Fundamentals of Combustion (Part 2)
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Lecture – 50
Stationary Flame Method for Burning Velocity Measurement

Let us start this lecture with a thought process. One has to pursue question earnestly, Like a faithful shadow meticulously, One should bear question in mind, Like a small innocent inquisitive child. It is very important to not only ask the question, but also pursue it vehemently. Unfortunately, with modern education, we are not really asking question and not even pursuing it, even though we are asking some time certain question to our self. And also this is happening because of very busy lifestyle or a fast lifestyle.

So, let us now recall what we learned in the last lecture. In the last lecture, we basically looked at various methods of measuring the burning velocity. And in all these methods, we really looked at the propagating films, and how it is moving, and what speed it is moving from that data, of course with the help of photographs and also the pressure sensors, we could measure the burning velocity out of it. And three methods we had discussed in the last lecture. One is cube method, other is the combustion-bum method, other is soap bubble method. Each one was having their own advantages and disadvantages.

Today, we will be discussing basically about another method of measuring burning velocity in which the flame will be stabilized; unlike in the previous case in which it was moving or propagating. So, let us look at a Bunsen burner flame in a Bunsen burner. You might recall that the Bunsen burner was device by Bunsen in around 1855; it is he who was really discover the premixed flame.

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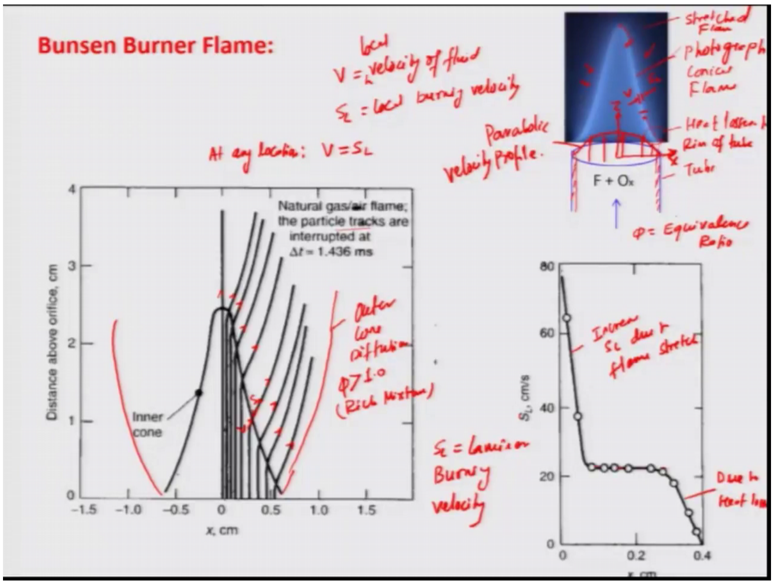

And typical flame, you can look at in a Bunsen burner like a this is your a tube, and which is having a wall thickness. And in this case fuel and oxidizer are premixed thoroughly, and at certain equivalent ratio. If you look at phi is your equivalence ratio, and then you can ignite and a flame can be stabilized with the rim. See this is your tube having certain finite thickness. This is your rim of this tube, and which you can call it is a rim of the burner, and which helps in stabilizing the flame. Because, the on the wall of this tube, there will be heat losses from the flame in this portion, which will be coming over here.

And a flame will be established a conical flame, this is a photograph of photograph of a conical flame. This flame is basically corresponding to the equivalence ratio less than equal to 1. Therefore, you get a very sharp feature, and only one flame. And, this is a very curved one. And this is this portion is curved due to the heat losses, losses to the rim of the tube or the burner. And this portion is a curved very much. And this is the flame is subjected to stretch flame and this region, where it is almost stretch, so it is not subjected to any stretch or the minimum amount of stretch.

So, let us now look at that flame in another figure, which I have shown here. And this is basically being obtained by conducting experiments, and measuring the shape of a flame. This is your in a natural gas air flame. And in this case the particles are being introduce at this end. And such that this particle will be moving along is this directions. And if you look at these are basically steady flame, and you can say this lines are the stream lines. And it is diverges in this zone, and this is your inner-cone zone.

And in some cases particularly, where equivalence ratio will be greater than one rather rich flame, there will be some outer diffusion flame will be coming. Outer cone diffusion flame will be coming particularly, when equivalence ratio greater than one, rather rich mixture flame. For rich mixture, these can come also. And keep in mind that to have this flame, it is very important to have a velocity profile, which can give you the conical shape kind of burner, which can be stabilized well. And keep in mind that velocity profile in this tube; one can get different depending on the length of the flame.

So, if sufficient length of the tube can be provided for the fuel air mixtures to travel, then we can get a fully developed velocity profile and that will be parabolic in nature right. If you look at this is your parabolic in nature, and one has to ensure that this velocity profile are the fully developed velocity profile must be ensure such that you can really get the same boundary condition for different set of readings. So, that is very important, what you can have for conducting experiment. So, this is a very important aspect one has to do for conducting experiments, and so that it can be repeated easily. And different equivalence ratio one can maintain, so that you can get a various things.

Let us, now look at for a one case, how this burning velocity that is S L is laminar burning velocity. And keep in mind that this if you look at this axis, if I can say this is your Z axis, and this axis is your X. So, if I take the velocity or the laminar burning velocity at each location, then I can really find it out what will be the I can plot with respect to X that is S L, S L versus the X. And keep in mind that in this case the flame will be travelling from this direction towards the incoming fuel air mixtures in such a way that wherever the local velocity right will be perpendicular, this is your fluid velocity V.

And this is your S L at a flame location, when V is the fluid velocity. This is the velocity of fluid rather I would say the local fluid velocity. S L is the local burning velocity. The flame will be stabilized, as we have seen earlier also V is equal to S L at any location. So, each place it will be having such that it will be you can have given. Now, this can be a very easily obtained earlier day’s people are using particle tracking method.

And nowadays one can have a method PIV method such that what we will do, we will have find out this velocity V. And then, you can say these velocity same as that. So, locally and then, you will find out V is equal to S L. And when you do that, you will find very interestingly S L is being plotted with respect to X, this is your X direction right. And you can see that the burning velocity is very higher in this zone that means, at this zone, this zone, right burning velocity is higher.

And in this zone as I have discussed earlier the burning velocity is remaining almost constant. After that of course it decreases, due to the locally heat loss, which will be there due to the room to the rim of the tube. So, therefore this is due to the burning velocity decreases due to heat losses. And this is increase S L, due to flame stretch.

So, what we will be taking basically the actual burning velocity is this, this is the one, which will be taking considering in this burner. So, therefore it is very important to take consider the proper burning velocities, and otherwise it will be wrong. Of course, we will be seeing some other method, which is little crude, but it can give some average value for the burning velocities. And this, whatever I have discussed is basically for the local burning velocity.

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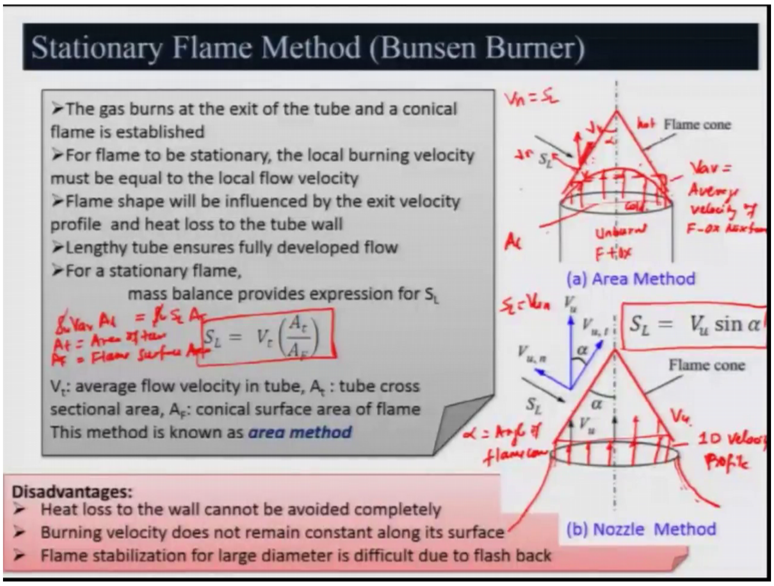

So, now look at a method, which is very simple to do, because just now we have seen that very sophisticated methods is required to measure the local burning velocity on the surface of a flame by using PIV or particle image velocimetry and other very sophisticated instrument. However, in the laboratory, we can use a very simple method and a for a stationary Bunsen flame by using one method, what we call ADM method. And what we will do in this case we will take a tube, and then consider basically the velocity profile proper, so that a flame shape will come.

And you can take a photograph of this flame. And then measure this area of the flame surface and from that one can calculate the burning velocity or average burning velocity of a flame. And if you look at like as I told that a conical flame is to be established at the exit of a tube, in which the fully developed flow is been ensured. And proper equivalence ratio fuel and oxidizer has to be maintained, so that the a flame can be conical flame can be established.

Keep in mind that the local burning velocity must be equal to the local flow velocity that is very important. For example, if I take here some velocity let us say this is having, this is your fluid velocity V right. Then what we will happen I can resolve this velocity, into if I take this is your angle alpha, into certain angle along with this direction. And then, I can resolve this into this direction, so that this will be V n, this is normal direction. And this is your V t tangential direction along with the flame surface. So, that what will happen you can the flame can be stabilized only when V n is equal to S L locally in this region.

But, however, in this case, we will be using area average method. So, there might be some velocity profile, which will be there here in this case, this is but however, in this calculation, what we will be doing we will be taking the average velocity of this profile. This may be like this average velocity, which will be remaining this is hypothetical. This is your V average that we are considering as a some hypothetical velocities.

As I told the flame shape will be influenced by the exit velocity profile, and heat losses to the tube. Length of the tube must be ensure that fully developed flow should be there at the exit of the this tube. And for stationery flame, we can have a mass balance that means, whatever the flow is passing through here in this flame surface, which will be taking. So, if you look at this mass balance, we can say this is basically un burned fuel air mixture, and which you assume that in this surface also that this will be unburnt.

So, we can say that this mixture this is the average velocity average velocity of fuel and oxidizer mixture. So, if I take that out, what I will get, I will get this rho u v average there is a mass flow rate which is passing through the tube into A t, A t is the area of A t is basically area of tube this is that direction, this is your basically cross section of A t is equal to rho u because this is the cold side and this is the hot side; this is your hot side and this is your cold side. This is your cold mixtures right.

Then that will be unburnt temperature density of the unburnt mixtures into S L, S L is the average burning velocity of this flame and is equal to in to the A F. A F is basically the flame surface area. So, this will cancel it out. So, you will get basically S L is equal to V t A t by A F. So, as I told that this is basically A F is the conical surface area of the flame which can be obtained by the photographs of course, nowadays people are using image processing to find out this conical surface area of flame. Earlier days people have measuring by taking still photography and. This is one of the method which will be very crude one, but it will give some values such that it can be utilize; unlike the previous methods this is relatively crude one. As I told earlier that this method; is known as the area method.

There is another method which is known as the nozzle method generally the nozzle will be designed in such that there is a increase in velocity. And the velocity profile at the exit of this nozzle will be almost like a flat velocity profile or one-dimensional velocity profile. Except in this region there might be a little bit change because of development of bound layer. Keep in mind for nozzle design one has to have a decrease of area the area ratio must be greater than the 4 is a thumb rule which is being used for designing a nozzle to have a velocity one-dimensional velocity profile.

And keep in mind that in this case the velocity V u is same everywhere so that if you can look at this is basically your V u; and then from this photograph, what you can do basically you can measure this angle alpha. If I know this angle alpha, it is very easy to find out S L. And if I resolve this V u into two component, one is along the flame surface V u t that means, the unburnt velocity tangent tangential velocity or tangential unburnt velocity on the perpendicular to this flame surface that is normal component of unburnt velocity.

And keep in mind that flame is travelling in this direction with S L; so therefore, S L is equal to V u n. And what is that V u n, V u n is nothing but your sin alpha because this is your angle alpha is the angle of flame cone. This is basically half angle. So, then I can get directly the burning velocity by measuring the angle of the flame cone. And of course, the v u is already you know because you know the mass flow rate. And you can get very easily by knowing the density, and also the cross sectional area of that nozzle.

So, this method is basically known as nozzle method which is superior as compared to area method, but problem with this method is that it can be used for a very limited range of the fuel air mixtures. Because, the it is difficult to stabilize the flame in this nozzle as compared to the Bunsen burner in which generally the area method is being used in the laboratory. Unless you are having a very sophisticated instrument to use; like PIV and also particle image velocity, where you can measure the local velocity not the average velocity. So, the also there it is very important to be careful otherwise, you will be land in getting some number which is not really congruent with the reported measurements of the burning velocity for particular fuel and air.

So, disadvantages of this method that heat loss to the wall cannot be avoided completely, therefore, there might be small error in that. And other is the burning velocity does not remain constant along its surface. And the flame stabilization for large diameter is difficult due to the flash back, because it will be a flame will be entering into the burner particularly when the fuel air mixtures is a either the lean or may be towards there when fuel air mixture is basically lean, the flame will be trying to flash back due to the low burning velocity.

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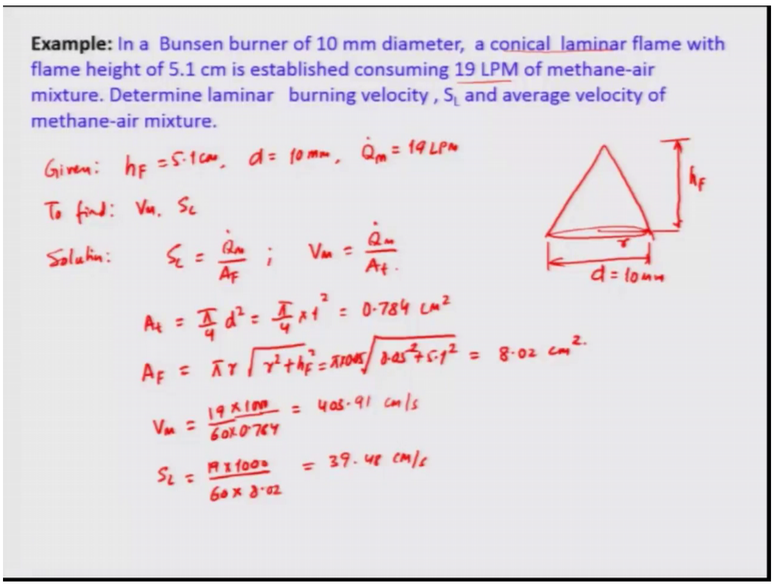

And let us look at example like where we can calculate the burning velocity is the example is very simple one that is in a Bunsen burner of 10 mm diameter, a conical laminar flame with the flame height of 5.1 centimeter is established consuming 19 LPM of methane-air mixture. And determine the laminar burning will S L, S L and also average velocity of methane-air mixtures.

So, it is already given that is a conical flame here. So, and the height of the flame is given. And it is having the mass flow rate of the volumetric flow rate is given for the methane-air mixtures it is given h F the flame height is 5.1 centimeter and diameter of the tube is 10 mm, and the mixture is something 19 LPM, LPM means is liter per minute. And we will have to find out V m the velocity of the methane-air mixture average velocity methane and S L burning velocity.

So, if you look at what is given is a conical flame, so it is h F is given. And this radius or the diameter is given, this is 10 mm. So, we can find out very easily that is S L is equal to Q m by A F; and we can also find out V m is equal to Q m divided by A t. So, if you look A t, A t is very easy that is pi by 4 d square if you do that multiply by that into 1 plus because 10 mm I can say this is basically 1 centimeter, then it is nothing but your 0.784 centimeter. And A F I can take it as a right angle cone and then I can find out that A F will be pi r r is basically d by 2 root over r square plus h F square and this nothing but your r. So, if you do that, you will get pi into 0.05 0.05 plus 5.1 square, so you will get 8.02 centimeter square.

So, similarly we will get basically V m is nothing but your 19 LPM divided by 60 into the area is 0.784 into 1000, this will be 403.91 centimeter per second. And S L is similarly 19 into 1000 divided by 60 into 8.02, you will get 39.48 centimeter per second. So, this is a method by which you can really calculate the burning velocity ok.

Thank you very much. We will stop over here. And in the next lecture, we will be discussing about few more method how to measure the burning velocity.