COMBUSTION

In order to operate a heat engine we need a hot source together with a cold sink

Occasionally these occur together in nature eg:-
geothermal sites or solar powered engines, but usually the heat source has to be 'artificially' provided.

The most common way of doing this is by the combustion of a fuel. (Nuclear fission/fusion & solar are alternatives)

Engines

Where the heat from combustion is transferred from the products (or process) of combustion to a separate working fluid , the engine is referred to as an EXTERNAL combustion engine eg:-

Steam engines / turbines
Stirling engines

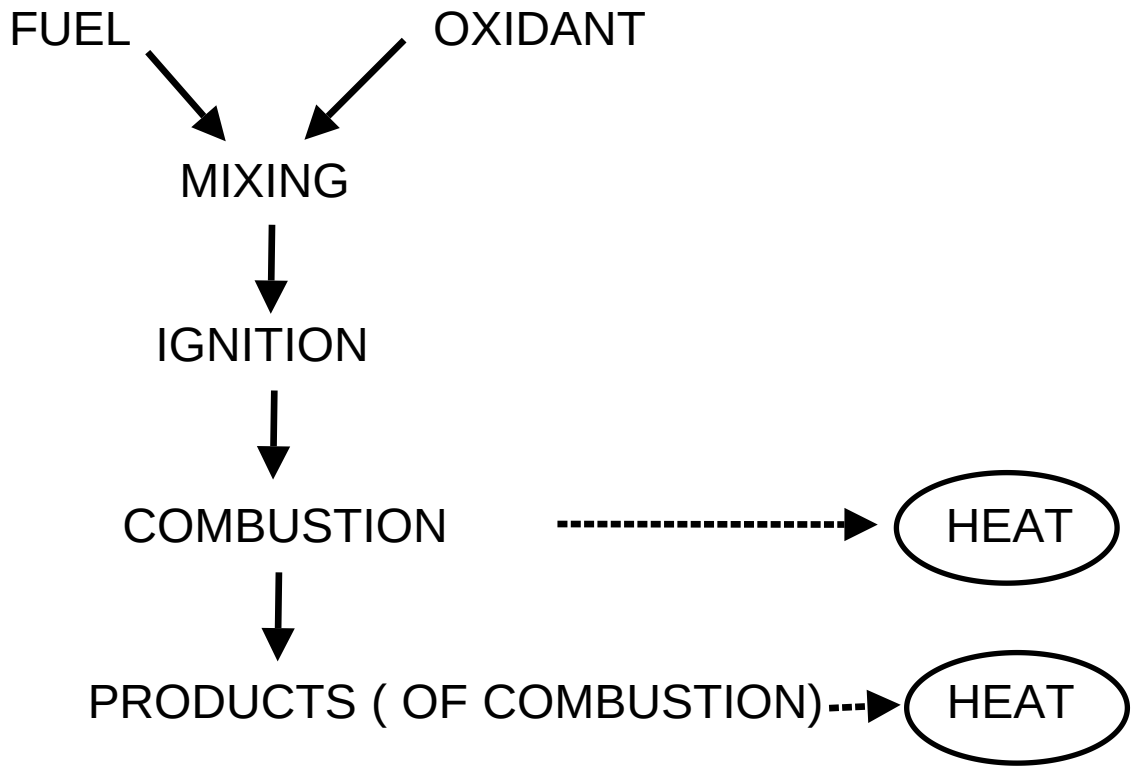
These constitute true 'heat engines' as we have studied to date.

Where the combustion occurs within the working fluid (usually air) the engine is referred to as an INTERNAL combustion engine ie:

Petrol & Diesel engines
Gas turbines

These are not true heat engines although we often analyse them as though they were.

THE COMBUSTION PROCESS



FUEL:-

Solid:- Coal, wood - consists mainly of C, H, & O + impurities

Liquid:- Large hydrocarbon molecules of varying boiling points mainly C & H : Petrol, Diesel, Fuel oil etc;

Gas:- Small hydrocarbon molecules - methane, ethane, propane, butane, etc; plus a range of manufactured gases ; eg H_2 , Acetylene etc..

OXIDANT:-

Usually air (the oxygen in the air)
Where air is unavailable the oxidant has to be carried as well as the fuel - space vehicles, rockets etc;

MIXING

SOLIDS :- pulverising to powder or small lumps

LIQUIDS :- spray nozzles, atomisers, vaporisers, carburettors, 'burners'.

GASES :- mixing valves, chambers, burners;
usually need precautions to avoid explosion and flash back .

IGNITION

Simply mixing methane and air will not cause it to burn.
The molecules need to reach a certain threshold energy level before the combustion process will proceed.
This may be provided initially by another flame, a spark or hot surface. The combustion process itself (if sustained) then continues the ignition process.

COMBUSTION

The chemical dissociation of the fuel and it's recombination with oxygen. Energy and Mass are conserved.

PRODUCTS

$C \rightarrow CO_2$ **complete** combustion

$H_2 \rightarrow H_2O$

partial combustion → C (soot)

partial combustion → CO (carbon monoxide)

Other products may also be formed :-
$N_2 \rightarrow$ NOx etc; often harmful pollutants (SO_2, SO_3)

COMBUSTION OF FUELS IN AIR

Use an example :-

Say we have a fuel that is 80% CH_4 (methane) and 20% C_2H_6 (ethane) by volume (UK natural gas) .

We could choose any quantity of fuel but for convenience we shall use 1 kmole, which can be written as :-

$(0.8\ CH_4 + 0.2\ C_2H_6)$

Let us say that this mixes with Y kmoles of air and that the combustion processes go to completion.

Now air is - 79% N_2 & 21% O_2

Therefore 1 kmole of air may be written as :-

$(0.79\ N_2 + 0.21\ O_2)$

We may therefore write a combustion equation :-

$(0.8\ CH_4 + 0.2\ C_2H_6) + Y(0.79\ N_2 + 0.21\ O_2)$
(the reactants)

$\rightarrow a\ CO_2 + b\ H_2O + c\ O_2 + d\ N_2$
(the products of complete combustion)

Because the combustion process does not create or destroy atoms, the number of atoms on the L.H.S. of the equation must exactly balance the number on the R.H.S.

No. of atoms in kmoles

	L.H.S.	R.H.S.	
CARBON C	0.8 + 2 x 0.2	a	(i)
OXYGEN O	2 x 0.21 x Y	2a + b + 2c	(ii)
HYDROGEN H	4 x 0.8 + 6 x 0.2	2b	(iii)
NITROGEN N	2 x 0.79 x Y	2d	(iv)

Solving equations (i) to (iv) simultaneously :-

from (i) $a = 1.2$

from (iii) $b = 2.2$

from (ii) $c = 0.21\ Y - 2.3$

from (iv) $d = 0.79\ Y$

EXHAUST GAS ANALYSES

The R.H.S. of a combustion equation indicates the products of combustion ie: the exhaust gases.

Stoichiometric Air-Fuel ratio

This is the air - fuel ratio (AFR) necessary to achieve complete combustion of the fuel **and no more.**

We can find this value from the combustion equation by setting the number of kmoles of Oxygen on the R.H.S. equal to zero.

ie In the above equation c = 0

Therefore $$Y = \frac{2 \times 1.2 + 2.2}{2 \times 0.21} = 10.95$$

Stoichiometric AFR = 10.95 : 1

N.B. this ratio is a ratio of *kmoles* (volume for gases)

How would we convert it to a mass ratio ?

10.95 kmol air = 10.95 x 29 kg/kmol = 317.62 kg

1 kmol fuel = 0.8 x 16 + 0.2 x 30 = 18.80 kg
(CH_4) (C_2H_6)

Therefore the AFR (**by mass)** is 317.62:18.80 or 16.89:1

(i) If the AFR is LESS than stoichiometric complete combustion cannot occur ie: we have an excess of fuel, or a rich mixture, leading to unburnt or incompletely burnt fuel. CO will be present. This clearly is undesirable as we will not be releasing the maximum available heat energy from the fuel.

(ii) If the AFR is GREATER than stoichiometric we can obtain complete combustion but we may be supplying too much air thus reducing the temperature of the combustion products* and therefore reducing the heat transfer from them.

* N.B. we sometimes do this deliberately eg: in diesel & gas turbine engines.

Excess air is usually expressed as a percentage of the stoichiometric AFR ie:-

$$\% \text{ excess air} = \frac{Y - Y_{stoic}}{Y_{stoic}} \times 100\%$$

If, in the above equation, Y = 12,

$$\% \text{ excess air} = \frac{12 - 10.95}{10.95} \times 100\%$$

$$= 9.6\ \%$$

FINDING THE AFR FROM AN EXHAUST GAS ANALYSIS

If we know the composition of a fuel and we measure the composition of the exhaust gas we can find the AFR.

Use an example :-

Same fuel as above (0.8 CH_4 + 0.2 C_2H_6)

(0.8 CH_4 + 0.2 C_2H_6) + Y (0.21 O_2 + 0.79 N_2)

$\rightarrow$ a CO_2 + b H_2O + c O_2 + d N_2

Normally, when we analyse a gas sample we dry it first: ie we condense out (or absorb) all the water. The remaining gases are then expressed as a percentage (by volume) of the total dry gas constituents - in this case CO_2, O_2, & N_2.

This is known as a DRY analysis.

Say we measure the %CO_2 = 10.5% (by vol.)

Therefore $$\frac{a}{a + c + d} = 0.105$$

but from the combustion equation :-

a = 1.2
c = 0.21 Y - 2.3
d = 0.79 Y

Therefore $$\frac{1.2}{1.2 + 0.21\,Y - 2.3 + 0.79\,Y} = 0.105$$

$$\frac{1.2}{Y - 1.1} = 0.105$$

$$Y = 12.53$$

or AFR = 12.53 : 1 (by vol)

$$\%\ \text{excess air} = \frac{12.53 - 10.95}{10.95} \times 100\% = 14.4\ \%$$

We could also have done the analysis using a figure for the percentage O_2 in the exhaust, but because this is normally small and is therefore more difficult to measure accurately, the calculation is less reliable.

A CO detector could be used to indicate a <u>rich</u> mixture .

The calculation assumes <u>complete combustion.</u>
If combustion is incomplete, further information is needed otherwise the combustion equation cannot be solved.

CALORIFIC VALUE OF FUELS

The calorific value of a fuel is the standard heat of reaction at constant pressure where the fuel burns completely with oxygen.

It is measured using a gas calorimeter (for gases)
bomb calorimeter (for liquids & solids)

(See S & C p.396 ff for description)

Note :- minor corrections are required when using bomb calorimeters because it is constant volume combustion.

HIGHER AND LOWER CALORIFIC VALUES

For fuels containing Hydrogen, water is a product of combustion and is always formed as steam. If we 'allow' the steam to condense to water then we will obtain a higher heat output/unit mass of fuel than if we did not allow it to condense. This measure of the calorific value is called the HIGHER CALORIFIC VALUE (HCV or gross).

If the steam does not condense (and this is more usually the case) we obtain the LOWER CALORIFIC VALUE (LCV or net). ie the 'latent' heat of steam is unavailable.

The two values are related by :-

$HCV = LCV + m\ h_{fg}$

where m = mass H_2O produced / kg of fuel

h_{fg} = enthalpy of evaporation of water at the standard temperature of 25 degrees Centigrade (2442.5 kJ/kg)

Some typical values :-	H.C.V.	L.C.V.	
Anthracite coal	34.583	33.913	MJ/kg
Wood	15.826	14.319	
Petrol	46.892	43.710	
Diesel	45.971	43.166	
U.K.Natural gas	36.38	32.75	MJ/m^3 **
Hydrogen	11.92	10.05	

** at SSL conditions (15 °C & 101.325 kPa]