat}(p)$ (°C)
HPT inlet	380	100	3032	6.116	311
HPT exit	248	35	2822	6.161	243
LPT inlet	264	35	2875	6.262	243
LPT exit	33	0.05	2101	6.892	33
Pump inlet	33	0.05	138	0.476	33
Pump exit	34	100	152	0.490	311
Economiser exit	311	100	1408	3.361	311

END OF PAPER

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