

Energy Efficiency for Sustainability 2 Exam 2016/17

Solution Q1 (3 marks for each part)

(a) Natural gas, oil and coal.

(b) Carbon dioxide, methane, nitrous oxide are the main contributors, but not CO, SO_x....

(c) Passive solar design features include: *any 2 of these*

Good thermal insulation.

- Main living rooms should be on the south facing side of the building.
- Glazing should be concentrated on the south face of the building.
- The building should not be shaded to winter sunshine.
- Building should be of thermally heavy weight construction (to reduce day to night temperature fluctuations).
- The heating system should be responsive and efficient.
- Other design features could include:
 - a sun space
 - a trombe wall
 - a convective loop

(d) Advantages of coal gasification are:

- Gas can be burned in more efficient plant – eg CCGT.
- Pollutants can be removed more easily before combustion.
- Gasifier gas can be further converted to mainly hydrogen and carbon dioxide, which facilitates carbon capture and storage – it is a clean technology for energy from coal.

(e) Maximum power output is given by Carnot Efficiency:

$$\eta = 1 - \frac{T_c}{T_h} = 1 - \frac{(17 + 273)}{(350 + 273)} = 53.5\%$$

So maximum power output is $0.535 \times 6 = \mathbf{3.2 \text{ MW}}$.

A common error
was not to use
temperature in K.

(f) Heat input $Q = \text{water mass flow} \times c_p \times (\Delta T)$

$$Q = 12/60 \times 4.2 \times (40 - 10) = \mathbf{25.2 \text{ kW}}$$

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

(h) Irreversible processes include:

Heat transfer across a temperature difference – examples would be in heat exchangers, combustion systems,

Friction (mechanical, fluid flow, electrical resistance...) – examples would be mechanical friction in engines and other machinery, electrical resistance heating, pressure losses in pipes.

Mixing processes – examples would be mixing water in a shower, using steam to heat water....

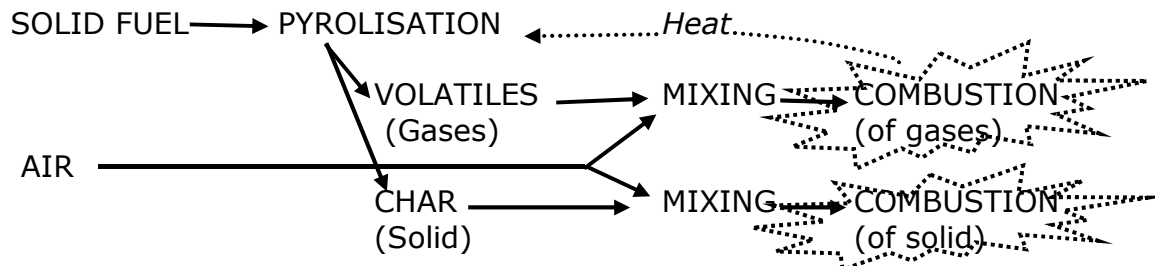
Uncontrolled expansion processes (throttling) – examples would be pressure losses in valves, throttle valve in spark-ignition engines...

- (i) Degree days are used by energy managers to compensate energy consumption for variations in weather conditions from year to year.
- (j) A heat pump can use primary energy more efficiently in providing low temperature space heating than any other conventional heating system. It is better to convert fuels to electricity and then use the electricity to drive a heat pump.

Solution Q2

(The word "Explain." was incorrectly added at the end of the second part of this question.)

The processes in the combustion of a solid are as shown below.



The volatiles burn quickly but the char burns more slowly.

[10 marks]

Incomplete combustion can lead to the formation of:

Carbon monoxide – this occurs through incomplete oxidation due to insufficient air or too low a temperature. It is a toxic gas.

Particulates – there are several ways in which these can be produced by incomplete combustion: from soot particles from pyrolisation of the volatiles, from condensed volatiles that have not combusted. They are formed when the volatiles are cooled before they have been completely burnt.

Soot particles are dirty, but may contain harmful organic compounds. Particles are also a precursor to photochemical smog.

If the gas velocities are too high in the combustion plant then char particles may also be carried out in the flue gases.

Unburnt hydrocarbons – these are caused by incomplete combustion of the volatiles. These can contain harmful substances and are also a precursor to photochemical smog.

Dioxins and furans – these can be produced when chlorine containing fuels are not completely burnt. They are harmful – potentially mutagenic and carcinogenic at very low concentrations.

[15 marks]

Incomplete combustion can be avoided by ensuring sufficient air (excess) with good mixing mixing with the fuel and sufficient temperature and residence time for the reaction to take place. The problem with solid fuel is ensuring that there is sufficient air mixing with both the volatile gases and the char as the combustion usually takes place in different parts of the combustion chamber. The volatiles burn quickly in the gaseous phase but the char which burns more slowly as a gas solid reaction.

Only a few students considered the issues associated with burning both the volatiles and the char in solid fuel combustion.

[10 marks]

Solution Q3



For 100% excess air there must be 4 moles O₂ for every mole CH₄

Reactants

	Moles	\tilde{m} kg/kmol	kg/kmol of fuel	m_i kg/kg of fuel
CH ₄	1	16	16	1.0
O ₂	4	32	128	8.0
N ₂	15.04	28	421.1	26.32

Products

	Moles	\tilde{m} kg/kmol	kg/kmol of fuel	m_i kg/kg of fuel
CO ₂	1	44	44	2.75
H ₂ O	2	18	36	2.25
O ₂	2	32	64	4.0
N ₂	15.04	28	421.1	26.32
	20.04			

a) Volumetric composition of products:

CO₂	5.0%
H₂O	10.0%
O₂	10.0%
N₂	75.0%

Some students did not use the SFEE, but used the simpler combustion efficiency calculation and assumed a fuel and air inlet temperature of 250°C. This gave an inaccurate answer as the fuel is not preheated and the enthalpies of the products are not calculated correctly.

Apply steady flow energy equation to combustion process:

$$Q = \dot{m}_f [\sum m_i (h_{\text{products}} - h_{p0}) - \sum m_i (h_{\text{reactants}} - h_{r0}) + \Delta h_{\text{fuel}}]$$

Where $\Delta h_{\text{fuel}} = -$ calorific value of fuel (-55640 kJ/kg)

In this formula the enthalpies at the standard stage h_0 should strictly be calculated at 25°C, however, no penalty was given to students who used 15°C.

For dry products, $(h_{\text{products}} - h_{p0})$ can be found using mean $c_p \Delta T$
 Mean product temp is 162.5°C (436K) Use c_p at 450K: (400K or an interpolated value also acceptable).

$$c_p \text{ CO}_2 = 0.978 \text{ kJ/kgK}$$

$$c_p \text{ O}_2 = 0.956 \text{ kJ/kgK}$$

$$c_p \text{ N}_2 = 1.049 \text{ kJ/kgK}$$

So enthalpy of dry products is:

$$(2.75 \times 0.978 + 4.0 \times 0.956 + 26.32 \times 1.049)(300 - 25) = 9383 \text{ kJ/kg of fuel}$$

Enthalpy of superheated water vapour at low pressure at 300°C is:

$$= 3077 \text{ kJ/kg}$$

Some students used a saturated enthalpy for water vapour rather than the enthalpy of superheated water vapour at low pressure.

Enthalpy of liquid water at 25°C is 104.8 kJ/kg

So enthalpy of water vapour in products is:

$$2.25 \times (3077 - 104.8) = \underline{6687 \text{ kJ/kg of fuel}}$$

For reactants – only air is preheated, but the fuel enters at 15°C.

Enthalpy can be found using $c_p \Delta T$.

Use c_p at 400K

$$c_p \text{ O}_2 = 0.941 \text{ kJ/kgK}$$

$$c_p \text{ N}_2 = 1.044 \text{ kJ/kgK}$$

So enthalpy of air reactants is:

$$(8.0 \times 0.941 + 26.32 \times 1.044)(250 - 25) \\ = \underline{7876 \text{ kJ/kg of fuel}}$$

For gas fuel (CH₄):

Take Use c_p at 300K

$$c_p \text{ CH}_4 = 2.226 \text{ kJ/kgK}$$

So enthalpy of gas fuel is:

$$1 \times 2.226(15 - 25) = -22.3 \text{ kJ/kgK}$$

No students allowed for the enthalpy of gas entering at a temperature below the standard temperature of 25°C. However this was not penalised. It is an insignificant enthalpy difference.

Substituting in energy equation: (note that heat input to furnace is a negative heat flow)

$$-2500 = \dot{m}_f (9383 + 6687 - (7876 + -22.6)) - 55640$$

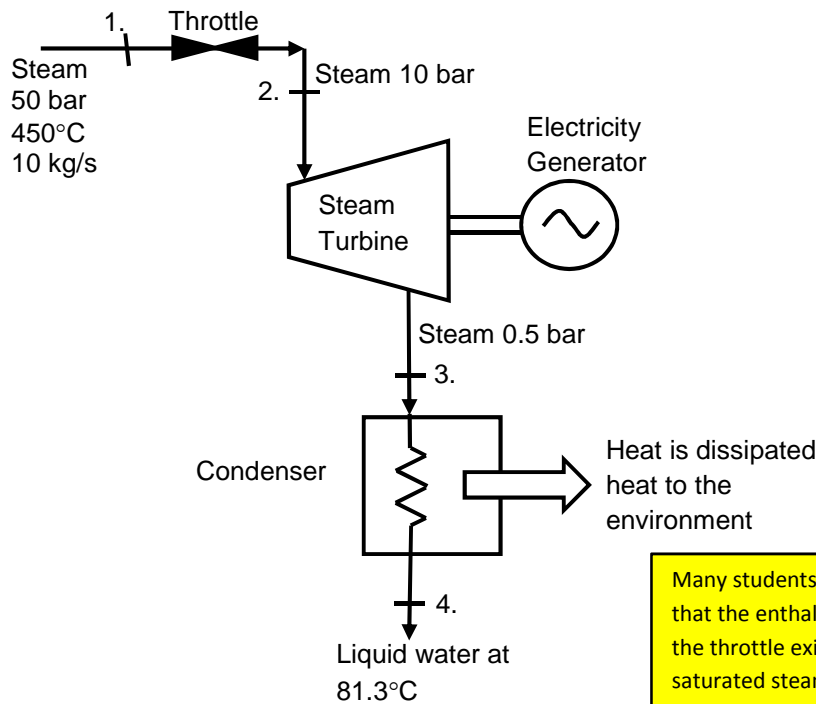
b) **mass flow rate of fuel** = $2500/47423 = \mathbf{0.053 \text{ kg/s}}$

c) Combustion efficiency of the furnace could be increased by:

- Reducing excess air
- Increasing preheat of air
- Increasing insulation of furnace structure
- Recovering heat from exhaust gases.

Solution Q4

a)



Many students incorrectly assumed that the enthalpy of the steam at the throttle exit was that of saturated steam at 10 bar and not steam with same enthalpy as inlet.

Throttle

Enthalpy of inlet steam is 3316 kJ/kg and entropy is 6.818 kJ/kgK
 Enthalpy is constant across the throttle, so look up entropy of steam with same enthalpy but at a pressure of 10 bar. Entropy increases to 7.536 kJ/kgK

Turbine

If turbine were isentropic, then outlet enthalpy is 2628 kJ/kg at 0.5 bar.
 So isentropic enthalpy change is 3316 – 2628 = 688 kJ/kg.
 But isentropic efficiency is 85%
 so actual enthalpy change is 688×0.85 = 585 kJ/kg
 And enthalpy of steam at exhaust is **2731 kJ/kg** and entropy is **7.823 kJ/kgK**.

Mechanical output from turbine is mass flow × enthalpy change = 10×585 = 5850 kW

Generator is 94% efficient, so electricity output from HP generator is 5499 kW

b) Electricity output from generator is **5.5 MW**.

c) Calculate exergy in steam and water flows using:

$$\text{Specific exergy } \varepsilon = (h - h_0) - T_0(s - s_0)$$

$$\text{Flow exergy} = \dot{m}\varepsilon$$

$$T_0 = 0^\circ\text{C} (273 \text{ K})$$

Enthalpy and entropy of liquid water are zero at 0°C.

	<i>h</i> kJ/kg	<i>s</i> kJ/kgK	ε kJ/kg	<i>E</i> MW
Main steam inlet	3316	6.818	1455	14.55
Steam into turbine	3316	7.536	1259	12.59
Steam out of turbine	2731	7.823	595	5.95
Condensate out.	340	1.091	42.2	0.42

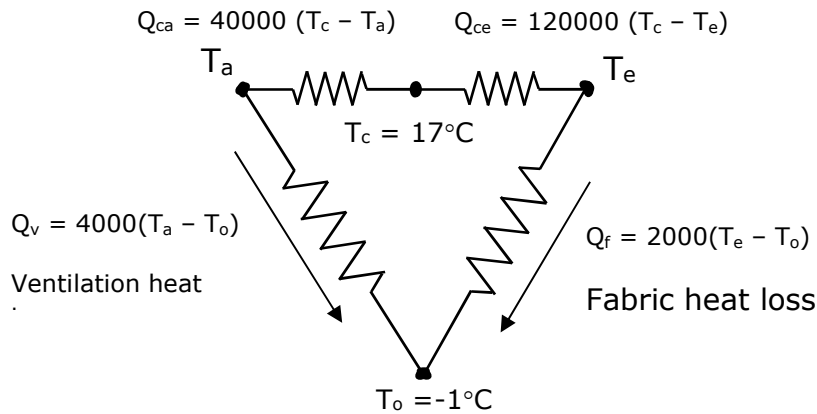
Irreversibility in throttle is $14.55 - 12.59 = 1.96$ MW
 Irreversibility in steam turbine is $12.59 - 5.95 - 5.85 = 0.79$ MW
 Irreversibility in generator is $5.85 - 5.5 = 0.35$ MW
(Irreversibility in steam turbine generator is 1.14 MW)
 Irreversibility in condenser and cooling system is $5.95 - 0.42 = 5.53$ MW

Overall rational efficiency is useful exergy output/net exergy input
 $5.5 / (14.55 - 0.42) = \mathbf{38.9\%}$

- d) The greatest irreversibility in the system is in the condenser as the exhaust steam from the turbine is at a high temperature and it would be better to improve the performance of the condenser to reduce the pressure at the turbine exhaust and condense at a lower pressure. There is a significant exergy loss in the throttle and decreasing this throttling would thus give a significant improvement in the system performance. The turbine generator is reasonably efficient, but improved isentropic efficiency and generator efficiency would improve performance. The consequences of reducing all these irreversibilities would be increase the electrical power generation.

Solution Q5

Use thermal network to analyse temperature:



a) For Heating System A

All heat input is at air temperature T_a , so there is no heat input at T_e .

$$Q_{c-e} = Q_{e-o} = \text{Fabric heat loss}$$

$$120000(17 - T_e) = 2000(T_e - -1)$$

$$T_e = 16.7^\circ\text{C}$$

$$\text{Fabric heat loss is } 2000 (16.7 - -1) = 35.41 \text{ kW}$$

$$\text{But } Q_{a-c} = Q_{c-e} = \text{Fabric heat loss}$$

$$40000(T_a - 17) = 35410$$

$$T_a = 17.89^\circ\text{C}$$

$$\text{So ventilation heat loss} = 4000(17.89 - -1) = 75.54 \text{ kW}$$

$$\text{Total heat loss} = 111 \text{ kW}$$

Heating System A needs to provide heat input of 111 kW

For Heating System B

All heat input is at T_e

$$Q_{c-a} = Q_{a-o} = \text{Ventilation heat loss}$$

$$40000(17 - T_a) = 4000(T_a - -1)$$

$$T_a = 15.36^\circ\text{C}$$

$$\text{Ventilation heat loss is } 4000(15.36 - -1) = 65.44 \text{ kW}$$

$$\text{But } Q_{c-a} = Q_{e-c} = \text{Ventilation heat loss}$$

$$120000(T_e - 17) = 65440$$

$$T_e = 17.55^\circ\text{C}$$

A common error in this question was not to calculate the energy balances correctly. Net energy flow into a node must be zero. Or energy flow out = energy flow in.

Fabric heat loss = $2000(17.55 - -1) = 37.1 \text{ kW}$

Total heat loss = 102.5 kW

Heating System B needs to provide heat input of 102.5 kW

- b) Heating system B can maintain the same comfort temperature in the building with a heat input of only 92.4% of that of Heating System A. So System B would be preferred.

The reason is that the building has a greater ventilation heat loss than fabric heat loss, so it is better to have a heating system with a greater radiant heat input rather than a warm air heating system.