ENGINEERING TRIPOS PART IIB

Thursday 2 May 2013 2-3.30

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.*

There are no attachments.

STATIONERY REQUIREMENTS
Single-sided script 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

sas05

1 An office block in the UK currently uses a gas (CH_4) fired boiler to provide 0.1 MW of heat. The office requires heat at 100 ºC. The management is considering schemes to reduce the carbon footprint of the office block. One scheme involves buying heat from a local combined heat and power plant (CHP), which is connected to the national electricity grid. This CHP currently has no customers for its heat, so simply rejects heat at the temperature of the environment (25 ºC), and has a heat input from fuel of 0.22 MW. The CHP can be approximated as a Carnot cycle taking heat from a source at 400 ºC, and the conversion of work to electricity can be assumed to be 100% efficient. The CHP can change the temperature at which it rejects heat, and can also change its fuel input (and hence power output). A second scheme involves using a heat pump to heat the building with a coefficient of performance (i.e. ratio of heat delivered to electrical power input) of 3.

(a) Using the data below, estimate the global warming potential (GWP) associated with heating the office block using the existing gas boiler, for a functional unit of 1 MJ of heat delivered. [20%]

(b) Briefly discuss the relative merits of allocating environmental burdens by energy content compared to expanding the system boundary or allocating by substitution when considering the products from the CHP. [15%]

(c) For the case where the electrical power output of the CHP is fixed (i.e. the CHP is contractually obliged to supply the same amount of electrical power to the grid), what is the annual saving in GWP if waste heat from the CHP is used by the office? [20%]

(d) If the CHP is allowed to vary its electrical power output, but its fuel input is fixed,

(i) estimate the GWP saving in using heat from the CHP, [15%]

(ii) estimate the GWP saving if electricity is instead supplied to a heat pump for heating. [10%]

(e) Based on your answers to (d) discuss the relative merits of using heat from the CHP or the heat pump. Given that in practice heat pump performance is a non-linear function of the outside temperature (which varies throughout the year) and the variation in fuel mix used for grid electricity, discuss the problems associated in using averages, and how your conclusion could change if data for a more sophisticated analysis were available. [20%]

Additional data for Question 1.

For each MJ of fuel energy used, the CHP has a GWP of 0.07 kg CO_2 equivalent.

In delivery of the natural gas, 10 % of gas delivered is lost to the atmosphere through leaks.

The potency of methane is 21 kg CO_2 equivalent/ kg of CH_4.

The existing gas boiler uses 10% excess air, ensuring there is complete combustion of the gas. The products of combustion leave the boiler at 250 ºC. All materials enter the boiler at 25 °C.

The average GWP for a unit of electricity from the grid is 0.53 kg CO_2 equivalent per kWh.

Enthalpy (kJ $kmol^{-1}$) with respect to a mutually consistent reference state.

Species	Enthalpy at 25 °C	Enthalpy at 250 °C
$CH_{4(g)}$	-74600	-65280
$O_{2(g)}$	0	6808
$H_2O_{(g)}$	-241826	-234083
$CO_{2(g)}$	-393510	-384162
$N_{2(g)}$	0	6597

Air can be assumed to be 79% N_2, 21% O_2 by volume.

2 A solar thermal station (shown schematically in Fig. 1) produces 1 kmol s^{-1} of pure H_2 by focussing solar energy onto a collector, allowing the collector to reach a very high temperature (T_{col}). Heat is transferred, by conduction to a water preheater (which heats the water to T_{react}) and to a reactor (at T_{react}). T_{react} is large enough to cause water to decompose into H_2 and O_2 which leave the reactor in separate streams.

(a) Starting from the steady flow forms of the first and second laws, derive an expression for the change in availability between the inlet and outlet streams of a steady flow system in terms of the heat and work flows into the system. [10%]

(b) (i) Considering the reactor, show that this process is feasible when

$$T_{react} \geq \frac{\Delta \dot{H}}{\Delta \dot{S}}$$

where $\Delta \dot{H}$ and $\Delta \dot{S}$ are the difference in enthalpy and entropy flows entering and leaving the process, respectively. Hence show that the proposed conditions, as indicated in Fig. 1, are feasible. [20%]

(ii) Calculate the loss in exergy in the reactor owing to irreversibility and that owing to the finite temperature difference between the reactor and the solar collector. Briefly comment on the relative magnitudes of the losses. [20%]

(c) The hot products (i.e. the H_2 and O_2) are to be cooled to 298 K and the heat released used to preheat the water to minimise the heat which must come from the solar collector (which can be regarded as a hot utility).

(i) Construct an energy cascade and hence determine the pinch temperature and the minimum hot utility. Use the data provided below and assume that heat capacities are constant. [20%]

(ii) For this heat integrated case, how much exergy would be lost in transferring heat across the finite temperature difference between the solar collector and the water in the pre-heater? [20%]

(d) Most thermally driven processes which split water to produce H_2 and O_2 run at temperatures far lower than those required here. Given your answer to (b) how can such processes be feasible? [10%]

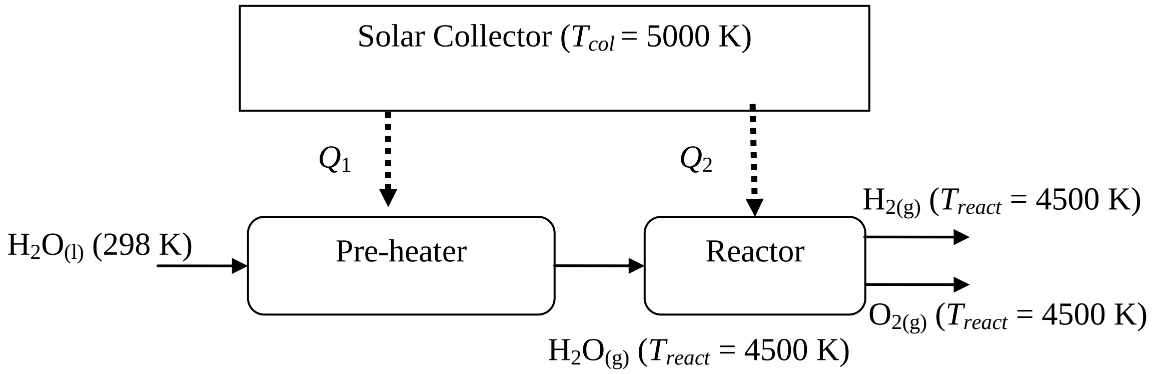

Fig. 1

Additional data for Question 2

The environment can be assumed to be at 298 K.

All material streams are at ambient pressure.

Table 2. Enthalpy (kJ kmol^{-1}) with respect to a mutually consistent reference state.

	Enthalpy		
T	**298 K**	**373.15 K**	**4500 K**
$O_{2(g)}$	-4.41		160032
$H_{2(g)}$	-4.33		146616
$H_2O_{(l)}$	-285841	-280170	
$H_2O_{(g)}$		-239291	-26083

Table 3. Entropy (kJ kmol^{-1} K^{-1}) with respect to a mutually consistent reference state at ambient pressure.

	Entropy		
T	**298 K**	**373.15 K**	**4500 K**
$O_{2(g)}$	205		301
$H_{2(g)}$	131		218
$H_2O_{(l)}$	70	87	
$H_2O_{(g)}$		196	311

Table 4. Average specific heat capacity (kJ kmol^{-1} K^{-1})

	C_p
$O_{2(g)}$	38.1
$H_{2(g)}$	34.9
$H_2O_{(l)}$	75.5
$H_2O_{(g)}$	51.7

3 Write brief notes on the following. It may be helpful to illustrate your answers with appropriate sketches.

(a) The arguments for and against exploiting solar power in the UK, given that at present, it is possible for home owners to place solar panels on their roof and obtain a "feed-in" tariff for any electricity generated. [20%]

(b) The mechanisms by which photosynthetic plants are able to exploit solar power and the limits this places on the efficiency of biomass as a renewable resource. [40%]

(c) The key features of solar collectors used in solar thermal power systems compared to those for domestic heating systems. [40%]

END OF PAPER

Answers

1. a) 0.1079 kg CO_2
   c) 0.00694 kg CO_2/s, 219 tonnes per year assuming system runs continuously.
   d i) 0.00709 kg CO_2/s, 223 tonnes per year assuming system runs continuously.
   d ii) 0.00588 kg CO_2/s, 185 tonnes per year assuming system runs continuously.

2. bii) 400 kJ/mol of H_2 owing to irreversibility, 1673 kJ/mol for temperature difference.
   c i) 33213 kJ/mol of H_2, pinch at 298 K.
   ii) Loss = 24698 kJ/mol H_2