Energy Efficiency for Sustainability 2   Exam 2017/17

Solution Q1

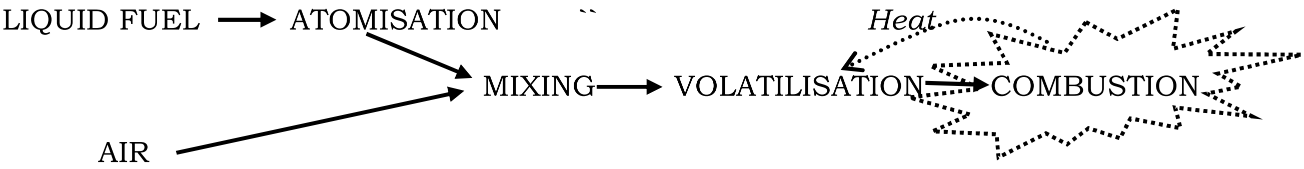
a) Natural gas and oil.

b) CO, Unburnt hydrocarbons, smoke particulates, PCDD and PCDF, carbon in ash.

A common error was to state that NO_x was a product of incomplete combustion.

c) As heat in active or passive solar thermal systems.
As electricity using PV cells.

d) Processes involved in combustion of a liquid fuel:



e) The two main types of heat exchanger are Recuperators and Regenerators.

f) Flow exergy is given by:

$$\dot{E} = \dot{m}[(h_1 - h_0) - T_0(s_1 - s_0)]$$

For dry saturated steam at 5 bar, h = 2749 kJ/kg and s = 6.822 kJ/kgK. At the environment temperature, h = 71.3 kJ/kg and s = 0.253 kJ/kgK for liquid water.
So the flow exergy is: 2.5[2749 – 71.3] – (273+17)(6.822-0.253)]
= 1931.7 kW.

g) Exergy is the maximum work potential of a system in its surroundings.

h) The thermal exergy associated with a transfer of heat is given by:

$$E^Q = \dot{Q}\left(1 - \frac{T_0}{T_1}\right)$$

If heat is removed from the warehouse then the heat flow is negative.

So: $$E^Q = -14\left(1 - \frac{(273+32)}{(273+21)}\right) = 0.524\ kW$$

A common error was not to use temperature in K.

i) The coefficient of performance of a heat pump decreases as the temperature between the cold and hot sides increases. So to maximise the COP, i.e. minimise the electric power input, the temperature at which the heat is supplied from the heat pump should be minimised.

j) An Energy Manager can reduce expenditure on energy by:
- Negotiating better energy tariffs
- Better housekeeping (e.g. using control systems effectively.)

- Retrofitting energy saving systems, e.g. heat recovery systems, improved controls….
- Installing new equipment to save energy eg CHP, more efficient boilers.

Solution Q2

Greenhouse gas emissions can be reduced through changes in the way that energy is used and the general principles that can be followed are summarized as follows:

- **Reducing demand for fuels through energy efficiency measures**

  Energy Efficient Supply of Energy:

    - More efficient combustion systems (e.g. higher efficiency boilers and furnaces……)
    - More use of combined heat and power (*this actually reduces the emission from the use of fuel to provide heat)*
    - More efficient generation of electricity (e.g combined cycle gas turbines, coal fired power plant with higher temperature and pressure in the steam cycle)

  Energy Efficiency measures to reduce demand for energy:

    - Better insulation of buildings
    - More energy efficient industrial processes
    - More efficient transport – electric vehicles, lighter weight vehicles and more public transport
    - More efficient domestic appliances
    - Heat recovery systems
    - Changing energy consuming processes to ones that use less energy.

- **Use of electricity only for essential purposes** and not for space heating with resistance heaters. (Heat pumps are a much more efficient way of using electricity to produce heat)
- **More widespread use of fuels that produce less carbon dioxide** such as natural gas. Use of lower carbon fuels for transport (e.g. biofuels, hydrogen produced from renewable energy, electricity from renewable energy)
- **Using more renewable sources of energy for both electricity and heat.** Use of wind, hydro, tidal and wave power. And burning biomass for heat. Biomass combustion does not make a net contribution to greenhouse gas emissions provided that new vegetation is grown at the same rate that it is burned.
- **Removing CO_2 from use of fossil fuels and storing it**. Carbon capture and storage is currently being considered for large electricity generation plant burning coal.
- **Increase use of nuclear energy**. This does not generate emissions of greenhouse gases but there are other environmental concerns over its use.

A common error was not to calculate the stoichiometric oxygen requirement correctly or to miscalculate the excess air.

Some students also thought that there would be CO_2 in the combustion products.

Solution Q3

Combustion equation with 25% excess air.

Stoichiometric oxygen = 0.5 kmol O_2/kmol of H_2

So oxygen in combustion air is 1.25×0.5 = 0.625 kmol.

$$H_2 + 0.625\ O_2 + 3.76\times0.625\ N_2 = H_2O + 0.125\ O_2 + 3.76\times0.625\ N_2$$

a) In the products of combustion

	kmol/ kmol fuel	$\tilde{m}$	kg/ kmol fuel	kg/ $m_i$kg fuel
Fuel				
H_2	1	2	2	1
Products				
H_2O	1	18	18	9
O_2	0.125	32	4	2
N_2	2.35	28	65.8	32.9
Total	3.475			

The volume fraction of water vapour in the flue gases is 1/3.475 = 28.9%.
So partial pressure of water vapour is 0.29 bar.
At this pressure the saturation temperature is ~68.3°C (by interpolation).

So when gases cool to 42°C, water vapour will condense and the partial pressure of the water vapour will be 0.082 bar.

Let x = no of kmols of water vapour remaining in products of combustion cooled to 42°C.

Then $$\frac{x}{x+2.475} = 0.082$$

A common error was not to consider the condensation of the water vapour.

x = 0.221

So therefore 1-0.221 kmols of water vapour have condensed.

a) **77.9% of water vapour has condensed.**

The products of combustion cooled to 42°C contain:

2 kg of oxygen/kg of fuel.
32.9 kg nitrogen/kg of fuel
0.779×9 = 7.011 kg of liquid water/kg fuel
0.221×9 = 1.989 kg of water vapour/kg of fuel

Dry Loss

Take mean product temperature as 300K
From tables:

c_p O_2 at 300 K 0.918 kJ/kgK
c_p N_2 at 300K 1.040 kJ/kgK

So dry loss $= \Sigma m_i c_{pi}(T_{products} - T_{inlet})$
$= (2\times0.918 + 32.9\times1.040)(42-25)$
$= 612.9$ kJ/kg of fuel

Wet Loss

Wet loss = $m_{liquidH2O}(h_{f\ 42°C} - h_{f\ 25°C}) + m_{water\ vapour}(h_{g\ 42°C} - h_{f\ 25°C})$

= 7.011(175.8 – 104.5) + 1.989(2577.2 – 104.5)

= 5418 kJ/kg of fuel

Gross calorific value of fuel is 142910 kJ/kg

Loss from boiler structure = 0.01×142910 = 1429 kJ/kg of fuel

Losses:	kJ/kg	
Dry loss	612.9	0.43%
Wet loss	5418	3.79%
Structure loss	1429	1.0%
Total loss	7460	5.22%

b) Boiler efficiency = 100-5.22 = **94.8%**

c) If there was an increase in excess air there would be two effects on efficiency:

- the dry losses would increase decreasing the efficiency.
- the partial pressure of water vapour in the products of combustion would decrease, this would mean that the water vapour would not start to condense until the products were cooled to a lower temperature and less water would condense, at a given temperature, as the increased mass of dry products would be able to contain more water vapour.

Solution Q4

Compressor

For an ideal compressor, then the outlet temperature T_2' is given by

$$T_2' = T_1\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = 283\ (8)^{\frac{1.4-1}{1.4}} = 512.6\ K\ \ (239.6^oC)$$

A common error was to use enthalpy values for steam rather than calculate temperature for air.

But the isentropic efficiency is 80%. So the actual outlet temperature can be found from:

$$T_2 = T_1 + \frac{(T_2'-T_1)}{\eta_s} = 283 + \frac{(531-283)}{0.8}\ 570K\ \ (297^oC)$$

So the actual work input required to the compressor is:

$$\dot{W}_{comp} = \dot{m}c_p(T_2 - T_1) = 0.15 \times 1.005\ (297 - 10) = 43.3\ kW$$

Motor

The motor has an efficiency of 90% and so the rate of electrical consumption is:

= 43.3/0.90 = 48.1 kW

Cooler

In the cooler the temperature of the compressed air is reduced back to 10°C. So the rate of heat rejection is

$$\dot{Q} = \dot{m}c_p(T_2 - T_3) = 0.15 \times 1.005\ (297 - 10) = 43.3\ kW$$

This is the same as the work input to the compressor. This is because the enthalpy of the compressed air at 10°C is the same as air at atmospheric pressure at 10°C.

Exergy Analysis

Consider the physical exergy of the flows using

$$\dot{E}_{ph} = \dot{m}\left[c_p(T_1 - T_0) - T_0\left(c_p \log_e\left(\frac{T_1}{T_0}\right) - R\log_e\left(\frac{p_1}{p_0}\right)\right)\right]$$

Environment temperature is 10°C (283K) and pressure is 1 bar.

1	Compressor inlet	Cooler inlet	Compressed air outlet
Air temperature	283 K	570 K	283 K
Air temperature	*10 °C*	*297 °C*	*10 °C*
Air pressure (bar)	1.0	8.0	8.0
Flow exergy (kW)	0	38.7 kW	25.3 kW

A common error was to assume that the compressed air at outlet (3) had zero exergy..

Irreversibility in each component is given by:

$$\dot{I} = \text{exergy input} - \text{exergy output}$$

For **compressor**:

$$\dot{I} = \text{Work input - increase in exergy of air}$$
$$\dot{I} = 43.3 - (38.7 - 0) = 4.6\ \text{kW}$$

For **cooler** there is no useful exergy output as the heat is rejected to the environment. So the irreversibility is the reduction in exergy of the air.

$$\dot{I} = 38.7\ 25.3 = 13.4\ \mathrm{kW}$$

For the **motor**

$$\dot{I} = 48.1 - 43.3 = 4.8\ \mathrm{kW}$$

Summary of irreversibilities:

Compressor	4.6 kW
Cooler	13.4 kW
Electric motor	4.8 kW

Total irreversibility is 4.6 + 13.4 + 5.1 = **22.8 kW**

Useful exergy output from the air compressor system is the exergy in the compressed air stream = 25.3 kW.

So the rational efficiency = exergy output/exergy input (electric input to motor)

$$\psi = \frac{25.3}{48.1} = 52.6\%$$

Note that the largest irreversibility in the system is the heat rejected to ambient in the cooler. The compressed air system efficiency could be improved if this heat were utilised in some way.

Solution Q5

a) There are four different periods of the year to consider when the electricity and gas prices are different (day/night and weekdays/weekends).
There are 45 working weeks at the site and so there are 45×5 weekdays = 225 and 45×2 = 90 weekend days.

Fuel input to CHP plant is 145/0.325 = 446 kW (based on gross CV)
Note that 1 kW for one hour (1 kWh) = 0.0036 GJ.

<u>Weekdays during the day</u>
Saving in electricity = 145×0.0036×35 = £18.27/hour
Saving in gas in boiler = 248×0.0036×10/0.85 = £10.50/hour
Maintenance cost = 145×0.02 = £ 2.9/hour
CHP fuel cost = 446×0.0036×10 = £16.06/hour
Total saving is £9.81/hour

<u>Weekdays during the night</u>
Saving in electricity = 145×0.0036×20 = £10.44/hour
Saving in gas in boiler = 248×0.0036×10/0.85 = £10.50/hour
Maintenance cost = 145×0.02 = £ 2.9/hour
CHP fuel cost = 446×0.0036×10 = £16.06/hour
Total saving is £1.98/hour

At weekends the heat demand reduces to 150kW which is less than the heat output from the CHP plant and so if it ran, some heat would have to be dissipated.

<u>Weekends during the day</u>
Saving in electricity = 145×0.0036×35 = £18.27/hour
Saving in gas in boiler = 150×0.0036×10/0.85 = £ 6.35/hour
Maintenance cost = 145×0.02 = £ 2.9/hour
CHP fuel cost = 446×0.0036×10 = £16.06/hour
Total saving is £5.66/hour

<u>Weekends during the night</u>
Saving in electricity = 145×0.0036×20 = £10.44/hour
Saving in gas in boiler = 150×0.0036×10/0.85 = £ 6.35/hour
Maintenance cost = 145×0.02 = £ 2.9/hour
CHP fuel cost = 446×0.0036×10 = £16.06/hour
Total saving is -£2.17/hour

It is only cost effective to operate the CHP during weekdays and the daytime at weekends. At night at weekends it is more cost effective to switch it off.

Saving during weekday days is 9.81×225×17 = £37530/year.
Saving during weekday nights is 1.98×225×7 = £3121/year.
Saving during weekend days is 5.66×90×17 = £8662/year.
So total annual saving is £49313

b) At weekends when the heat demand of the site is less than the heat output of the CHP plant then heat has to be dumped as the CHP plant can only operate at full output. A plant that could be modulated to operate at a lower output would be better as this could operate in "heat matching" mode at the weekend and this would improve the overall cost effectiveness. This could also be achieved by installing two smaller CHP units rather than one large one. One of the units could then be turned off at weekends, but the other could be used to meet the heat demand.

During the night period when electricity is much cheaper, the cost savings from the CHP plant are marginal and it may be better not to run at night in any case.