

Engineering Thermodynamics
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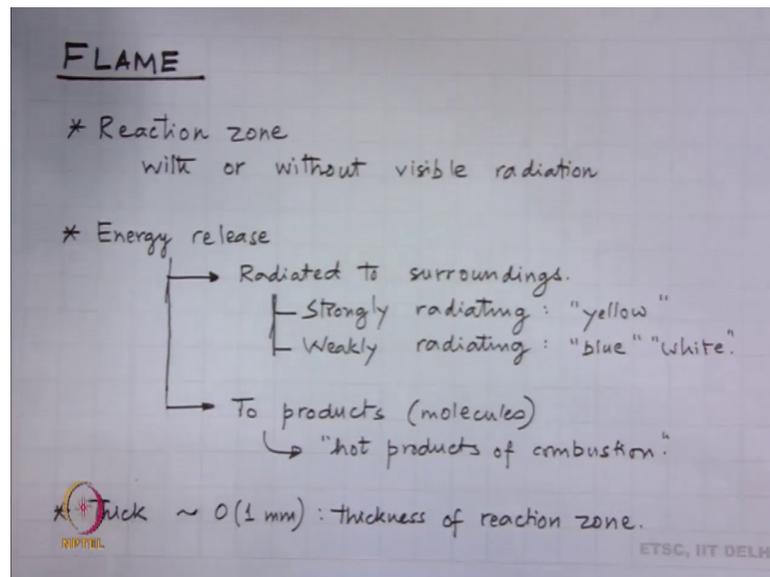
Lecture - 51
Thermodynamics of Reacting Systems: Flames. Stoichiometry.

This is the second lecture on Reacting Systems. In the first lecture, we had looked at reacting systems in general and said that we will focus in this part of the course on combustion. Combustion is a sub family of reacting systems where a fuel burns in the presence of an oxidizer, usually air or oxygen to release energy. We saw many applications involving gaseous fuels, liquid fuels and solid fuels and how the process actually takes place.

What we also realise is that all the reactions and the combustion was happening in the gaseous phase, so that is where we actually see the reactions taking place and the what we see as a flame which is the reacting zone of the domain take shape. The flame may be steady, it may be fluctuating, but that is the place where the chemical reaction takes place. And in this lecture, we want to know something about what happens in the reaction, how much energy is released, what type of temperatures do we get?

So, we will start by looking at some aspects of the flames, then we decide what type of a system that we want to look at, what are the how we apply the conservation of mass and conservation of energy to finally, answer questions like how much energy is released by burning a fuel, what is its calorific value, what is the maximum possible flame temperature that one can get. So, those are the type of questions we want to ask.

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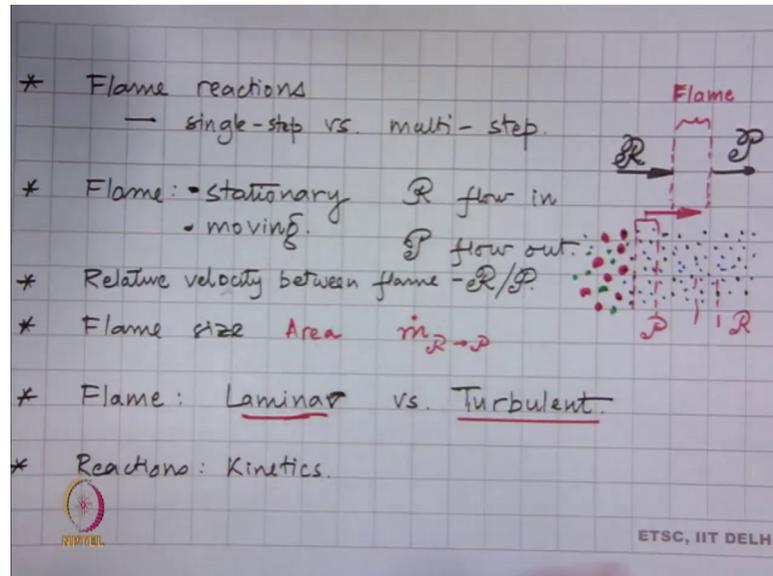
So, we will begin by revisiting the flame and seeing what are the characteristics of a flame. So, we see that flame is a reaction zone part of which is visible to the eye we see that as a blue flame or whitish flame or yellowish flame and part of it we do not see it, but that is where also reaction takes place which is in the infrared part. So, there is a visible flame and there is an invisible flame. Because of the chemical reaction that takes place in that zone energy is released and this is the energy that is released by the breaking of some bonds in some molecules and forming of new bonds and the difference in the energies of the bonds before and after is what is released.

But this energy if it is in a visible flame it could be radiated out and it could be a strongly radiating flame which would be a yellowish or (Refer Time: 02:53) or a blackish flame; that means, there are a lot of the energy release by the reaction is lost to the surrounding. Or it could be a weakly radiating flame where the flame is bluish or whitish and then the amount of energy radiated because of the release of reactions is much less.

The extreme case of this would be that you have a system where there it is adiabatic, there is no loss from that reacting system. So, all the energy that is released remains in the system and that is manifested itself as high temperature of the products of combustion. So, that is what we get, with or without energy loss from the reaction we will finally, have products coming out which are which may call hot products of combustion. So, these are the molecules whose temperature is high. Physically, the flame

has a finite thickness it is of the order of about a millimetre, it may be 0.5, 0.6, 0.7 millimetres depending on what type of a flame it is. So, it is in a very small distance that all this chemical reactions are actually taking place.

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So, we can denote the flame by this sort of a little sheet into which the reactant flow chemical reaction takes place and the product flow. So, this is what you would say and say your LPG burner or a candle that the flame is stationary and relative to the flame, the reactants moving to the flame get combusted and move out of the flame. What happens inside this is a set of very complex reactions and the simplest one of that is what is called a single step reaction.

So, this is a nice assumption which is actually never takes place. When we say that all the molecules that are there that are reacting, they all come together in one shot they are converted into the products. In reality this does not happen, but for analysis this is what we will assume in this part of the course. Advanced courses in combustion deal with the fact that no such reaction takes place, there are lots of sequence of reactions one after the other hundreds of them which finally transform the reactants into the products. So, we will not be looking at this part of the kinetics.

The flame itself can be either stationary as we saw in the LPG flame or the candle flame and the reactance flow into it and products out of it or it could be a moving flame such as what happens in spark ignition engine, where you have a mixture which is been ignited.

A flame is formed there this flame moves through it and the reaction takes place there. So, at some point the flame is over here, at some other point the flame could be somewhere here and so all these reactant which were there these get converted into the products. Ahead of the flame we have reactance behind the flame we have the products.

What it tells us is at there is always a relative motion between the flame and the reactants and the products. This is an important parameter which tells us lot of things about how the flame will happen, it also tells you that if you blow a candle very fast the flame dies. The reason for that or if you have the gas flow in a burner put too high flame could even blow off. Why does that happen is partly something to do with this. We will not be looking into the details of this part in this course.

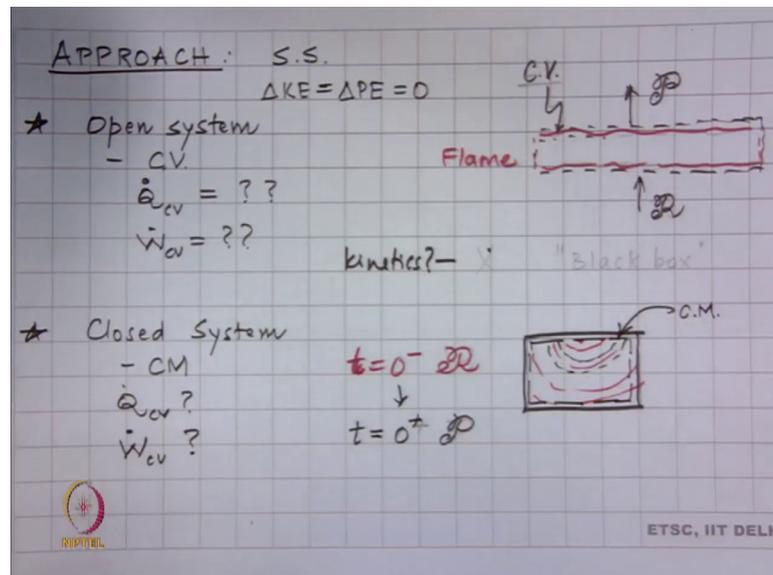
Flame size, it is a physical flame size which can be looked at upon two ways more first part is the area of the flame. So, area normal to the flow of the reactants that is what is telling us and this becomes important because in a particular area there is only a finite rate at which the reactants can be converted into products, the reaction can take place. So, it is reaction rate per square millimetre is got something which is within certain limits and so the flame will adjust itself to get a certain area, so that the total amount total reactance coming in to it are combusted.

Flames can be laminar or turbulent. Laminar and turbulent have the same definition as what we have learnt in fluid mechanics in that laminar flames are stationary with respect to time and they are steady, turbulent flames are fluctuating, they have a time dependency unit and they are random. LPG flame at flow rates or medium flow rates, it looks very steady, looks very straight, is largely laminar, large fires with say your burning a big log of wood the flame at the top is all wiggling, waggling and moving around and that is a turbulent flame.

We will not worry about it at this point of time, then we will see how we are going to consider this in our analysis. And detailed understanding of what happens in a flame as for as the reaction go is to go into the details of the kinetics of it. So, this is sort of a applied chemistry that we are looking at, for now we will look at the little bit of it in a macro sense not go into the integrity details of this.

So, here the summary of the approach that we will take; we will look at we need to define a system and then ask certain questions about it. The first way to ask the question is to say that look my system that I want to study is the flame itself.

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So, that is why the reaction take place let us try to ask questions about it. So, we can do that say in an open system where there is a flame into which the reactants are going in and coming out of this flame are products. So, what you have here is a sort of a control volume that we made here with just about includes the flame.

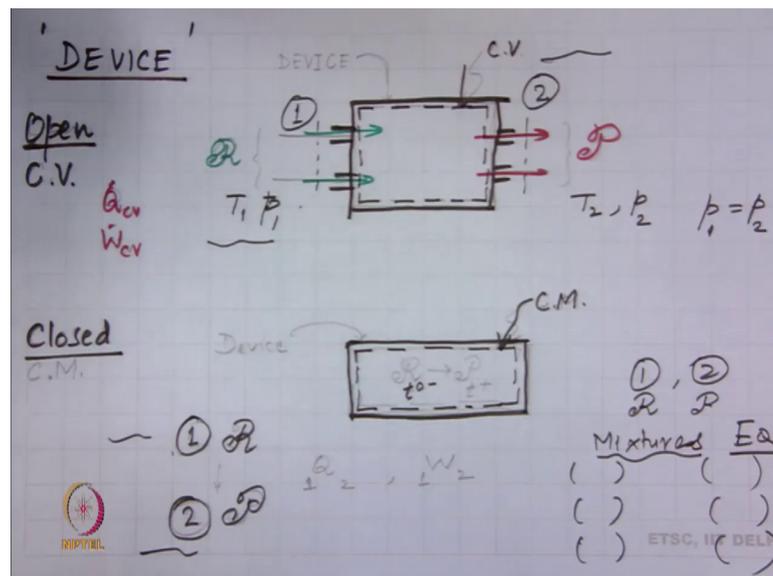
So, this becomes a well-defined system to which we can pose a question as to what is the heat transfer through this, what is the work transfer through this, what are the temperatures enthalpies and all of that. We could also look at the same thing in a closed system such as a spark ignition engine, what happen inside there or even in a compression ignition engine that you have a fixed space in which the fuel and air over there and then at some point we put the spark and the flame went out and combusted all the products. So, there at time t equal to; just say at time t equal to 0 minus we had only reactants in the control volume. So, this is our control volume, we will draw that. It contains all the chemicals that were there inside this control volume, so control mass.

And then in a very short while after all this reaction has happened and it takes a few milliseconds to do it we will call it at time t at 0 plus. This control mass now has only products. So, what we are seeing here is that here we have had a reaction take place and

then again we have the same questions what is the heat released in the system and if the volume did not change when there was no other things happening we can even ask in general what is the work done by the system. For instance, during the during the combustion process the volume increase by certain amount against a opposing pressure it did some work at the same time. So, this is one way to formulate the problem.

In this case, it is somewhat difficult to say what is the control volume if we have to take only the flame because the flame itself is moving the analysis becomes quite complicated. But instead of looking at a flame we have the other option of asking you know this is not bother, what happens inside the flame and what is the where the flame was laminar turbulent or moving around here and there, we will just look at a large macro system which we will call a device and we will only study what happens in the device with the reactants and one side products on the other side.

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So, that is how we will pose the problem now by saying that this is there are two formulations again like before. First, we look at an open system which is the control volume approach and in that we say that we have inlets and outlets and our control volume is the space inside this device. So, what we are having is, we have reactants going in there and there and coming out of this are the products and our question again is what are the heat and work transfer rates associated with this. So, what is $Q \dot{CV}$ and what is $W \dot{CV}$. This is one way.

The second thing to look at is a closed system and here again we just take a large device which contains all these substances that are going to participate in the chemical reaction and define this as the control volume in which everything is going to happen. So, in this case this was our control volume, in this case this is our control mass and this whole box outside represent a device. And as before you have the reactance at some instant going in to make becoming the products.

So, now, let us look at this and define a few things. First, we will not worry what goes on in to the details in each one of these systems, we will only look at two parts. In this case we will only look at here and we will call this as state 1 and then we look at what happens here and we call it at state 2; that means, the reactants each one of them is at state 1 entering here the products whatever what the species they are all coming out at state 2.

What distances is that all of them are at the same temperature and pressure. For example, if it was methane and air going in for into a burner, methane and air we say are both are the same state same pressure and we can then uniquely define properties of both of them. And what is coming out is again at the same pressure and at the same temperature. So, going in this T_1 and P_1 coming out we have products at T_2 and P_2 . It could so happen that P_1 is equal to are almost equal to P_2 this is entirely possible in an open system.

In the close system, the states are slightly different. We say that just before the reaction takes place at t equal to 0 minus, this is state 1 which is the state of the reactants. So, we will interchangeably use in both cases 1 and R. So, here 1 means the reactants before the chemical reaction took place and after the reaction is happened, we will call this as state 2 which is only the products. And in both cases, we assume that this mixture this thing this and this, these are all mixtures.

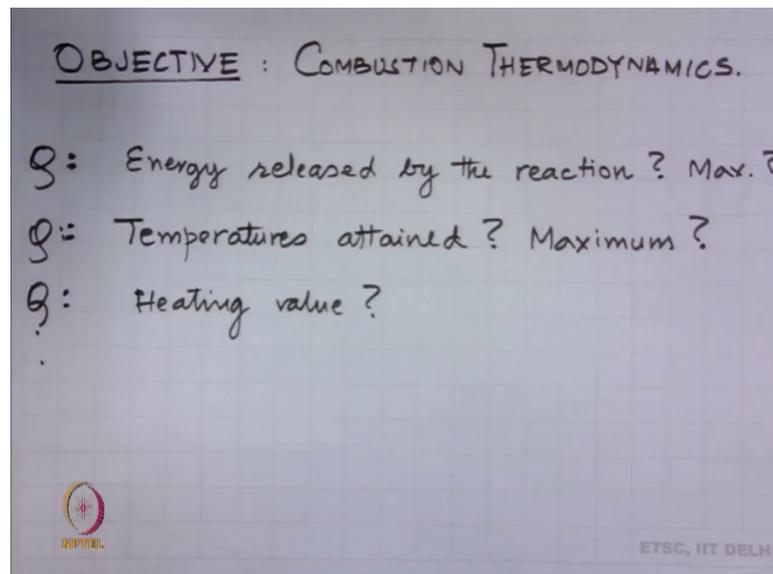
So, we can say 1 and 2 or reactants and products, each one of them we can say is a mixture or both are mixtures of different species. The reactance have certain species in them, products have some other species in them. If it is a methane and air reaction, this side you will have methane, oxygen and nitrogen and if no other products were formed during combustion on the right side in the products, we would have carbon dioxide, water and nitrogen. So, we are looking at mixtures, that is number 1 and second, we will also say that these mixtures are in equilibrium.

These are reasonably good assumptions you can call for getting the properties that define the system well and the moment we have done these two it also tells us that we can whatever we have learnt in the earlier lectures about mixtures all of that can be applied over here. In most cases this mixture will be all of these will be in the gaseous phase, so will be here.

There could be some cases for example, if a liquid fuel was being burned that liquid fuel would be in the liquid phase, others could be gases and on this side the H_2O may have condensed to become a liquid phase. So, there could be a mixture of some liquid phase and some vapour phases. But by and large all the things we have learnt about mixtures in the previous lectures can now easily be applied to both of these states.

So, now we say that this is our system and what are the questions to which we seek answers. We would like to know when such a reaction takes place from our knowledge of combustion thermodynamics, we should be able to answer the question that what is the energy released by the reaction? Is there a maximum amount of energy that is released? How does the energy released depend on the state of the reactants or the products or both? So, that the type of questions that we want to ask in the first part.

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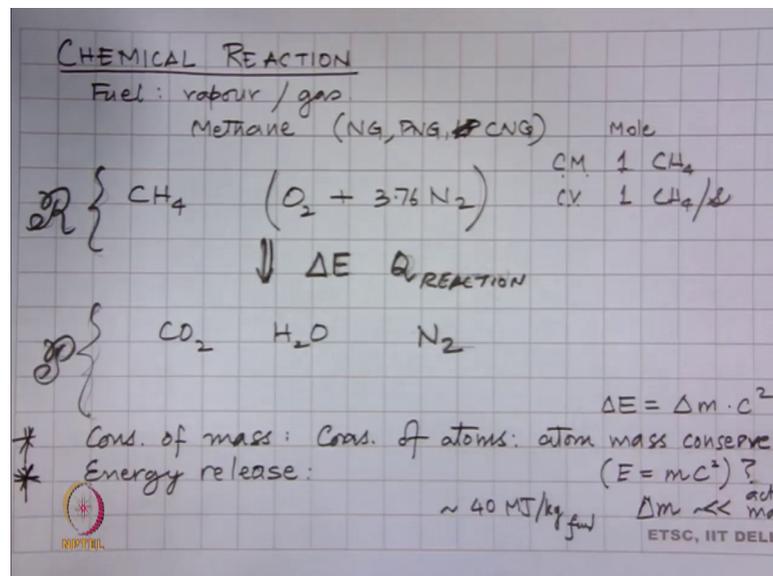
Second is, what is the temperatures attained during the reaction? And in particular what can we say about the maximum temperature that is possible in a particular chemical reaction? That is an important number because if you recall thermodynamics one of the

things that we talked when we are looking a gas power cycles or vapour power cycles what is the maximum possible temperature we can get and we would like to have had that because the Carnot cycle efficiency of the ideal cycle efficiency is maximum when t_1 when source temperature is highest and sink temperature is the lowest. So, this is got implications from that perspective. We could also ask another question as to what is the calorific value or the heating value of a fuel. That means, if you have unit mass of the fuel and you burn it completely how much energy will it give. So, that is another thing.

So, these are type of questions we want to ask and for this we will now go ahead and develop a methodology begin by first looking at the chemical reactions, looking at some macroscopic properties of the mixtures and then we will go into the conservation of mass and energy to answer finally, all these questions.

So, we start by looking at the chemical reaction and we will not worry now that we make that box and we say we are not going to worried about what happens in the box except that there is one particular chemical reaction taking place.

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We will look at for example, burning of methane in air this could be due to natural gas or CNG and this is air O 2 plus 3.76 N 2. So, this is what we will call our reactants. And this burns out completely form carbon dioxide H 2 O and of course, all of this nitrogen continues to come here.

Now, nitrogen does not take part in the chemical reaction. In that sense nitrogen is inert, but the energy released by the burning that is happening over here is distributed amongst all the products. So, all not only do CO_2 and H_2O attain high temperature, so does the nitrogen. That means, the total energy released in the reaction what they will be call it as a ΔE or maybe Q , the heat of reaction or the enthalpy of reaction. This energy goes to heat up all this including the nitrogen. In some cases that is with us, in some cases we realise that this is not a very nice thing to have.

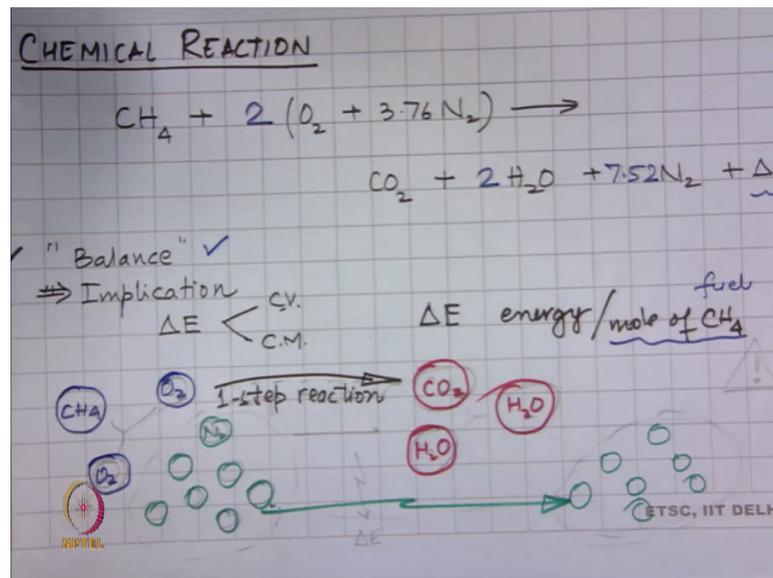
All of this is what we call the products, and the way this reaction manifest itself that in a closed system we will write this reaction for 1 mole of CH_4 , that makes life easy to and bookkeeping becomes easier, air of course, I have not been defined this way. So, this is in the control mass approach. In the control volume approach strictly, it will be one mole of methane per second against which we will do everything. So, what was the reaction looks some straightforward like this, it is we are interpreting this that in a closed system which is a control mass approach it is exactly masses like this, whereas in a flow system which is an open system we can say that this is the flow rate at which this thing is going through. So, the same reaction actually defines both the closed system as well as the open system.

And we say that mass is conserved in this reaction in that every atom here appears here. So, every atom that was there in the reactants will be there in the products they do not disappear, one can always ask and say that look if there are some energy going out is not there a change of mass because of this, and you can say that ΔE from relative mistake considerations the change in mass times c^2 .

One can do a quick calculation and say look what is the typical energy released in a chemical reaction, say any hydro carbon fuel is of the order of say 40 mega Joules per kilogram of fuel is a energy released and with that the corresponding change in the mass of the products Δm which is the mass of the reactants minus mass of the products this is going to be very small much less than the masses that we are looking at. And so for all practical consideration we say that there is no change in the mass this change of mass is absolutely negligible and we can quite conveniently say that this is not an issue and the mass of the atoms is conserved.

When you look at nuclear reactions this assumption is no longer valid and we have to factor that in. But in all the chemical reactions that we are looking at not just in combustion, but in general in all reaction engineering this is a justified assumption. So, the first thing we do is do what you have been taught in school is balance the chemical reaction, and when you say balance the reaction, we have basically saying that we are conserving atoms from products and reactants.

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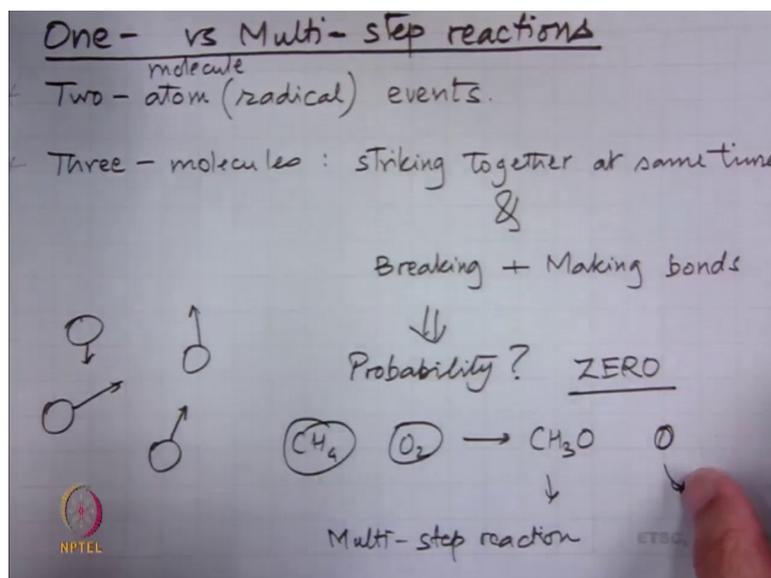
So, we write $\text{CH}_4 + 2\text{O}_2$ this is air, going to $\text{CO}_2 + 2\text{H}_2\text{O}$ and nitrogen and say when (Refer Time: 23:22) is released and we have been taught how to do the balancing. So, we will very quickly put those numbers there that is one carbon atom comes here there are 4 hydrogen atoms and this H_2O here, so this has to be 2 and to get this right amount of oxygen this has to be 2. So, the oxygen is balance and all of that results in 7.5N_2 which is of this side which also appears on this side. So, the equation is balanced it means that basically we got atom balance or atom mass is balanced.

We can then say that what is the energy released under different conditions and we can then normalize it on energy per mole of the fuel with in this case it is methane. And how does this energy get released? If we can make a sketch and see what is going on here. So, we can say that this is a methane molecule; this is an oxygen molecule here, another oxygen molecule there and then with in this there are that many a bunch of nitrogen molecules roaming around. So this, all this thing is our reactant and this is in the gaseous

phase, so they are all moving around bumping into each other. And this gets converted into the products which on this side we have carbon dioxide H_2O and a second molecule of H_2O . And of course, all this nitrogen atoms molecules which were there on this side appear on this side also.

So, this nitrogen comes there except that its temperature is not exactly the same as what it was and what we are seeing in this reaction and we are ignoring everything else is that three of these molecules come together, magic happens they all three come together at the same time and immediately they get converted into three new molecules CO_2 , H_2O and a second molecule of H_2O . This is what we meant when we said that this is a 1-step reaction. It is a nice theoretical thing to have, practically it never happens.

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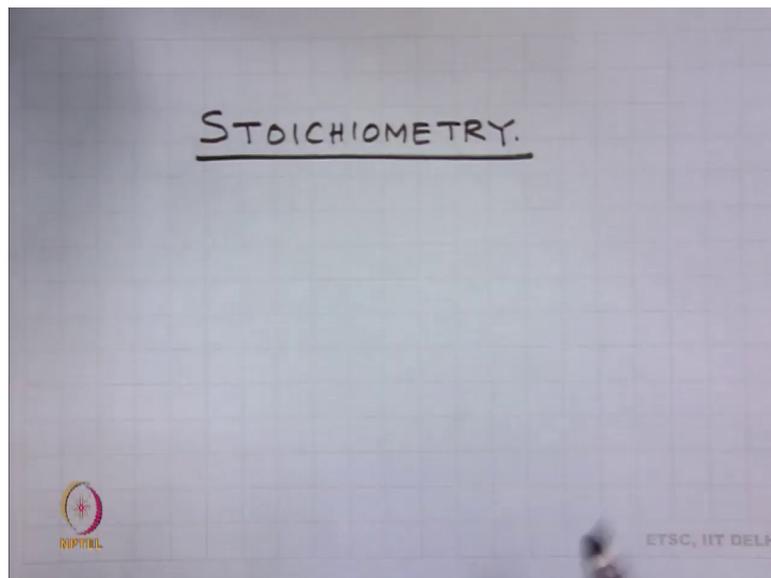
And the reason is that if you look at kinetic theory of gases where we treat all the molecules as rigid spheres, which are all moving with a certain random velocity, bouncing and colliding with each other. Then it tells us that the probability what is the probability by which two of them will come and have a collision, what is the probability that three of them will come together and have a collision have a and in this particular case not just an illusion but have the type of energy for the breaking and making of bonds; that probability is practically 0.

All if reactions or two atom reactions which tells you that the CH_4 at molecule reacted with say one O_2 molecule to form CH_3O and O radical. So, this is a two molecule or a

two molecule radical reaction. And like that then this has another reactance with some other entity, this with another entity like that you have lots of two reactions of involving two of these at the end of which all of it goes down to making CO_2 and H_2O . This is what is called a multi-step reaction.

This is how the real process is take place. It is quite complicated and it is not in the preview of a beginning course in thermodynamics. This is what advanced thermodynamics is all about and unless you understood this, we will not be able to understand pollutant emissions that are formed in various combustion systems. But at this point we will not bother whether it was a one-step reaction or multi-step reaction or a device which is the control volume or control mass we just say the reactance went in whatever happens we do not care, at the outlet we have the products coming out.

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So, over that it is now begin by looking at the first important thing within combustion which is called stoichiometry, which is telling us how can I qualify at the macro level, what is it that we are burning. These are important things from a practical perspective this is very essential. We are always looking at what is the stoichiometry of different flames because that determines how well and how completely the fuel burns that is one, and second also tells you how much pollutants like nitrous oxide or carbon monoxide or maybe even some of the unburnt hydrocarbon fuel itself how much of that will remain.

This is a key to answering those questions. So, how do we go about defining what is stoichiometry?

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STOICHIOMETRY (Macro level)

bulk Fuel + oxidizer MIXTURE.

- Stoichiometric quantity of oxidizer:
Amount of oxidizer needed to just completely burn a quantity of fuel.
- Oxidizer provided (available) > Stoichiometric quantity?
- more oxidizer than needed
⇒ fuel-lean mixture (Lean mixture)
- Oxidizer provided (available) < Stoichiometric quantity
not enough oxidizer
⇒ fuel-rich mixture (Rich mixture)

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So, first we are looking at the macro level which is a bulk; that means, we are looking at the whole mass, we are not looking at a molecule at a time or an atom at a time. And we are looking at a mixture of fuel and oxidizer. And now we define a few things here, that first what we say is what is if the amount of oxidizer needed for just completely burning a quantity of fuel then we say that we have the stoichiometric quantity of oxidizer.

So, what it means is that we have to have complete burning of the fuel; that means, if your hydrocarbon all the carbon becomes carbon dioxide and nothing remains as carbon monoxide or a something else and all the hydrogen becomes H_2O , water. Now, to make that happen we could have given a certain amount of oxidizer, but if I had given more amount of oxidizer the reaction will still have been complete, but we would have had some of the oxidizer remained unneutralized and that is why this word just comes in here. That when we say that you just completely burn the quantity of fuel which means that all the oxidizer that was given is also consumed and we also at the same time I have only carbon dioxide and water.

If this condition were met, we say that particular mixture we are supplying it the stoichiometry quantity of oxidizer. In reality very difficult to maintain that because practically admit any something exact is next to impossible will always be of by few

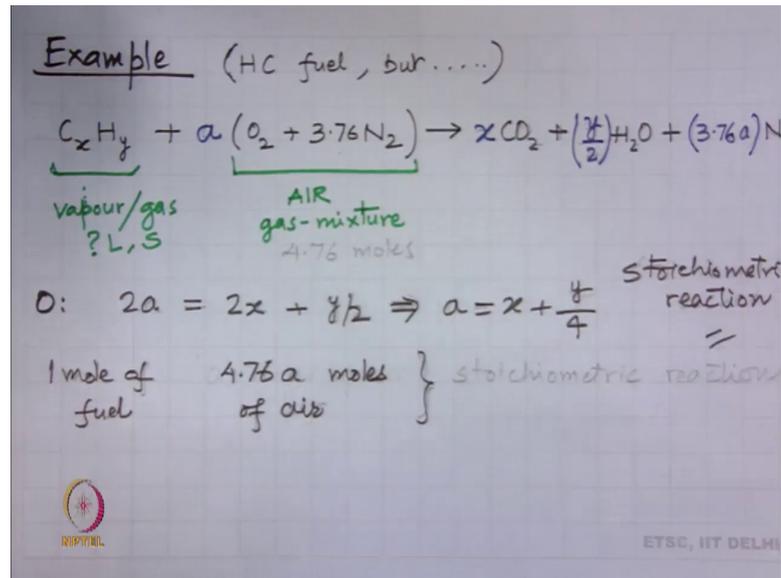
percentage this way that way and in many cases we actually consciously decide are we going to give more oxidizer or are we going to give less oxidizer. So, that leads us to the next two definitions, that if the quantity oxidizer provided or which is available for the fuel to burn in is more than the stoichiometric quantity which is exactly what was required to burn all the fuel then we know that we have more oxidizer than what is needed in which case we say that this particular condition it is a fuel lean mixture. That means, there is more oxygen than the fuel and we just call it as a lean mixture.

In many combustion systems like say burning coal or in power plants which are burning coal or oil we always put in a few percentage more the of air than what is needed for complete combustion with the hope that we are going to get complete combustion. Now, that there is lot of research that has happened and still going on we know how we can reduce that extra amount of oxidizer or air that is going in and still have complete combustion. It has lot of advantages.

The other condition that can happen is that the oxidizer provided or available is actually less than what is stoichiometric quantity is there. So, stoichiometry quantity wants a certain amount of oxidizer to be given to the mixture, to the fuel, but actually we are putting something less than that. That means, that there is not enough oxidizer in the mixture, there is more fuel than oxidized oxidizer and this is what we call a fuel rich mixture or rich mixture.

In practical situations we encounter both the situations. And in some cases, we manipulate the design of the combustor should I get some place we have rich mixture and in another place, we have a lean mixture. This is the type of burners that are been developed which are much more efficient than older burners, but they rely on a very intricate knowledge of this type of issues. So, we have seeing what is a stoichiometric mixture or a stoichiometric quantity of oxidizer and let us look at in the example which is are in general hydrocarbon burning in air.

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So, we have in general hydrocarbon C_x H_y is what we are writing and this burns in air which is a gaseous mixture of oxygen plus nitrogen going to carbon dioxide water and nitrogen. So, to balance this we have put x there, this is a y number of this. So, this side becomes y by 2 and all the oxygen that gets added up if this O₂ was there a and nitrogen has to be conserved, so this becomes 3.76 times a. So, the reaction is now balanced in that this side also is a and with get this much C O₂ plus H₂ O plus N₂.

And we do an atom balance on this for oxygen atoms and we say that this side we have 2 a number of oxygen atoms and this has to equal to the number of oxygen atoms on that side which is 2 x plus y by 2 which implies that a should be equal to x plus y by 4. If this condition is met then we say that we have a stoichiometric reaction. What is also tells us is that on this side we had 1 mole of fuel and on this side 3.76 moles of nitrogen 1 mole of oxygen all of this multiplied by a, so 3.76 plus 4.76 multiplied by a this many moles of air are there on the left side and this is what is required to produce the stoichiometric reaction. Now, we take this further and say look if this was a stoichiometric reaction then this and this ratio seems to be fixed.

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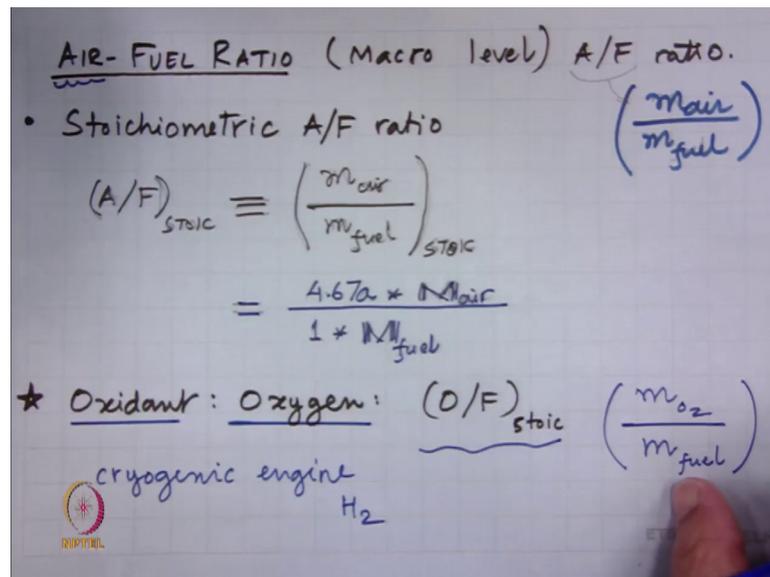
AIR-FUEL RATIO (Macro level) A/F ratio.

- Stoichiometric A/F ratio

$$(A/F)_{\text{stoic}} \equiv \left(\frac{m_{\text{air}}}{m_{\text{fuel}}} \right)_{\text{stoic}}$$
$$= \frac{4.67a \times M_{\text{air}}}{1 \times M_{\text{fuel}}}$$

★ Oxidant: Oxygen: (O/F)_{stoic} $\left(\frac{m_{\text{O}_2}}{m_{\text{fuel}}} \right)$

cryogenic engine
H₂



Now, we will define this ratio as in two ways one as the air fuel ratio and then the inverse of this as the fuel air ratio. So, in general air fuel ratio is nothing but mass of air divided by mass of fuel which is actually there in the mixture. And this thing for a stoichiometric condition it becomes air fuel ratio for the stoichiometric condition, this is defined as this whole thing mass of air divided by mass of fuel for stoichiometric condition is we just did stoic.

And we have seen that for the methane reaction we can write this as 4.67 a multiplied by M which is the molecular mass of air divided by 1 mole which was the number of moles of the fuel multiplied by the molecular mass of the fuel and that is what this is. Now in all this cases we have use the word air. So, we are presuming by default that oxidizer is air which basically is that the oxygen in the air is the oxidizer. In many applications this need not be the case where instead of air you are actually burning oxygen.

So, your, if the oxidant is oxygen then we cannot call it air fuel ratio in that case we call it oxygen fuel ratio or the O F ratio and define it exactly the same way, that this is mass of oxygen O 2 divided by the mass of fuel. An example of this is your oxyacetylene flame where the fuel is acetylene and the oxidant is oxygen. Another example is the cryogenic engine which is used for a space launches and rockets where oxidizer is O 2 and the fuel is hydrogen, stored as a liquid hydrogen and then pumped and made into a gaseous form. Most of the time we are looking at chemical combustion reactions of fuels

with air, so this is the most common used term, but in case if oxygen we got to make a small differentiation.

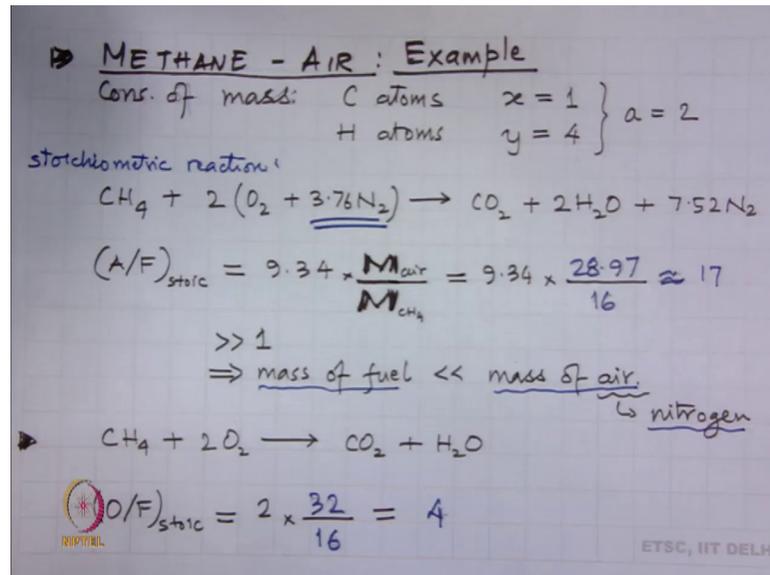
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$$\begin{aligned} \text{FUEL-AIR RATIO} \\ (F/A) &= \frac{m_{\text{fuel}}}{m_{\text{air}}} \\ &= \frac{1}{(A/F)} \end{aligned}$$

STOIC s

The fuel air ratio is exactly the inverse of that the fuel air ratio is mass of fuel over mass of air which is 1 upon A F and then again, we can define it as a stoichiometric air fuel air ratio you know like that. Somewhere mostly air fuel ratio is used in few cases fuel ratio is used, but this is what it means, both are identical and can convey a similar meaning. Now, to get a feel for what type of numbers we are looking at let us look at the same methane air reaction and we say that from the general hydrocarbon reaction that we have written $C_x H_y$, x is now 1, y is 4 and a is 2.

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So, that stoichiometric reaction for methane burning in air is C H 4 plus 2 times O 2 plus 3.76 N 2 and bracket this is air C O 2 to H 2 O plus 7.52 nitrogen. So, the air fuel ration for stoichiometric condition will become 9.34 which is this plus this multiplied by 2 multiplied by the molecular weight of air divided by the molecular weight of methane which is 28.97 and this is 16 and so you can see that this is like of the order of something like 16 or 17. Basically, it is must greater than 1.

And this is the general case for most hydrocarbon fuels, which tells us that in the burning reaction the mass of fuel that is actually going into the burning is a small fraction of the total mixture mass. And that the mass of air dominates the mass of the products and this is in large part cause by the large amount of nitrogen 3.76 into which is there in air.

In the case of methane burning in oxygen we have this thing, CH for plus 2 O 2 go in CO 2 plus H 2 O and the stoichiometric oxygen fuel ratio would then be 2 is to 1 into molecular weights is 32 by 16 which is 4. So, we see that there is a very big difference in the mass flow rates depending on whether it is air as the oxidizer or oxygen as the oxidizer. Now, based on the air fuel ratio or a fuel air ratio will define an another term with basically tells us whether if the mixture is rich, it is lean or it is stoichiometric and this is called the equivalence ratio denoted by phi.

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EQUIVALENCE RATIO, Φ

? Fuel - oxidizer mixture is rich, lean, or stoichiometric

$$\Phi = \frac{(A/F)_{\text{stoic}}}{(A/F)_{\text{actual}}} = \frac{(F/A)_{\text{actual}}}{(F/A)_{\text{stoic}}}$$

$\Phi = 1$: stoichiometric ...

$\Phi > 1$: $(A/F)_{\text{actual}} < (A/F)_{\text{stoic}} \Rightarrow$ more fuel: Rich

$\Phi < 1$: $(A/F)_{\text{actual}} > (A/F)_{\text{stoic}} \Rightarrow$ more oxidizer: Lean

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And this is defined as air fuel ratio for the stoichiometric mixture or air fuel ratio which we can say is actual or one that is provided or the reverse of this would be the fuel air ratio which is there actually divided by the fuel air ratio for stoichiometric condition. So, this type of relation tells, so that a phi is equal to 1; that means, air fuel ratio actual is equal to the stoichiometric air fuel ratio. So, you have a stoichiometric reaction taking that will be there.

If phi is greater than 1; that means, the actual air fuel ratio is less than that for the stoichiometric condition which means that there is more fuel, so this is a rich mixture. And if phi is less than 1, air fuel ratio actual is greater than the stoichiometric air fuel ratio which implies there is more oxidizer which means that you have a lean mixture. So, phi is one quick indicator and in a quantitative way it tells us whether the fuel is rich lean or stoichiometry.

And important parameter that comes in the design of combustors and reacting systems is how much air to provide and as I mention be a little bit on the conservative side that we want to make sure that all the fuel burns. So, there is been a tendency for all these years that we provide a little more extra air or extra oxygen then what is needed.

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% EXCESS AIR : Lean, air

$$\% \text{ excess air} \equiv \frac{1 - \Phi}{\Phi} \times 100\%$$

X Rich mixture : short on air

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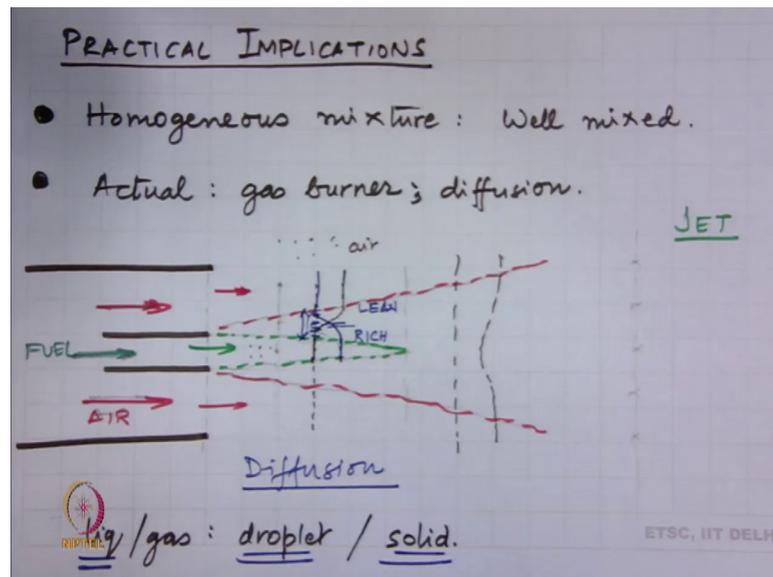
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And yet another mm indicator of how much excess is there is directly call it percentage excess air which means that we are by default, looking at lean mixtures and air is the oxidized. We are providing excess air in very definition of this term and this is 1 minus phi upon phi into 100 percent we do not define it for a rich mixture at all. So, there is no question of defining it its already shot on air this is no point in calling it anything.

So, percent excess air we can say it is 5 percent excess air or maybe 2 percent excess air or 15 percent excess air like that. Historically, 50 years back 80 years back when combustors were designed for burning coal or oil or anything excess air one of the order of 15 percent, 20 percent; that means, that the products has lot of nitrogen going out which carry energy that was released by the combustion reaction. It is a loss of energy, so historically people have tried to make combustors with less and less excess air. So, 5 percent, 3 percent, 6 percent is what today's combustors are working with the some come combustors that are even trying to go even below that.

So, let us see what are the practical implications of all these definitions. And now we are looking at a micro level we are not looking at the macro level system about which we were talking in few minutes back we will come back to it there. But here is an example.

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So, here is the example of a combustor where we have fuel going in this side and around it inside this is the fuel this could be methane or anything else in gaseous form of course, and outside all around this is a circular pipe, all around this we are sending in say air ok. This is typical design of a burner. If it were oil burner it is the fuel is liquid, but then here there is a small hole the oil comes out and then becomes some (Refer Time: 45:18) it is a atomized becomes droplet us with then vaporize and all sorts of things happen.

Looking at a gas, here is what will happen. As this gas comes out into air it will form what in fluid mechanics is called basically a jet. And what was the jet will do is that because of momentum this will go out and gradually because this air is also coming in, there will be transfers mixing as we go in the direction of the flow. So, we will have a region here where there is fuel going in and on this side we have air coming out. So, there will be upper limit there where this impact of this jet is felt, what is the shape and size of this is what we can look at the fluid mechanics and get from there.

So, what you are seeing here is that inside this here we only have the fuel, say methane and outside this zone here we only have air. And because of mixing which is taking place in a layer here if we take any line cutting through the axis of this what we will see is that this side we have only fuel, no air, which is for this region and for that side we would we have only air. So, what happens is that if we draw the fuel concentration relative to this

as being like that this is the fuel amount then here it becomes 0 and in between it goes through a variation.

Exactly the opposite happens with the air. Outside you have air is there completely up to this point then it gradually decreases and becomes 0 in the core. And it is only when you get over here that we do not see any such region, but still we will see a mixture where you have different varying quantities of air on one side and different quantities of fuel. So, what we are seeing now is that we have a region here which is this region here to here where at some point we have certain stoichiometry, here there is some other stoichiometry, here there is some at stoichiometry, here there is some other stoichiometry.

On this side the mixture is rich, on this side the mixture is lean. So, in reality and the flame itself will stabilize itself somewhere over there and so what you have is that we have a flame as a region where there is some place where there is a lean mixture, somewhere there is a rich mixture and it is not a uniform homogeneous thing everywhere. This is unlike say in a closed system where you have perfectly mixed methane with air and then you put a spark. Then of course, everywhere the stoichiometry was the same and its behaviour would be the same.

But real systems which are like this and this is typical of what you call a diffusion flame and this is also what happens in combustion of liquid fuels, which could be as droplet us or combustion of solid fuels, whereas we saw yesterday the solid fuel because of heating gives out volatiles which are in the gaseous phase and then they undergo a diffusion process which causes a diffusion flame. So, this is good to know that this is how combustion takes place at the micro level and that is what designers will work with. For our purpose now, we will only look at all of this as one gross system ignore all the mic micro details that are happening and only ask that if this went out and something came out how can I get the energy released or the temperatures at end.

So, with that we will conclude this part of the lecture. And in the next part of the lecture we will look at how do we get the analysis of this reacting system, how do we get the enthalpies and answer the questions of energy input, output and temperatures.

Thank you.