CHAPTER 1

FUNDAMENTAL OF COMBUSTION

Definition

Rapid oxidation of a fuel accompanied by the release of heat and/or light together with the formation of combustion products

Fuel + oxygen ➔ Heat/light + combustion product

Fuel → natural gas, fuel oil, coal and gasoline
Oxygen → O_2 (from air)
Combustion product → CO_2 and H_2O

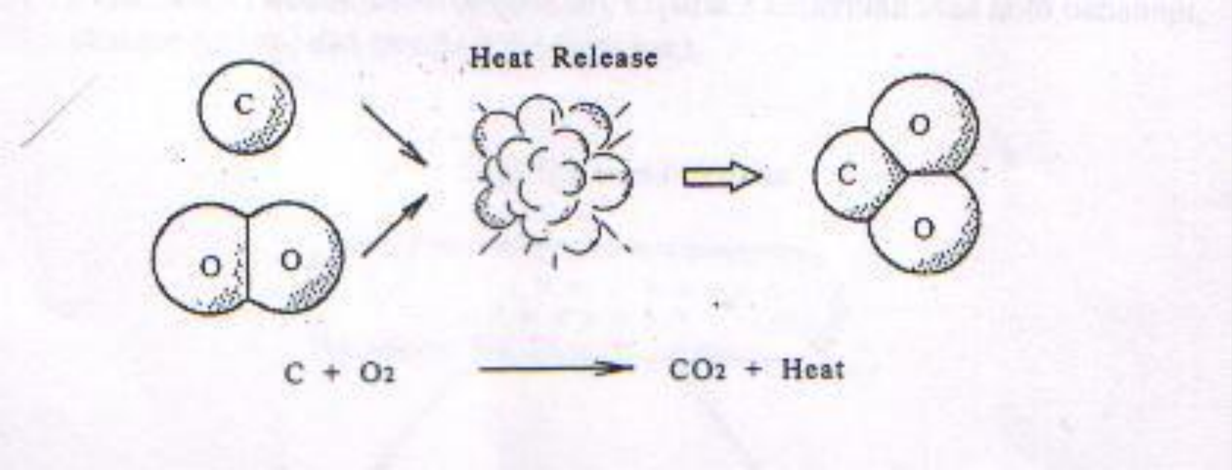
Combustion products

↓

Carbon monoxide (CO)
Aldehydes (e.g. H)
Unburned Fuel
Radicals

} mainly due to incomplete combustion

Oxides of nitrogen (NO_x) and Oxides of Sulphur (SO_x)



Carbon + oxygen ➔ heat + carbon dioxide

$C + O_2$ ➔ heat + CO_2

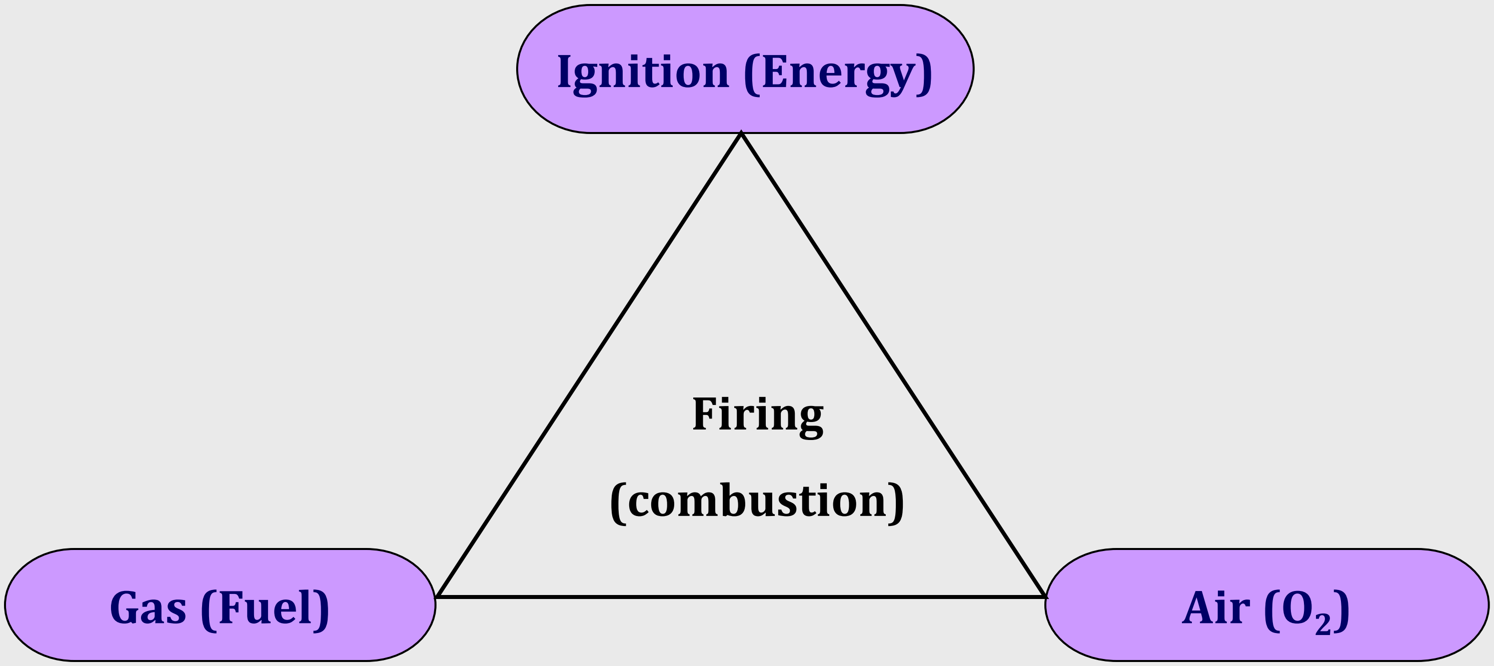
Combustion equations

$CH_4 + 2O_2$ ------> $CO_2 + 2H_2O$

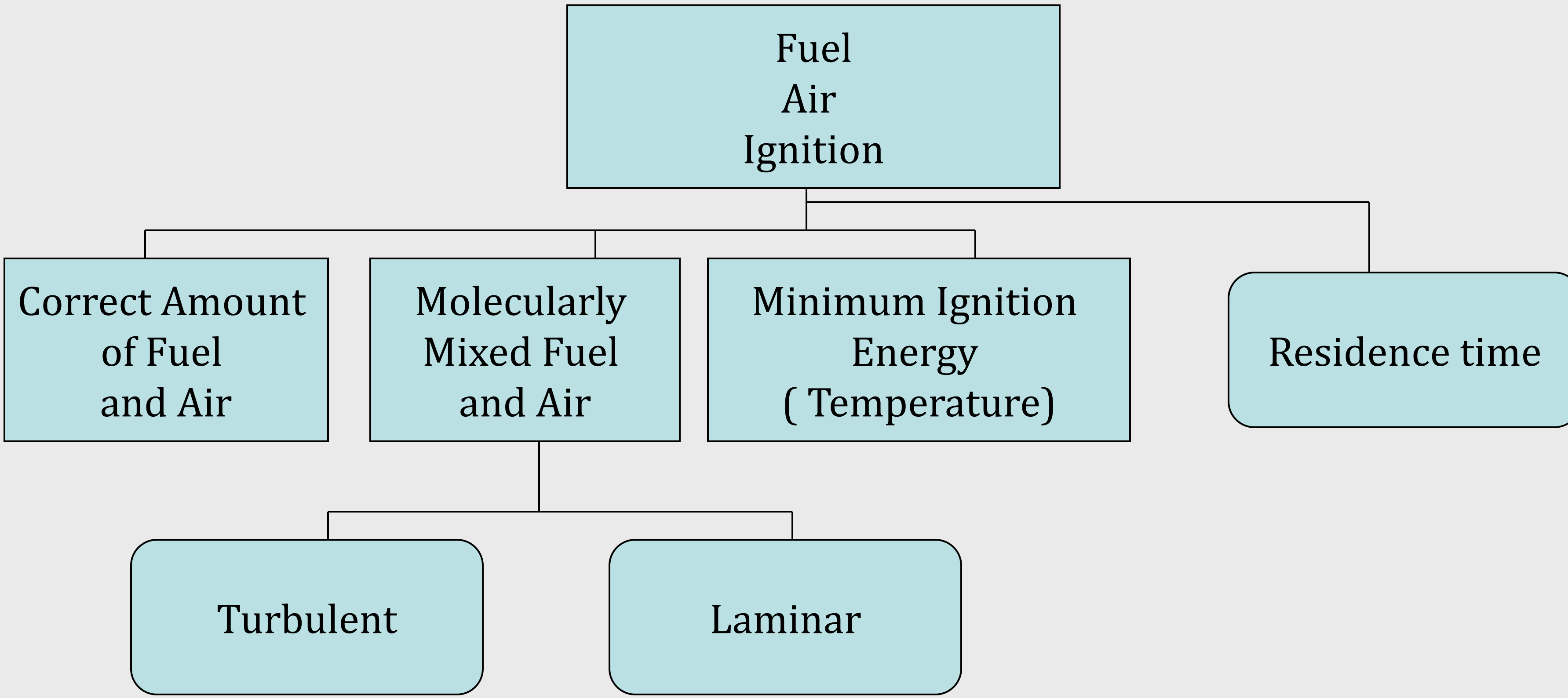
Reactants ------> Products + Heat

Combustion Requirement

❖ Combustion triangle



Requirement for Successful Combustion



Categories of Combustion Process

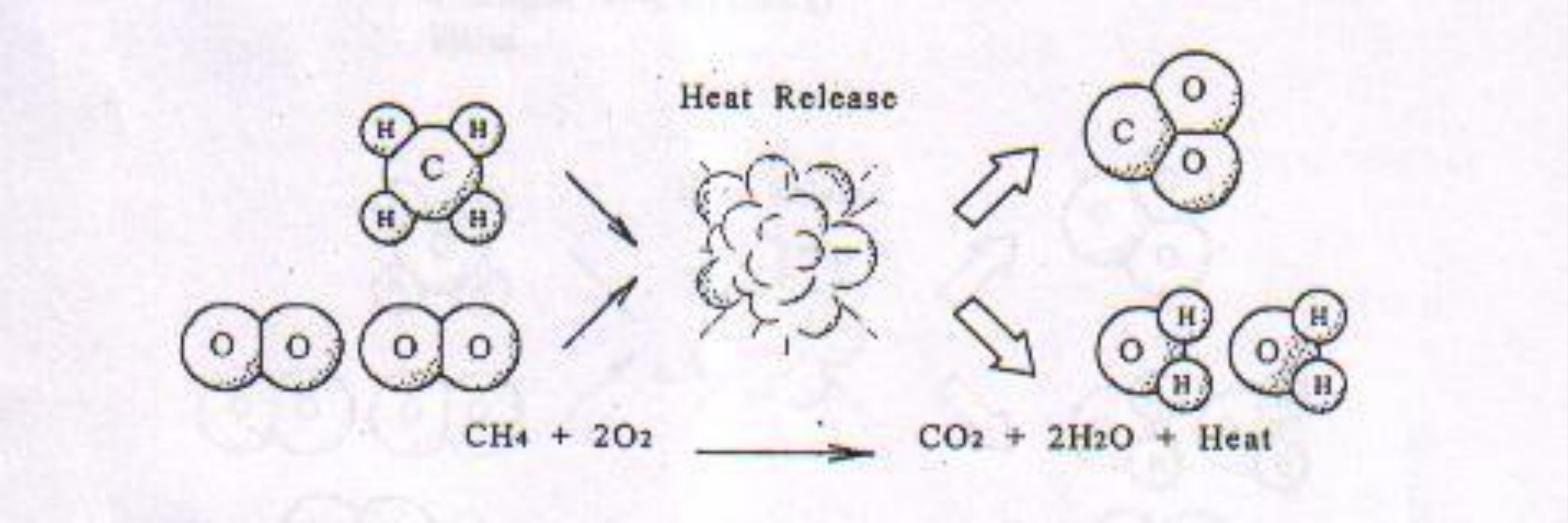
3 types of combustion process which depend on the oxygen being supplied;

- Stochiometric Combustion
- Excess Air or Oxygen Combustion (Fuel Lean Combustion)
- Excess Fuel Combustion (Fuel Rich Combustion)

Stoichiometric Combustion

- Stoichiometric or Theoretical Combustion is the ideal combustion process where fuel is burned completely
- **<u>chemically-correct</u>** proportion of fuel and air quantities
- no unburned fuel
- no residual oxygen present in combustion products
- combustion products – CO_2, H_2O, N_2 (from air) and heat byproduct is absent

Stoichiometric Combustion

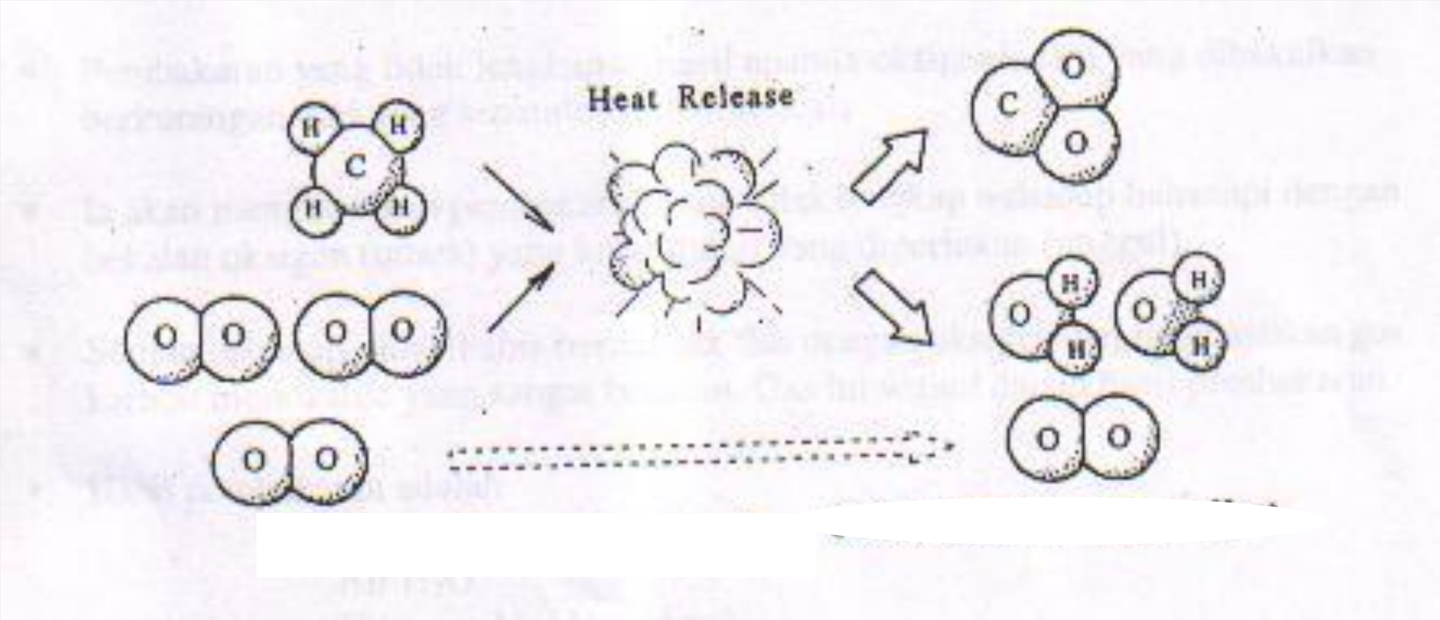


$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + Heat$$

Excess Air or Oxygen Combustion

- Also known as ‘fuel lean’ or ‘positive excess air’
- Occurs when oxygen or air is supplied more than the stoichiometric proportion
- All fuel will react with O_2 however excess left over O_2 will remain in the product.
- Combustion products - CO_2, H_2O, O_2 (from air), N_2 (from air) and heat

Excess Air or Oxygen Combustion

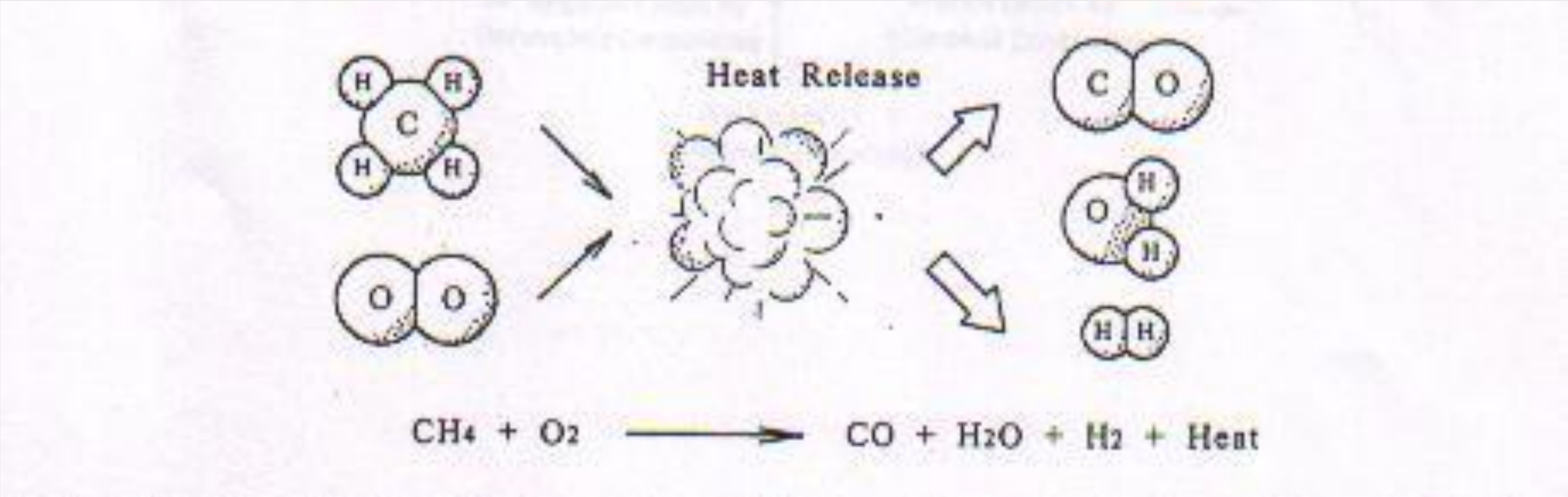


$CH_4 + 3O_2 + \text{ignition} \rightarrow CO_2 + 2H_2O + O_2 + \text{Heat}$

Excess Fuel Combustion

- Also known as ‘fuel rich’ or ‘negative excess air’
- Occurs when fuel is supplied more than the stoichiometric proportion.
- Insufficient amount of oxygen or air available to burn in the fuel-rich mixture caused <u>incomplete combustion</u>
- All fuel not completely react with O_2 thus produce CO in the product
- Combustion products – CO, H_2O (from air), N_2 (from air) and Heat

Excess Fuel Combustion



$CH_4 + O_2 + \text{ignition} \rightarrow CO + H_2O + H_2 + \text{Heat}$

Incomplete Combustion

Incomplete combustion should be avoided due to economy and safety factor;

Economy – Excess fuel which is not being used in combustion is wasted. This will **reduce the combustion efficiency** as it will use up the heat produce from the combustion reaction which is to be used in heating or other process.

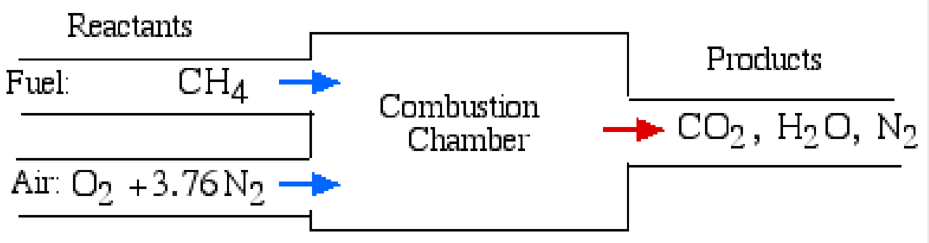
Safety – CO is a toxic gas that is dangerous to health and environment

Excess air

- Usually combustion chamber incorporates a modest amount of **excess air** - about 10 to 20% more than what is needed to burn the fuel completely.
- 150% theoretical air = 50% excess air
- If an insufficient amount of air is supplied to the burner, unburned fuel, soot, smoke, and carbon monoxide exhausts from the boiler - resulting in heat transfer surface fouling, pollution, lower combustion efficiency, flame instability and a **potential for explosion**.

Combustion Terminology

- Reactants
- Fuels
- Oxidizer
- Products
- Complete combustion
- Inerts (Nitrogen, Argon)
- Modeling Combustion Air
- Fuel/Air Ratio
- Theoretical Air
- Dew point
- Adiabatic Flame Temperature



$$CH_4 + 2(O_2 + 3.76N_2) \Rightarrow CO_2 + 2H_2O + 7.52N_2$$

Modeling Combustion Air

- Air consist N_2, O_2, CO_2, Argon and traces of other gas
- Only O_2 is reactive component in air, N_2 is inert (un-reactive)
- Molar basis, air consists of 79% N_2 and 21% O_2.
- 1 mole of air contain 0.79 mole of N_2 and 0.21 mole of O_2
- Thus each one mole of O_2 needed to oxidized hydrocarbon is accompanied by 79/21 = <u>3.76</u> moles of N_2

Combustion equations

$$CH_4 + 2O_2 \text{ -----> } CO_2 + 2H_2O$$

$$\downarrow$$

$$CH_4 + 2(O_2 + 3.76N2) \text{ -----> } CO_2 + 2H_2O + 7.52N_2$$

Fuel/Air Ratio

- The standard measure of the amount of air used in a combustion process is the **Fuel/Air Ratio (FA)**
- Defined as

FA = mass of fuel/mass of air

$$\underset{\text{fuel}}{CH_4} + \underset{\text{2 kmol air}}{2(O_2 + 3.76N_2)} \leftrightarrow \text{Reactants}$$

$$FA = \frac{m_{fuel}}{m_{air}} = \frac{1\,[\text{kmol}](12+4)[\text{kg/kmol}]}{2(4.76)[\text{kmol}]\;29[\text{kg/kmol}]} = 0.058\,\frac{\text{kg-fuel}}{\text{kg-air}}$$

*M_{air} = 29kg/kmol

Theoretical air

- The minimum amount of air for complete combustion
- Product contain no oxygen
- If supply is less, CO may be present in product
- Normal practice to supply more than the theoretical air
- Excess air will result in O_2 appear in products

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

- 1 molecule CH_4 requires 2 molecules O_2
- Theoretical O_2 is $2Nm^3$ per 1 Nm^3 of CH_4

Theoretical air requirement

Because oxygen proportion in air is about 21 percent at volume basis, theoretical air requirement is calculated as follows.

Combustion equation:

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

So theoretical air requirement for 1 Nm^3 of CH_4 is

$$2Nm^3 \times 100/21 = \underline{9.52}\ Nm^3/Nm^3$$

Problem 1

Air/gas Ratio

Air/gas ratio is defined as the proportion of actual air volume to theoretical air volume, as follows:

Air/gas ratio = A_a / A_t

where

A_a is actual air volume of combustion

A_t is theoretical air requirement of fuel

Excess air ratio is calculated as follows:

Excess air ratio = (air/gas ratio) – 1

= $(A_a / A_t)-1$

Dew point

- Minimum temperature below which the water vapour in the combustion products will condense

- Dew temperature of natural gas ~ 60^oC

Adiabatic Flame Temperature

- The **maximum achievable temperature** is reached when the furnace or combustion chamber is well insulated
- Typical $T_{ad} \sim 1950^{o}C$
- T_{ad} is calculated from energy balance

Combustion Stoichiometry

$$CH_4 + 2(O_2 + 3.76\ N_2) \rightarrow CO_2 + 2H_2O + 7.52\ N_2$$

$$C_2H_6 + a(O_2 + 3.76\ N_2) \rightarrow bCO_2 + cH_2O + dN_2$$

$$C_3H_8 + a(O_2 + 3.76\ N_2) \rightarrow bCO_2 + cH_2O + dN_2$$

$$C_4H_{10} + 6.5(O_2 + 3.76\ N_2) \rightarrow 4CO_2 + 5H_2O + 24.4N_2$$

Example 1

Find the theoretical air requirement for propane combustion

Equation :

Theoretical O_2 :

Theoretical air :

Example 2

Calculations of theoretical oxygen and air requirements for natural gas supplied before ’95 shown below;

Symbol	Combustion equation	Component (Vol %) (A)	O_2 Required (m^3 / m^3) (B)	Total O_2
CH_4	$CH_4 + 2\ O_2 = CO_2 + 2\ H_2O$	84.75	2.0	1.695
C_2H_6	$C_2H_6 + 3.5\ O_2 = 2\ CO_2 + 2\ H_2O$	10.41	3.5	0.364
C_3H_8	$C_3H_8 + 5\ O_2 = 3\ CO_2 + 4\ H_2O$	0.98	5.0	0.049
C_4H_{10}	$C_4H_{10} + 6.5\ O_2 = 4\ CO_2 + 5\ H_2O$	0.11	6.5	0.007
N_2	Non combustion (no effect)	0.19	0.0	-
CO_2	Non combustion (no effect)	3.36	0.0	-
TOTAL		100.00	-	2.115

Example 2

Theoretical oxygen requirement per unit of volume is $2.115\ m^3/m^3$.

Air requirement is calculated using 21 per cent of oxygen content in air as follows:

$2.115\ m^3 \times 100/21 = \underline{10.07\ m^3/m^3}$

Example 3

Calculations of theoretical oxygen and air requirements for LPG

Symbol	Combustion equation	Component (Vol %) (A)	O_2 Required (m^3 / m^3) (B)	Total O_2
C_3H_8	$C_3H_8 + 5\ O_2 = 3\ CO_2 + 4\ H_2O$	30.00	5.0	1.500
C_4H_{10}	$C_4H_{10} + 6.5\ O_2 = 4\ CO_2 + 5\ H_2O$	70.00	6.5	4.550
N_2	Non combustion (non effect)	0.19	0.0	-
CO_2	Non combustion (non effect)	3.36	0.0	-
TOTAL		100.00	-	6.050

Theoretical oxygen required is 6.050 m^3/m^3

Theoretical air required is 28.810 m^3/m^3

Question?

Exercises

Now please complete the solution for Example 4 (page 13)

THE END

Thank You for the Attention