Module 5: Combustion Technology

Lecture 37: Flame Properties

Key words: Flammability, premixed flame, diffusion flame, flame front, velocity of flame propagation

5.6 **Flame properties**

Formation of Flame

If the combustible substances produce vapour during burning process, a flame is produced. Flame is a luminous zone of the rapid exothermic reaction in combustion of vapour with the formation of light and heat energy. A non-luminous region is appeared just after the flame where the temperature is slightly reduced. A flame is bounded between the iginition zone and a non-luminous gaseous zone. The combustion of gaseous fuels in a flame need the intimate contact of fuels with an oxidant, either oxygen or air prior to the reaction. The ranges of flammability and the point at which the mixture spontaneously ignites must be known. They must be heated to the combustion temperature and the flame produced will be at a high temperature. Then the reaction take place in within a narrow zone or region in the flame. This combustion zone is called the flame front with this mixture is often several thousand degrees.

Types of Flames

Flames may be of different types depending on the extent of mixing of fuel and oxidizer or how the mixture reach the reaction zone. The flow patterns in the reaction vessel, such as well mixed and plug flows are the major tools to classify the flames in different types. The flame may be turbulent and laminar types depending on the flow behaviour of the combustion gases.

In a premixed flame the fuel and the oxidant are molecularly mixed before the combustion process takes place.

The flames are mainly classified as:

i) Non -Premixed or Diffusion Flames and ii) Premixed flames. These flames may be both laminar or turbulent types.

Non-Premixed Flames

In many combustion processes, the fuel and air are often initially not mixed. The fuel and oxidizer are kept on either side of the reaction zone and moved to the reaction zone. The resultant flame is termed as the diffusion or non-premixed flame. In some cases, the gas and air are injected in a coaxial parallel tubes and ignited. The flow behaviour of the non-premixed flame is laminar type. Molecular or turbulent diffusion is responsible for the mixing of the gases in non-premixed flames.

In a laminar flow region, the reach the reaction front by diffusion, before the reaction takes place. The products of combustion also diffuse to come out from the reaction zone. The flame is also called Laminar Non-Premixed Flames or Diffusion Flame. The diffusion flame occurs at the interface of the gaseous fuel and air. With the progress of time as the flame propagates, the thickness of the reaction zone increases. In diffusion flame the combustion rate will solely controlled by the diffusion rate, not by the kinetic rate of reaction. The mechanism of this flame is very complicated. The fuel approaches gradually towards the flame zone, there is a deficiency of oxygen and it is pyrolysed to smaller molecules or radicals. Then, there will be the formation of carbon soot and fuel burns with a bright luminous yellow flame.

As the flame propagates, the oxygen concentration in the zone increases and the product of pyrolyzed products are further reacted. Gradually the reaction occurs under the stoichiometric proportion of oxygen and combustible. Under this circumstances, the total enthalpy of the reactants will be equal to the total enthalpy of the products and the energy losses. The non-

premixed flames at stoichiometric conditions optimize the flame temperature with a definite fuel-air ratio.

Premixed Flames

In this type, the fuel and oxidant gas are mixed together at ambient condition before being delivered to the flame zone. As the mixture approaches the flame front, it is heated by conduction and radiation. A reaction takes place before reaching the flame front. Gradually the mixture is sufficiently heated at the reaction front and the chemical reaction takes place.

If the fuel and the oxidant gas are thoroughly mixed prior to reaching the flame front, the location of the flame front does not depend on the diffusion of reactants. The flame speed or the velocity of the reactants in the reaction zone is important. In another case, the fuel is injected into the oxidant gas flow in the upstream side of the flame front but the mixing is improper.

The turbulent pre-mixed flame plays an important role in the various practical applications because, it increases the ignition of fuel with the reduction in the emission of gases. Both the laminar premixed or laminar non-premixed flames (diffusion flame) are slow processes and not economic. Turbulence actually results in a reduction in flame length. The turbulence can be increased by recirculation of the fuel-air mixture.

Flame Structure

The example of the laminar premixed flame is the flame in a Bunsen Burner as shown in Fig.1. In the premixed type, the laminar flame is the most simple type. The structure of the flame may be analysed by a flame in the burner. The flame consists of four distinct regions as shown in Fig 1.

1. Zone containing unburnt gases, 2. Reaction zone, 3. Incomplete combustion zone, and 4. Complete combustion zone. The idealized shape of the reaction zone of a laminar premixed flame is a cone. The height of the cone represents the flame length, and depends on the velocity at the burner outlet.

Flame Propagation

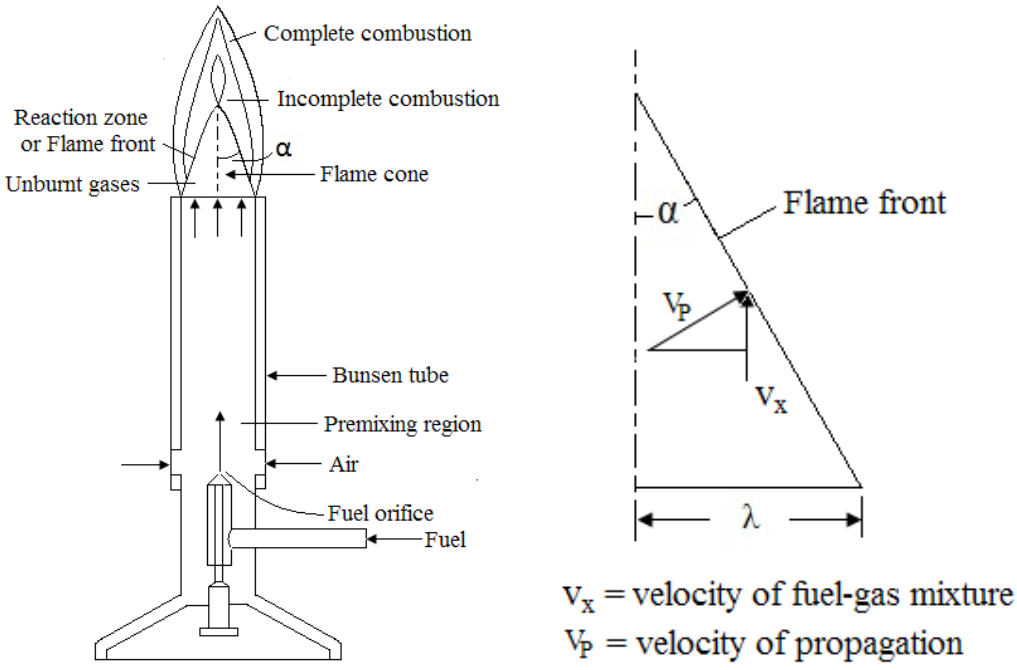

Fig.1 Laminar premixed flame in a Bunsen Burner.

Since the flame front is stationary, the velocity of flame propagation v_p , with respect to the unburnt mixture will be equal to the flow velocity of the unburnt mixture normal to the flame front . This is also called burning velocity.

Velocity of flame propagation , $v_p = v_x \text{ Sin } \alpha$

Where, α = flame cone angle and v_x is the velocity air fuel mixture.

Velocity of flame propagation depends on the properties of the fuel-air mixture, pressure and temperature of the process. A premixed flame of a particular fuel-air combination is characterized by three main parameters, the burning velocity, flame temperature and flammability limit, which are also determined by the pressure, temperature and, air-flue ratio. Dilution of the burning mixture with an inert gas, such as helium or nitrogen, lowers the temperature and, consequently, the reaction rate. Higher amounts of inert gas extinguish the flame.

The Propagation Velocity in a Tube

The propagating flame along a vortex axis is completely different from the 'normal' flames, which propagate in a tube or expand spherically from an ignition point. Its propagating speed is nearly equal to the maximum tangential velocity in the vortex.

For a fuel oxidizer mixture enclosed in cylindrical tube whose one end is closed while other end is opened, let us consider the flame front is perpendicular to the direction of flow.

For the premixed gases in a laminar flow, the flame speed V_f is obtained from the burning velocityV_b. Burning velocity is equal to normal velocity of flame propagation.

In the case of a flame propagating in a tube, the flame speed or outlet gas velocity is given as

$V_f = V_b \frac{S_f}{S_t}$. Where S_f and S_f are the cross section of flame and tube respectively.

Also for a spherically expanding flame propagating axially in a cylinder, the flame speed is given by

$V_f = V_b \frac{\rho_i}{\rho_o}$. Where, V_b is the burning velocity relative to unburnt gas velocity, ρ_i and ρ_o are densities of inlet and outlet gases. As $\rho_i \gg \rho_o$, $V_f \gg V_i$. It is observed that the gas velocity will change across the flame front by the changes of gas concentration, temperature

and density. In the explosive flame, the velocity of flame front will be obtained from the algebraic sum of normal velocity of flame propagation and gas velocity.

Flammability limit

A spontaneous or explosive reaction of fuel may be possible when ignited in presence of either air or oxygen for a particular range of gas composition at fixed temperature and pressure. Flammability limits describe the range of fuel concentration in terms of volume % and this reaction may occur even when the mixture is cold. For example, the lower flammability limit for aviation kerosene is about 0.7% by volume and the higher flammability limit is about 5% by volume. For hydrogen gas, lower limit 4%, and higher is 75%. Flammability limits also are much wider in oxygen than in air. So it highly depends on the burning atmosphere, pressure, temperature, and on the ignition source.

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