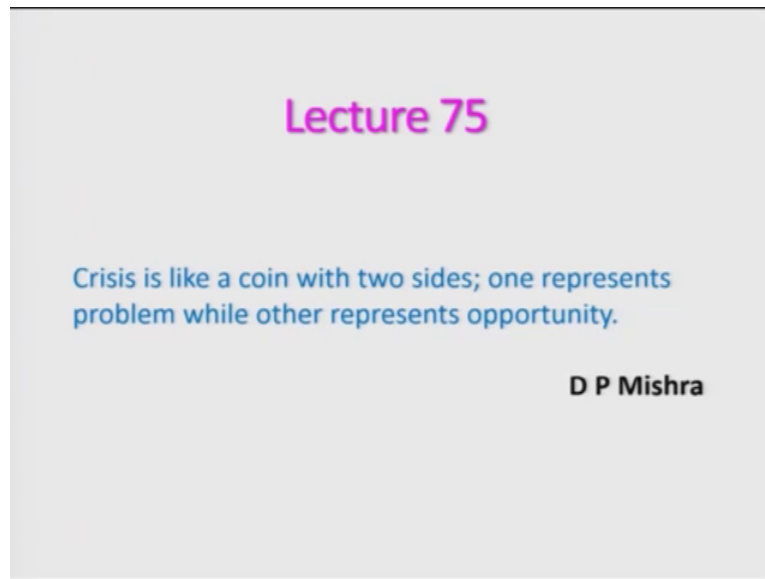


Fundamentals of Combustion (Part 2)
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Lecture – 75
Carbon Burning Rate (Contd.)

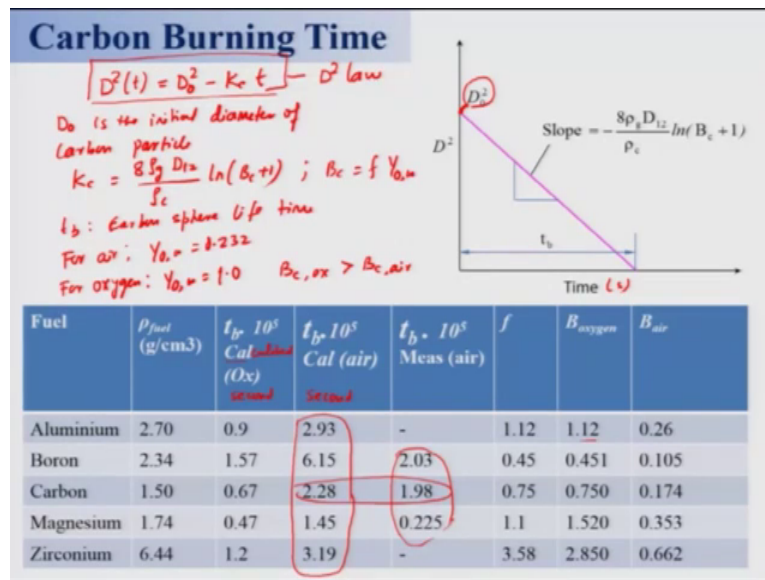
Let us start this lecture with a thought process.

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Crisis is like a coin with two sides, one represents problem while other represents opportunity. Always we are get bog down whenever we face the crisis. A crisis is a part and parcel of human life. And with this thought process let us start this lecture, and let us recall what we learnt in the last lecture. We basically looked at the carbon burning rate in the process we have derived a relationship for how does the diameter of a carbon particle will vary with respect to time.

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If you look at the relationship what we had derived is basically D^2 versus t is equal to D_0^2 minus $K_c t$. And D_0 is the initial diameter of carbon particle. And K_c is a constant we had derived that K_c is basically $\frac{8 \rho_g D_{12}}{f_c} \ln(B_c + 1)$. So, keep in mind that ρ_g is the density of the gas, ρ_c is the density of carbon. And D_{12} is the diffusivity between the carbon and the oxygen. And B_c is your mass transfer number, sometimes people call it as a spalding number.

And let us look at how does this D^2 vary with the time, and keep in mind that this D^2 , this relationship is known as D^2 law for carbon sphere. And this is also similar for the any liquid droplet sphere. If you recall that we are derived similar relationship earlier, only that K_c will be different, but the form is similar. And when we plot this D^2 versus time, you will see that this is your initial droplet diameter square right; this is the this one. And as the time progress it reduces of course, linearly and the slope from this relationship D^2 law, it will be coming as $\frac{8 \rho_g D_{12}}{\rho_c} \ln(B_c + 1)$.

And keep in mind that when the droplet diameter becomes 0 right and the time duration for complete combustion of carbon sphere is known as t_b that is carbon sphere life time because, this is the time required to for burning complete burning of carbon sphere. And this can be different depending on the various properties like $\rho_g B_c$, and other things and this will be we know that B_c is basically f . We know that B_c is equal to f into $Y_{O_2, \infty}$

basically it is oxidizer. And the mass fraction of oxidizer can be 1 if it is oxygen atmosphere. If it is air it will be 0.232, and if it is varying then it will be different; f is your basically fuel and oxidizer ratio.

So, note that this D square law will be valid not only for carbon sphere, but it will be valid for other fuel particle or and metal particles. So, therefore, only thing is that properties will be changing. And so, also the other parameters like diffusivity. And but however, the law will remain same. And let us look at some data which I have considered in this table. If you look at the aluminium is of course, the density is given here gram per centimetre cube, and t_b it is in calculated and this is oxygen atmosphere.

And if you look at this is point 0.9, and because the b oxygen is different values. And if you look at air, it is 0.26 and it takes more time whenever the air atmosphere is there like, and if only oxygen will be there the time required for the complete burning of the aluminium sphere is reduced. And boron of course, it is little higher even for oxygen $1.57 \cdot 10^{-5}$ second, this unit is in second. And, if the atmosphere is air or surrounding is air, then the time is basically $6.15 \cdot 10^{-5}$ second. And if you look at the measure value is much lower $2.03 \cdot 10^{-5}$ for air atmosphere this is your measured value, right.

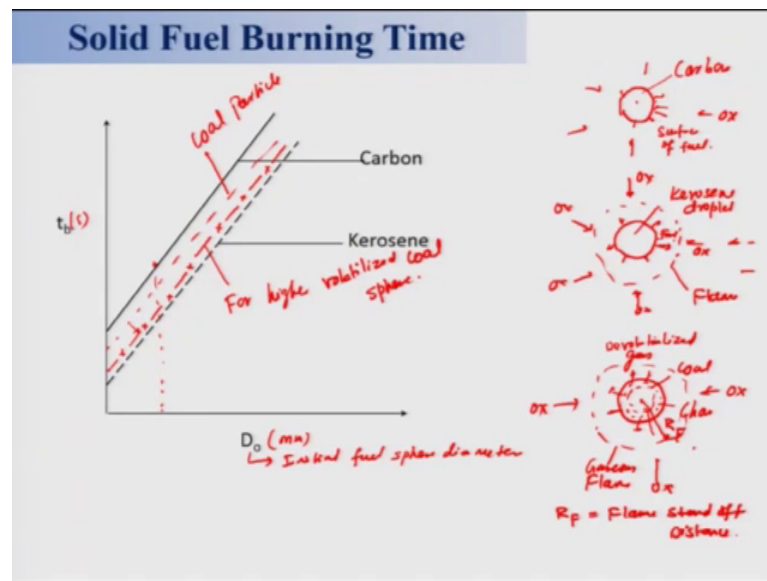
Question arises why it is so? And similarly if you look at your carbon-carbon it takes also you know calculated is higher values is 2.28, 1.98 when you measure; that means, you conduct experiment and measure the life time of the carbon sphere, then it is much lower than the calculated value. And that is true also with magnesium and of course, the experimental data is available for zirconium if you look at no experimental data is available. But however, the calculated life time of zirconium particle is higher for air atmosphere as compared to oxygen.

And that is true for all the cases. As I have already explained that this B_c will be different for air Y_{O_∞} is 0.232 whereas, for oxygen atmosphere Y_{O_∞} is 1. So, therefore, B_c for oxygen is always greater than B_c of air. Therefore, even the of course, the other properties like ρ_g will be different and ρ_c is different diffusivity will be different. Therefore, always of course, the t_b for oxygen atmosphere is lower than as compared to the air, because vigorous reaction will be taking place there is no diluents and therefore, it is high.

And beside this if you look at the measured values is basically smaller as compared to the calculated values, right. These values any one of them if you take consider any one of them, then you will find this measured life time burning of carbon in this particular is lower as compared to calculated value. Why it is so? Because in our analysis we have consider the constant thermodynamic properties; for example, density, diffusivity, but in real situation it is not the case.

So, therefore, why because this property is will be varying with respect to temperature, and as the like it is calculated; the temperature will be varying will see little later on that temperature does vary from the fuel surface to the infinity. So, therefore, that will be affecting the properties. Therefore, the measured values is always lower than the calculated values. And of course, we have done a lot of other assumption; like, there is no radiation, and this is a one dimensional in nature and several other things that will be also contributing for lower values of measured life time of the any fuel sphere.

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So, now if you look at the solid fuel burning, if you consider the carbon here, and this is of course, the life time burning of this, this is the initial diameter, you can say this is in mm t_b in second. You will find that carbon is having basically on the upper portion, and this is your kerosene, and this D_0 is basically initial fuel sphere diameter. Now if you look at this curve, you can see that for a particular initial fuel sphere of both carbon and the kerosene if we will compare, that this is having higher values t_b ; that means,

more time is required for carbon same initial diameter of carbon burning as compared to the same initial kerosene droplet.

Why it is so? That is the question might be coming to your mind. If you compare the carbon, this is your carbon, and the oxygen will be coming from the atmosphere of course, the gas will be going out here. And then the oxygen molecule has to reach the surface, and then there will be some reaction will be occurring at the surface of the fuel, right. And so, oxygen has to travel a larger distance as compared to a liquid droplet, and let us say this is your kerosene droplets.

Now, what will happen? The vaporization will be taking place of the kerosene. Kerosene will be travelling, and then so also oxygen will be travelling from other places around the. And then at some surface will be formed and this is known as flame. And here the kerosene or the fuel, like you will say fuel, fuel will be travelling and oxygen will be travelling here.

So, therefore, in this kerosene droplet, the oxygen has to travel a shorter distance as compared to the carbon sphere. Therefore, the burning will be faster and the time required for kerosene droplet of same size will take less time as compared to the same size carbon sphere. And that is the reason why it takes less time and if you look at the coal, which is a pyrolyzing combustion. If you look at let us say this is a coal, and then what will happen? This is your coal particles, right and to start with and this will be char; that means, this all these gases are released from due to the devolatilization, devolatilize lize gases are released.

And then the flame will be formed because the oxygen this is your flame, oxygen will be coming from atmosphere and then the flame is formed. So, therefore, if you look at if for the coal, this curve will be between somewhere in between. Like this is your corresponding to the coal particle. Because the coal particle combustion will be similar to the kerosene, because the volatilize or the pyrolyzed gas from the coal will be going away from the carbon surface to meet the oxygen to have a gas phase flame.

This is a gas gaseous flame gaseous flame or gas phase flame, but if the devolatilization rate is more, then what will happen? This curve will be coming towards the kerosene. This is for higher volatilized coal particle, coal sphere. In other words, more gases will be going. So, that what will happen? The flame standoff distance I can call this distance

R F, R F basically flame standoff distance. If the rate of volatilization of the coal particle is higher than the flame standoff distance will be higher.

As a result, the oxygen has to move lesser distance to meet the flame have a combustion is lower down. So, therefore, the time required for complete combustion of the coal particle will be closer will be reduced, and it may closer to the kerosene or any other liquid fuel combustion. So, therefore, that is the things what I would like to say that, we can really find out from that. Why we need to find out the life time of a solid fuel particle or the sphere? Because, of fact that when we are designing a combustors; of course, the various kinds of particle size will be there, but we can take a representative particle size.

And then find out the life time of a solid sphere; such that length of the combustors can be determined. In other words, you will have to give enough length of the combustor; such that the all the fuel particle will be burnt it out before it being exhausted out of the combustor. So, that is a reason why this life time is estimation of a carbon particle or coal particle or any other fuel particle is essential. So, by this we can also use that and design it. Now, we will be discussing about basically temperature profile.

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Temperature Profile

Energy conservation Equation:

$$\dot{m}''_s r^2 \frac{dT}{dr} = k_g \frac{d}{dr} \left(r^2 \frac{dT}{dr} \right) \quad \text{--- (1)}$$

By integrating Eq. (1) we can have

$$\dot{m}''_s r^2 T = k_g r^2 \frac{dT}{dr} + C \quad \text{--- (2)}$$

At fuel surface:

$$\dot{m}''_s \Delta H_c = \dot{m}''_s T - k_g \frac{dT}{dr} \quad \text{--- (3)}$$

Eq. (2) because

$$\dot{m}''_s r^2 T = k_g r^2 \frac{dT}{dr} + C$$

$$\Rightarrow \left(\dot{m}''_s T - k_g \frac{dT}{dr} \right) r^2 = \dot{m}''_s \Delta H_c r^2 = C$$

By substituting the value of C in Eq. 2, we can have

$$\dot{m}''_s r^2 T = k_g r^2 \frac{dT}{dr} + \dot{m}''_s \Delta H_c r^2 \quad \text{--- (4)}$$

And if you look at we are considering the carbon, keep in mind that this is a non pyrolyzing fuel particle. And for this purpose is what we will do? We will have to basically consider the energy equation, and keep it mind that, this is the oxygen will be coming from this side, this is also oxygen will be coming. And I have already explained

ok. And to find out the temperature profile how does the temperature vary with respect to radial direction from the surface, this is your fuel surface, from the fuel surface.

So, we will have to invoke the energy equation that which we had already derived that is energy equation, energy conservation; that is, basically if you look at mass flux rate at the surface I can write down that $r^2 C_p \frac{dT}{dr}$, this is your convection term is equal to $K \frac{dT}{dr}$. Now we will have to integrate this equation, right.

If we will integrate, if I say this is equation 1 by integrating equation 1 we can have r^2 square, and this is a constant mass flow rate right. So, C_p is also constant. I can take it out, and then that will be T is equal to K/g is also constant, I can get this $r^2 dT/dr$ plus constant. Let us say this is equation 2. And what we will do? We will have to basically apply the boundary condition at the surface; such that you know we can evaluate the constant C .

So, at fuel surface what is happening? If you look at the fuel surface, this is your fuel surface. So, when the oxygen will come and meet this carbon will be reacting with the oxidizer. As a result, some of the heat will be released, right. So, the amount of heat release, if you look at what it will be? This will be at the surface \dot{m}_s , \dot{m}_s into ΔH_c , ΔH_c is the of combustion of carbon, you can consider. And that will be equal to the amount of heat convected out; this is the gas which is convected out.

So, that will be equal to the mass flux, whatever it is coming out, and this is with the C_p and with certain temperature T and minus there will be conduction. Due to conduction, this is the convection and then there will be conduction $K \frac{dT}{dr}$. And this is the condition at the fuel surface. This is your fuel surface right, considered any surface. Now we will be using now at r the equation 2 becomes basically $\dot{m}_s R^2 C_p T$, this is equal to $K/g R^2 \frac{dT}{dr}$ right, is equal to basically plus C .

Now, if you look at this is nothing but your C becomes I can write down here that $\dot{m}_s C_p T$ minus $K/g \frac{dT}{dr}$, I can take R^2 square is nothing but your this much. You can say this is your 3 right, the equation 3, this is equation 3. So, that is nothing but a $\dot{m}_s \Delta H_c R^2$ right. So, is equal to what? Is C , now then we will put this C , the equation 2 substituting the values of C in equation 2. We can have basically $r^2 C_p T$ is equal to $K/g r^2 \frac{dT}{dr}$ plus $\dot{m}_s \Delta H_c R^2$.

So, this is the thing what we got it, and let us say this is your equation 4. And we will now basically integrate this equation; that we will do in the next lecture. And see that what we are getting out of it.

Thank you very much, and we will again look at this aspect in the next lecture.