Combustion

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Combustion

- Applies to a large variety of natural and artificial processes
- Source of energy for most of the applications today
- Involves exothermic chemical reactions
- But for rare exceptions reactions occur in gas phase

Chemical Reactions

- Reactants $\rightarrow$ Products
- From the view point of combustion reactants can be classified into fuels and oxidizers
  - Hydrogen, carbon, sulfur, metals, etc. are examples of fuels
  - Oxygen, halogens, etc. are examples of oxidizers
- Fuels and oxidizers can also be compounds of these elements
- Hence in general combustion reactions can be written as
- Fuel + Oxidizer $\rightarrow$ Products
- In some cases exothermic decomposition of a single compound is also considered a combustion reaction

Fuels and Oxidizers

- Examples of fuels are petroleum fuels, coal, biomass, hydrogen, methane, carbon.
- Some oxidizers are oxygen, air, chlorine, etc.
- Some fuels may contain oxidizer elements and vice versa.
- Example is methanol (CH_3OH)

So how do we know whether a compound is a fuel or oxidizer?

- Depends on which element is in excess.
  - For example methanol contains one oxygen atom along with four hydrogen and one carbon atom. The oxygen atom can take two hydrogen atoms to form water and the rest two hydrogen atoms and one carbon atom can react with other oxidizers.
- Most common fuels contain the elements carbon, hydrogen and oxygen and possibly small amounts of metals, sulphur, etc.
- Most common oxidizer is air, which for most practical purposes can be considered as a mixture of oxygen (21 % by volume) and nitrogen.

Stoichiometry

How much oxidizer is required to just completely react with unit mass of the given fuel.

This ratio is called the stoichiometric ratio.

Example

$$2\ H_2 + O_2 \rightarrow 2\ H_2O$$

This equation states that 4 grams of hydrogen react with 32 grams of oxygen. Hence the stoichiometric ratio is 32/4 = 8.

- For typical hydrocarbon fuel burning in air,
- $CH_n + (1+n/4)(O_2 + 79/21\ N_2)$

  $\rightarrow CO_2 + n/2\ H_2O + 79n/84\ N_2$

➔ $s = (32+3.76\times 28)(1+n/4)/(12+n)$

- For Diesel/gasoline, $n \approx 1.8$, $s = 14.4$
- For methane, $n = 4$, $s = 17.1$
- If we take typical biomass combustion,

  $CH_{1.4}O_{.6}N_{.002} + 1.05\ (O_2 + 79/21\ N_2)$

  $CO_2 + 0.7\ H_2O + 3.949\ N_2$

  $s = 6.3$

- In general,

  $CH_nO_mN_p$ + (1+n/4–m/2) (O_2 + 79/21 N_2)

  CO_2 + n/2 H_2O + [3.76 (1+n/4–m/2)+p/2)] N_2

  s = (32+3.76×28)(1+n/4-m/2)/(12+n+16m+14p)
- In an actual situation air provided for combustion may be more or less than the stoichiometric ratio.
  - If more than necessary air is provided then the mixture is fuel lean
  - If the air is less than necessary, the mixture is fuel rich.
  - A mixture which is balanced is called stoichiometric mixture.
- There are many ways of expressing the relative *leanness/richness* of the mixture.

Equivalence Ratio

- The ratio $(A/F)_{stoichiometric}$ / $(A/F)_{actual}$ is termed the fuel equivalence ratio or simply equivalence ratio.
- The inverse of this is also sometimes referred to as equivalence ratio.
- Equivalence ratio of unity indicates stoichiometric mixture.
- Rich mixtures result in emission of CO and hydrocarbons.
- In most combustion systems designed for industrial applications, the mixture ratio is maintained slightly lean.
- Excess air ratio is also another way of specifying the leanness of the mixture.
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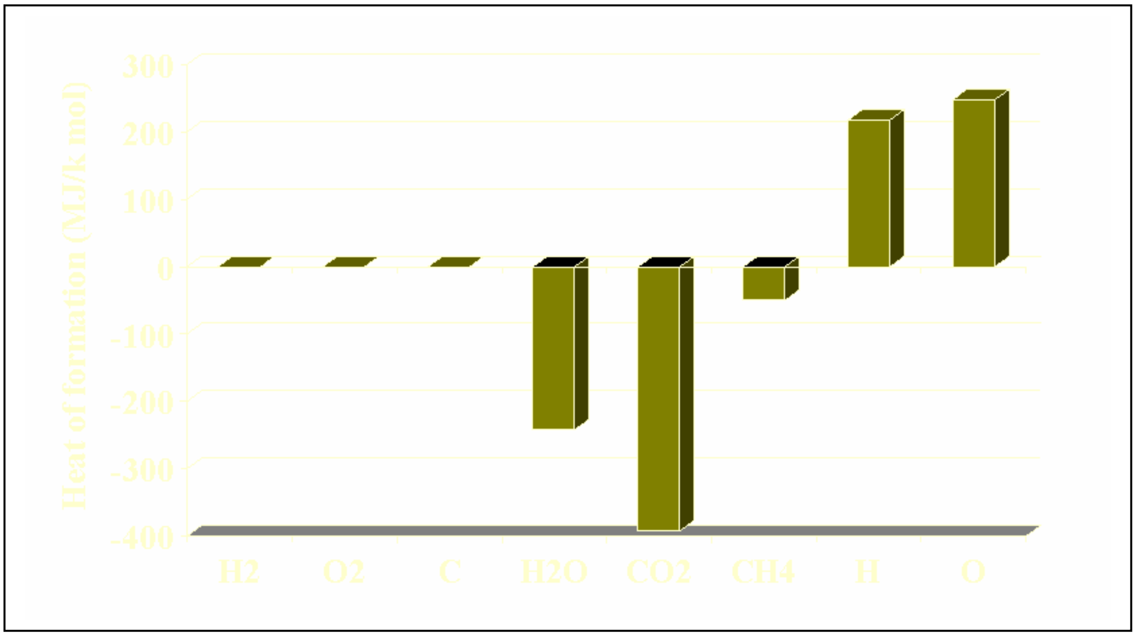
Energetics of Reactions

- The overall combustion reactions are *exothermic.*
- This implies that the reactions are accompanied by release of heat energy.
- The amount of heat energy released by burning unit mass of fuel is called the *calorific value* of the fuel.

Heat of Reaction and Heat of Formation

- If after a chemical reaction, the products are brought back to the initial temperature of the reactants by removing heat from the reacting mixture, the amount of heat removed per unit mass of the fuel is the heat of combustion.
- Since some heat is removed from the system, it can be concluded that the products have lower energy compared to the reactants at the same temperature for an exothermic reaction.
- The difference between the energy (enthalpy) of the products and that of the reactants is called the heat of reaction.
- The heat of reaction is negative for an exothermic reaction.
- Since different compounds have different energy levels at the same temperature, it is convenient to specify a standard datum relative to which the energy levels of compounds can be specified.
- Elements in their stable states at 25°C have been chosen as such a datum relative to which energy levels of any substance at any temperature can be specified.
- The enthalpy of a compound relative to this datum is called the standard heat of formation of a species.
- The standard heat of formation of a species can also be defined as the heat of that reaction in which the only reactants are the elements in their standard state and the species is the only product.

Heats of Formation



The Adiabatic Flame Temperature

- The temperature that will be achieved when no heat is added or removed from the system.
- The adiabatic flame temperature is maximum when the mixture is stoichiometrically balanced.
- The flame temperature decreases as the equivalence ratio moves away from unity.
- The flame temperature for a hydrocarbon – air system is about 2300 K.
- Wood burning in air produces an adiabatic flame temperature of 1900 K.
- With pure oxygen, a flame temperature of about 3500 can be achieved using hydrocarbon fuels.

Additional Requirements for Combustion

- Combustion reactions can proceed only when the fuel and oxidizer are brought into intimate contact.
- The rate at which the reactions proceed is a strong function of temperature.
- Depending on the ways in which these requirements are met creates different modes of combustion.

Modes of Combustion

- Depends on the state of the fuel (solid, liquid, or gas)
- Depends on the mode in which fuel and oxidizer are brought into contact.

Gaseous fuel combustion

- Most combustion reactions (with a few exceptions) occur in gas phase whether the fuel is solid liquid or gas.
- If the fuel is in gas phase, the process of vaporization is eliminated.
- If the fuel and oxidizer are mixed before they are ignited, the flame generated in the process is called premixed flame.
- If the fuel and oxidizer diffuse to the reaction zone and burn, the the flame produced is called diffusion flame.

Premixed Flame

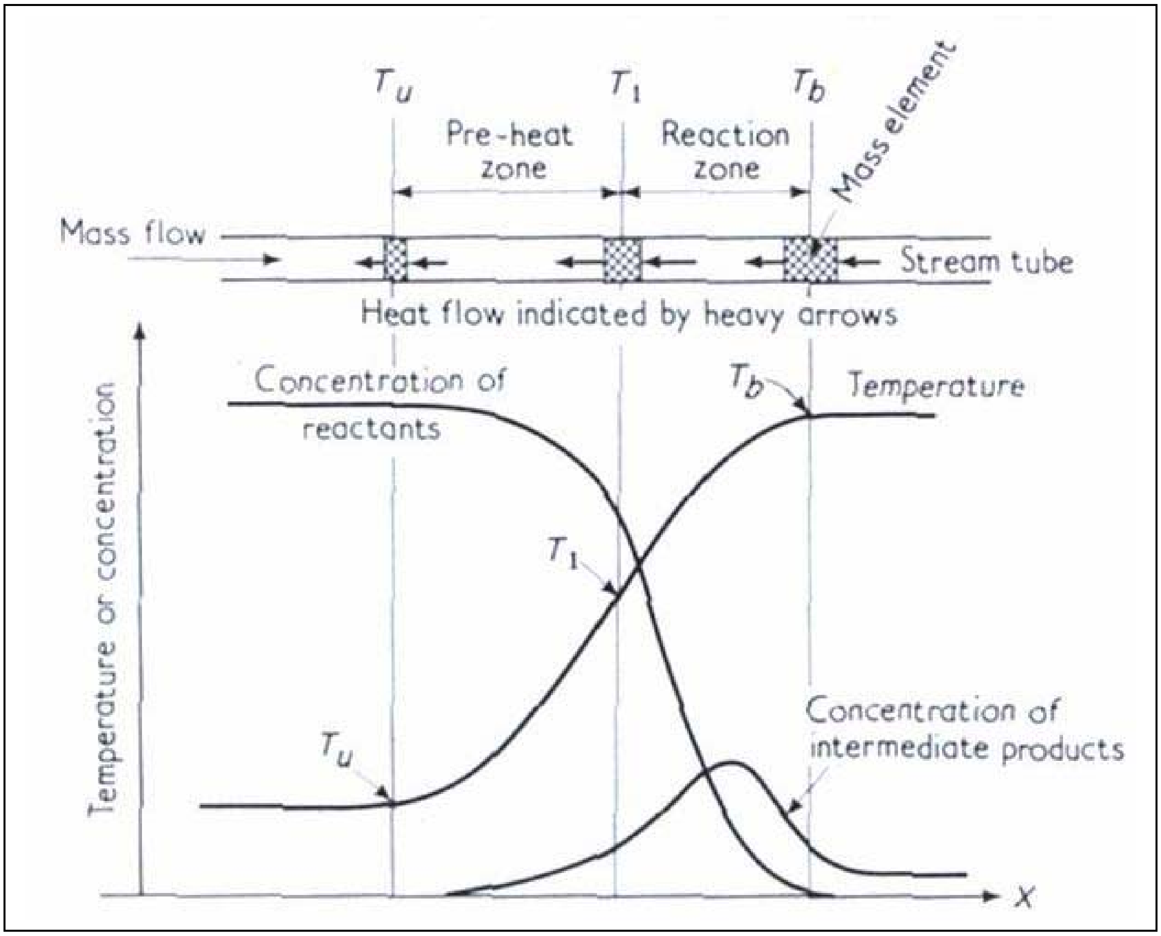
- Fuel and air are mixed before they are ignited.
- The reaction does not proceed immediately because the rate of reaction is very low at the low temperature of the reactants.
- The mixture is ignited by increasing the temperature of the mixture locally.
- The reaction rate increases as the temperature increases releasing energy and further increasing the temperature.

- This mutually supporting processes of increasing temperature and reaction rate creates a run-away condition and the reaction goes to completion in a very short time.
- Meanwhile the neighboring gas get heated by conduction from the hot combustion products.
- The next layer is ignited.
- The flame propagates as a wave from the point of ignition to the cold end consuming the entire mixture.
- The rate at which the flame moves into the unburnt mixture is called the flame speed or the burning velocity.

Burning Velocity

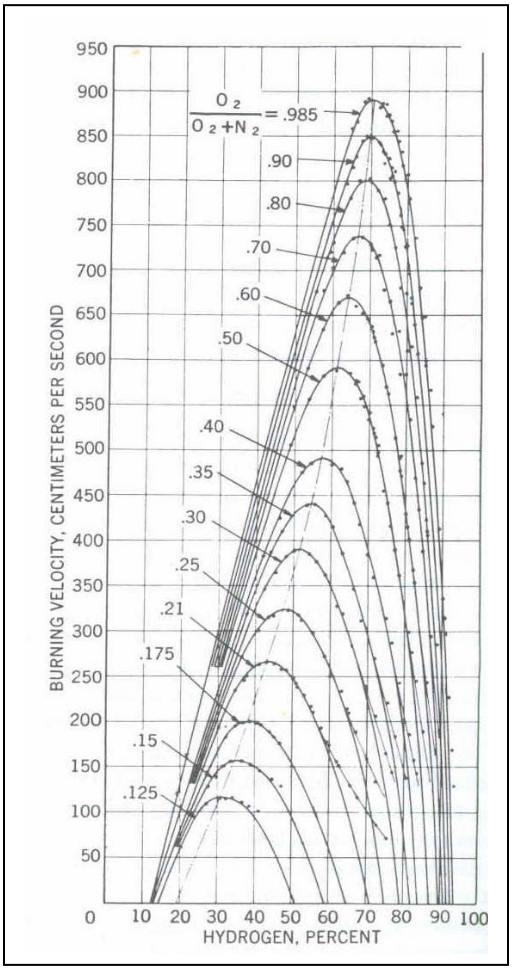
- The burning velocity is a function of the fuel and the oxidizer and the mixture ratio.
- Burning velocity of a given fuel-oxidizer combination is maximum at mixture ratio close to stoichiometric, but slightly towards the rich side.
- A notable exception is hydrogen-air flame for which maximum burning velocity occurs at equivalence ratio of 2.

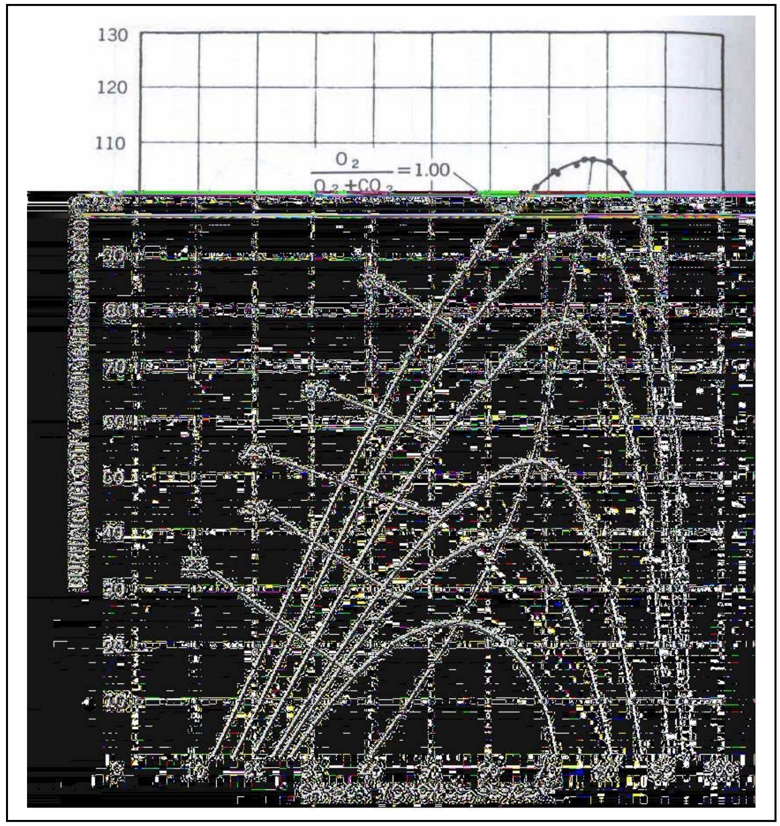
Profiles of Temperature and Concentrations



Burning Velocities of Some Common Fuel-air mixtures (stoichiometric)

Mixture	Maximum Burning velocity (m/s)
Hydrogen - air	1.8
Methane - air	0.39
Propane - air	0.45
Hydrogen - Oxygen	10





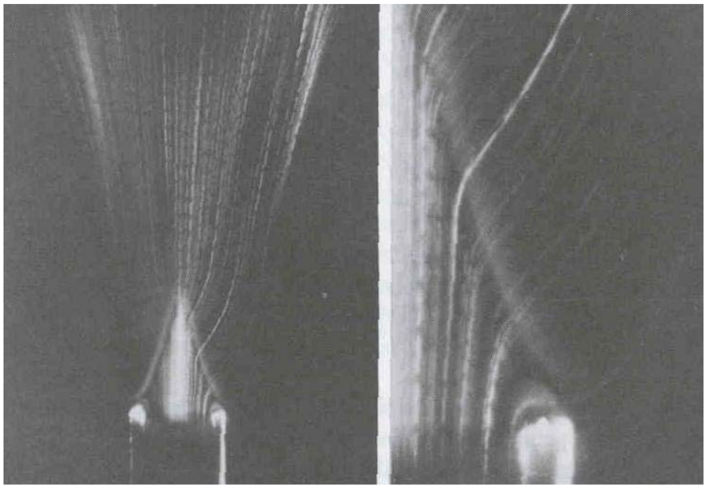
Premixed Flame in Continuous Combustors and Burners

- In a flowing stream the flame will be located such that the velocity component normal to the flame is equal to the flame speed.
- Flame speed can be significantly modified by turbulence level in the flowing fluid.

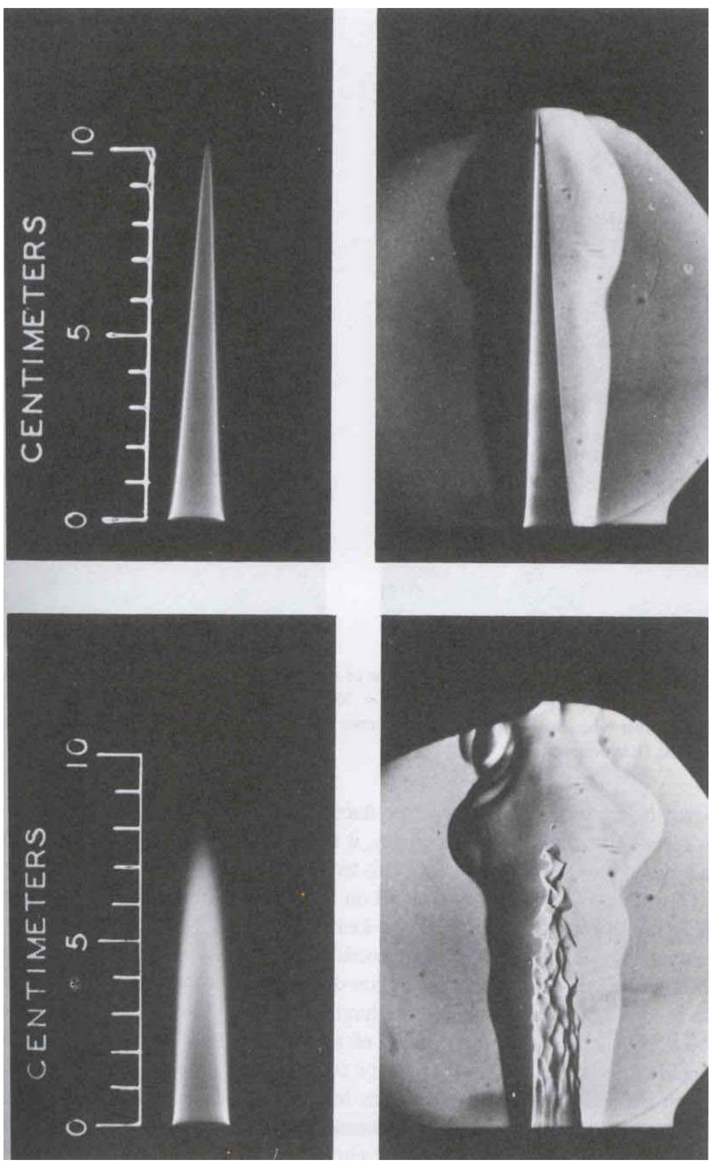
Examples of pre-mixed flames

- Burner flames
- After burners
- Domestic stoves
- Most of the industrial gas burners

Burner flame



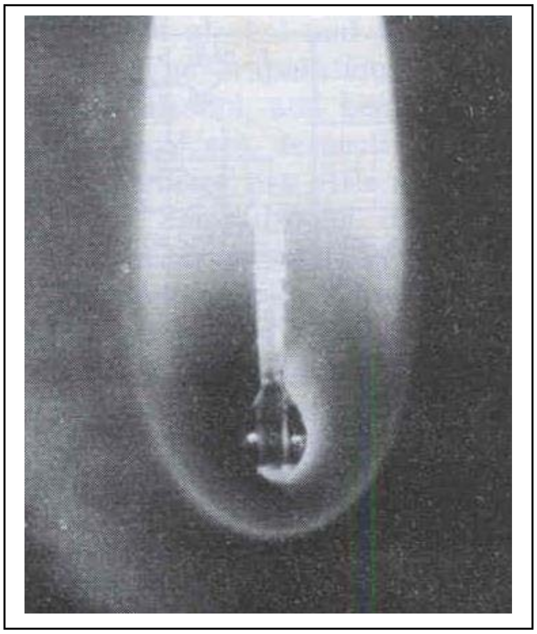
Laminar and Turbulent flames

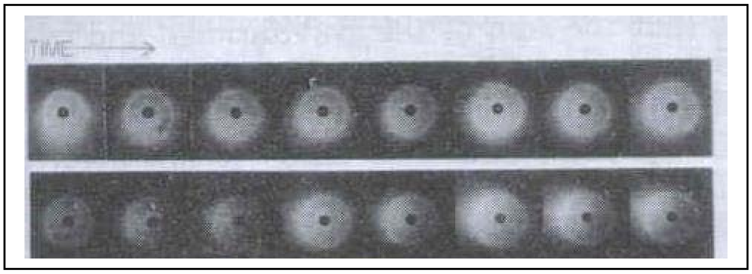


- **<u>Diffusion Flames</u>**
- Most naturally occurring flames are diffusion flames.
- The fuel and the oxidizer are separated by the flame
- Examples are flame from a fuel gas jet and combustion of solid or liquid fuels.
- Fuel and oxidizer react as they reach the flame.
- The rate of reaction is limited by the rate at which the reactants are transported to the flame.

- **<u>Liquid Fuel Combustion</u>**
- Additional process of liquid vaporization before combustion can take place.
- Modes of liquid fuel combustion are droplet combustion, pool fire, burning from a wick, spray combustion.
- Premixed flame can be generated from liquid fuels by pre-vaporizing and mixing with air prior to ignition.

<u>Liquid Droplet Combustion</u>





Solid Fuel Combustion

- Melting, vaporization, and/or decomposition of fuel take place during solid fuel combustion.
- Some fuels like wax cleanly vaporize without decomposition.
- Many solid fuels pyrolize leaving carbon residue (fixed carbon) behind and volatiles burn in gas phase.
- The reaction between the carbon residue (char) and oxygen takes place on the carbon surface unlike most combustion reactions.

Modes of Solid Fuel Combustion

- The requirements in a combustor is power and mixture ratio control.
  - Grate combustion
  - Fluidized bed combustion
  - Pulverized fuel combustion
  - Cyclone combustion