Environmental Air Pollution

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Lecture No. 11
Internal Combustion Engine and Air Pollution – 1

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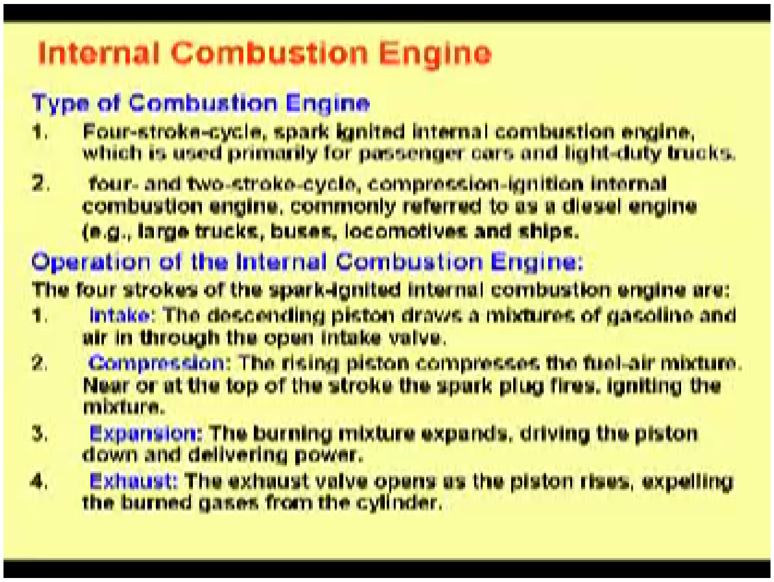

Internal Combustion Engine

Type of Combustion Engine

1. Four-stroke-cycle, spark ignited internal combustion engine, which is used primarily for passenger cars and light-duty trucks.
2. four- and two-stroke-cycle, compression-ignition internal combustion engine, commonly referred to as a diesel engine (e.g., large trucks, buses, locomotives and ships.

Operation of the Internal Combustion Engine:

The four strokes of the spark-ignited internal combustion engine are:

1. **Intake:** The descending piston draws a mixtures of gasoline and air in through the open intake valve.
2. **Compression:** The rising piston compresses the fuel-air mixture. Near or at the top of the stroke the spark plug fires, igniting the mixture.
3. **Expansion:** The burning mixture expands, driving the piston down and delivering power.
4. **Exhaust:** The exhaust valve opens as the piston rises, expelling the burned gases from the cylinder.

What we will do today is talk about more about combustion because we identified that combustion was one of the main reasons for most of the air pollutants that you see in the atmosphere. We will quickly see what you have done probably in your undergraduate. We are looking into the thermodynamics or engines. You study a little bit about engines irrespective of what branch you come from. We all understand there are two-stroke engines and there are four-stroke engines. Two-stroke engines are a little dirtier because ah we are not giving enough time for the combustion to complete and not getting the equivalence in the process.

Anyway, let us have a quick look at four-stroke-engines that are spark ignition engines. In fact, in India, a policy decision has been taken that we will not produce any more two-stroke engines. I would like that you recall the two-stroke engines and four-stroke engines. Within that, there are two types of engine – one is the spark ignition engine and the other is the compression engine or that can be ignited on its own. When we talk about compression-ignition internal engines, these are largely trucks, buses, locomotives, ships and so on. Some large engines are compression engines but they may also be two-stroke. They are very very few. Apart from that, we should understand or at least recall that there are four cycles or four strokes – intake, compression, expansion and exhaust. Do not read so much in here because there is a little figure that you will all recall. That is much better and easier to understand.

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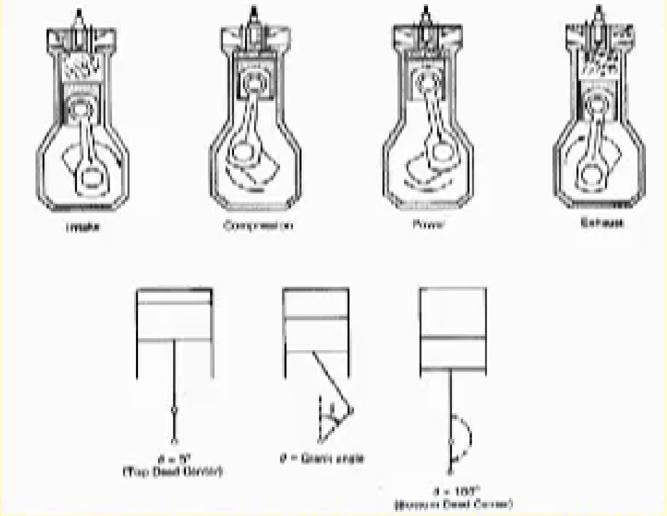

Figure: Four-stroke-cycle, spark-ignited internal combustion engine: stroke 1, intake; stroke 2, compression; stroke 3, power; stroke 4, exhaust.

The first stroke is intake. What you see on the top of this is the intake valve. The fuel is withdrawn and the piston is moving down. This is the outlet or exhaust – you see that it is closed here because there is a closing here. Once this is completely filled with air and fuel, then compression starts. So the piston is moving up and both are closed – see here, the intake is also closed and the exhaust is also closed (the little line you see). So we get a compression stroke.

Then, there is a power or expansion stroke. In that case also, both the valves – inlet as well as outlet or exhaust – should be closed. These are closed. Once you have the exhaust, the inlet is closed, the exhaust should open, things move out from there and as a result, the cycle goes on and then we continue to get the power stroke. You can also see that this position where the theta is 0…. Theta is called the crank angle between the piston rod and the crank rod and then this is called as theta. When it is in this position, this is called top dead center – we all know that, then theta is zero. Whatever the angle is, that is theta. When it is at the bottom dead center, the theta is equal to 180.

In two-stroke engine, there will be only two strokes but most of the time, we in India are talking mostly about the four-stroke engines. In fact, you see that all scooters have been converted to four-stroke engines. We will probably see in the lecture that four-stroke engines are cleaner than two-stroke engines. In two-stroke, you get the power very quickly. Every second stroke, you are getting the power but in four-stroke…. The kind of pickup that you have in scooters that were two-stroke (Priya and all) will be much more than the other scooters, but the technology is changing very rapidly in this case. We do not want to be experts on this but we still want to understand a few things.

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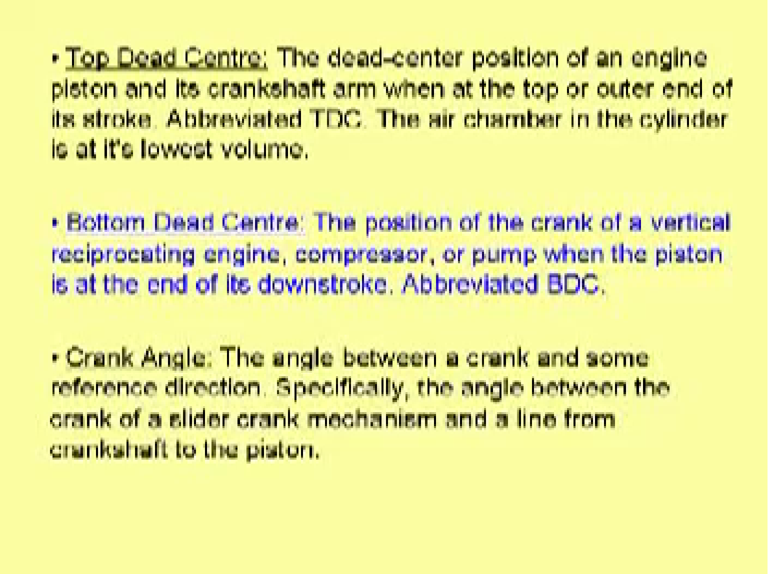

- Top Dead Centre: The dead-center position of an engine piston and its crankshaft arm when at the top or outer end of its stroke. Abbreviated TDC. The air chamber in the cylinder is at it's lowest volume.

- Bottom Dead Centre: The position of the crank of a vertical reciprocating engine, compressor, or pump when the piston is at the end of its downstroke. Abbreviated BDC.

- Crank Angle: The angle between a crank and some reference direction. Specifically, the angle between the crank of a slider crank mechanism and a line from crankshaft to the piston.

This is the same thing that we described – the top dead center, the bottom dead center and the crank angle. Sometimes, the emissions also depend on the position where the piston is. I will pass this on to you, so you do not have to worry about this. I want to tell you a little bit about fuels – not so much into detail but what are the fuels.

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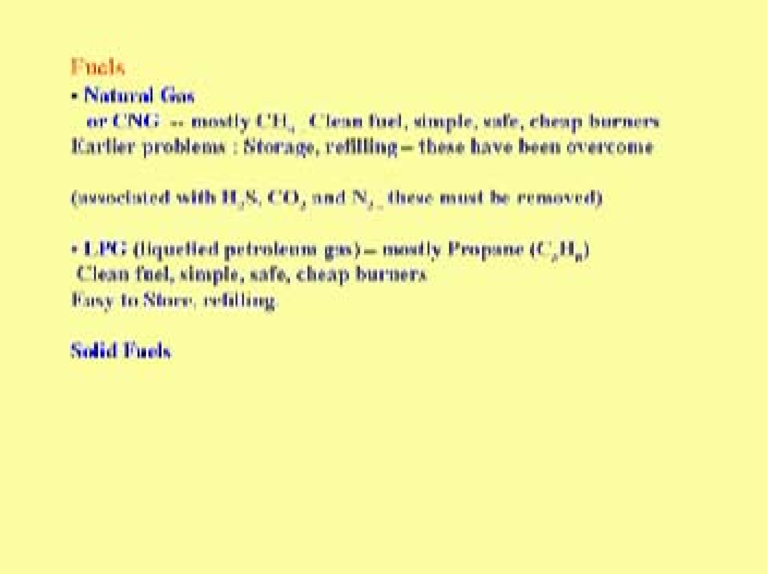

Fuels

- **Natural Gas**
  or CNG -- mostly CH_4 Clean fuel, simple, safe, cheap burners

Earlier problems : Storage, refilling – these have been overcome

(associated with H_2S, CO_2 and N_2 these must be removed)

- LPG (liquefied petroleum gas) – mostly Propane (C_3H_8)
  Clean fuel, simple, safe, cheap burners

Easy to Store, refilling

Solid Fuels

We all know natural gas or CNG (compressed natural gas). You are all seeing that there is a revolution – more and more people are using CNG now. Earlier, most of the time, it was gasoline but you see that CNG has become very popular now. CNG is largely methane; it is a very clean fuel, simple and safe. It is not proper for somebody to say it is not safe – it is safe. The burners that you require to burn CNG are very cheap burners because the cost of the burner sometimes is exorbitant.

The earlier problem as to why methane was not used was largely with storage and refilling. It was not easy to store at the petrol pumps or in the engine and refilling was more of a problem – how do you refill the whole thing. But these problems have been taken care with technology and now, you can find more and more outlets. It takes a while. First, of course, you bring the pipeline and then the transport through the trucks is a little difficult. Moreover, how to transfer the CNG was a problem.

The other associated problem with natural gas is that when it comes out from its source, there is a significant amount of H_2S along with this. CO_2 and then nitrogen and H_2S especially must be removed. Sometime, the H_2S can be in percentage. Just imagine in percentage. Suppose there is a plant dealing with methane production and there are some leakages there. Leakage of the methane in the atmosphere because there is already a significant amount of methane in the atmosphere.

But if the H_2S leaks along with this, there will be a hue and cry. The order threshold of H_2S is as low as 40 micrograms per meter cube. A little amount of methane makes people uncomfortable. They may find there is something terribly wrong when H_2S is in percentage. Earlier because of these problems and storage and transportation, people were not using methane. In fact, in many of the oil fields, methane was simply burnt because they were interested in the liquid product but things have changed with technology and we are using a lot of CNG.

Liquefied petroleum gas that we use in houses is largely propane. It is a clean fuel, simple, safe, cheap burners, easy to store and refill because you cannot liquefy CNG whereas you can liquefy this because it is a higher molecular compound. You can liquefy this and store it and right in the atmospheric temperature with the pressure that you are dealing with, it can be liquefied as well as in the vapor phase also and then you can use this. It is easy to store and refill. Many things are using LPG – not just in houses but even in automobiles, we have started using LPG.

[Conversation between student and professor - Not Audible (08:37 min)]

Both reasonably burn well but methane is directly available at the source. Wherever you are doing the exploration, methane is a product along with liquid crude that you get. LPG is to be produced and processed at the plant. LPG will not come out because CNG is in the gas form and so it will come automatically but LPG is produced in the refinery. The problem with LPG is refilling.

If you go to CNG outlets, they are able to fill CNG for you but for LPG, the cylinders are exchange because you cannot do refilling of LPG so easily – this needs to be liquefied and stored. This little bit reminds me… suppose you are at home and you have the LPG cylinder… we are drifting from our topic but ….

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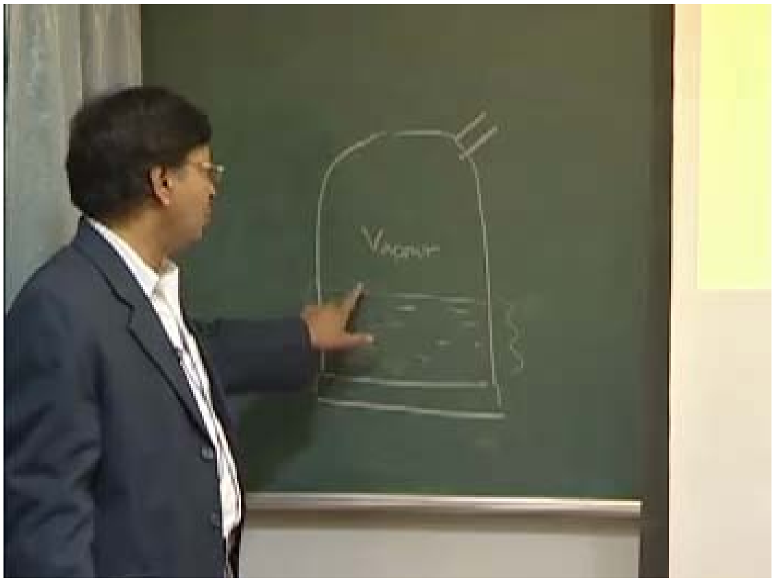

This is the storage. LPG is really liquid inside and there is a vapor above this. So it has vapor pressure and then this vapor constantly comes out. You are burning this vapor. This is the problem. Since it is the pressure that is maintained by this and the pressure is always the same, the problem with LPG in households is that you will never know when LPG cylinders are likely to be emptied unless you put then on the weighing scale.

We all know that housewives suddenly say that gas is finished. Gas is finished because pressure is always there here because of this (Refer Slide Time: 10:35). Pressure is not reduced but suddenly as this goes by, the pressure is still maintained and then this disappears suddenly. This is a very simple mechanism. It takes the heat from the surrounding environment and then this becomes in the vapor phase and what you need is the latent heat, which it takes from the surroundings.

Suppose you run into the problem, try this. When you run into the problem and your mother or your wife or whosoever you are working with suddenly says the gas is finished, you can…. You might have even observed that shopkeepers or restaurant people will not keep it vertical. Of course, you should keep it vertical but they will put it upside down and in the winter especially, if you can put a little hot water on this – not very advisable but during an emergency, you put hot water on this, lay it down and put a little hot water because you can get hot water from electricity or you have the hot water somehow, you might still be able to reuse the remaining little liquid that you have because that was not able to vaporize because you need a little heat in that area. You have laid it down so that the pressure is built up on this side and this can vaporize because this is a liquefied gas and you can still use it.

Some people wrap the clothes and put a little hot water and then your LPG cylinder will work a little bit longer than ordinarily. But now, people have ways by which they can even directly from the petrol pump fill the propane into the vehicle. Of course, there is stationary combustion – people do use this easily. Let us also talk about solid fuels. I will pass on this table. Just have a look at this as to what are solid fuels because the major problem of air pollution is largely from solid fuels.

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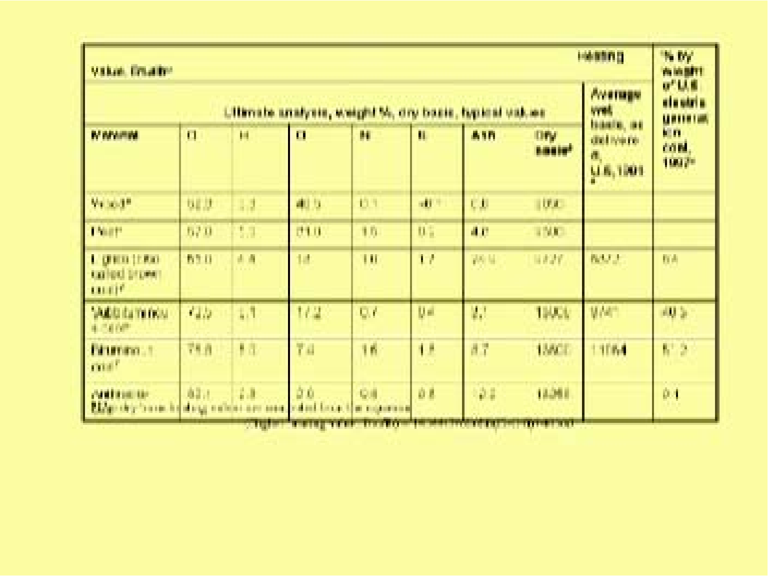

You see coal and all. This is a little analysis that is taken from a book. You can burn wood, heat, lignite, sub-bituminous and bituminous coal. As the ageing process happens, the carbon content goes up. You have the [13:20] wood. You have carbon, hydrogen and oxygen, some amount of nitrogen is there, some amount of sulfur is there and ash of course is a very significant part. These are the typical numbers. They can vary significantly depending on what source we are talking about.

There are coals that may have sulfur content as high as 4 percent, there are coals from certain [13:45] that may have the ash content or especially the bituminous coal, ash content as high as 50 percent, but we still burn them because we get energy. Therefore, the coal will have many things that can burn other than carbon and hydrogen. Solid fuels will have a lot of emissions of ash, a lot of emissions of oxides and nitrogen and also a lot of emissions of sulfur dioxide. Here, what you need to see is the carbon, hydrogen, oxygen and nitrogen sulfate.

When you want to reduce the carbon dioxide emissions, when you want to reduce the carbon dioxide emission, these fuels are obviously no good because nowadays, people are looking very comprehensively at what kind of fuel we should use to reduce CO_2 emissions because of global warming. Some of the students may know this – now, you can trade. This also becomes a factor that you want to use this coal or this coal because the emissions of carbon dioxide will be much lower here.

This is the general formula for getting the heating value of the coal in terms of the dry values computed from the equation. The high heating values as the British thermal unit per pound, you can always do the conversion, is times of the carbon and times the hydrogen minus oxygen because if the oxygen is more, that is not going to burn plus this quantity with the sulfur. This becomes very very small in terms of the heat value but this sulfur can also burn and it can give you some heat. This will be in very very small quantities. Just do some calculation. We have some values here.

Average wet basis as delivered receiving [15:43], heating values are given here and then this is on the dry basis. I do not know if you want to try this. Try this and see that you get this number to indicate as to how much heat will be available. Depending on your source, you can use…. Why I am talking to about especially about the carbon content is we might just quite relate it to…. Some of you know but let me also….

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Kyoto Protocol

CDM –

Rich Countries can
invest in developing
Countries in terms of
low CO_2 emission technol
and get CARBON CREDIT.

We all know that we have to reduce the CO_2 emissions. One of the techniques is CDM. In this case, rich countries can invest in developing countries in terms of low CO_2 emission technology and get carbon credit. Here, the idea is…. Suppose I have mostly anthracite coal in the country and I am going to burn most of the anthracite. I am a developing country and I have no choice, I have to still develop. Suppose some country comes forward and says, “Please do not burn this. For part of the coal, we will supply you with better coal, which has low carbon”, the CO_2 emission will reduce but the reduction in the CO_2 emission that will occur will go to as a credit to the other country and that is called as CDM. This is the mechanism. CO_2 is a global issue. Wherever you can control, it is an advantage. That is what I wanted to tell you about fuels. Let me also tell you about the SO_2 issue, which you see here.

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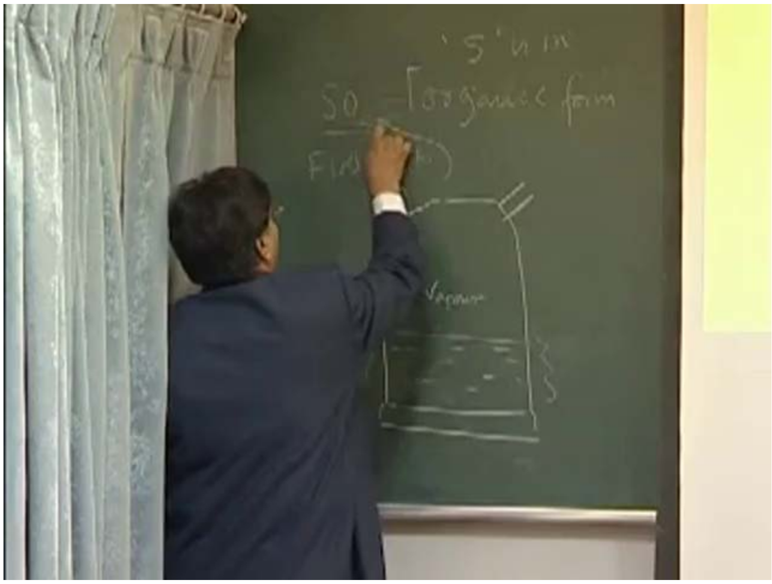

SO_2 is largely in the organic form and it can even burn much before the carbon burns. The moment you fire, you might not able to burn some carbon and then carbon may appear in your ash, but sulfur will never appear in your ash because sulfur will quickly take off and burn. That is very very important to understand because sometimes, people will say some sulfur will be in the ash, some sulfur will not burn but most of the… I should say sulfur. One of the first things to burn is SO_2. You should have an idea of the fuels, what kind of [19:53], what is lignite and what is wood.

Wood has very low ash content but then again, the energy per ton of coal is more here. When compared to what we burn in India, it is a little bit on the higher side because in India, the ash content will be very very high. These are not the picture from the…. Are we burning lignite somewhere in India? NLC. Neyveli Lignite Corporation. They have a huge power plant based on lignite and they also have other uses for the lignite.

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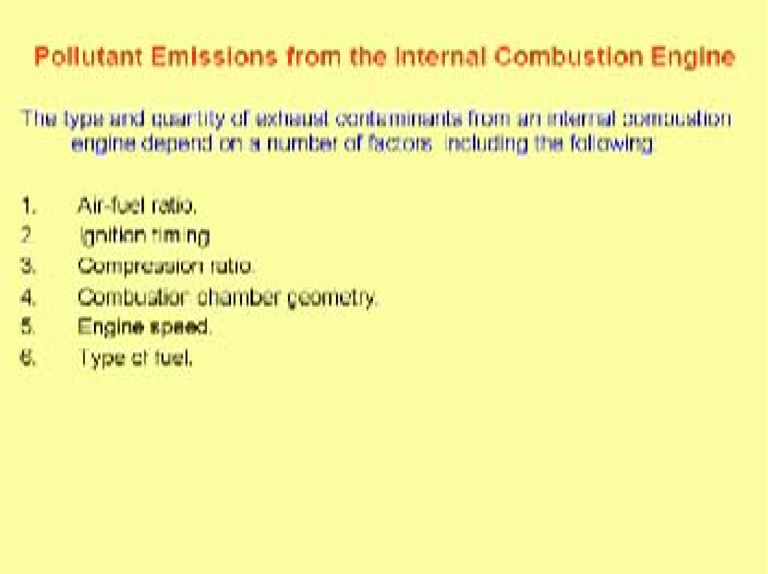

Pollutant Emissions from the Internal Combustion Engine

The type and quantity of exhaust contaminants from an internal combustion engine depend on a number of factors, including the following:

1. Air-fuel ratio.
2. Ignition timing.
3. Compression ratio.
4. Combustion chamber geometry.
5. Engine speed.
6. Type of fuel.

I am still talking about the engines. The emission depends on the air-fuel ratio – we will examine that in detail, ignition time, compression ratio, combustion chamber geometry, engine speed and type of fuel. The pollutant emission will depend on the internal combustion. We will see some of them and we will not see some of them because it depends on what extent we want to go. We can skip this slide because I do not want to discuss so much.

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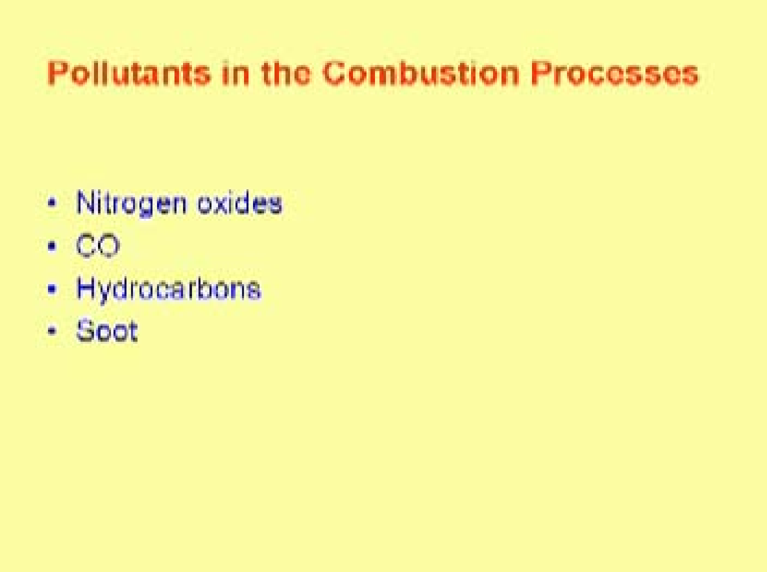

Pollutants in the Combustion Processes

- Nitrogen oxides
- CO
- Hydrocarbons
- Soot

The pollutants in the combustion processes are nitrogen oxides, CO, hydrocarbons and soot. You can add sulfur dioxide, because sulfur dioxide is also a very very important issue. Let us see how it is happening.

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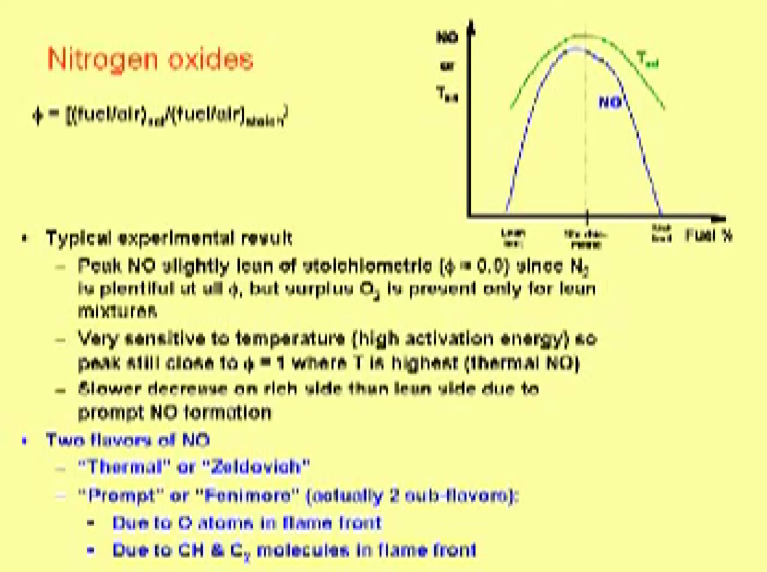

Nitrogen oxides

$\phi = [(fuel/air)_{act}/(fuel/air)_{stoich}]$

- Typical experimental result
  - Peak NO slightly lean of stoichiometric (ϕ = 0.9) since N_2 is plentiful at all ϕ, but surplus O_2 is present only for lean mixtures
  - Very sensitive to temperature (high activation energy) so peak still close to ϕ = 1 where T is highest (thermal NO)
  - Slower decrease on rich side than lean side due to prompt NO formation
- Two flavors of NO
  - "Thermal" or "Zeldovich"
  - "Prompt" or "Fenimore" (actually 2 sub-flavors):
    - Due to O atoms in flame front
    - Due to CH & C_2 molecules in flame front

Let us talk about nitrogen oxide because that is a very serious issue we have and let me also define phi. You remember that we defined the equivalence ratio last time. What was that if you wrote that?

[Conversation between student and professor - Not Audible (21:43 min)]

This is the same thing, the equivalence ratio. Now, quickly tell me if the equivalence ratio is less than 1. Am I on the leaner side or am I on the richer side? Leaner side. Leaner side, okay. If that is the case, let us have a look at some…. We have defined phi. When the people look at the actual thing, I am trying to give the reason behind this, when is the peak NO? NO is only formed… happens when the slightly lean of stoichiometric and phi is close to 0.9.

If it is on the leaner side, here you see the NO peak is not here at stoichiometry but it is here somewhere. The formation is somewhere here, because the oxygen surplus is there. Then in that case, we are talking about the excess oxygen. It does not necessarily mean that NO levels will continue to go high as you increase the emissions. Why? It is because you need certain temperatures also. What happens? It is very sensitive to the temperature because you need high activation energy. In the process when you are going too much on the leaner side, it means you are not supplying enough fuel, so temperature will drop.

As the temperature drops, then NO will not form although you may have a lot of oxygen because as you are moving this side, you are having more and more of oxygen or excess of fuel on this side. But two combinations are required – you should have excess air [23:35] also we talked and high temperature. When you want to manage things, you can either manage by controlling the oxygen or by controlling the temperature. We will see that maybe today or maybe in the next class.

Note there is a terminology here. You see prompt NO – we will see that in a moment, but stay with the term prompt NO. Prompt NO is that NO which is formed first and we will see how that is formed. Before you can think of anything else, prompt NO happens. These methods with thermal NO were devised by Zeldovich and so, that is sometime called Zeldovich NO. The person who identified prompt NO was Fennimore. It could be due to oxygen atoms that are in the flame front or due to carbon and hydrocarbons and C_2 molecules in the flame, which is in the front. Before even nitrogen and oxygen in the atmosphere can react, what you see here is that this thing can occur and you will see that even this hydrocarbon can react to some extent with the nitrogen and can produce nitrogen dioxide. Earlier, we were talking about just N and O. That is fine, that is one route.

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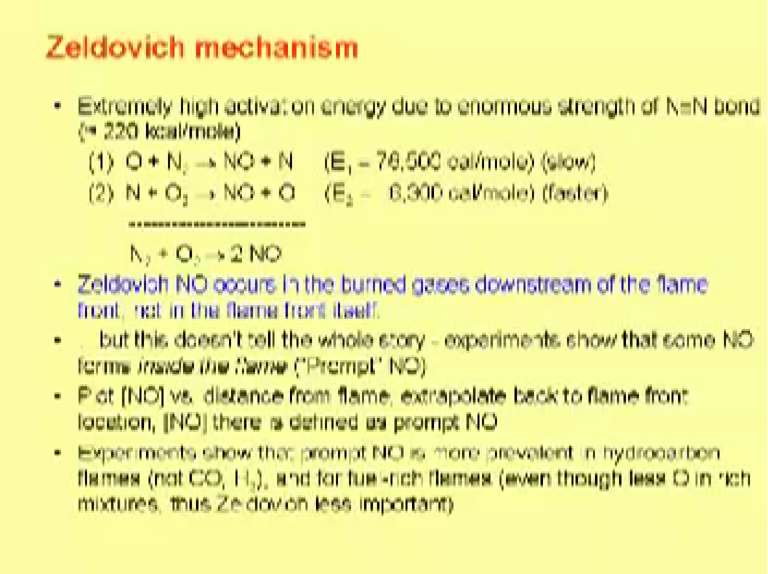

Zeldovich mechanism

- Extremely high activation energy due to enormous strength of N≡N bond (≈ 220 kcal/mole)
  - (1) $O + N_2 \rightarrow NO + N$ ($E_1 = 76{,}500$ cal/mole) (slow)
  - (2) $N + O_2 \rightarrow NO + O$ ($E_2 = 6{,}300$ cal/mole) (faster)

$N_2 + O_2 \rightarrow 2\,NO$

- Zeldovich NO occurs in the burned gases downstream of the flame front, not in the flame front itself
- … but this doesn't tell the whole story - experiments show that some NO forms *inside the flame* ("Prompt" NO)
- Plot [NO] vs. distance from flame, extrapolate back to flame front location, [NO] there is defined as prompt NO
- Experiments show that prompt NO is more prevalent in hydrocarbon flames (not CO, H_2), and for fuel-rich flames (even though less O in rich mixtures, thus Zeldovich less important)

What you see here…. One route is of course if you have the O, if you have this, then this can be quickly formed because the activation energy requirement is…

This is a slow process, the activation requirement is high and with this, it can react and it can form NO. The activation requirement is this reaction must faster. Zeldovich NO occurs in the burned gases because [25:37] excess everything had happened. This reaction of formation of N_2O_2 is slow and the burned gases are downstream of the flame front and not in the flame front itself. But this does not tell us the whole story because something else occurs right in the flame. What happens? Experiments show that some NO forms inside the flame that is called prompt NO. It may not depend on temperature, it may not depend on the nitrogen in the fuel.

We will show you the plot of NO versus distance from the flame. Extrapolate back to the flame front location. This is defined as…. I will show you this picture in a moment. Experiments show that prompt NO is more prevalent in the hydrocarbon flames and for fuel-rich flames. Even if the fuel is rich even though there is less oxygen in the rich fuel, this situation, for prompt NO, this is not very important – what is the temperature and so on but the reactions that may occur ….

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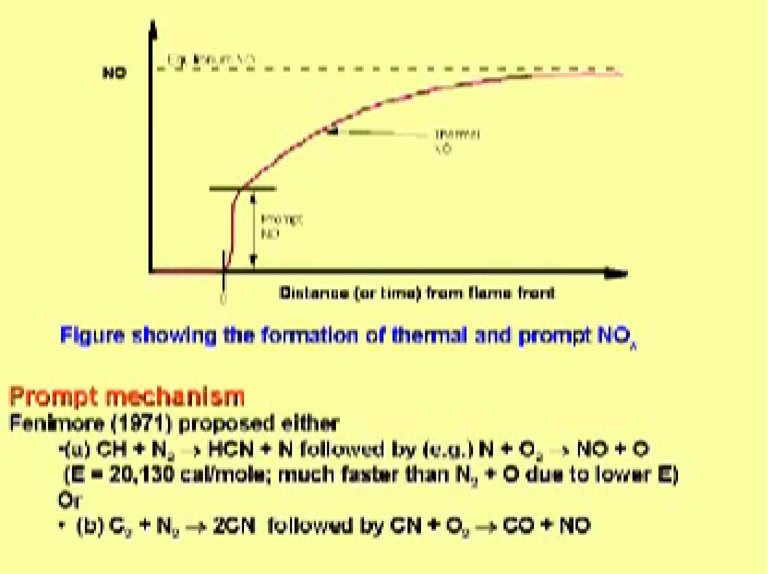

Figure showing the formation of thermal and prompt NO_x

Prompt mechanism

Fenimore (1971) proposed either

- (a) $CH + N_2 \rightarrow HCN + N$ followed by (e.g.) $N + O_2 \rightarrow NO + O$ (E = 20,130 cal/mole; much faster than $N_2 + O$ due to lower E)

Or

- (b) $C_2 + N_2 \rightarrow 2CN$ followed by $CN + O_2 \rightarrow CO + NO$

You see here when people plotted this, they found that there was a quick NO level and then stabilized. That was more because of the thermal NO as we moved away from this. The point I am trying to make here is that for this formation, it does not even matter whether you have excess air or not. A part or a very small amount of the oxygen that you are supplying even for the combustion might just be taken by the nitrogen there. How it happens is that you have some hydrocarbons. With this hydrocarbon [27:22], there are two routes possible. [27:25] people are still discussing how it happens. This hydrocarbon can react with nitrogen also, which is there along with the air and it can make atomic nitrogen. This atomic nitrogen can react with oxygen. If you recall from the last slide, was this reaction faster or slower? Faster. It was much faster.

This reaction can happen and you can get some NO because it is much faster than the [28:03] form and 2 plus O. Some people also say that some carbon may be available for the nitrogen to form CN. CN can react with the oxygen to give CO and NO. This can also happen. You can also see that although you may have a lot of oxygen, you may still produce CO in the process. But the most likely process is the one where you can get the prompt NO_x. There is nothing much you can do about prompt NO_x – that will be formed. You cannot do much about that because this happens right in the flame. People are always looking at the ways and means to control the prompt NO but again, this is not a very significant amount. I do not really know how much it is but it could be 2 percent, 3 percent or 4 percent.

The new thing that you have learnt is prompt NO. It is formed because of the reaction between the hydrocarbon and nitrogen before it can be taken up by the oxygen. It may produce atomic nitrogen and that can very quickly react with the oxygen even before this oxygen can take on the hydrocarbons. That is what is called the prompt NO. This is a little picture that you should…. Let us spend some time on this.

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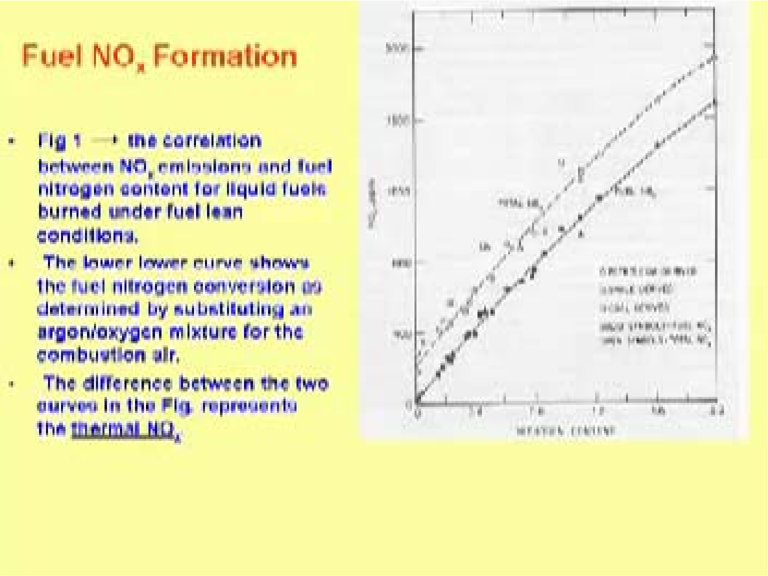

Fuel NO_x Formation

- Fig 1 → the correlation between NO_x emissions and fuel nitrogen content for liquid fuels burned under fuel lean conditions.
- The lower lower curve shows the fuel nitrogen conversion as determined by substituting an argon/oxygen mixture for the combustion air.
- The difference between the two curves in the Fig. represents the <u>thermal NO_x</u>

People did two experiments to say how much can be thermal NO_x and so on. First, they did with the normal oxygen. They were burning petroleum, dried fuels, shell fuel and coal-derived. The coals are shown as little squares as you can see there – one, two, three, four. They did a regular operation. Nitrogen content was there in the fuel. Then, the next time they did the same experiment with different fuels with different matter in content but this time what they did was they supplied pure oxygen or pure oxygen along with the argon. Obviously, the NO_x formation will be much less.

Probably I should say the same thing. The lower curve shows the fuel nitrogen conversion as is determined by substituting an argon/oxygen mixture for the combustion air. Obviously, it will be only the fuel NO_x that will be formed so that with the difference, they could find out what is the quantity of the total and this will be largely with the thermal NO_x.

That is what probably you can control or you can try to minimize this NO_x as opposed to the NO_x that may come out from the fuel. Then, you can also see that well this thing is somewhat higher than the coal that you will see here. This is here, this is here and the corresponding revaluation will be somewhere here because all need to have one-to-one correspondence. Coal is in fact a very significant source of oxides of nitrogen. This gives you a little idea of how people could figure out that part of this was NO_x. There is another picture that is very similar to what we have shown you earlier.

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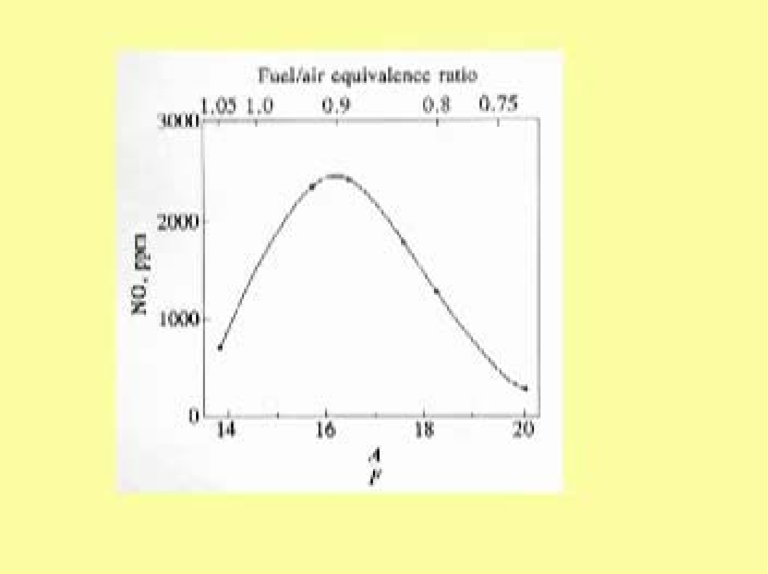

Now, I am not talking in terms of the…. It is a reverse. Same thing. Here, we are plotting air to fuel ratio and in [32:08], we were talking about the equivalence ratio. Equivalence ratio will be something like reciprocal of the two ratios – af by and this [32:17]. Again, this peaks at this point. If I have to plot stoichiometry, where will be the stoichiometry? Will the stoichiometry be on this side or this side?

[Conversation between student and professor - Not Audible (32:40 min)]

You have to answer this. Stoichiometry has to be on which side? Left side. See the one on the top. That is stoichiometry because equivalence ratio is (fuel to air ratio)$_{\text{actual}}$ divided by (fuel to air ratio)$_{\text{stoichiometry}}$. If it is 1, it means we are at stoichiometry. You see here on this side, in terms of the air to fuel ratio, as we go on putting more and more air, then NO_x formation is more and more. Then why does it decrease? It is because although there is more nitrogen and more oxygen, your mixture is becoming so lean that the temperatures that you are getting are not very high. When the temperatures are not high, it will tend to decrease because you need both temperature as well as excess oxygen. Very funny but very very important graph.

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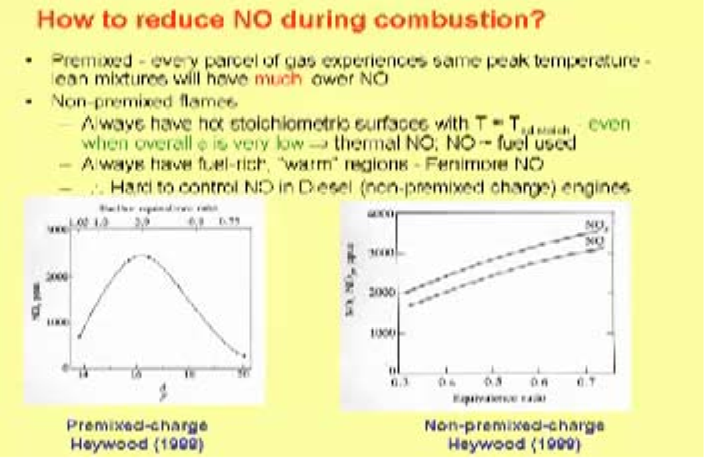

How to reduce NO during combustion?

- Premixed - every parcel of gas experiences same peak temperature - lean mixtures will have much lower NO
- Non-premixed flames
  - Always have hot stoichiometric surfaces with $T = T_{ad\,stoich}$ – even when overall ϕ is very low → thermal NO; NO ~ fuel used
  - Always have fuel-rich, "warm" regions - Fenimore NO
  - ∴ Hard to control NO in Diesel (non-premixed charge) engines

Premixed-charge
Heywood (1988)

Non-premixed-charge
Heywood (1999)

It is the same thing and it is more of a mechanism for the formation. This is the same graph that we need to understand. It is showing both NO and NO_x. You see here largely it is NO. Very small amount of NO_x can be formed depending on the equivalence ratio that you have. Then as you are increasing the equivalence ratio, it will peak until 0.9 or so and then, this will come down. Let us talk about the unburned. We are not talking about the control – we will talk about control in the next class but let us talk about the hydrocarbons.

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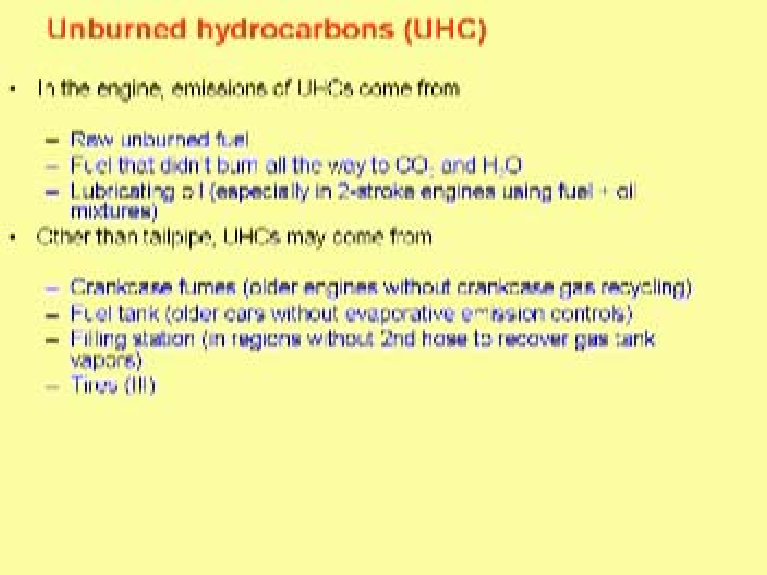

Unburned hydrocarbons (UHC)

- In the engine, emissions of UHCs come from
  - Raw unburned fuel
  - Fuel that didn't burn all the way to CO_2 and H_2O
  - Lubricating oil (especially in 2-stroke engines using fuel + oil mixtures)
- Other than tailpipe, UHCs may come from
  - Crankcase fumes (older engines without crankcase gas recycling)
  - Fuel tank (older cars without evaporative emission controls)
  - Filling station (in regions without 2nd hose to recover gas tank vapors)
  - Tires (!!!)

In the engine, emissions of unburned hydrocarbon come from the raw unburned fuel because some fuel can escape unburned, fuel that did not burn all the way to CO_2 and H_2O. Some might just escape as such. Some might escape – they are converted into something else but [35:03] hydrocarbon but did not burn because you start with some hydrocarbon and they are the intermediate oxidation of the fuel that can take place.

(Refer Slide Time: 35:19)

You started with let us say methane. Some may burn directly and some may convert something like… and then, what you might find is that some might [35:37] as unburned and you may find this could not burn in the process. This was never in there but this might also be seen at the exhaust. That is the difference between raw unburned and fuel that did not burn all the way to CO_2 and water.

Lubricating oil is a serious problem. We all use lubricating oil in engines, especially in two-stroke engines [36:03] using the fuel plus oil mixture. What happens is that in the two-stroke engine, if you recall, what we do is we put the lubricating oil every time along with the fuel. I do not know if you recall it but in old scooters, you would go and add 2 liters of petrol and 3 percent of that was lubricating oil – you always add that from outside. In that case, you are adding the lubricating oil especially in the two-stroke engine and sometimes, the lubricating oil causes a lot of emissions because in the process, that can also get burned and can give out fumes.

Is anyone from Delhi here? Have you seen the petrol pumps in Delhi? Earlier, what people were doing was that they would put the oil from outside, the lubricating oil. That may be dirty or people had the tendency of using more oil. They think there should be better lubrication, but you do not need more oil. More oil can lead to more problems. It can be raw unburned fuel or it can be fuel that did not burn all the way to CO and H_2O. There could be lubricating oil because of the two-stroke engine – those emissions are more because people put more and more lubricating oil.

Then, other than the tailpipe which are more or less these things…. I was giving the example in Delhi. In Delhi, they have banned that you cannot put the lubricating oil from outside. There is a dispensing machine along with the petrol machine. The petrol delivery pump you put this and then it will dispense the exact amount of the lubricating fuel in there. You cannot buy it from outside.

Other than the tailpipe, there are crankcase fumes that can come out, fuel tank – older cars did not have any evaporative emission control system, filling stations in regions without second hose to recover the gas tank vapors and we also know that tires give a lot of organic vapors, but that is not from the combustion sources. It may be a good idea that I do not leave you thinking. We might talk about this a little bit latter but I want to give you a little feel of the emissions here – the crankcase fumes.

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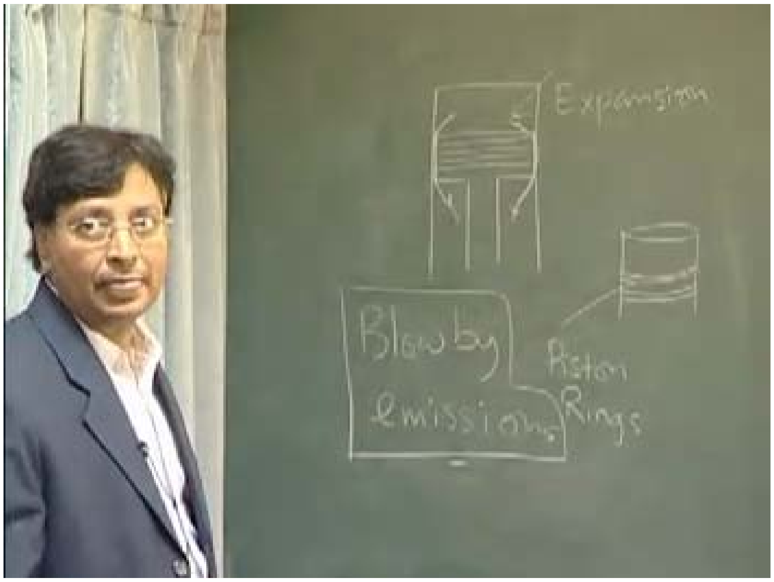

This is a piston and this is inside the cylinder. At the piston, what do you find? A round thing? You always find piston rings are there. The piston is here and the piston rings. Not a very good picture. What is the role of piston rings? To keep it tight. They are a little flexible. They can press and then, they will expand themselves so that it becomes a little fixed. What happens when you have the piston rings here?

As the engine gets old, there is wear and tear of everything. Of course, there are two metal parts hitting each other all the time. What happens with this? This thing is worn out and the piston rings are also worn out. As a result, when you have the expansion stroke or power stroke, there is a huge pressure here and because of this pressure, which is very high here, because of the wear and tear, even before it burns or is partially burned, the hydrocarbon can come out from the space here and then come out in the crankcase. This can also come from this side. Obviously once this comes out, there is no way that you can burn it. These are called the crankcase emissions or more popularly known as blow-by emissions.

Combustion engineers or IC engine people will be experts on everything but we need to know at the air pollution level what are these emissions and why these crankcase emissions can be of huge significance. We will talk about the control of this maybe in the next class, but in most of the control that they do, the blow-by emissions are recaptured and recycled in the car only. But at least now, you know that this is what we were referring to – crankcase fumes (older engines without crankcase gas recycling). If you can recycle these emissions back in there, we are more or less handling the situation but if you do not, then these emissions occur.

Therefore, we say that for old cars, we say that you must get the engine done well, the maintenance is very important. Sometimes, the old engines can go so bad that that there is a government regulation that engines more than 15 years old should go out of business, because these emissions can become very very significant. This will be the emissions of hydrocarbons. You can also see the fuel tank emission – maybe we will talk a little later about the fuel tank.

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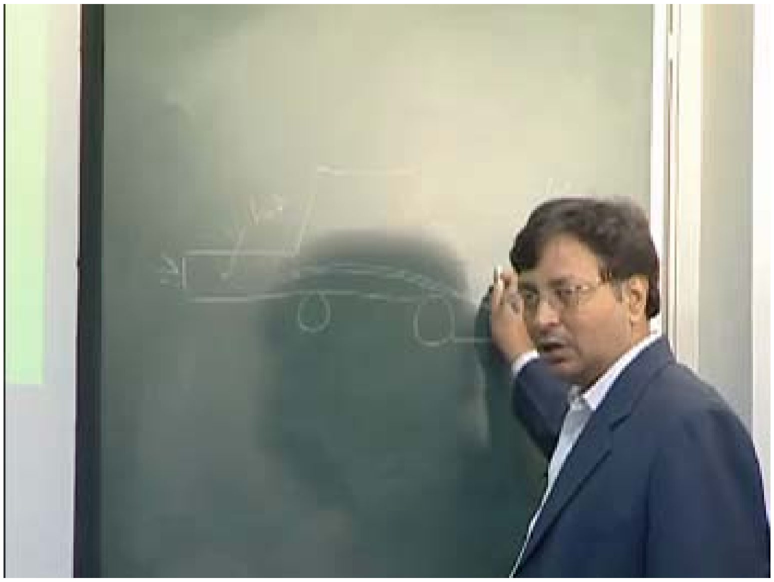

But if you have a car (I do not know how good or bad the car looks), if this is the front, you have the light on this side and then you will have the fuel tank here. When they fill this, the petrol is up to here. As you are filling, the pressure here builds up and then there leakage starts. This is called as the evaporation losses in the tank. This can occur all the time – it is not only when you are filling it up. That time, it is more because you have opened the valve and that is the time the emissions are more, but this occurs all the time – there will be some leakages.

Even if there are no leakages, you can see…. In a petrol vehicle, where is this fuel taken through the fuel pump? It is taken to the carburetor. Of course, the new technologies have changed but in the old thing, you have the carburetor. The carburetor vaporizes this and then you mix the oxygen with that. Even if your pipeline is open, the fuel is going to your carburetor and this engine is hot, the fuel continues to go there and then this is the liquid but it can evaporate from here and there could be constant emissions from here. There can be just evaporation unless the whole thing is cooled off and there can emissions. Some people say that in earlier scooters, the moment you are off the scooter, then you switch this off so that at least this thing does not go anywhere.

But now what people are doing is (we will probably see this in the next class) that they are able to recapture these vapors and put them back in there so that you can completely recycle. We will probably see a line diagram because you should know and have an idea of the latest things that people are doing. I do not know if you have notice that as you are driving, they say your car is showing the empty kind of thing. Then, you stop somewhere for half an hour or one hour and this slightly goes back and it seems as if you have more petrol in your car.

This is all captured by the [44:49] operations. It is very complicated. The amount of research and development that has gone into cars, I think there is no other machine where changes or technology have so many efforts – from the comfort to combustion, from air-conditioning to heating and then adjustment of the seats. Sometimes, the seats have four or five motors so that you can adjust it back and forth. Everything is there. Otherwise if you do not have these, there will be very significant emissions from the…. Filling stations, of course, have to have some [45:28] system that they can capture even at the filling stations.

We will see the sources of hydrocarbon that comes. We will do this and you really need to pay attention. This is a very interesting and useful figure. What I am trying to do is that I am running the engine, I am trying to see what is happening in the exhaust. I am running the engine let us say for different conditions of the air to fuel ratio and trying to look at three important things – carbon monoxide, hydrocarbon and NO_x.

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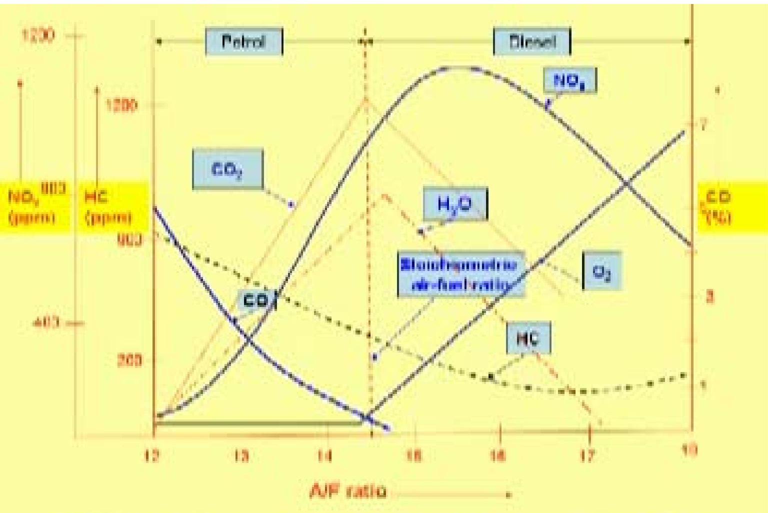

Fig: Exhaust hydrocarbon, carbon monoxide, nitric oxides etc as a function of air-fuel ratio.

Their concentration can definitely look very very different. Be careful about the units. CO is in percentage, hydrocarbon is in ppm – it can even be more and then NO_x is again in ppm. Thanks to [46:24] – he has put this animation into this. For example, our stoichiometry is here. I have put my engine on and then you see this here. In this region, I am not putting enough of oxygen. I will have a lot of CO, which can be of the order of 5 percent or so. We have some measurement of CO. Sometimes, we have found CO up to 8 percent in old Ambassador cars of '70s. You see that here. As you supply more and more oxygen almost up to stoichiometry, you see the emissions are quite [47:08]. Fair enough, simple thing but then the CO emissions will reduce depending upon where you are.

Look at the hydrocarbon. Now we are in the measurements of ppm. Again, what you are doing is you are putting more and more hydrocarbon. The hydrocarbon is reducing because you are able to burn more and more hydrocarbon, but it does not really go very low like CO because the emissions can vaporize before it can burn – something like blow-by or something. These emissions can continue to happen and they may reduce at this point to minimum but it does not go so low also. There is a little tendency here that it may go up. Why?

It is because now, there is not enough of the fuel – not able to burn; chances of the unburned fuel also escaping become larger and larger here. You do not have enough things to burn. In fact, even if you go so low below 20 or so, you may not even be able to fire because you have made your mixture very very lean. If you have made it very very lean, then hydrocarbon might just escape because you are not even able to burn. This side also, you may not be able to burn anything if you have just the fuel and not the oxygen.

These are the two extremes. Your engine cannot operate beyond this and the engine cannot operate beyond this. So you see hydrocarbon emissions will continue to be there – it does not go to 0 so easily. Obviously, we have discussed a lot about NO_x. As you go higher air to fuel ratio, something like this, it will peak here and the equivalence ratio will be close to 0.9. We have also explained the reasons as to why the NO or NO_x for that matter will come down. If you are operating your engine somewhere here, there is a lot of emissions that we have.

I have explained to you earlier and that also is very clear. We will complete this, do not worry. Water is being produced. I can also show how the water will change. This water will change something like this – increase, increase, it will go up to here and then, this water will decrease. Why will it decrease? Water also you can think in terms of the pressure. Why would the water decrease? It is because of the simple dilution effect. You have more and more air. These are all concentration units. So it will peak up to there and after that, I am drawing in more air and the air to fuel ratio is becoming higher. The concentration will decrease. The mass is probably the same. In fact, mass is the same but the concentration decreases because I am putting more and more air.

You see here, it will probably decrease. There is no dilution for the oxygen but at some point, oxygen should…. Will it continue to rise – the concentration of the oxygen? At some point, it will stabilize to the atmospheric oxygen. It will be in percentage. Maybe if I go a little bit more on this side, this becomes stable. Agreed? So I can draw this. Before we go to the next slide, normally, my petrol vehicles operate somewhere close to here. It means I am really supplying less oxygen because you want the good pickup and so on.

If I ask you what are the issues with petrol engines, your answer will be carbon monoxide and hydrocarbons and not so much of NO_x. Do you agree or you disagree?

[Conversation between student and professor - Not Audible (51:35 min)]

Sorry, carbon monoxide.

[Conversation between student and professor - Not Audible (51:39 min)]

No, if you come this side somewhere here, you will see that the carbon monoxide is again in percentage. It is not small – 1.5 to 2 percent. These units are in percentage. Let us see the issue in the relative sense. If I am operating my engine somewhere here, then I am likely to get a huge amount of hydrocarbon, huge amount of CO for that matter (in the relative sense) and not so much of NO. Agreed? Look at how the two engines will give you different emissions. As I operate on the diesel side somewhere here, I get a lot of power, I get a lot of energy, I can drive huge trucks and I can drive huge locomotives. You see here that hydrocarbon may not be so much of a problem. If you go and measure in the diesel truck, you will not get any CO but what will you get? Huge NO_x.

NO_x is a serious problem in the diesel engine. The other thing is smoke – the smoke from the diesel engine. We will talk about that maybe in the next class, but you can see how with this little knowledge of stoichiometry, we can deal properly with the petrol-driven vehicles and diesel-driven vehicles. We can set standards for petrol-driven vehicles. For petrol-driven vehicles, you set the standard that all NO_x should be less than this. Where is the problem?

NO_x should be they will say all happily, but then, you have to set the standard for CO and hydrocarbon for petrol vehicles. In fact if you see the regulations Euro 1, Euro 2, Bharat I, Bharat II…. You are all aware of Bharat I, Bharat II, Bharat III. Bharat I, Bharat II and Bharat III for petrol-driven vehicles, then they will say for CO and hydrocarbon. Bharat II and III for diesel-driven vehicles. Then it will be largely about smoke because diesel produces smoke – we have not discussed that in the class but there is huge amount of NO_x. I do not think that we have a summary here. What else is drawn? CO_2. CO_2. Have we done CO_2? Where is the CO_2 going?

[Conversation between student and professor - Not Audible (54:00 min)]

This one?

[Conversation between student and professor - Not Audible (54:04 min)]

That also should correspond with the CO. Decreasing CO_2 will increase obviously and after some time, what will happen is that because of…. These are all the dilution effect. More oxygen, more air so that will …. This is one important thing that we learned today. Something more? [54:29].

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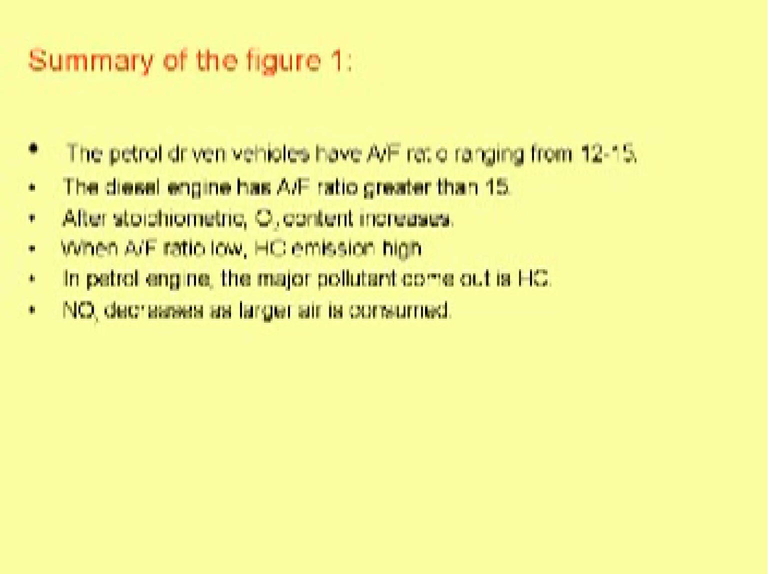

Summary of the figure 1:

- The petrol driven vehicles have A/F ratio ranging from 12-15.
- The diesel engine has A/F ratio greater than 15.
- After stoichiometric, O_2 content increases.
- When A/F ratio low, HC emission high
- In petrol engine, the major pollutant come out is HC.
- NO_x decreases as larger air is consumed.

Summary of the figure 1. [54:38] summary. We got it wrong here – there is not so much of hydrocarbon, which a little comparatively.

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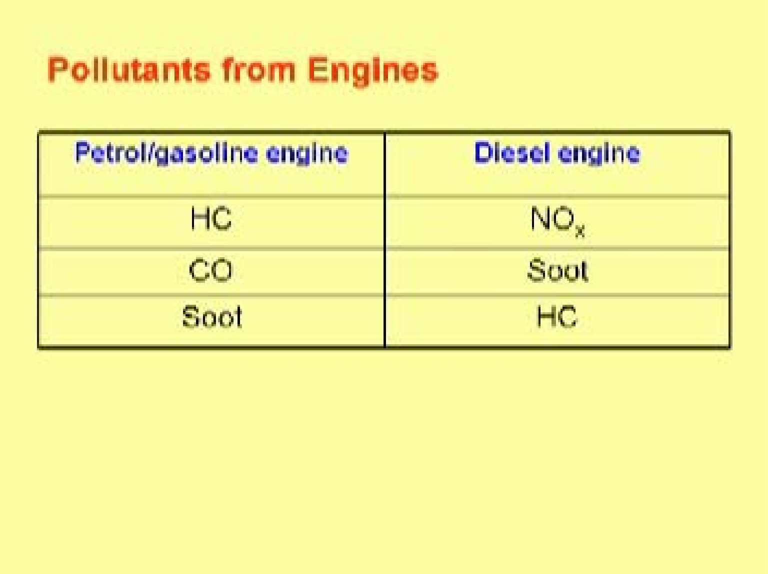

Pollutants from Engines

Petrol/gasoline engine	Diesel engine
HC	NO_x
CO	Soot
Soot	HC

NO_x is the highest, soot is low here and hydrocarbon is low here. Sometimes, hydrocarbons can be more in the diesel engine because you are going up and you try to push more and more fuel, which cannot even burn; that can come out. We will stop here.