Fundamentals of Combustion (Part 2)
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Lecture – 72
Solid Fuel Combustion (Contd.)

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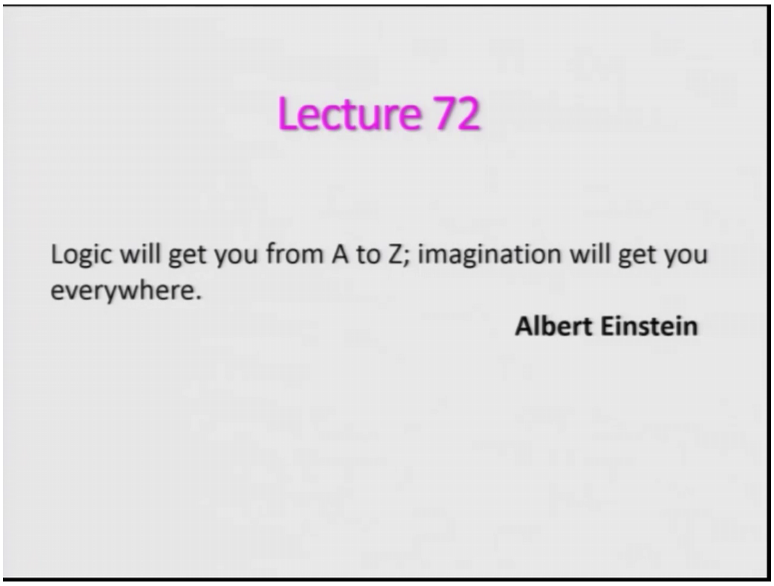

Let us start this lecture with a thought process from great scientist Albert Einstein who says, logic will get you from A to Z; imagination will get you everywhere. This is a very profound statement if you recall, I had discuss about the creativity and creativity can only be materialised can be manifested, if you have imagination. In modern time, you people do not have time to have a wonderful imaginary imagination power.

So, let us look at now what we had learnt in the last lecture, we basically initiated a discussion on the solid fuel combustion and we have looked at where solid fuel combustion can be utilised. And as of now we are using it profusely in various application like; domestic application, space application, power generation application and metal combustion and several other places. And we also looked at what are the processes involved in the solid fuel combustion and we learnt it is quite complex in nature and we divided the solid fuel combustion two kind one is pyrolysing solid fuel combustion and non-pyrolysing combustion.

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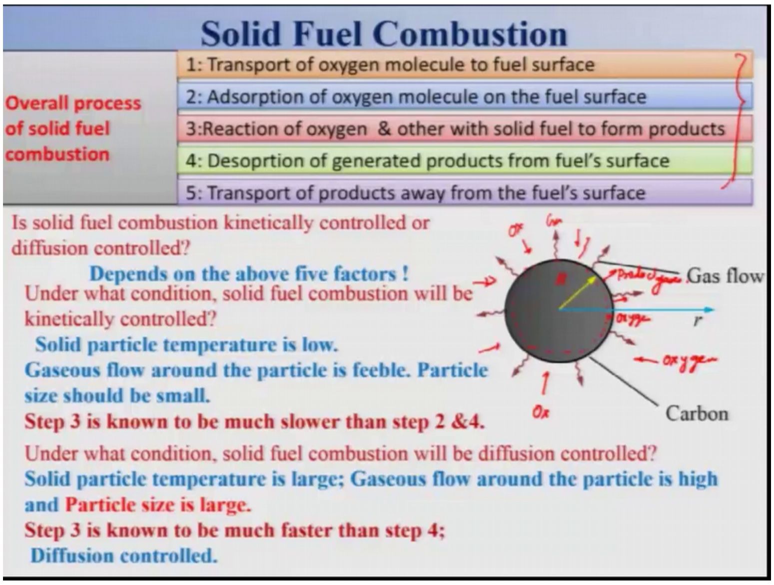

And let us now look at little bit more about it and we will recall now overall processes of solid fuel combustion and if you recall that there is a solid fuel carbon, we are considering. Now, we are considering non pyrolysing combustion where the solid fuel is not undergoing any pyrolysis. Inside the solid fuel, whatever it is happening on the surface and the transport of oxygen is taking place because this is your ambient.

So, therefore, oxygen is getting transport toward the fuel right. From various region, we have taken considered as a solid carbon sphere right just to make it life simpler. And therefore, the oxygen molecule will be transported towards the solid fuel. The other one will be there will be adsorption of oxygen molecule on the fuel surface because it will be adsorbed. And then once it is adsorbed particularly for pyrolysing fuel where it will be inside this one like if it is solid fuel right.

And this region oxygen already enter into that there is a oxygen and it will be reacting with the fuel surface right on the fuel surface. And the reaction of oxygen and other like a gases like a carbon monoxide, it will be reacting with the fuel to form the products like products of course, it can be several of them, but the final product will be carbon dioxide water.

And then these desorption generated from the product from the fuel surface. Because this will be product gases which will be going these are the product gases which will be going out and then this will be basically transport products away from the fuel surfaces, it will be transported away from this.

These are the gases which will be transported away such that it may react with the oxidizer and then maybe flame is formed. If flame is not formed, it can be glowing will be taking place. So, therefore, there will be kind of combustion which will be taking place so, these are the processes which will be taking place basically during the solid fuel combustion what we have already discussed. And if it is pyrolysing one, then what will happen that there will be also the pyrolysing gases will be going out and the flame is being formed and then you will get. So, is solid fuel combustion kinetically controlled or diffusion controlled?

So, if you remember the terminology kinetically control and diffusion control we have already discussed about that. And kinetically control means basically where the chemical kinetics plays a very important role and not the diffusion. We know that in case, of premixed flame where fuel and oxidizer are mixed beforehand the kinetics plays a very important role.

In other words the time required for chemical reaction to occur will be binding or the detecting factors for the combustion of the premixed flame or premixed combustion. So, therefore, the kinetic control chemical reaction is very important, but whereas, the diffusion control the chemical reaction is quite fast as compared to the mixing of fuel and oxidizer due to the diffusion. So, therefore, that is thing, but question is a whether a solid fuel combustion will be kinetically controlled or diffusion controlled.

And in order to talk about it depends on the above 5 factors what we have discuss because these are the factors which will be dictating or which will be telling us whether it is a kinetically controlled or the diffusionally controlled. So, in other words, under what condition solid fuel combustion will be kinetically controlled.

And if the particle size is small and the gaseous flow around the particle is quite feeble and the another condition is that the solid particle temperature should be low. If the particle size is small; that means, oxidizer and the fuel are already having more chance to come in contact and the flow is really not much. So, therefore, it is not affecting the solid surface so, of course, the temperature should be low so, that the gradient will be not much

And as a result what will happen that reaction of oxygen and other gases like carbon monoxide solid fuel will be much slower as compare to the adsorption oxygen molecule on the fuel surface. And the desorption of generated product from the fuel surface; that means, this is a very fast process the slower process is your reaction. Therefore, it is kinetically controlled and why it is occurring because of fact that the particle size is small and the velocity around the particle is not much. And of course, the particle temperature is quite small as compared to of course, the other cases where the diffusion control combustion will be taking place.

So, let us look at under what condition solid fuel combustion will be considered as a diffusion control? In this case the of course, the solid particle temperature will be quite large and gaseous flow around the particle is high as compared to kinetical control and particle size is large. So, that really under this condition the what will happen, the reaction is between the oxygen and with the solid fuel is quite faster as compared to the adsorption oxygen molecule on the surface of fuel surface and transport a products away from the sorry desorption of generated product from the fuel surface.

So, these are basically the slow processes and that is we will dictate as compared to the reaction between the solid fuel and the oxygen and other products. So, therefore, under this condition it will be taking place that is this kind of combustion is considered as diffusion controlled.

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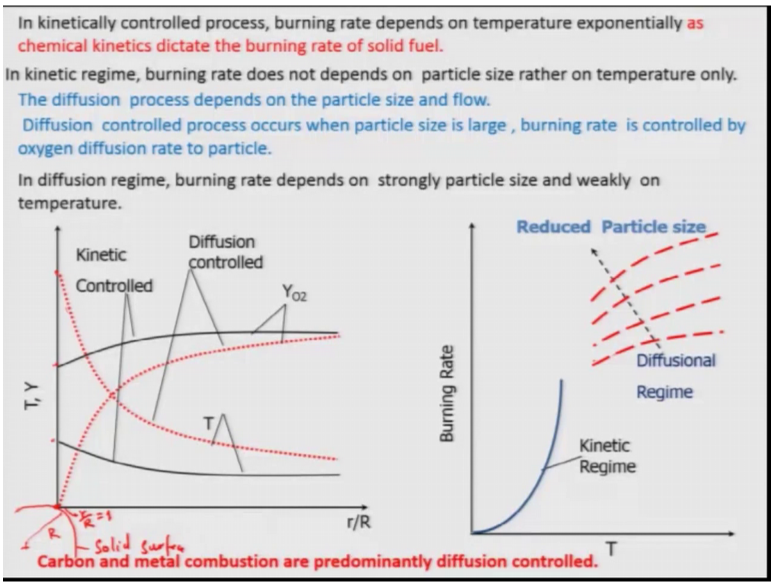

So, in kinetically control process, the burning rates depends on temperature exponentially because the chemical kinetics dictate the burning rate of solid fuel. Because, that is the governing factors of the for controlling the burning of solid fuel because the time required for chemical kinetics is much larger as compared to the transport of oxygen into the solid fuel.

And if you look at the burning rate is basically changes drastically with the temperature change. And this thing will occur only when the particle size is quite small and there is very little amount of velocity around the particle surface. And keep in mind that in this kinetically control, if you consider this is your solid surface or I can say this r by R is equal to 1 and this is the place right and this is your solid surface.

And in this condition if you look at temperature is a little higher, but the it is changing along with the radial direction, but the difference between the temperature at the solid surface and the at infinity or far away from the surface not much. And similarly, if you look at oxygen concentration here for kinetically control or the solid surface, this corresponding to the solid surface is little low as compared to the away from the solid surface, but however, the difference is not much. In case of a diffusion kinetical regime; in kinetic regime, the burning rate does not depend on the particle size because, the particle size are small and temperature is really not very high kind of things.

So, therefore, it is not really depend on the particle size rather the burning rate depends on temperature exponentially. So, the diffusion process depends on the particle size and also the flow around it. You can see that whatever I have shown here, the burning rate is basically changing with respect to temperature here in this. And also the as the particle size gets reduced the burning rate also gets changed rather increased in this case.

And so therefore, the when the particle size is large; burning rate is controlled by oxygen diffusion rate to the particles. And of course, with reduction in the particle size then the burning rate gets increased because more oxygen diffusion will be taking place and then such that the increase in burning rate will be occurring.

And of course with temperature it does change, but that is not really much as compared to the reduction of the particle size. So, therefore, in diffusion rate and the burning rate depends on strongly on the particle size, weakly on the temperature as it is being indicated here. So, if you look at the detailed structure of the diffusion controlled combustion of solid fuel, you will see that oxygen level at the solid surface is very higher; the temperature at the solid surface is quite high and it changes it with drastically as it is far away from the solid surface. Unlike the kinetic control the temperature change between the solid surface and infinity r by R tending towards infinity is really very high in case of diffusion controlled combustion.

And oxygen level on the solid surface for diffusion control combustion is quite bit low even some cases that it becomes almost 0. And then of course, it increases asymptotically to the actual oxygen values which will be available in the ambient or in the atmosphere; if it is the combustion is occurring on the open condition. So, therefore, you can see there is a drastic difference between the kinetic control combustion of solid fuel and diffusion controlled combustion of solid fuel. So, you should keep in mind that and keep in mind that the carbon and metal combustion are predominantly diffusion controlled unless, the particle size is quite small; then maybe you can get a premix combustion, but which is very unlikely to occur.

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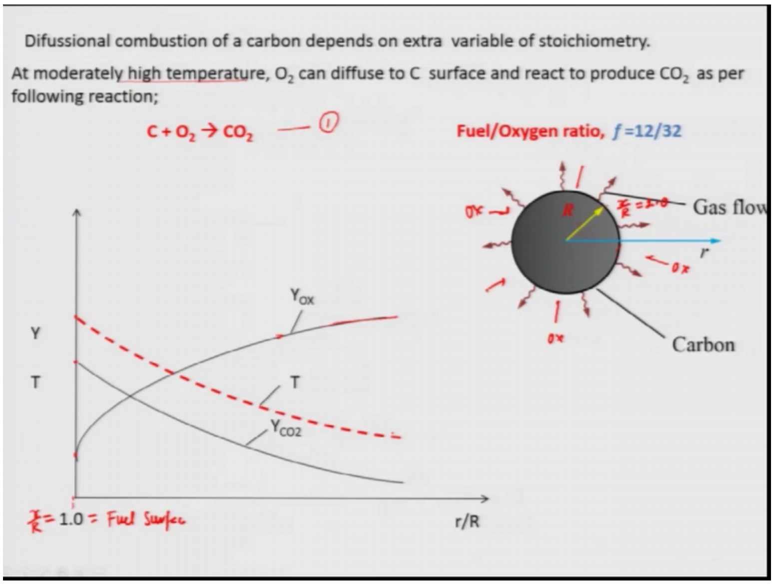

So, let us look at what really happens say considering a particle diffusion combustion carbon depends on extra variable stoichiometry. Whatever we have discussed till now there is a another variable which plays a very important role that is the fuel and oxygen ratio at moderately high temperature; as we have seen that the diffusion controlled combustion of solid fuel occurs at a high temperature.

Oxygen can diffuse to the carbon surface as I told here, that oxygen will be diffusing into carbon surface right and react with the to produce the carbon dioxide as per the following reaction that is C carbon, 1 mole of carbon reacting with 1 mole of oxygen getting into carbon dioxide. And if you look at basically the stoichiometry the fuel oxygen ratio will be 12 by 32 right, if you take this reaction 1. And as a result the, if the carbon dioxide is formed here, then it will be maximum here carbon dioxide and then it will be diffused to the atmosphere as a result like it will be decreasing right along with that.

And this is r by R equal to 1 and that is your basically corresponding to this is the point and this corresponding to the fuel surface at this point right. So, that is r is equal to this is r and this is basically r by R equal to 1. And at this condition the oxygen level is very quite low and sometimes, it goes to the 0 values right or it is a very low values and then it goes increases asymptotically to of course, in this region it increases more, but afterwards it is asymptotically towards the whatever condition in the ambient condition. And temperature surface will be high here at the surface and then it decreases along with the r direction.

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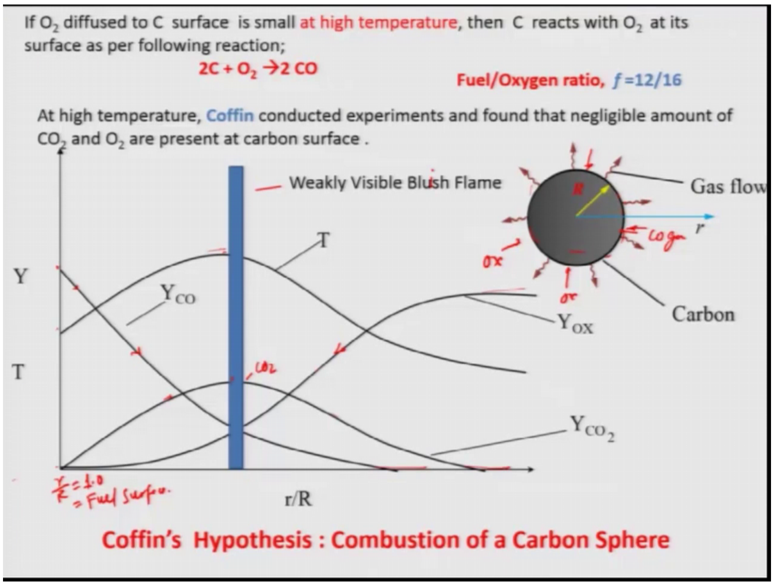

So, if you look at that is if oxygen defused to the surface; if the amount of oxygen defused to the surface is quite small and at a high temperature, then the carbon reacts with oxygen at this surface as for the following reaction. As I told that amount of oxygen which is getting into this surface is quite small and also it is at high temperature. Then what will happen? That two moles of carbon will be reacting with one mole of oxygen getting into two moles of carbon monoxide and this is a different thing, what happens instead of carbon dioxide is being formed earlier what we have learnt. Here the carbon monoxide will be formed; that means, at this surface the carbon monoxide gas will be formed and of course, the fuel oxygen ratio is 12 by 16.

And what people have found out that particularly the coffin who conducted several experiments about the carbon sphere at high temperature. He found that negligible amount of carbon dioxide oxygen are present at the carbon surface unlike what we had discussed earlier. So, and his data shows like this that if you look at Y is the mass fraction of carbon monoxide and the mass fraction of carbon monoxide decreases from the solid surface this is your r by R equal to 1 and that is basically a corresponding to fuel surface. And it is and decreases this mass fraction of carbon monoxide decreases and then it becomes a very small value at the in far away from the carbon sphere.

And oxygen of course, will be very low; it is almost small quantities, then it increases and attains the asymptotic values at far away from the carbon sphere. But there is a very interesting thing what is happening the carbon dioxide, it goes on increases reach a peak value here in some distance from the carbon sphere and then it decreases and reaches asymptotic value far away from the carbon sphere. And so, also the temperature from certain temperature at the carbon surface it increases away peak values and decreases. So, this is a very peculiar values, peculiar data he got and then, he hypothesized how does the combustion of a carbon takes place?

So, he assumed that this is basically a flame surface, weakly visible blush flame and of course, the sintering flame you know which will be taking place that is the on the surface that is a defending. But this is having a higher temperature, then what he says that the carbon monoxide which is being liberated at the surface of this carbon right.

And being transported to this region where it will be mixed with the oxygen because oxygen will be transported from outside to this one. And then what will happen it will be reacting with the carbon monoxide and as a result this carbon dioxide is being formed and this carbon dioxide is transported towards the solid surface. And also it will be transported towards the outside far away from the solid surface whenever it will be coming in contact with the solid surface and reacted with the carbon.

And as a result the carbon monoxide will be formed and this carbon monoxide again transported and then, the flame weakly visible flame Bluish flame being formed on this in this region little away from the solid surface. And this hypothesis is basically being confirmed by other researchers later on. So, this is the way how the combustion takes place and it is quite complex.

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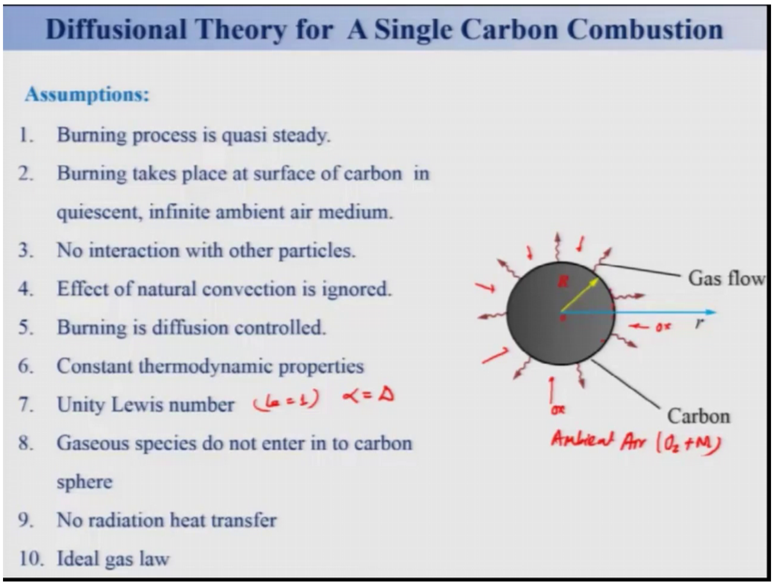

Now, we will have to look at basically the diffusional theory of a single carbon particle. We are not considering a pyrolysing solid rather we are considering a non pyrolysing solid fuel combustion considering the carbon which is a very simpler to handle. So, for that what we will do? We will take this carbon sphere and I will take this as centre and this in the r direction and then this is your the radius of the carbon sphere.

As I told earlier, there will be some oxygen which will be considering diffusing into this because of ambient it is under the quiescent atmosphere condition. Keep in mind that we will be analysing these considering making several assumptions. First of all the we will assume the burning process is quasi steady; that means, whatever the process is taking place is not changing with respect to time whenever you considered a certain amount of time. Of course, the time duration if we are considering small in that it is not changing; however, the this carbon sphere gets consumed as it is burning take place.

So, therefore, we are assume actual process is not steady it is unsteady, but however, we are considering for certain time it should be steady. And burning takes place at the surface of the carbon as I told it is a non-pyrolysing fuel solid fuel. So, therefore, the burning will be taking place at the surface of carbon in a quiescent and infinite ambient air. This is basically ambient air which will be containing oxygen right and which is at a faraway or in a quiescent atmosphere, there is no motion, no velocity will be there.

So, no interaction with other particle this is the single particle what we are considering therefore, it there would not be any interaction, but in keep in mind there in actual situation there will be a lot of interaction among the particles right. Here, we are just considering to have an analysis that we will understand what is happening.

There is a no gravitational force is acting, as a result the effect of natural convection is ignored which is not possible in surface of earth, but whenever you will go to space or some kind of a situation or you can control experiment it can be possible. So, it is being done for two simplify the analysis, burning is diffusion control as we had a discussion about it and constant thermodynamic properties keep in mind that in actual situation the properties of gases do change with the temperature.

Therefore, it cannot be really considered as constant for to make the analysis tractable, we will be using it basically constant. And the unity Lewis number is basically, that means, Le is equal to 1 what we are considering to make it analysis simpler; that means, alpha thermal diffusivity is equal to basically mass diffusivity.

And therefore, that is again another assumptions, we are making. And gaseous spaces do not enter into carbon it is not entering into carbon, sphere as I told it is a non-pyrolysing solid fuel combustion and no radiation heat transfer is taking place because which is case occurs in nature. And so, that the in analysis will be simpler and we will be assuming the gas to be ideal therefore, will be using ideal gas law. So, in the next lecture we will be basically discussing about how to analyse by invoking various governing equation. We will stop over here and we will continue this analysis in the next lecture.

Thank you very much.