## 11. Stoichiometric combustion

A *stoichiometric* reaction is one where all the oxygen is used up and all the fuel is burnt to the ultimate products ($CO_2$, $H_2O$ and $SO_2$).

**Meaning of stoichiometric:**Greek *στοιχεῖον* element + -metry

The word means 'metering/measuring of elements'

Stoichiometric combustion is an ideal combustion process. It tells us the lowest amount of $O_2$ required to react the fuel. It is the benchmark against which we measure real combustion processes.

*Stoichiometric oxygen to fuel ratio*

If ethane is burned in oxygen, the equation is:

$$C_2H_6 + 3\tfrac{1}{2}\ O_2 \rightarrow 2\ CO_2 + H_2O$$

The stoichiometric **oxygen**/fuel ratio of $C_2H_6$ (by volume) is oxygen:fuel = 3.5/1 = 3.5 – i.e. by number of moles.

This is so because of $V_i/V=n_i/n$, i.e. molar proportions represent volume proportions. The reaction by atom numbers, is proportional to the moles, which is proportional to the volumes of each gas species.

**Examples:**

*Determine the stoichiometric equation for benzene burning in pure oxygen, writing the mass and volume fractions of the reactants and products.*

*Determine the stoichiometric combustion for 1 kg coal burning in pure oxygen, writing the mass fractions of the reactants and products. The coal is 81%C, 5%H, 5% O, and 9% ash.*

Stoichiometric combustion:

| Constituent | $m_i$ [kg], per kg of coal | $O_2$ required to burn per kg of coal |
|---|---|---|
| C | 0.81 | |
| H | 0.05 | |
| O | 0.05 | |
| Ash | 0.09 | |
| Total | 1.00 | |

Note that the ash does not burn because it is made of rocks and the like, and is inert. The oxygen bound into the coal in the petrification process is at first liberated and then combined in combustion – so it reduces the required amount of atmospheric oxygen required to burn the coal.

Any solid combustion process will proceed approximately according to evaporating moisture first, heating up further to cause

A combustion process can be:

*Complete:* where sufficient $O_2$ is available to convert all carbon and all hydrogen in the *hydro-carbon* fuel to $CO_2$ (carbon dioxide) and $H_2O$ (water).

*Incomplete:* where not enough $O_2$ is available and other products such as CO appear.

*Note that oxygen prefers to react with hydrogen, so the reaction balances by hydrogen stealing all $O_2$ it needs from the carbon reactions.*

**12. Combustion in air**

In this course, all fuels are burned in air, and it is assumed that air contains 23.3% $O_2$ , 76.7% $N_2$ by mass as found in the back of the tables.

Alternatively this can be expressed as the proportions by volume: 21 % $O_2$ , 79% $N_2$ by volume**.**

These analyses correspond to a mean $\widetilde{m}$ of 28.85 and a mean *R* of 0.287 kJ/kgK.

If the small percentage of $CO_2$ and Ar are included, then $\widetilde{m}$ = 28.96 and *R* = 0.287 kJ/kg K.

*Stoichiometric air to fuel ratio (AFR) by volume*

Nitrogen is brought in with oxygen at a fixed ratio of: 3.76 x ($O_2$ volume) – from approximate air data. Total air volume includes the $O_2$, i.e. air volume is (1+3.76)x($O_2$ volume). The stoichiometric **air**/fuel ratio (AFR) in the case of the ethane combustion before is:

*AFR* = ($O_2$/fuel vol ratio) x 4.76

= 3.5 x (3.76+1) = 16.7 *(by volume)*

The air to fuel ratio is useful in order to know physically how big a combustor needs to be in order to manage the air and fuel flow rate.

*Convert to stoichiometric AFR by mass*

Since $n = {}^{m}/_{\widetilde{m}}$ the AFR by mass can be found:

$$AFR_{mass} = \frac{m_{air}}{m_{fuel}} = AFR_{volume}\frac{\widetilde{m}_{air}}{\widetilde{m}_{fuel}}$$
$$= 16.7 \times \frac{29}{30} = 16.14$$

The complete reaction equation for the air and ethane stoichiometric case will include $N_2$ terms ($N_2$ is treated as inert)

$$C_2H_6 + 3.5O_2 + 3.5 \times 3.76N_2 \Rightarrow 2CO_2 + 3H_2O + 3.5 \times 3.76N_2$$

**Examples continued:**

*Determine how much air is required for the stoichiometric combustion of propane burning in air. Determine the AFR by mass and by volume.*

*Do the same for benzene burning in air. Determine the AFR by mass and by volume.*

*Determine the AFR by mass for 1 kg of the coal burning in air (can't do AFR by volume because the fuel is a solid and difficult to compare moles of fuel given that the H and O are bound in the fuel)*

## 13. Non-stoichiometric combustion

This can either be ***fuel rich*** (insufficient $O_2$)

or ***air rich*** (excess $O_2$).

In these cases, combustion products can contain incomplete products such as CO and free oxygen as well as $CO_2$, $H_2O$, $N_2$ etc.

***Excess fuel***

The incomplete combustion of the fuel leads to $CO_2$ and CO products ( this is in the case of hydrocarbon fuels).

In real processes, there may be both the oxygen ($O_2$) and CO in the products, because of incomplete mixing of fuel and air.

***Excess oxygen***

The products will include free oxygen, but the fuel is burnt to the ultimate products. The % excess air supplied, is a useful indicator for mixture quality. This is defined as:

$$\%excess\ air = \frac{air\ supplied - stoichiometric\ air}{stoichiometric\ air}$$

This is the same by volume and by mass

## 14. Wet and dry products of combustion

Combustion of fuels containing hydrogen gives products which include $H_2O$. Products containing $H_2O$ are sometimes dried ($H_2O$ absorbed or condensed out) before analysis, hence the terms:

dry analysis ($H_2O$ removed first) and

wet analysis ($H_2O$) included.

A gas analyser is used to measure the component gases of a combustion exhaust stream.

So $CH_4 + 2O_2 \rightarrow CO_2 + 2\ H_2O$

16 64 44 36

kg kg kg kg

So mass fraction with and without water can be determined by considering the products with and without water, i.e. 100%$CO_2$ dry, or 44/80 x 100 % $CO_2$ and 36/80 x 100 % $H_2O$ wet.

**Examples continued:**

*Propane is burned with 30% excess air. Determine the volume and mass fractions of reactants and products.*

| Products | $n_i$ | $n_i/n$ | $\widetilde{m_i}$ [kg/kmol] | $\widetilde{m_i} n_i/n$ | $m_i/m = (n_i/n)(\widetilde{m_i}/\widetilde{m})$ |
|---|---|---|---|---|---|
| $CO_2$ | | | | | |
| $H_2O$ | | | | | |
| $O_2$ | | | | | |
| $N_2$ | | | | | |
| Total | | | | | |

Note that the 3rd column is the volumetric proportions, column 5 uses the proportion by mol of each species to work out the mean molar mass by 'invoking' the law of partial pressure. Column 6 is the proportions by mass, $n_i\widetilde{m_i}$ is the mass of each species in the mixture, and $n\widetilde{m}$ is the total mass of the mixture.

*Benzene is burned with a fuel rich condition such that there is 2% CO by volume in the wet products and no $O_2$. What is the AFR by mass to cause this?*

*The dry products of the coal combustion contain 10%$CO_2$, 1%CO, 8% $O_2$. What was the excess air?*