Version sas/7

EGT3
ENGINEERING TRIPOS PART IIB

Tuesday 28 April 2015   9.30 to 11

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 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.

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

1 There is interest in applying carbon capture to fossil fuel plants. A high temperature post combustion scrubber consists of two reactors: (1) a carbonator where calcium oxide, $CaO_{(s)}$, reacts with CO_2 to form calcium carbonate, $CaCO_{3(s)}$; (2) a regenerator where the $CaCO_{3(s)}$ is converted back to $CaO_{(s)}$ by burning fuel (taken here to be pure carbon) in pure O_2 to provide the heat required by the endothermic reaction. This system is to be used to separate the CO_2 from the flues gases of an ***old*** power station (also burning pure carbon), which generates 120 MJ of electricity for each kmol of CO_2 it emits.

(a) (i) How much heat is given out by the carbonator? [10%]

(ii) How much oxygen must be supplied per kmol of CO_2 captured? [15%]

(b) The heat available in the product streams and reactors in Fig. 1 is used to generate additional work output. Saturated water at 150 bar (available from elsewhere in the power station) is sent to heat exchangers in the post combustion scrubbing plant. This water is heated at constant pressure to 500 °C, and then expanded via an additional turbine (producing 1000 kJ of work per kg of steam) and is returned to the power station. The old steam system in the power station must be upgraded to accommodate the diverted water flow, resulting in any additional work requirements or heat losses being compensated for by improvements to the old steam cycle, i.e. the efficiency of the old cycle remains unchanged.

(i) Sketch the hot and cold composite curves for the capture plant in Fig. 1 and for the process of heating up the water used to recover the heat; hence calculate the maximum amount of high pressure steam which can be fed to the additional turbine. [30%]

(ii) The energy penalty for a carbon capture plant is defined as the difference in power output between burning all of the fuel in the original (old) unabated plant compared with burning the same amount of fuel in the power station equipped with carbon capture. Give an estimate of the best-case energy penalty which could be obtained by the carbon capture scheme in Fig. 1. [20%]

(c) Comment on the sign of the energy penalty calculated in (b) and briefly discuss why the carbon capture scheme outlined in Fig. 1 is attractive compared with, for example, building an amine scrubbing unit or refitting the power station to use pure oxygen. [25%]

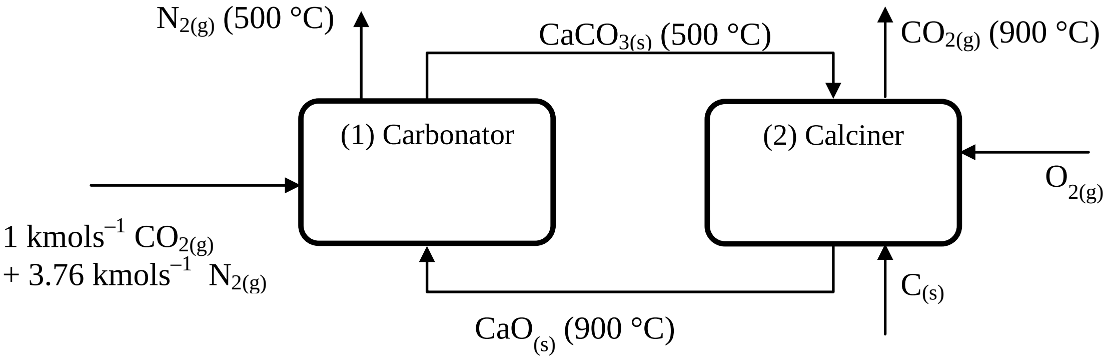

Fig. 1

Additional data for question 1

The calciner is adiabatic.

Within the calciner a stoichiometric amount of oxygen is used to completely combust the carbon.

All of the heat released in the carbonator is released at 500 °C.

The environment can be assumed to be at 25 °C and 1 atm. The environment consists of an atmosphere containing 21 mol% O_2, 79 mol% N_2 and 0.04 mol% CO_2.

All material streams are at ambient pressure and at 25 °C unless stated.

The hot product streams must be cooled to 25 °C before leaving the capture plant.

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

T (°C)	25	342.16	500	900
$O_{2(g)}$	0			
$CO_{2(g)}$	–393510	–379874		–350542
$N_{2(g)}$	0	9356	14204	
$CaCO_{3(s)}$	–1206600		–1156837	–1107403
$CaO_{(s)}$	–634920		–611825	–591383
$C_{(s)}$	0			

 (TURN OVER

2 A large power station currently burns coal. The efficiency of the power station is 40%. There are plans to build a wood-to-ethanol plant adjacent to the power station (Fig. 2). The ethanol will be used to replace petrol as a transport fuel. Fig. 2 shows the main flows into and out of the bio-ethanol plant per tonne of bio-ethanol produced. The contribution to the lifecycle inventory and impact for streams not shown in Fig. 2 is negligible and the only greenhouse gas of any significance arising from combustion can be assumed to be CO_2.

(a) (i) Describe the embodied energy and CO_2 footprint of a material. [10%]

(ii) Explain what is meant by a background system in the context of life-cycle analysis and comment on when its use is appropriate. [10%]

(b) Per metric tonne (i.e. for 1 t) of bio-ethanol produced, calculate the embodied energy of the bio-ethanol and potential greenhouse gas saving if average UK electricity from the grid is used and the waste can be combusted in the adjacent power station to displace coal. [25%]

(c) Discuss how your answer to (b) would change under the following scenarios. You should illustrate your discussion with calculations where appropriate, comment on any assumptions you make, and highlight any issues faced when trying to perform calculations. Finally, comment on the merits of using the wood-biomass to make bio-ethanol.

Scenario A: Rather than burning coal, the adjacent power station used a mixture of 50% wood 50% coal (by calorific value).

Scenario B: As for scenario A, but with only a finite supply of woody biomass feedstock available in the country, so that any use of wood to produce the ethanol reduces the amount available for the power station, forcing the power station to burn more coal. Since the power station is incentivised to burn biomass, the waste from the bio-ethanol plant can be assumed to displace coal. [55%]

 (cont.

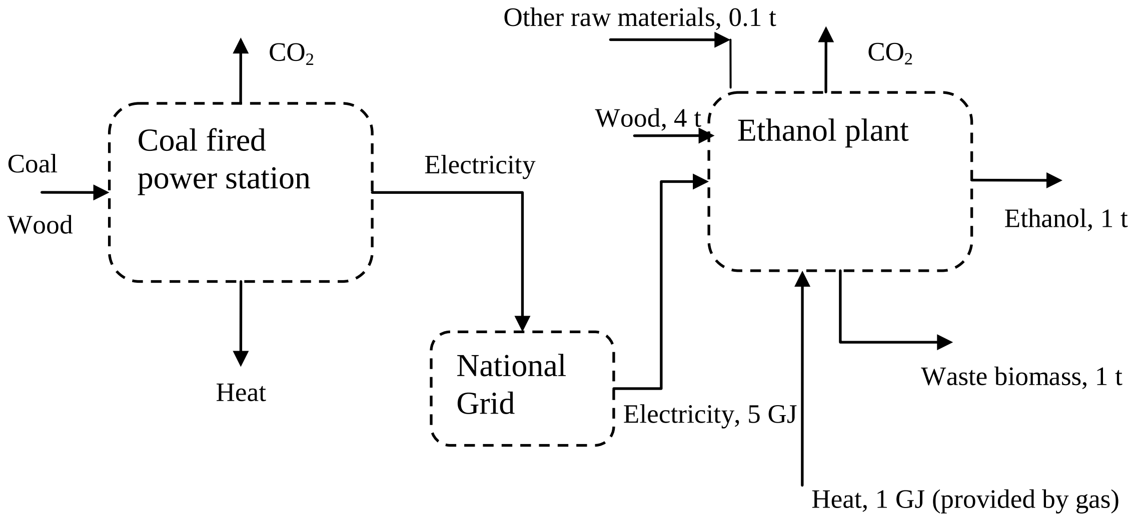

Fig. 2

Additional data for question 2

1 GJ of electricity from the national grid has an average CO_2 footprint of 0.15 t CO_2 and embodied energy of 2.3 GJ.

When used as a transport fuel, 1 GJ of bio-ethanol will displace 1 GJ of petrol (based on calorific value).

Table 2. Embodied energy, CO_2 footprint and calorific value of the material streams shown in Fig. 2.

Material	Embodied energy ($GJ\ t^{-1}$)	CO_2 footprint ($t\ CO_2\ t^{-1}$)	Calorific value ($GJ\ t^{-1}$)
Coal ($CH_{0.5}$)	33	0.3	30
Wood ($C_6H_{12}O_6$)	0.5	0.2	13
Other raw materials used in the bio-ethanol production (do not contain carbon)	50	0.4	0
Bio-ethanol (C_2H_5OH)			28
Gasoline (C_8H_{18})	47	0.4	43
Waste biomass from ethanol plant ($C_6H_{12}O_6$)			12
Natural Gas (CH_4)	50	0.3	48

The CO_2 footprint in the above table does not include the CO_2 which would be released on combustion.

(TURN OVER

3 "All the problems associated with large scale deployment of wind turbines in the UK can be solved by building larger turbines offshore, designed to run at the absolute maximum capacity factor". Discuss this assertion with reference to the characteristics of the wind resource and the wider economic system. [100%]

END OF PAPER

Answers

1 ai) 118 MJ/s

aii) 0.61 kmol per kmol of CO_2 entering the plant, or 0.38 kmol per kmol of CO_2 captured

ci) 108 kg/s

cii) - 32 MW (i.e. an increase in power output)

2 b) Embodied energy, 6.34 GJ/tonne, GHG saving 2.2 tCO2 per t of bioethanol