ENGINEERING TRIPOS PART IIB

Monday 5 May 2008 2:30 to 4

Module 4M15

SUSTAINABLE ENERGY

*Answer not more than **two** questions.*

All questions carry the same number of marks.

*The **approximate** percentage of marks allocated to each part of the question is indicated in the right margin.*

Attachment: Thermodynamic Data Sheet (1 sheet)

STATIONERY REQUIREMENTS
Single-sided script paper.
Single-sided graph paper.

SPECIAL REQUIREMENTS
Engineering Data Book.
CUED approved calculator allowed.

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

1 A sugar producer wants to take heat from a nearby power station. A diagram of the most energy intensive part of the sugar producing process, which involves the evaporation of water from a sugar solution, is shown in Fig. 1. The first evaporation is carried out at 120 °C and 1.985 bar. The resulting solution is then cooled to 100 °C before the second evaporation at 1 bar. The steam leaving the evaporators must be condensed (at constant pressure) and cooled to 40 °C before the water can be released into a nearby river.

(a) Considerable savings in energy can be achieved by heat integrating the process shown in Fig. 1.

(i) Plot the hot composite curve for the process (i.e. streams [1], [2] and [3]). Assuming the boiling takes place at a constant pressure, how much heat must be supplied to each of the evaporators? [30%]

(ii) By interval analysis (or otherwise), and treating the heat load required by an evaporator as a "cold stream", calculate the minimum amount of heat which must be supplied to this process. In this limiting case, plot the cold composite (i.e. the heat sinks) on the same graph as the hot composite curve and suggest why the answer is physically unreasonable. [30%]

(iii) From your plots of composite curves, suggest why a temperature difference of ΔT_{min} = 20 °C at the pinch is reasonable. For ΔT_{min} = 20 °C, how much heating must now be supplied? Sketch how the process would look if this was realised in practice. [20%]

(b) What is the **absolute maximum** amount of work which could be generated by the power plant at a marginal efficiency of 100%, if the heat source at the power plant is at 1200 K? [10%]

(c) The owner of the sugar factory argues that since all the heat used by the sugar factory is now waste heat, the environmental burden (i.e. emissions of CO_2) of the sugar factory arising from its heat demand is now zero. The operator of the power plant which sells the heat disagrees. Describe another way in which the environmental burden could be allocated. [10%]

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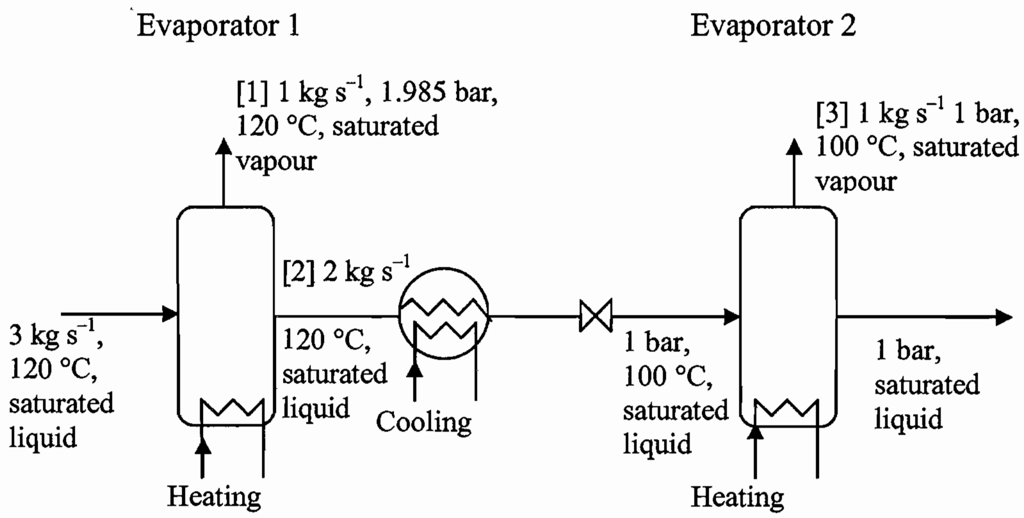

N.B. stream [2] is to be cooled to saturated liquid at 1 bar before entering evaporator 2

Fig. 1

Data:

For simplicity, the properties of the sugar solution can be considered to be those of pure water. The heat of vapourisation of water should be assumed to be independent of pressure and have a value of 2260 kJ kg^{-1}. The heat capacity of the water should be assumed to be constant at 4.2 kJ kg $^{k-1}$. The liquid and vapour leaving the evaporators are saturated.

2 (a) A partial oxidation plant (Fig. 2) is used to produce pure H_2 for use in fuel cell vehicles. The purpose of the shift reactor is to remove all of the CO (the shift reaction may be assumed to go to completion). The partial oxidation and shift reactors are both cooled via cooling coils which are supplied with saturated water at 2 bar, whose flow rate is adjusted to produce saturated steam at the same pressure. This steam is then exported to other processes which use it as a heat source. Any heat rejected by the separation unit is simply released into the environment.

(i) For a feed of 1 kmol s^{-1} of CH_4, how much steam does the plant export **in total** (i.e. from both the partial oxidation and shift reactors) ? [20%]

(ii) What is the **total** exergy loss due to irreversibilities in the partial oxidation and shift reactors? [30%]

(iii) What is the exergetic efficiency of the overall process, given that the exergy of the methane entering the plant is 829.8 MJ $kmol^{-1}$? You may neglect the input of exergy to the plant associated with the O_2. [25%]

(b) The hydrogen is to be compressed (isothermally and reversibly) to 300 bar for storage on board the vehicles. The hydrogen is throttled isenthalpically to 1 bar and 298.15 K, before being fed to the fuel cell. What is the CO_2 foot-print of 1 km of travel using the H_2 fuel? Assume that the CO_2 in (a) is released into the atmosphere and that only the production of H_2 and its compression significantly contribute to the lifecycle of H_2 fuel. Comment on your answer. [25%]

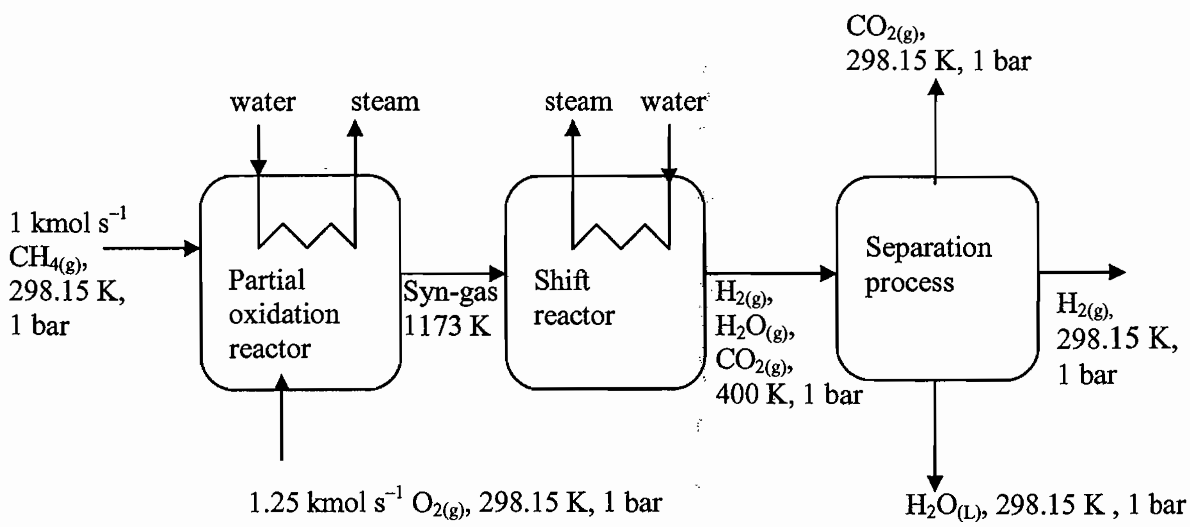

Fig. 2

Data:

The environment is defined to be: T_o = 25 °C (298.15 K), P_o = 1 bar. The atmosphere may be assumed to consist of 79% N_2, 21% O_2, 0.04% CO_2 (molar composition). Water may be assumed to be a pure liquid in the environment.

Electricity from the national grid provides the work needed for compression with a CO_2 footprint of 0.166 kg of CO_2 per MJ delivered.

The exergetic efficiency of the fuel cell operating on H_2 at 1 bar is 50%. The fuel cell must deliver 2 MJ of work to the drive system, per kilometre driven.

The relative molecular mass of CO_2 is 44 kg kmol^{-1}.

A data sheet is provided which gives thermodynamic data for various chemical species relative to a mutually consistent standard state. All gases may be assumed to be ideal.

3 A lobby group thinks that the Government's target of a 20% cut in CO_2 emissions from the transport sector can be met entirely through the use of biofuels. Others disagree and think that these cuts can be achieved by changes to the powertrain of cars to give a radical increase in efficiency. Discuss the technologies involved and present a reasoned argument for the pros and cons of these two approaches to cutting emissions. Illustrate your answer with a graph of the torque *vs.* speed characteristics for a typical petrol engine; on this graph sketch the contours of constant specific fuel consumption and constant power, with justifications. [100%]

END OF PAPER

Enthalpy of various species when pure, relative to a consistent standard state

Temperature (K)	Enthapy ($kJ\ kmol^{-1}$)							
	CO_2	CO	H_2	H_2O	$H_2O_{(L)}$	CH_4	N_2	O_2
298.15	-393510	-110535	0.0	-241826	-285830	-74600	0	0
300	-393441	-110481	53.4	-241764	-285691	-74534	54	54
400	-389506	-107559	2959.8	-238374	-278121	-70731	2971	3026
500	-385203	-104604	5882.5	-234901	-270171	-66374	5911	6086
600	-380601	-101594	8810.7	-231325	-260447	-61410	8894	9245
700	-375754	-98514	11748.3	-227634		-55845	11937	12500
800	-370701	-95360	14701.5	-223823		-49714	15046	15838
900	-365478	-92136	17676.0	-219887		-43056	18223	19244
1000	-360110	-88848	20679.0	-215823		-35915	21462	22707
1100	-354622	-85503	23717.1	-211629		-28336	24760	26219
1200	-349032	-82108	26794.3	-207308		-20359	28109	29771
1300	-343357	-78671	29914.4	-202862		-12023	31503	33356
1400	-337610	-75196	33078.7	-198297		-3364	34936	36971
1500	-331801	-71690	36287.3	-193620		5587	38405	40613
1600	-325938	-68155	39539.3	-188836		14801	41903	44281

Notes:

All species are assumed to be ideal gases, except $H_2O_{(L)}$, which is saturated liquid water

Standard state
P = 1 bar
T = 298.15 K

Entropy of various species when pure, relative to a consistent standard state

Temperature (K)	Entropy ($kJ\ kmol^{-1}\ K^{-1}$)							
	CO_2	CO	H_2	H_2O	$H_2O_{(L)}$	CH_4	N_2	O_2
298.15	213.8	197.7	130.7	188.8	69.9	186.4	191.6	205.1
300	214.0	197.8	130.9	189.0	70.4	186.6	191.8	205.3
400	225.3	206.2	139.2	198.8	92.2	197.5	200.2	213.9
500	234.9	212.8	145.7	206.5	109.9	207.2	206.7	220.7
600	243.3	218.3	151.1	213.0	127.5	216.2	212.2	226.5
700	250.7	223.1	155.6	218.7		224.8	216.9	231.5
800	257.5	227.3	159.5	223.8		233.0	221.0	235.9
900	263.6	231.1	163.1	228.5		240.8	224.8	239.9
1000	269.3	234.5	166.2	232.7		248.3	228.2	243.6
1100	274.5	237.7	169.1	236.7		255.6	231.3	246.9
1200	279.4	240.7	171.8	240.5		262.5	234.2	250.0
1300	283.9	243.4	174.3	244.0		269.2	236.9	252.9
1400	288.2	246.0	176.6	247.4		275.6	239.5	255.6
1500	292.2	248.4	178.8	250.7		281.8	241.9	258.1
1600	296.0	250.7	180.9	253.7		287.7	244.1	260.5