Course Name: PETROLEUM TECHNOLOGY

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Lecture 37: Fundamentals of thermochemistry: Flame

Hello, and welcome to the 37th lecture on Petroleum Technology. In this lecture, we will talk about the fundamentals of thermochemistry under which we will learn about flame. All the combustion processes are associated with or characterized by the formation of flame. So, if the combustible substances produce vapor during the burning process, a flame is produced. So, the flame is a light and heat-emitting gaseous zone during the combustion, which separates the combustion product from the fuel. Flame is a luminous zone of rapid exothermic reaction in the combustion of vapor with the formation of light and heat energy, which I said.

So, the flame is the light and heat-emitting zone; it is a luminous zone of the rapid exothermic reaction that occurs during the combustion process. The flame appears as soon as the fuel is ignited. A non-luminous region appears just after the flame, where the temperature is slightly reduced. In the exothermic reaction zone, a very high temperature is obtained. However, when the temperature is slightly reduced, a non-luminous zone appears.

A flame is bounded between a gaseous zone and a non-luminous gaseous zone. So, the flame covers the burning part and an after-burning part. The burning part is a gaseous luminous zone, and the after-burning part is a non-luminous gaseous zone. The combustion of gaseous fuels in a flame requires the intimate contact of the fuel with the oxidant, either oxygen or air, prior to the reaction. During combustion, we need oxygen or air as one of these oxidants, and for gaseous fuel, a flame requires the intimate contact and well-mixing of the fuel with the oxidant, whether it is oxygen or air, prior to the reaction.

And the reaction takes place in a narrow zone within the flame. This combustion zone is called the flame front, and its temperature often rises to several thousand degrees. In a flame, the reaction occurs in a very narrow surface – the surface that separates the unburned fuel from the luminous zone where the reaction happens. This zone is called the flame front, and its temperature often reaches several thousand degrees, typically around 2000 to 3000 degrees. The difference between a simple chemical reaction and a flame lies in the fact that in a flame, a very fast combustion reaction – an exothermic reaction –

occurs with luminescence. At the same time, there is a rapid increase in concentration and temperature.

Now, let's consider the types of flames. Flames can be of different types depending on the extent of mixing of fuel and oxidizer or how the mixture reaches the reaction zone. The nature of the flame depends on how well the fuel and oxidizing agent are mixed together – whether they are well-mixed initially or mixed later. The way the mixture reaches the reaction zone, whether it is a well-mixed fuel vapor and air mixture going directly to the burning zone or a plug flow, is essential. Flow patterns in the reaction vessel, such as well-mixed and plug flows, are crucial tools for classifying flames into different types. Various flame types exist based on the flow pattern – whether it is a well-mixed fuel vapor and air mixture or a plug flow characterized by discrete plugs.

The flame can be of turbulent or laminar types, depending on the flow behaviour of the combustion gases. Whether the flame is turbulent or laminar is entirely dependent on the flow behaviour of fuel and air. When fuel and air flow from either side of the burner at equal and low velocities and mix together to form the flame, it is called a laminar flame. On the other hand, if the flow of fuel and air makes an angle, and the flow velocity is high, the resulting flame is called a turbulent flame. A laminar flame is well-shaped and longer, while a turbulent flame is irregular in shape and unsteady.

Flames are mainly classified as non-premixed or diffusion flames and premixed flames. In non-premixed flames, the fuel and air or oxygen are not mixed beforehand. In many combustion processes, the fuel and air are initially not mixed and are mixed later. The fuel and oxidizer are placed on either side of the reaction zone and move towards the reaction zone from two different directions. As they reach the reaction zone, they mix, and the combustion reaction occurs there.

In a laminar flow region, the fuel and air reach the reaction front through diffusion before the combustion reaction takes place. Diffusion, a type of mass transfer, is involved in this process. The products of combustion, such as carbon dioxide and carbon monoxide, also diffuse out from the reaction zone. The entire process is diffusion-controlled, and the resulting flame is termed a laminar non-premixed flame or diffusion flame. In a diffusion flame, the combustion rate is solely controlled by the diffusion rate, not by the kinetic rate of the reaction. Thus, mass transfer governs the entire combustion process in a diffusion flame.

On the other hand, in a premixed flame, the fuel and oxidant gases are mixed together at ambient conditions before being delivered to the flame zone. A premixed flame is formed by a well-mixed fuel and oxidant gas before they reach the flame zone. As the mixture approaches the flame front, it is heated by conduction and radiation. The well-mixed fuel and air or oxygen mixture is slowly heated as it approaches the flame front during its pathway.

In a turbulent premixed flame, the mixture is sufficiently heated at the reaction front when it reaches the reaction zone, and the chemical reaction takes place. Turbulent premixed flames play a crucial role in various practical applications by enhancing fuel ignition and reducing gas emissions. Due to the high velocity in turbulent premixed flames, the residence time in the reaction zone is very low. This leads to rapid fuel ignition and complete combustion, resulting in reduced emissions of gases.

The turbulent premixed flame has a shorter flame height compared to the diffusion flame. One key difference is that in a diffusion flame, both the fuel and air are preheated. In contrast, in a premixed flame, they are mixed well and continuously heated while moving towards the flame. The flame speed or the velocity of reactants in the reaction zone is important, as it determines how fast the reaction will occur. Both laminar premixed and laminar non-premixed flames are diffusion types, as they are slow, non-economic processes that cannot produce a large amount of heat compared to diffusion flames. Turbulence tends to reduce flame height in turbulent flames due to their irregular and unsteady nature.

Turbulent velocity cannot form a long flame, but turbulence can be increased by recirculating the fuel-air mixture continuously. This increased turbulence leads to more heat generation. In a combusting flow with turbulence, there is a significant increase in the reaction rate due to the mixing of hot, unburnt fuel product gases with cold, unburnt reaction gases. As the fuel and air mixture moves towards the flame-forming region, it gradually heats up, but it is colder compared to the hot burnt product gases formed during combustion. The mixing of these hot burnt product gases with cold unburnt reactant gases results in a substantial increase in the reaction rate.

The strong effect of turbulence on flame propagation rate poses a challenge in modeling turbulent combustion events, requiring the coupling of fluid mechanics and chemical kinetics. Unlike laminar flow, where the reaction is mass transfer-controlled and only diffusion-controlled chemical kinetics are considered, modeling turbulent combustion involves both fluid mechanics and chemical kinetics.

Now, looking at flame structure in premixed types, the laminar flame is the most simple type, forming a long, smooth flame. The flame structure in premixed flames can be analyzed using examples like the Bunsen burner, a common laboratory apparatus. The Bunsen burner serves as an example of a laminar premixed flame.

The idealized shape of the reaction zone of a laminar premixed flame is a cone. You have seen the shape of the flame, which is a cone, and within the flame, there is a narrow region where the combustion reaction happens, producing a large amount of heat in the shape of a cone. The height of the cone represents the flame length. The higher the cone, the longer the flame, depending on the velocity of the burner outlet where the product gases exit.

In the depiction of a laminar premixed flame in a Bunsen burner, the flame consists of four distinct regions: **Zone Containing Unburned Gases:** This region contains the unburned gases, where the fuel-air mixture ascends in a premixed fashion. Air is introduced through one pathway, and fuel is atomized inside, going up and mixing with the air. The mixture, after premixing, moves towards the flame formation zone, continuously getting heated by conduction and radiation. **Reaction Zone:** The reaction zone is the flame cone, where unburned gases carry out the combustion reaction. The surface representing the flame front forms a vertical line at an angle alpha with the vertical line. **Incomplete Combustion Zone:** This portion may represent the incomplete combustion zone. **Complete Combustion Zone:** This region represents the complete combustion zone. Understanding these distinct regions helps in analyzing the characteristics and behavior of a laminar premixed flame, providing insights into combustion processes within the flame.

When the air hole in the Bunsen burner is closed, the flame takes in only atmospheric oxygen, resulting in incomplete combustion. This incomplete combustion produces carbon particles in the form of soot. In the incomplete combustion zone, the flame appears yellow, unsteady, and wavy due to the presence of carbon particles. On the other hand, when the air hole is open, introducing air into the burner, complete combustion occurs. Complete combustion results in a blue, steady, and clean laminar flame. Now, let's focus on flame propagation. In the illustration, the flame front surface is shown, making an angle alpha with the vertical line. The unburned fuel-air mixture ascends, and the flame propagates with a velocity represented by v_p. Since the flame front is stationary, the flame propagation velocity with respect to the unburned mixture equals the flow velocity of the unburned mixture. This flame propagation velocity (v_p) is perpendicular to the flame front and is expressed as v_p = v_x * sin (alpha), where alpha is the flame cone angle, and v_x is the velocity of the air-fuel mixture. The velocity of flame propagation depends on the properties of the fuel-air mixture, as well as the pressure and temperature of the process.

Now, let's discuss flammability limits. Flammability limits refer to the range of compositions for a fixed temperature and pressure within which an explosive reaction is possible when an external ignition source is introduced. This means that not every mixing ratio of fuel and air in a fuel-air mixture will result in a flame. Instead, there is a specific range of compositions for the fuel and air mixture at a fixed temperature and pressure that can support an explosive combustion reaction when exposed to an external ignition source.

Flammability limits describe the range of fuel concentration in terms of volume percent. For example, the flammability limit of a fuel may range from 10 percent fuel plus 90 percent oxygen on the lower side to 90 percent fuel plus 10 percent oxygen on the higher side. Within this composition range, an explosive mixture can form, and introducing an external source of fire will result in the formation of a flame. It's important to note that this reaction may occur even when the mixture is cold, but preheating the mixture can enhance the likelihood of combustion and reaction initiation.

Flammability limits are also influenced by the type of atmosphere. For example, the limits are much wider in pure oxygen compared to air. If the mixture involves fuel and oxygen instead of air, the flammability limits may be extended. Additionally, flammability limits depend on the pressure and temperature of the atmosphere.

A mixture that contains less than a critical amount of fuel is known as the lean or lower flammability limit. This represents the critical amount of fuel and air mixture on the lower side. On the other hand, if the mixture surpasses the critical limit of fuel, it is termed rich or upper flammability limit. Mixtures that are leaner than the lower flammability limit or richer than the upper flammability limit will not be flammable. So, any mixture cannot be able to form a flame. Only if the mixture is within the flammability limit. Then, only it can proceed to make a flame or combustion reaction. These are the references through which you can go. Thank you for your attention.