Advanced Thermodynamics and Combustion
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Module - VIII
Combustion and Flames
Lecture - 32
Engine Combustion and Pollution

Dear learners, greetings from IIT, Guwahati. We are in the MOOCS course Advanced Thermodynamics and Combustions, module VIII, Combustion and Flames.

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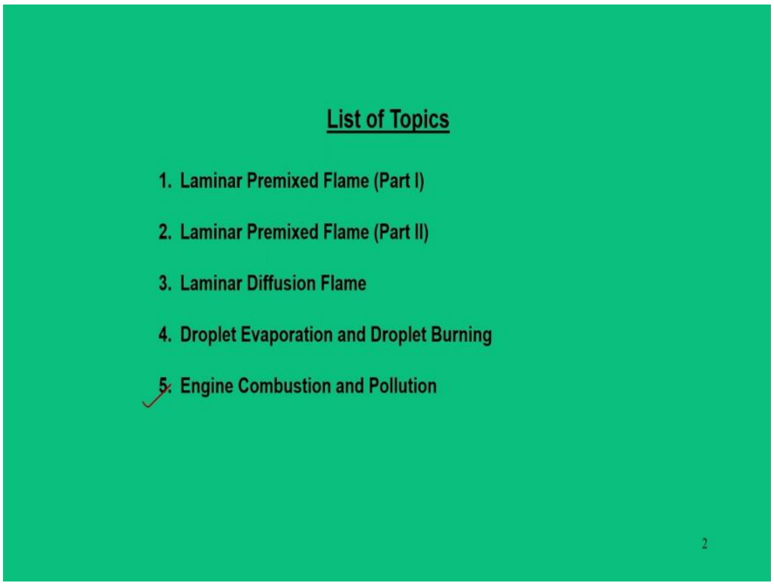

List of Topics

1. Laminar Premixed Flame (Part I)
2. Laminar Premixed Flame (Part II)
3. Laminar Diffusion Flame
4. Droplet Evaporation and Droplet Burning
5. Engine Combustion and Pollution

Till this point of time, we covered four lectures on Laminar premixed flame, laminar diffusion flame, droplet evaporation and droplet burning. Today, we are going to focus on the last lecture of this module that is Engine Combustion and Pollution. Till this point of time we have covered all the basic aspects of theoretical backgrounds and mathematical modeling of combustions and in this lecture, we will try to focus on application part, number 1.

Number 2, also we will look into the pollution levels or pollutions that comes out after the engine combustions and if pollution has come out then what is the criteria of its quantifications. So, these things will be the focal point of our discussion today.

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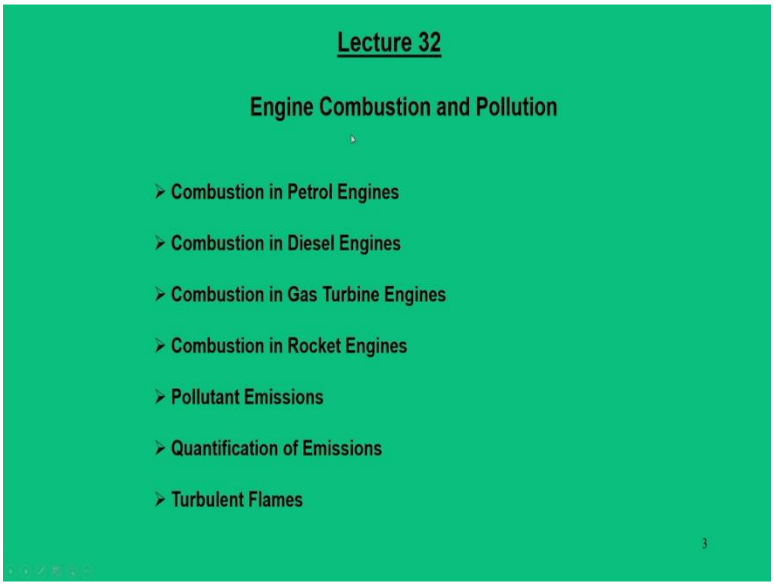

Lecture 32

Engine Combustion and Pollution

- Combustion in Petrol Engines
- Combustion in Diesel Engines
- Combustion in Gas Turbine Engines
- Combustion in Rocket Engines
- Pollutant Emissions
- Quantification of Emissions
- Turbulent Flames

So, on this lecture number 32, that is engine combustion and pollutions, we will discuss about the combustion phenomenon in petrol engines, diesel engines, gas turbine engines, and rocket engines and all these things will be just a preliminary conceptual thought, how this combustion phenomena happens.

Subsequently, till this point of time whatever methodology or mode of combustions we have looked into, we will try to put a glimpse that how those concepts can be utilized in these engine combustions and towards the last part of our discussions we will discuss about pollutant emissions and how to quantify these emissions.

And, one of the important aspects which was supposed to be in this combustion course that was turbulent flames, but due to lack of time we will not be able to cover this, but rather I will just put an introductory remark on this turbulent flame towards the end of this lecture.

So, let us start the first thing the combustion in petrol engines. We all know about the basic UG course which is combustion in SI engines, spark ignition engines where the combustion phenomena is mostly viewed that fuel and air mixtures enters into the engine combustion engine cylinders. And, towards the end of the compression stroke the spark block ignites the charge and as a result the combustion happens. This was the thought we put when you discuss in the IC engine course.

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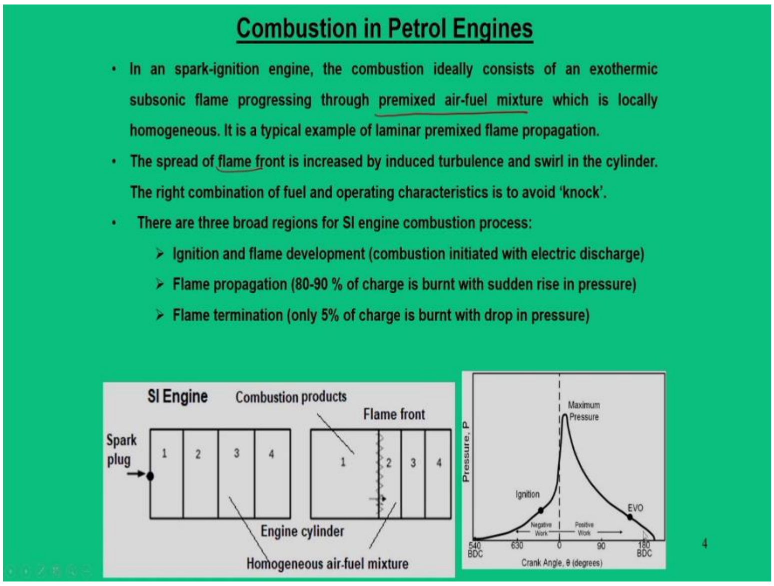

Combustion in Petrol Engines

- In an spark-ignition engine, the combustion ideally consists of an exothermic subsonic flame progressing through premixed air-fuel mixture which is locally homogeneous. It is a typical example of laminar premixed flame propagation.
- The spread of flame front is increased by induced turbulence and swirl in the cylinder. The right combination of fuel and operating characteristics is to avoid 'knock'.
- There are three broad regions for SI engine combustion process:
  - Ignition and flame development (combustion initiated with electric discharge)
  - Flame propagation (80-90 % of charge is burnt with sudden rise in pressure)
  - Flame termination (only 5% of charge is burnt with drop in pressure)

Now, I will just add or something further that and whatever discussions we have made so far, this particular nature of combustions falls as the pre-mixed combustions where the premixed air and fuel combustions happens or prepared locally and it is a homogeneous mixtures and when it enters spark gets generated or we ignite the fuel through a spark. And, through this we generate a flame front and this flame front propagates into in the combustion space.

What we can see is that if you can just typically view this is the combustion zone. We can think about many numbers of layers 1, 2, 3, 4 like these zones. Now, in this entire zone, we have this homogeneous fuel and air mixture. Now, when the spark is ignited, the zone one gets affected. So, a flame front is initiated and slowly this flame front moves to the zone 2, zone 3, zone 4.

And, as and when it propagates into the different zone we can see that once it completes the zone 1, zone 1 will be full of combustion products whereas, zone 2, 3, 4 and combustion has not been attempted or has not started. And, subsequently when the flame front moves through the zones it keeps on igniting the subsequent fuels. As a result, the entire cylinder space is covered with the complete combustion products.

And, this combustion process can be thought of three major regions, one is ignition and flame developments and here this ignition happens through an spark plug because it creates an electric discharge. Then during the flame propagation phase almost 80 to 90 percent of the charge is burnt and because of this, we find a certain rise in the pressures and towards the flame termination; that means, when the flame front reaches to the last zone, only 5 percentage of charge is burnt and that is viewed as the drop in pressures.

Now, if you look at the pressure and crank angle diagrams or the subsequent pressure time diagram, we can see that at one particular location of the crank angle ignition happens and it starts with a slow rise in the pressures, and followed by a sudden rise in pressures. And, when the flame front is in the termination mode, the pressure peak drops down and we will see that towards the expansion stroke the pressure drops.

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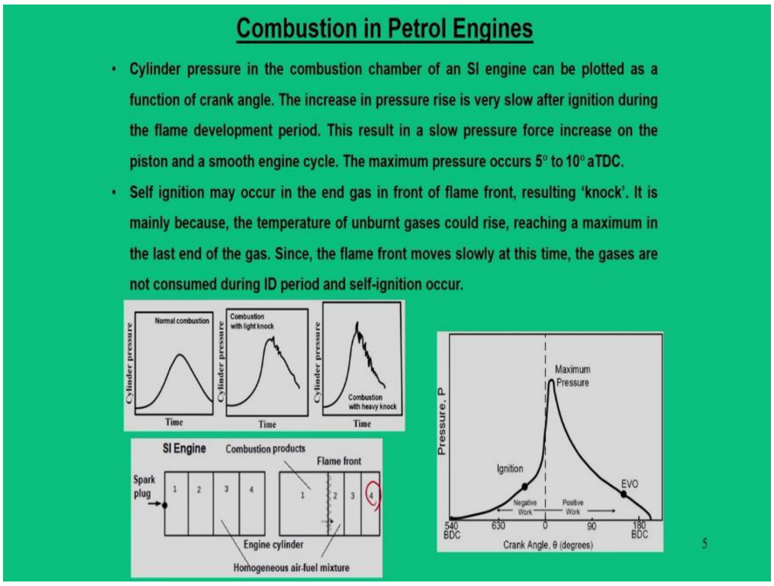

Combustion in Petrol Engines

- Cylinder pressure in the combustion chamber of an SI engine can be plotted as a function of crank angle. The increase in pressure rise is very slow after ignition during the flame development period. This result in a slow pressure force increase on the piston and a smooth engine cycle. The maximum pressure occurs 5° to 10° aTDC.
- Self ignition may occur in the end gas in front of flame front, resulting 'knock'. It is mainly because, the temperature of unburnt gases could rise, reaching a maximum in the last end of the gas. Since, the flame front moves slowly at this time, the gases are not consumed during ID period and self-ignition occur.

Another important phenomena in the spark ignition engine is the knocking. So, what could have happened is that in during a normal combustion process if the flame front which is initiated in the zone 1 subsequently burns the subsequent charge in the different zones then we will have a normal combustions.

And, due to variety of regions if there is a rise in the pressures or rise in the temperatures due to some regions in the zone 3 or 4, not due to flame front rather due to self ignitions, then we can think about some kind of disturbances in the pressure pulse and those disturbances are typically called as knock. So, in a normal combustion phenomenon, the trace of the pressure time diagram is smooth and whereas, with a knocking situations we will find towards the expansion stroke that is a kind of oscillations that drops in towards the end phase of the combustions.

So, what we can say is that knocking if at all has to happen, it is very likely that zone four is the most affected zone or we can say zone 4 is the locations at which we can expect a self ignition as a result of knocking.

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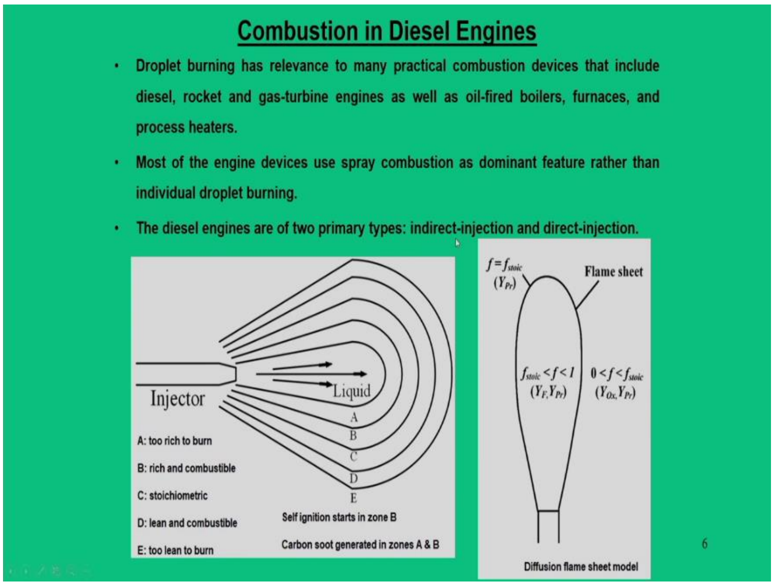

Combustion in Diesel Engines

- Droplet burning has relevance to many practical combustion devices that include diesel, rocket and gas-turbine engines as well as oil-fired boilers, furnaces, and process heaters.
- Most of the engine devices use spray combustion as dominant feature rather than individual droplet burning.
- The diesel engines are of two primary types: indirect-injection and direct-injection.

A: too rich to burn

B: rich and combustible

C: stoichiometric

D: lean and combustible

E: too lean to burn

Self ignition starts in zone B

Carbon soot generated in zones A & B

Diffusion flame sheet model

Then we will move to combustion in the diesel engines. We all know that diesel engines are governed with auto cycles and it is a constant pressure based combustions, and here instead of the pre mixed air fuel mixture, we normally do that air is compressed within the engine cylinders and fuel is injected into this chamber through an injection process.

And, we all know in our earlier discussions that we have seen two important concepts one is diffusion flame other is droplet combustions. First thing is that when a fuel jet comes through the injectors, it forms flame jet as you can see here it is a diffusion flame jet.

And, when we have a constant density mode we have analyzed one thing that fuel jet injected into a quiescent to air, same thing we can view here that when it is injected it is in the liquid form and when it forms it sees a medium where it is a medium with heated air. So, this liquid droplet gets vaporized by seeing this environment.

So, in this case what happens the fuel gets injected from an injector and when it comes out from the injector, it sees an ambience which is a compressed air at elevated pressure and temperatures. So, as a result, the self ignition will occur. Now, such self ignition process is modeled through a layer of diffusion sheets.

So, here we can say that there are different zone A B C D E. So, A can be considered as a too rich to burn, B can be considered a rich, but combustible, C can be considered as a stoichiometric; that means, on this flame sheet it is stoichiometric combustion happens, D is lean, but combustible and E is too lean to burn.

So, all these things the different zone happens here. Such a things if has to be modeled through a diffusion sheet model, then we can say on this particular flame sheet one situation could be the fuel layer is in the stoichiometric proportions. And, within this flame sheet, we may have combination of fuel as well as products and outside these things we may have combination of oxidizer and products because it is a lean mixture.

So, just try to correlate this fact that same thing happens that is two important phenomena one is through flame sheet other is that droplet combustion; that means, liquid droplets that comes through the injector it gets vaporized. And in fact, the droplets have certain lifetimes and the subsequent droplets gets created and they also dies down after the lifetime is over.

And, entire phenomena that happens only in a few millisecond durations and of course, when you look at specifically in the diesel engines there are different ways that fuel injection can take place one is indirect-injection, other is direct-injections.

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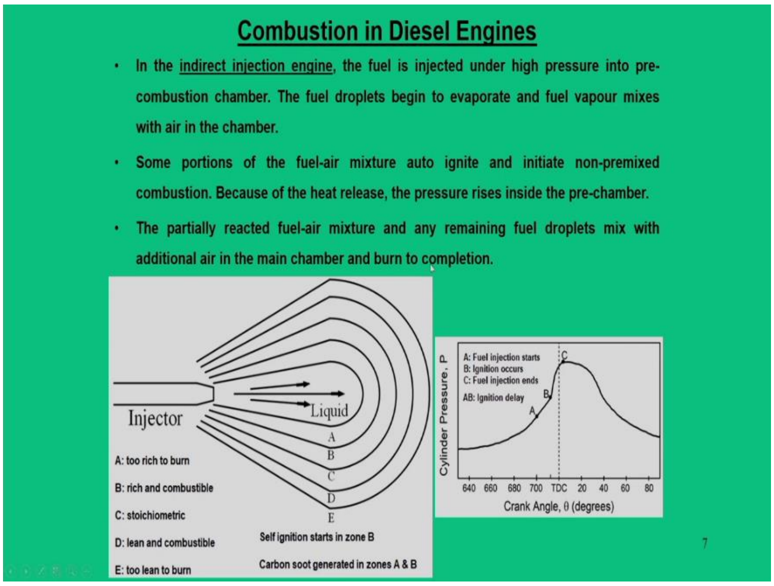

Combustion in Diesel Engines

- In the indirect injection engine, the fuel is injected under high pressure into pre-combustion chamber. The fuel droplets begin to evaporate and fuel vapour mixes with air in the chamber.
- Some portions of the fuel-air mixture auto ignite and initiate non-premixed combustion. Because of the heat release, the pressure rises inside the pre-chamber.
- The partially reacted fuel-air mixture and any remaining fuel droplets mix with additional air in the main chamber and burn to completion.

So, in a indirect injection what happens the fuel is injected under high pressure into the pre combustion chamber the fuel droplets begin to evaporate and fuel vapor mixes with air in the chamber. And, some portion of the fuel and air mixture auto ignite and this initiate a non-pre-mixed combustion and because of the heat release pressure rises in the combustion chamber.

And, subsequently the partially reacted fuel mixture and the remaining fuel droplets mix with additional layer in the main chamber to complete the burning process.

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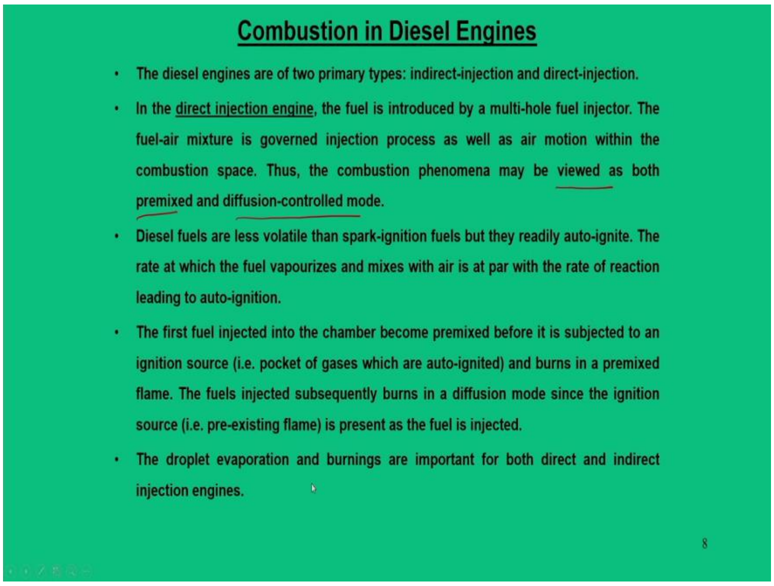

Combustion in Diesel Engines

- The diesel engines are of two primary types: indirect-injection and direct-injection.
- In the direct injection engine, the fuel is introduced by a multi-hole fuel injector. The fuel-air mixture is governed injection process as well as air motion within the combustion space. Thus, the combustion phenomena may be viewed as both premixed and diffusion-controlled mode.
- Diesel fuels are less volatile than spark-ignition fuels but they readily auto-ignite. The rate at which the fuel vapourizes and mixes with air is at par with the rate of reaction leading to auto-ignition.
- The first fuel injected into the chamber become premixed before it is subjected to an ignition source (i.e. pocket of gases which are auto-ignited) and burns in a premixed flame. The fuels injected subsequently burns in a diffusion mode since the ignition source (i.e. pre-existing flame) is present as the fuel is injected.
- The droplet evaporation and burnings are important for both direct and indirect injection engines.

The other category of the injection systems is the direct injection systems. So, recent advantage is that instead of looking for this earlier version pre-combustion chamber, we can think of the injecting the fuel through a multi hole fuel injector systems because it is a quite efficient process in the burning of the fuel.

And, in this process what happens the fuel air mixture is governed by the injection process as well as the air motion within the combustion space. So, here the combustion phenomena is viewed as pre mixed as well as the diffusion controlled mode. And, we all know that diesel fuels are less volatile than that the SI engine fuels because they readily auto ignite. So, the rate at which the fuel vaporizes and mixes with air at par with the rate of reaction leading to the auto ignitions.

Then other important aspect is that when the first fuel is injected into the chamber, then before it is subjected to an ignition source; when you talk about the ignition source which means in the entire combustion space there are some pockets or zones where it is expected that fuel can be auto ignited.

And, slowly once that auto ignition takes place, the flame front generated at that point and subsequently with that zone the information is transferred to the other zones or the flame propagates to the other zones and side by side there are also parallelly fuels that is subsequently injected.

So, the entire process is governed through a diffusion mode since the ignition source which is a pre-existing flame is present, I mean the fuel is injected. The droplet evaporation and burning are also important for direct and indirect engines. So, here when you think about the mode of combustions, we can bring the concept of droplet evaporation and burning.

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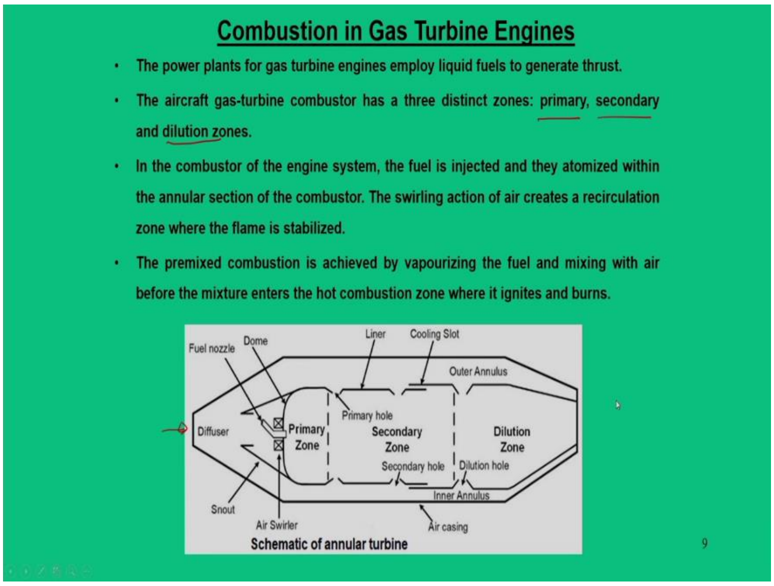

Combustion in Gas Turbine Engines

- The power plants for gas turbine engines employ liquid fuels to generate thrust.
- The aircraft gas-turbine combustor has a three distinct zones: primary, secondary and dilution zones.
- In the combustor of the engine system, the fuel is injected and they atomized within the annular section of the combustor. The swirling action of air creates a recirculation zone where the flame is stabilized.
- The premixed combustion is achieved by vapourizing the fuel and mixing with air before the mixture enters the hot combustion zone where it ignites and burns.

Schematic of annular turbine

Moving to next type of combustions that we normally do in gas turbine engines, these gas turbine engines are usually employed in the aircrafts. So, here also it is similar concept as that of diesel engines, but with a different philosophy or different technology.

So, if you look at the particular figure that talks about the schematic of annular turbine which consists of a diffuser as well as nozzles or it is basically an annular section and in this annular section, entire combustion process is a rich model. So, if you look at this combustor it has three different zones – one is primary zone, secondary zone and dilution zone.

So, air that comes into the system; that means, compressed air from the compressor unit comes into the combustor and in this combustion, we have fuel nozzles and typically they are incorporated in the primary zones. So, the fuel is injected into the air and side by side the air motion; that means, speed of the air is also very high, side by side the mixing takes place.

So, in fact, this is one such nozzle there are multiple nozzles; that means, the fuel is injected into air at multiple locations of this annular space. So, as a result this mixing takes place and during this process already it is a heated temperature; so, we can say that they are atomized within the annular section of the combustor.

Of course, to have the sustained combustions, we can do a swirling actions or air circulation zones which is created within this annular portions to have a stabilized flame. And, the pre-mixed combustion is generally achieved by vaporizing the fuel and mixing with air before the mixture enters into the hot combustion zone where it ignites and burns. Now, this is what happens in the primary zone.

And, subsequently, when it comes to the secondary zones; that means, in the entire combustor there are different zones and these different zones have different purposes. Because when sustain flame gets initiated in the primary zone and, it moves to through this annular sections, then we expect that a regulated tailored flame has to be generated when it enters into the turbines because at that point the entire combustion products has to happen.

Now, to have those things, the secondary zone or dilution zones have a important role. What does they do is that in the secondary zones we also supply fuel and also the mixing or swirling actions such that when it enters we get a stabilized combustion or the flame gets stabilized.

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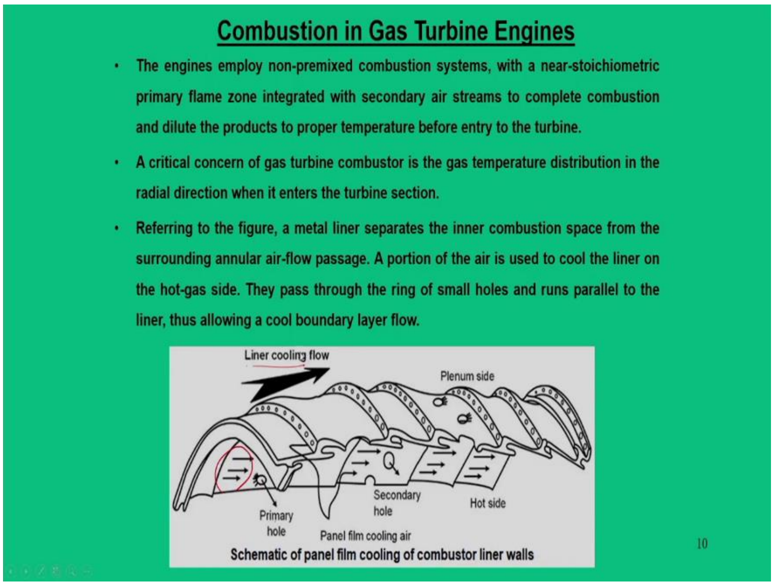

Combustion in Gas Turbine Engines

- The engines employ non-premixed combustion systems, with a near-stoichiometric primary flame zone integrated with secondary air streams to complete combustion and dilute the products to proper temperature before entry to the turbine.
- A critical concern of gas turbine combustor is the gas temperature distribution in the radial direction when it enters the turbine section.
- Referring to the figure, a metal liner separates the inner combustion space from the surrounding annular air-flow passage. A portion of the air is used to cool the liner on the hot-gas side. They pass through the ring of small holes and runs parallel to the liner, thus allowing a cool boundary layer flow.

Schematic of panel film cooling of combustor liner walls

There is a concept called liner cooling flow. So, what does this mean is that if you look at another view of the sections, so, this is one particular sections. So, if you can see the arrow lines these are nothing but air and this is the air flow; arrow lines refers to the air flow and these are the holes which are kept as in the primary zone, secondary zone and maybe the dilution zone.

And, what we have is that in addition to this primary air we also have a secondary air that comes from this compressor and they call it as a liner cooling. Now, this liner cooling is required because what happens is that we expect a particular temperature distribution towards the end of the combustor.

That means, when the flame is about to enter into the turbines, we expect the flame temperature distributions along the radial direction in such a way that the turbine gets the minimal thermal stress. So, to have this, we require this liner cooling.

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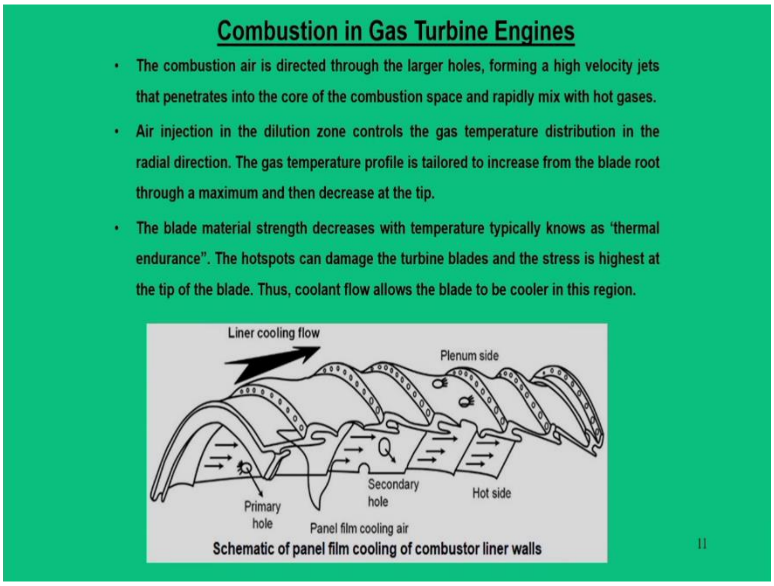

Combustion in Gas Turbine Engines

- The combustion air is directed through the larger holes, forming a high velocity jets that penetrates into the core of the combustion space and rapidly mix with hot gases.
- Air injection in the dilution zone controls the gas temperature distribution in the radial direction. The gas temperature profile is tailored to increase from the blade root through a maximum and then decrease at the tip.
- The blade material strength decreases with temperature typically knows as 'thermal endurance". The hotspots can damage the turbine blades and the stress is highest at the tip of the blade. Thus, coolant flow allows the blade to be cooler in this region.

Schematic of panel film cooling of combustor liner walls

So, what do we mean by this minimal stress means that is where the role of dilution zone comes into pictures. What we expect is that if you look at turbine viewpoint, turbine normally faces the highest temperature in a gas turbine engines and because of this high temperatures or hot spot gases, they can damage the turbine blades.

So, in order to reduce this thermal endurance, we expect that there has to be a particular temperature distribution across the turbine blades and what we expect is that the gas turbine temperature has to be tailored to increase it from blade root through a maximum, then decrease at the tip.

So, the temperature profile has to be tailored in such a way that it should increase first again while it reaches the blade tip, the temperature should fall down. So, there the role of dilution zone comes into pictures and through this dilution zone, we tailor the frame or give a particular temperature distribution pattern to the flame such that the thermal endurance at the turbine blades gets minimized.

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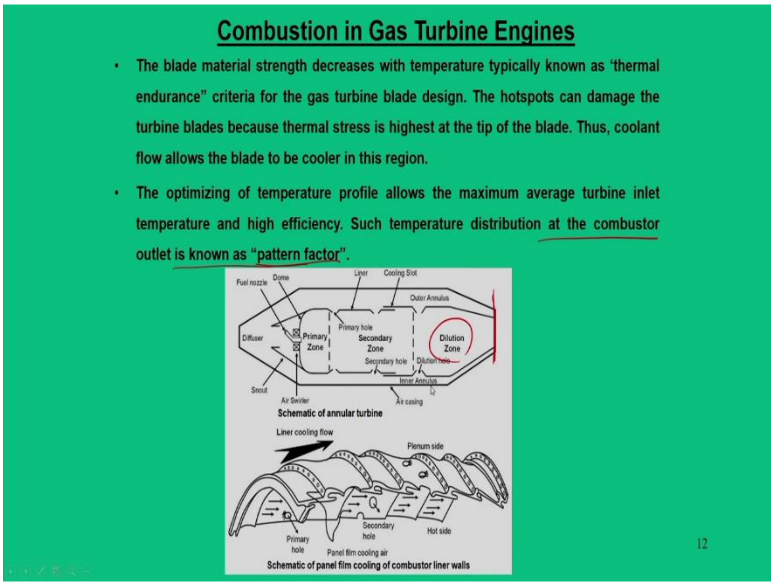

Combustion in Gas Turbine Engines

- The blade material strength decreases with temperature typically known as 'thermal endurance" criteria for the gas turbine blade design. The hotspots can damage the turbine blades because thermal stress is highest at the tip of the blade. Thus, coolant flow allows the blade to be cooler in this region.
- The optimizing of temperature profile allows the maximum average turbine inlet temperature and high efficiency. Such temperature distribution at the combustor outlet is known as "pattern factor".

Schematic of annular turbine

Schematic of panel film cooling of combustor liner walls

And, such a temperature distribution pattern for the gas turbine combustor outlet is known as pattern factors. Normally, what type of temperature distribution we require at the end of the combustor is nothing, but your pattern factor that has to be taken into account while doing this.

And, for this the dilution zones, normally, it is a kind of a cooling effect that is produced for the flame to quench and subsequently entire combustion products has to expand. So, this is a different part of discussions. So, this particular concept talks about the gas turbine combustor.

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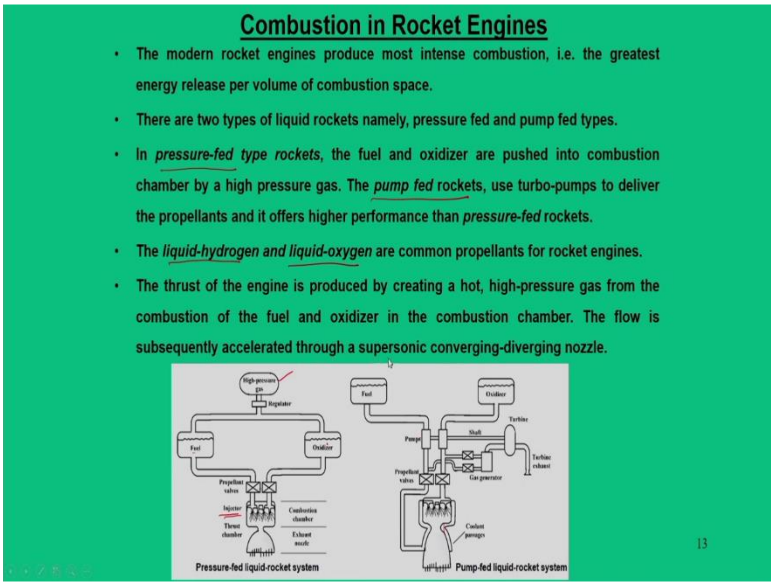

Combustion in Rocket Engines

- The modern rocket engines produce most intense combustion, i.e. the greatest energy release per volume of combustion space.
- There are two types of liquid rockets namely, pressure fed and pump fed types.
- In *pressure-fed type rockets*, the fuel and oxidizer are pushed into combustion chamber by a high pressure gas. The *pump fed* rockets, use turbo-pumps to deliver the propellants and it offers higher performance than *pressure-fed* rockets.
- The *liquid-hydrogen and liquid-oxygen* are common propellants for rocket engines.
- The thrust of the engine is produced by creating a hot, high-pressure gas from the combustion of the fuel and oxidizer in the combustion chamber. The flow is subsequently accelerated through a supersonic converging-diverging nozzle.

Pressure-fed liquid-rocket system

Pump-fed liquid-rocket system

The next part or when you travel faster the gas combustion will not happen, we require some kind of other technology where we should avoid the use of mechanical devices, rather we expect that the phenomena through shock waves or assisted combustion comes into pictures. So, what happens is that when you travel faster and when you are going to very high altitudes, there is a lack of oxygen or oxidizers.

So, the rocket engines normally carry fuel and oxidizers in separate tanks and this fuel and oxidizers are normally liquid hydrogen and liquid oxygen. And, the concentration in liquid is done because they have large energy density as compared to the gas phase mode.

And, there are two types of combustor – one is pressure-fed type, other is pump fed-type. What happens if you look at this particular figure, the we have a high-pressure gas and this high-pressure gas pressurizes the fuel and oxidizer tank through this propellant valve as a result, the fuel is injected into the thrust chamber.

Whereas, in a pump fed type we do not have this high-pressure gas medium, rather we have two different pumps that gives necessary pressures for this propellant valve to inject the fuel into the combustion zone. The thrust of the engine is produced by creating hot high-pressure gas from the combustion of fuel and oxidizer in the combustion chamber. The flow is subsequently accelerated through the supersonic diverging nozzles.

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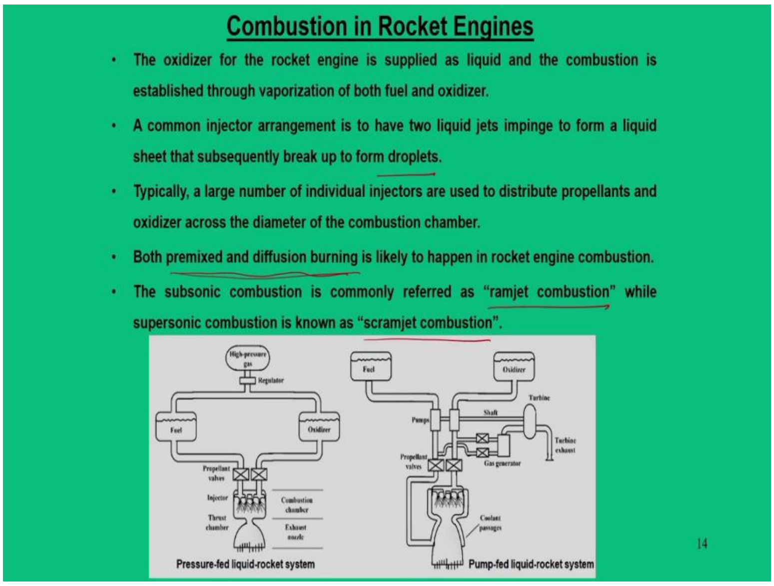

Combustion in Rocket Engines

- The oxidizer for the rocket engine is supplied as liquid and the combustion is established through vaporization of both fuel and oxidizer.
- A common injector arrangement is to have two liquid jets impinge to form a liquid sheet that subsequently break up to form droplets.
- Typically, a large number of individual injectors are used to distribute propellants and oxidizer across the diameter of the combustion chamber.
- Both premixed and diffusion burning is likely to happen in rocket engine combustion.
- The subsonic combustion is commonly referred as "ramjet combustion" while supersonic combustion is known as "scramjet combustion".

In fact, the type of combustion that is going to happen is one is droplet because that it is a droplet kind of combustions and here also we can think premix and diffusion burning which is likely to happen in a rocket combustion mode. Another important aspect is that when you think about rocket combustions the subsonic combustions is normally referred as ramjet combustions and supersonic combustions are referred as scramjet combustions. So, these are different terminology that are used in the rocket engines.

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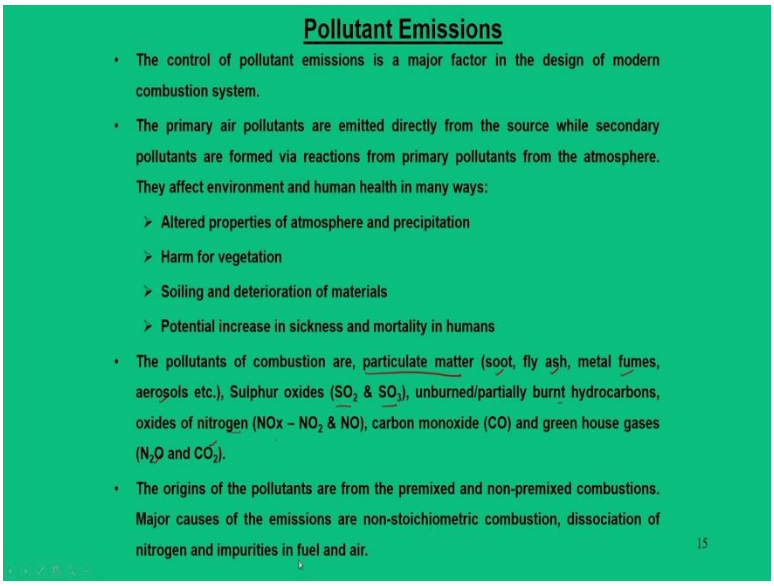

Pollutant Emissions

- The control of pollutant emissions is a major factor in the design of modern combustion system.
- The primary air pollutants are emitted directly from the source while secondary pollutants are formed via reactions from primary pollutants from the atmosphere. They affect environment and human health in many ways:
  - Altered properties of atmosphere and precipitation
  - Harm for vegetation
  - Soiling and deterioration of materials
  - Potential increase in sickness and mortality in humans
- The pollutants of combustion are, particulate matter (soot, fly ash, metal fumes, aerosols etc.), Sulphur oxides (SO_2 & SO_3), unburned/partially burnt hydrocarbons, oxides of nitrogen (NOx – NO_2 & NO), carbon monoxide (CO) and green house gases (N_2O and CO_2).
- The origins of the pollutants are from the premixed and non-premixed combustions. Major causes of the emissions are non-stoichiometric combustion, dissociation of nitrogen and impurities in fuel and air.

The next important aspect that we are going to discuss is the pollutant emissions. In fact, the control of pollutant emissions is a major factor in the design of modern combustion systems because the primary air that are emitted directly from the source via many chemical reactions affect the atmospheres.

So, when such reaction takes place they affect environment as well as the human health in many ways. First is, altered properties of the atmosphere because this combustion phenomena changes the atmosphere air quality. They are harmful for vegetations. They also damage soils and of course, deteriorate the materials and there is a potential increase in the sickness and mortality of the human beings. So, these are the kind of societal loss due to the pollutions.

Now, typically in the engine combustions the type of pollutants are first thing is particulate matter. So, particulate matters come as a soot particle, fly ash, metal fumes, aerosols that we can see in the atmosphere. Then we have sulfur dioxide in the form of SO_2 and SO_3; then we may have unburnt or partially burnt hydrocarbons. Then we can have oxides of nitrogen NOx typically NO_2 or NO, we may have carbon monoxides then greenhouse gases the N_2O and CO_2. So, all these things are the culprits for the human civilization.

So, the origins of all these things are nothing but the premixed combustion and non-premixed combustions. Other possibilities could be we do not operate the combustion through a non-stoichiometric mode or normally the combustion processes occur through non-stoichiometric mode or dissociation of nitrogen and impurities in the fuel and air.

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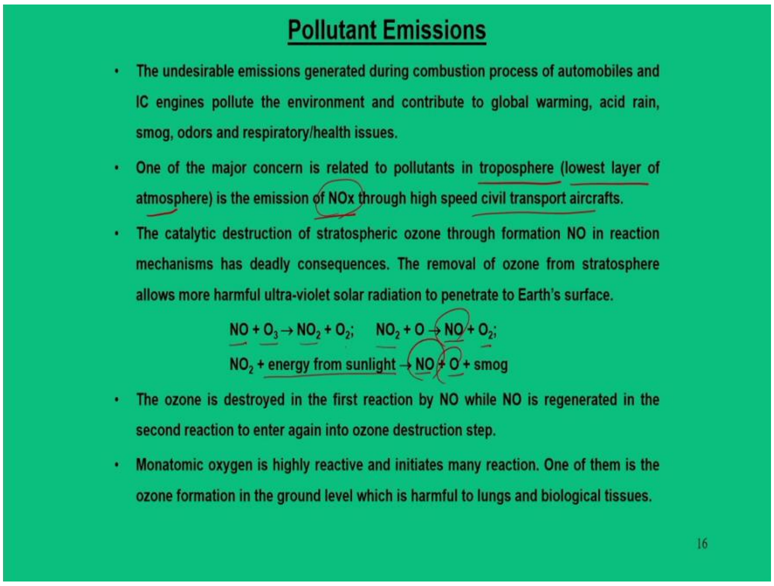

Pollutant Emissions

- The undesirable emissions generated during combustion process of automobiles and IC engines pollute the environment and contribute to global warming, acid rain, smog, odors and respiratory/health issues.
- One of the major concern is related to pollutants in troposphere (lowest layer of atmosphere) is the emission of NOx through high speed civil transport aircrafts.
- The catalytic destruction of stratospheric ozone through formation NO in reaction mechanisms has deadly consequences. The removal of ozone from stratosphere allows more harmful ultra-violet solar radiation to penetrate to Earth's surface.

$$NO + O_3 \rightarrow NO_2 + O_2; \quad NO_2 + O \rightarrow NO + O_2;$$

$$NO_2 + \text{energy from sunlight} \rightarrow NO + O + \text{smog}$$

- The ozone is destroyed in the first reaction by NO while NO is regenerated in the second reaction to enter again into ozone destruction step.
- Monatomic oxygen is highly reactive and initiates many reaction. One of them is the ozone formation in the ground level which is harmful to lungs and biological tissues.

Now, let us see how those pollutant emissions are affecting the human life and the atmosphere. The undesirable emissions generated during a combustion process of automobiles and IC engines pollute the environment and they contribute to global warming, acid rains, smoke, order, respiratory and health issues.

Now, one of the major concerns of the pollutants is in the troposphere and this troposphere is nothing, but the lowest layer of the atmosphere. And, what happens there the emission of NOx and when you talk about the civil transport aircrafts; so, they are at lower altitudes normally they travel at 30000 feet altitude. So, at that locations the question of emission of NOx becomes a vital factor.

What happens there is that if you look at atmosphere it is covered with ozone layer and these ozone layers protect the sunlights. So, various wavelength forms of the sunlight gets protected through the ozone layer and they do not come back to the earth surface. And, but what this pollution does is that these pollutions create or breaks the ozone layer.

How? That is known as catalytic destructions. The catalytic destruction of stratospheric air ozone is through the formation of NO in the reaction mechanism has a deadly consequences. The removal of ozone from the stratosphere allows harmful ultraviolet solar radiations to penetrate into earth atmosphere.

How? First thing is that when you have this NO formations when it reacts with O_3, it gives it gives NO_2 and O_2 and this NO_2 again mix with O it gives NO plus O_2. Now, again this NO_2 when it gets energy from the sunlight it forms NO plus O. So, in other words means NO and O they act as a catalyst. Every time those things are there it keeps on forming NO and because of this NO, O_3 it breaks the ozone layer. because NO only reacts with O_3 to form O_2.

So, because of this reason we can say the ozone is destroyed first by reaction NO while NO is again regenerated in the second reactions and another important aspect is that mono atomic oxygen is highly reactive. So, it initiates many reactions, one of them is the ozone formation at the ground level as well and which is harmful for lungs and biological tissues. Ozone, although it protects the sunlight, but at the ground level, the ozone has a harmful effect for the human bodies. So, these are the side effects of the pollutants.

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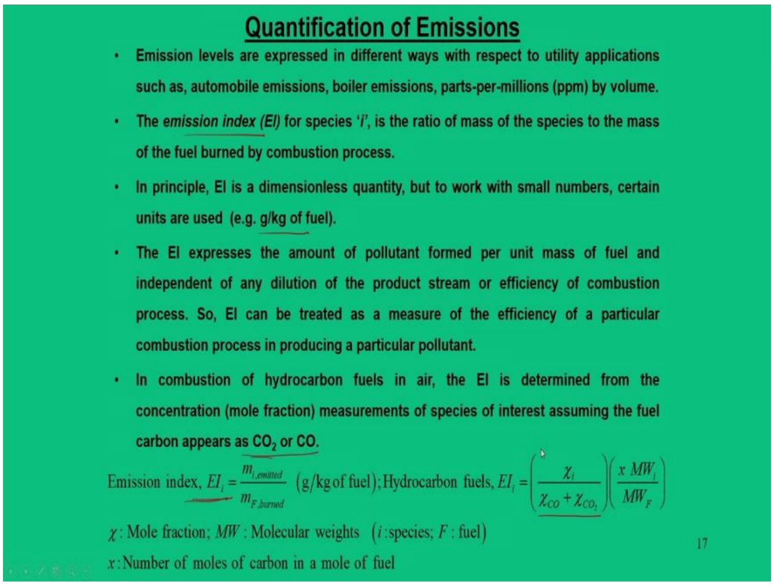

Quantification of Emissions

- Emission levels are expressed in different ways with respect to utility applications such as, automobile emissions, boiler emissions, parts-per-millions (ppm) by volume.
- The *emission index (EI)* for species '*i*', is the ratio of mass of the species to the mass of the fuel burned by combustion process.
- In principle, EI is a dimensionless quantity, but to work with small numbers, certain units are used (e.g. g/kg of fuel).
- The EI expresses the amount of pollutant formed per unit mass of fuel and independent of any dilution of the product stream or efficiency of combustion process. So, EI can be treated as a measure of the efficiency of a particular combustion process in producing a particular pollutant.
- In combustion of hydrocarbon fuels in air, the EI is determined from the concentration (mole fraction) measurements of species of interest assuming the fuel carbon appears as CO_2 or CO.

Emission index, $EI_i = \frac{m_{i,emitted}}{m_{F,burned}}$ (g/kg of fuel); Hydrocarbon fuels, $EI_i = \left(\frac{\chi_i}{\chi_{CO} + \chi_{CO_2}}\right)\left(\frac{x\, MW_i}{MW_F}\right)$

χ : Mole fraction; MW : Molecular weights (i : species; F : fuel)

x : Number of moles of carbon in a mole of fuel

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Now, let us see how we can quantify the emissions. So, one way to look at the emissions is representing as an emission index. The emission index for any species which is formed due to combustion if you denote that EI is the ratio of mass of the species to the mass of the fuel burnt by the combustion process.

In particular, this emission index EI is a dimensionless quantity, but we typically represent like grams per kg of fuels so that we can quantify in a proper manner. This EI expresses the amount of pollutant that is formed per unit mass of the fuel and independent of any dilution of the product streams or efficiency of the combustion process.

And this EI can be treated as the measure of efficiency of a particular combustion process in producing a particular pollutant. The combustion hydrocarbon fuels in the air is determined through the concentration or mole fraction measurements assuming the fuel carbon appears as a CO_2 or CO. So, one way to look at is define the term emission index EI for the species I, mass of the species I which is emitted to the kg of the fuel burnt.

Now, such things if you want to express in the molar form we can say that particularly the parameter of interest is either CO_2 or CO and we have to normalize this species I with respect to CO and CO_2 and each of them we can find out through this chemical reactions. And, here x is the mole fraction; MW stands for the molecular weight.

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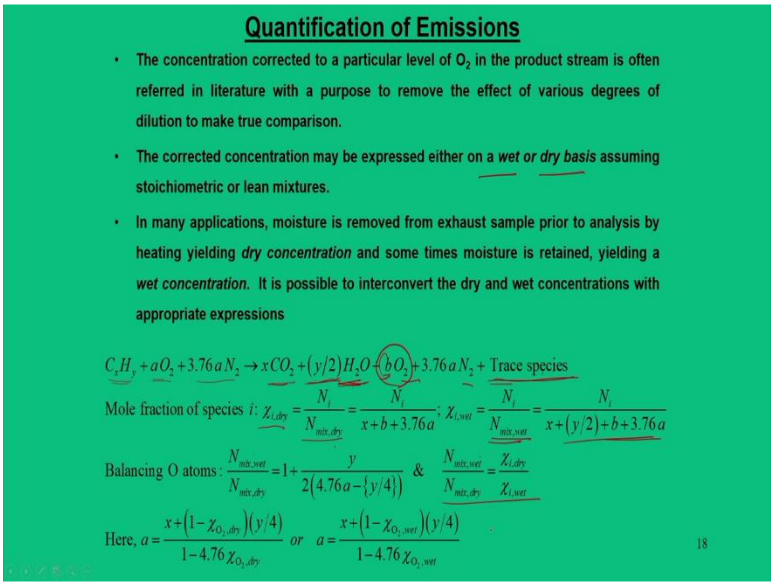

Quantification of Emissions

- The concentration corrected to a particular level of O_2 in the product stream is often referred in literature with a purpose to remove the effect of various degrees of dilution to make true comparison.
- The corrected concentration may be expressed either on a *wet or dry basis* assuming stoichiometric or lean mixtures.
- In many applications, moisture is removed from exhaust sample prior to analysis by heating yielding *dry concentration* and some times moisture is retained, yielding a *wet concentration.* It is possible to interconvert the dry and wet concentrations with appropriate expressions

$$C_xH_y + aO_2 + 3.76aN_2 \rightarrow xCO_2 + (y/2)H_2O + bO_2 + 3.76aN_2 + \text{Trace species}$$

Mole fraction of species i: $\chi_{i,dry} = \frac{N_i}{N_{mix,dry}} = \frac{N_i}{x+b+3.76a}$; $\chi_{i,wet} = \frac{N_i}{N_{mix,wet}} = \frac{N_i}{x+(y/2)+b+3.76a}$

Balancing O atoms: $\frac{N_{mix,wet}}{N_{mix,dry}} = 1 + \frac{y}{2(4.76a-\{y/4\})}$ & $\frac{N_{mix,wet}}{N_{mix,dry}} = \frac{\chi_{i,dry}}{\chi_{i,wet}}$

Here, $a = \frac{x+(1-\chi_{O_2,dry})(y/4)}{1-4.76\chi_{O_2,dry}}$ *or* $a = \frac{x+(1-\chi_{O_2,wet})(y/4)}{1-4.76\chi_{O_2,wet}}$

So, these are the by definitions, normally the emission analysis is done through a gas analyzer, we take a strip of gas or certain quantity of the gas at the end of the combustion pipe. So, taking that sample we try to measure. Now, if you look at particular combustion equation for a hydrocarbon fuel if you say $C_xH_y + a(O_2 + 3.76N_2) \rightarrow xCO_2 + \left(\frac{Y}{2}\right) H_2O + (3.76a)N_2 + Tracer\ species.$

And, the tracer species could be formation of CO, NO depending on the nature of the mixtures they can be like this. Now, here the one important point is that whatever trace species that appears in the reactions that can be controlled through the quantity b means that can be linked or that can be correlated the equivalent quantity of oxygens through the parameter b. So, for that reasons we say that we define a parameter called as a concentration corrected to particular level of O_2 in the product stream.

That is typically referred in the literatures to have a kind of a proper comparisons. And, this corrected concentration is either represented as a wet basis or dry basis. Now, to represent dry basis what do you say that if you look at reactions. So, if you want to calculate on dry basis $X_{i,dry} = \frac{N_i}{N_{mix,dry}}$.

Now, when the total mixture number of moles needs to be calculated then this H_2O has to be ignored. Now, when you calculate with respect to wet. the H_2O has to be included; that means, the coefficients of H_2O that is Y/ 2 has to be included in the total number of moles. I am not going into details.

So, once you take the balancing different formulations can be made like $\frac{N_{mix,wet}}{N_{mix,dry}} = \frac{X_{i,dry}}{X_{i,wet}}$

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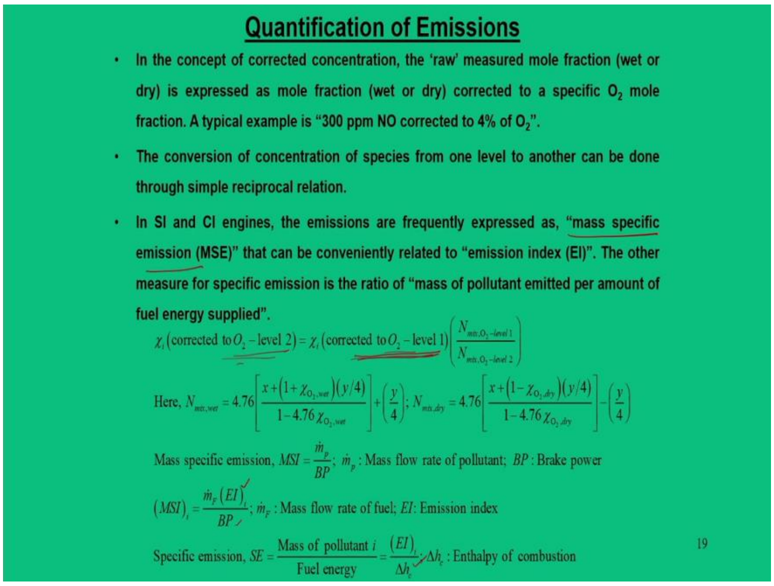

Quantification of Emissions

- In the concept of corrected concentration, the 'raw' measured mole fraction (wet or dry) is expressed as mole fraction (wet or dry) corrected to a specific O_2 mole fraction. A typical example is "300 ppm NO corrected to 4% of O_2".
- The conversion of concentration of species from one level to another can be done through simple reciprocal relation.
- In SI and CI engines, the emissions are frequently expressed as, "mass specific emission (MSE)" that can be conveniently related to "emission index (EI)". The other measure for specific emission is the ratio of "mass of pollutant emitted per amount of fuel energy supplied".

$$\chi_i(\text{corrected to } O_2 - \text{level 2}) = \chi_i(\text{corrected to } O_2 - \text{level 1})\left(\frac{N_{mix,O_2-level\,1}}{N_{mix,O_2-level\,2}}\right)$$

$$\text{Here, } N_{mix,wet} = 4.76\left[\frac{x+(1+\chi_{O_2,wet})(y/4)}{1-4.76\chi_{O_2,wet}}\right]+\left(\frac{y}{4}\right);\ N_{mix,dry} = 4.76\left[\frac{x+(1-\chi_{O_2,dry})(y/4)}{1-4.76\chi_{O_2,dry}}\right]-\left(\frac{y}{4}\right)$$

Mass specific emission, $MSI = \frac{\dot{m}_p}{BP}$; $\dot{m}_p$: Mass flow rate of pollutant; BP : Brake power

$(MSI)_i = \frac{\dot{m}_F (EI)_i}{BP}$; $\dot{m}_F$: Mass flow rate of fuel; EI: Emission index

Specific emission, $SE = \frac{\text{Mass of pollutant } i}{\text{Fuel energy}} = \frac{(EI)_i}{\Delta h_c}$; Δh_c : Enthalpy of combustion

Another way of looking at is when we are measuring the emissions through gas analyzers, we are measuring at certain level of level 1. So, in the level 1, we are measuring some O_2 and this things has to be corrected to another level O_2 which means that if if I control the combustion parameters so that we can get another level O_2, then what would be the concentration of the species.

So, basically the trace species regulations can be controlled with an appropriate measure related to the oxygen concentrations. So, a simple algebraic equations can be from formed for this particular trace species I with respect to its concentration at level 2 and level 1 and they can be correlated with respect to mixtures of oxygen at level 1 and level 2.

So, these things we will explain when we solve a numerical problem towards the end of this class, we will explain more details on this. So, this is all about the quantification of emissions. And, there are some other methods which are typically called as mass specific emission MSE which is defined in terms of emission index and break power.

And, also we have specific emissions defined in terms of fuel and energy that is enthalpy of combustions and emission index. So, different philosophies or different applications require the quantification of emissions in a different perspectives.

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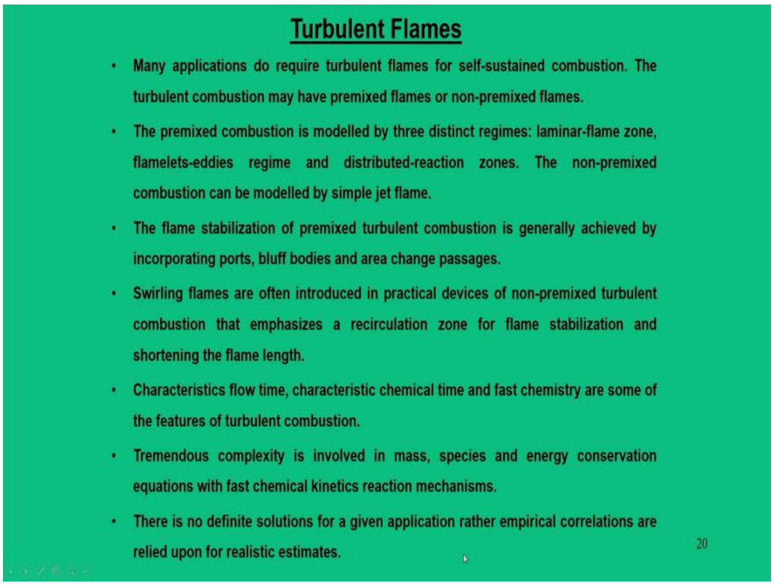

Turbulent Flames

- Many applications do require turbulent flames for self-sustained combustion. The turbulent combustion may have premixed flames or non-premixed flames.
- The premixed combustion is modelled by three distinct regimes: laminar-flame zone, flamelets-eddies regime and distributed-reaction zones. The non-premixed combustion can be modelled by simple jet flame.
- The flame stabilization of premixed turbulent combustion is generally achieved by incorporating ports, bluff bodies and area change passages.
- Swirling flames are often introduced in practical devices of non-premixed turbulent combustion that emphasizes a recirculation zone for flame stabilization and shortening the flame length.
- Characteristics flow time, characteristic chemical time and fast chemistry are some of the features of turbulent combustion.
- Tremendous complexity is involved in mass, species and energy conservation equations with fast chemical kinetics reaction mechanisms.
- There is no definite solutions for a given application rather empirical correlations are relied upon for realistic estimates.

This is all about the content. Now, I am going to the last segment that is which was supposed to be the part of this course, but due to the lack of time and lack of the nature of the course it is very difficult to follow this turbulent flame. But, rather I will just end this combustion with an introduction to turbulence flames.

So, in the combustion mode we discussed premixed combustions, non-premixed combustions, laminar premixed flame, diffusion flames, droplet combustions, droplet burning, all this concepts we have introduced. Also to some extent we tried to see how they can be mathematically modeled.

By looking at the equations we can make a judgment that when you bring more number of equations the complicacy becomes tremendous means it is a very significant complication happens. This is exactly what happens in a turbulent flow situations. Typically same concept that is pre mixed combustion and non pre mixed combustion can be equally applicable, but due to the nature of equations, we land off having a complicated equations and those equations is almost difficult to solve.

To give my final notes on this turbulence combustions, I can say many applications require turbulent flames for self sustained combustions. The turbulent combustions can have premixed flame as well as non-premixed flame. The premixed flame combustion is modeled by three distinct zones – one is laminar-flame zone, flamelets-eddies regime and distributed-reaction zones whereas, non-premixed flames are normally modeled through the simple jet flames.

The flame stabilization of premixed turbulent combustion is generally achieved by incorporating ports, bluff bodies and area change processes. We can have swirling flames that are often introduced in the practical devices for non-premixed turbulent combustion and it emphasizes recirculation zone for flame stabilization and settling the flame length.

The characteristics flow time, characteristics chemical times, fast chemistry are some of the important features for the turbulent combustions. And, because of this region, there is a tremendous complexity which is involved in mass, species and energy conservation equations with fast chemical kinetics reaction mechanisms.

So, this I will leave it to the research space that individuals can look into, and of course, the final note I can say of course, that there is not a definite solutions for a given applications and many a times the empirical correlations are relied for realistic estimates.

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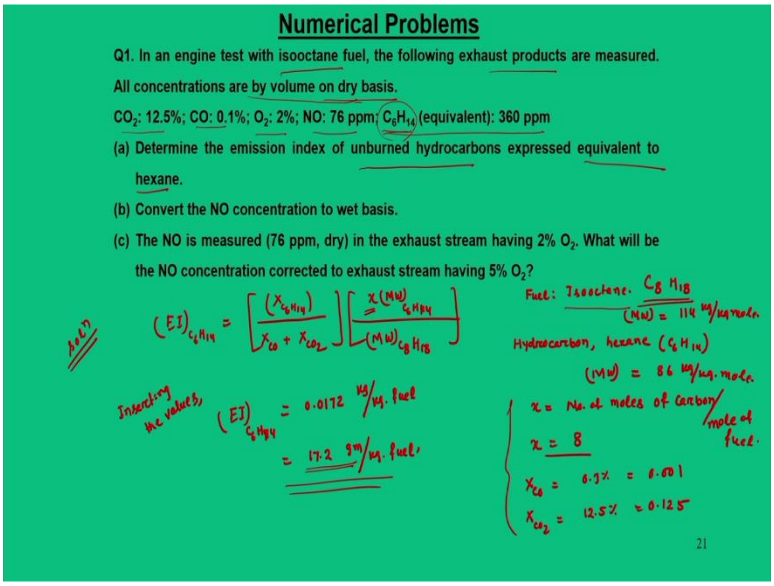

Numerical Problems

Q1. In an engine test with isooctane fuel, the following exhaust products are measured. All concentrations are by volume on dry basis.

CO_2: 12.5%; CO: 0.1%; O_2: 2%; NO: 76 ppm; C_6H_{14} (equivalent): 360 ppm

(a) Determine the emission index of unburned hydrocarbons expressed equivalent to hexane.

(b) Convert the NO concentration to wet basis.

(c) The NO is measured (76 ppm, dry) in the exhaust stream having 2% O_2. What will be the NO concentration corrected to exhaust stream having 5% O_2?

Soln

$$(EI)_{C_6H_{14}} = \left[\frac{(X_{C_6H_{14}})}{X_{CO} + X_{CO_2}}\right]\left[\frac{x(MW)_{C_6H_{14}}}{(MW)_{C_8H_{18}}}\right]$$

Fuel: Isooctane. C_8H_{18}

$(MW) = 114$ kg/kg mole.

Hydrocarbon, hexane (C_6H_{14})

$(MW) = 86$ kg/kg. mole.

x = No. of moles of carbon/mole of fuel.

$x = 8$

$X_{CO} = 0.1\% = 0.001$

$X_{CO_2} = 12.5\% = 0.125$

Inserting the values,

$$(EI)_{C_6H_{14}} = 0.0172 \text{ kg/kg. fuel}$$

$$= 17.2 \text{ gm/kg. fuel}$$

The last part I will try to solve a numerical problem which is based on the quantification of emissions the problem statement says that in an engine test which uses isooctane fuel, we measure the exhaust products by volume by volume on dry basis. And, they are CO_2, CO, O_2, NO, C_2H_4 equivalent; that means, these are the trace species which need to find out and they are nothing, but the C_6H_{14} equivalent and we need to find out the emission index of unburnt hydrocarbons.

So, instead of unburnt hydrocarbons we have introduced C_6H_{14}or hexane equivalent. So, to do this, first thing that we have to recall that what is the definition of emission index.

$$EI_{C_6H_{14}} = \left[\frac{X_{C_6H_{14}}}{X_{CO} + X_{CO_2}}\right]\left[\frac{x(MW)_{C_6H_{14}}}{(MW)_{C_8H_{18}}}\right]$$

So, here we say fuel as isooctane and that is C_8H_{18}, its molecular weight is 114 kg by kg mole. And, when you talk about hydrocarbon and this is hexane equivalent that is C_6H_{14}, its molecular weight is 86 kg per kg mole. Now, what is x? x is number of moles of carbon per mole of fuel. So, 1 mole of fuel C_8H_{18}, contains number of carbon as 8.

$$EI_{C_6H_{14}} = \left[\frac{X_{C_6H_{14}}}{0.001 + 0.125}\right]\left[\frac{8 \times 86}{114}\right] = 0.0172 kg/kg\ of\ fuel$$

So, ideally we write it as 17.2 gram per kg of fuel which means if you take 1 kg of isooctane it will give you 17.5 grams of unburnt hydrocarbons equivalent to hexane. So, this is what it means.

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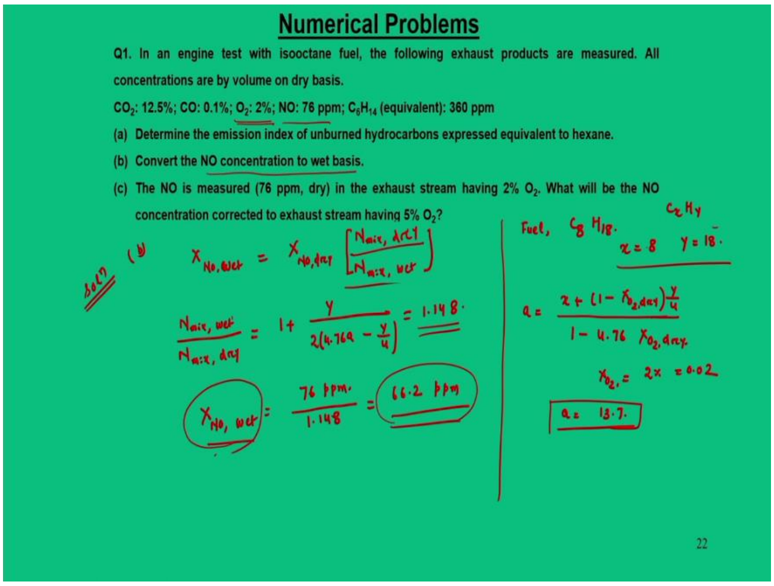

Numerical Problems

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CO_2: 12.5%; CO: 0.1%; O_2: 2%; NO: 76 ppm; C_6H_{14} (equivalent): 360 ppm

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(b) Convert the NO concentration to wet basis.

(c) The NO is measured (76 ppm, dry) in the exhaust stream having 2% O_2. What will be the NO concentration corrected to exhaust stream having 5% O_2?

Sol^n (b)

$$X_{NO,wet} = X_{NO,dry}\left[\frac{N_{mix,dry}}{N_{mix,wet}}\right]$$

$$\frac{N_{mix,wet}}{N_{mix,dry}} = 1 + \frac{y}{2\left(4.76a - \frac{y}{4}\right)} = 1.148.$$

$$X_{NO,wet} = \frac{76\ ppm.}{1.148} = 66.2\ ppm$$

Fuel, C_8H_{18}. C_xH_y

$x = 8 \quad y = 18.$

$$a = \frac{x + (1 - X_{O_2,dry})\frac{y}{4}}{1 - 4.76\, X_{O_2,dry}}$$

$X_{O_2} = 2\% = 0.02$

$a = 13.7.$

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Next thing for the same problem we are going to find out NO concentration on wet basis and for this problem, we have to recall the conversion of dry concentration to wet concentrations. So, for that things we have to recall the expressions.

$$\frac{N_{mix,wet}}{N_{mix,dry}} = \frac{X_{NO,dry}}{X_{NO,wet}};\ \frac{N_{mix,wet}}{N_{mix,dry}} = 1 + \frac{Y}{2\left(4.76a - \frac{y}{4}\right)};\ a = \frac{x + \left(1 - X_{O_2,dry}\right)\left(\frac{y}{4}\right)}{1 - 4.76X_{O_2,dry}}$$

So, we have fuel C_8H_{18}, where we can say $x = 8$, $y = 18$.

$$X_{O_2,dry} = 2\% = 0.002; a = 13.7; \frac{N_{mix,wet}}{N_{mix,dry}} = 1.148$$

$$X_{NO,wet} = \frac{76\ ppm}{1.148} = 66.2\ ppm$$

What we see is NO concentration in wet form is less than the NO concentration in dry form. So, this is the problem demonstrate how you need to compare the wet concentration and dry concentrations.

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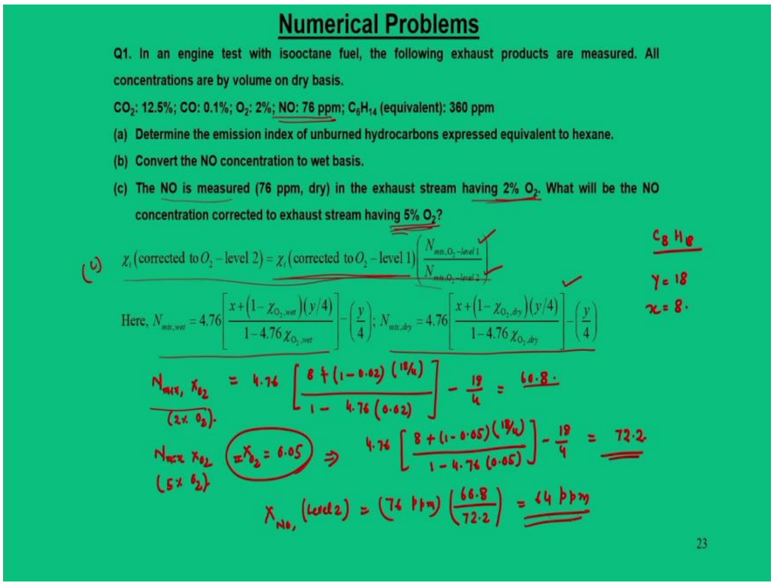

Numerical Problems

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(c) $$\chi_i(\text{corrected to } O_2-\text{level 2}) = \chi_i(\text{corrected to } O_2-\text{level 1})\left(\frac{N_{mix,O_2-level\,1}}{N_{mix,O_2-level\,2}}\right)$$

Here, $$N_{mix,wet} = 4.76\left[\frac{x+(1-\chi_{O_2,wet})(y/4)}{1-4.76\chi_{O_2,wet}}\right]-\left(\frac{y}{4}\right);\ N_{mix,dry} = 4.76\left[\frac{x+(1-\chi_{O_2,dry})(y/4)}{1-4.76\chi_{O_2,dry}}\right]-\left(\frac{y}{4}\right)$$

C_8H_{18}

$y = 18$

$x = 8.$

N_{mix}, X_{O_2} (2% O_2). $= 4.76\left[\frac{8+(1-0.02)(18/4)}{1-4.76(0.02)}\right]-\frac{18}{4} = 60.8.$

$N_{mix}\ X_{O_2}$ (5% O_2) $X_{O_2} = 0.05$ $\Rightarrow 4.76\left[\frac{8+(1-0.05)(18/4)}{1-4.76(0.05)}\right]-\frac{18}{4} = 72.2.$

X_{NO}, (level 2) $= (76\ ppm)\left(\frac{66.8}{72.2}\right) = 64\ ppm$

The last part of the problem where we are trying to correlate the two different streams of exhaust streams with different concentration of O_2. So, in the stream 1 in the level 1 we have concentration of O_2 as 2 percent; in the level 2 we need to have concentration of O_2 as 5 percent. So, how these two concentration regulates the NO measurements. This is the things that we need to address.

Now, for this problem we almost have this data which are available with us. So, we have to use two expressions NOx mixture dry and mixture wet expressions.

$$Fuel: C_8H_{18}; x = 8, y = 18$$

$$N_{mix,X_{O_2}} = 4.76\left[\frac{8+(1-0.02)(18/4)}{1-4.76(0.02)}\right]-\frac{18}{4} = 60.8\ (\because X_{O_2} = 0.02)$$

$$N_{mix,X_{O_2}} = 4.76\left[\frac{8+(1-0.05)(18/4)}{1-4.76(0.05)}\right]-\frac{18}{4} = 72.2\ (\because X_{O_2} = 0.05)$$

So, we have two numbers one is this number, other is that number.

$$X_{NO}(level\ 2) = X_{NO}(level\ 1)\left(\frac{60.8}{72.2}\right) = 64\ ppm;\ (\because X_{NO}(level\ 1) = 76\ ppm)$$

So, what it says is that by regulating the oxygen concentration to 5 percent, we can see that NO concentration drastically reduces. So, in other words we can control our unburnt mixture in such a way so that we can regulate the oxygen concentration to 5 percentage. So, that means, on dry basis when the oxygen concentration increases from 2 to 5 percent we can see NO concentration reduces from 76 ppm to 64 ppm.

This is what the idea for reducing the pollutants during a combustion process by regulating the oxygen concentrations and that is where the importance of this expression is realized.

So, with this, I conclude this particular lecture this particular module and till date we have completed all the modules and thank you for your attentions. I hope you have enjoyed all the modules and best wishes and best of luck for your future career.

Thank you.