Fundamentals of Combustion

Prof. V. Raghavan

Department of Mechanical Engineering

Indian Institute of Technology, Madras

Lecture - 44

Laminar Diffusion Flames - Part 4

Diffusion flame structure and Flame regimes

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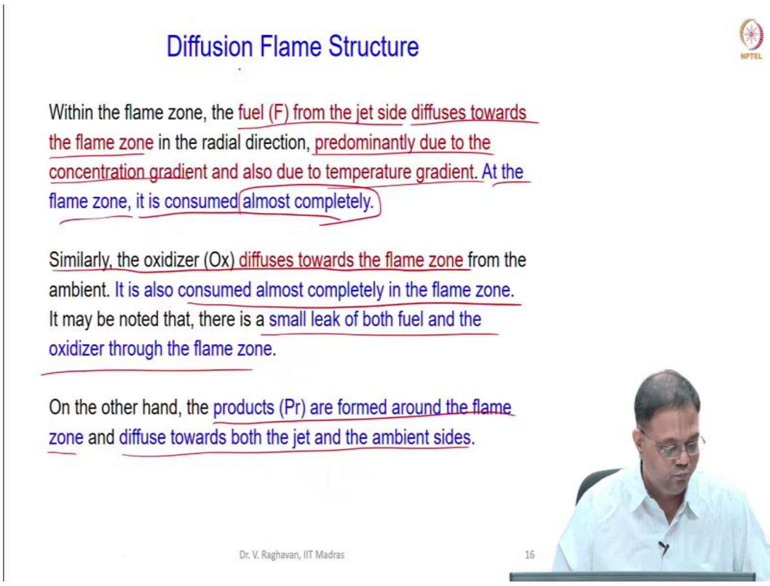

So, that is what we are trying to put up here. You can see that within the flame zone, fuel on the jet side diffuses towards the flame zone predominantly due to concentration gradient and temperature gradient. At the flame zone the fuel is consumed that means, at the flame zone where the maximum temperature occurs, the products are formed the fuel is consumed.

I am saying almost completely keeping in mind some small leak which may happen because there was finiteness in the flame zone; finiteness in the flame thickness basically. Similarly, oxidizer in the ambient diffuses from the outer side towards the flame zone and it is consumed almost completely in the flame zone like fuel. So, that is what is depicted here.

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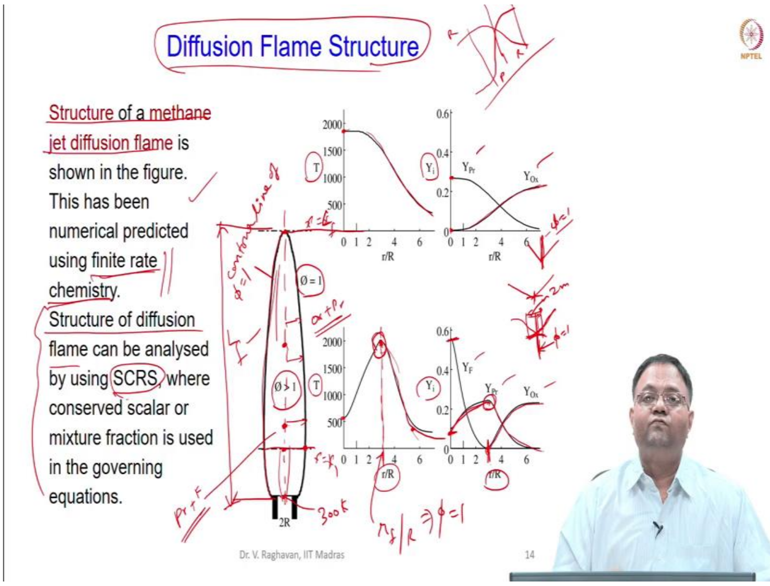

You can see that it is almost consumed. It is not like exact 0, this is fuel and oxidizer it is not exact 0 here, it will be like this small leak will be there due to some thickness. So, if it is exact 0 like this, then the flame will have 0 thickness here like this. But it is not exact 0 here, it goes to 0 slightly away from this.

So, this is the point what I am plotting, this is the point Φ = 1, but towards the Φ < 1 side or Φ > 1 side also we can see some small amount of oxygen coming into the flame slightly and fuel going outside the flame slightly, I mean there will be. So, this is the very small thickness, finite thickness say 1 mm or 2 mm something like that, in the order of mm which is important due to the finite rate chemistry.

But if you assume infinite rate chemistry, then it will have 0 thickness, exactly at this flame zone or Φ = 1, the oxygen goes to 0, fuel will go to 0 straight away. So, this is the difference in this. But predominantly, we can say that almost all the fuel and oxygen is consumed at the flame zone. Small leak of both fuel and oxidizer is formed due to the finite rate chemistry.

Similarly, products are formed at the flame zone and diffuse towards both the jet and the ambient sides. That is the products are also convected inside in the axial direction in the jet side basically. So, this is very important to understand there, profile within the flame.

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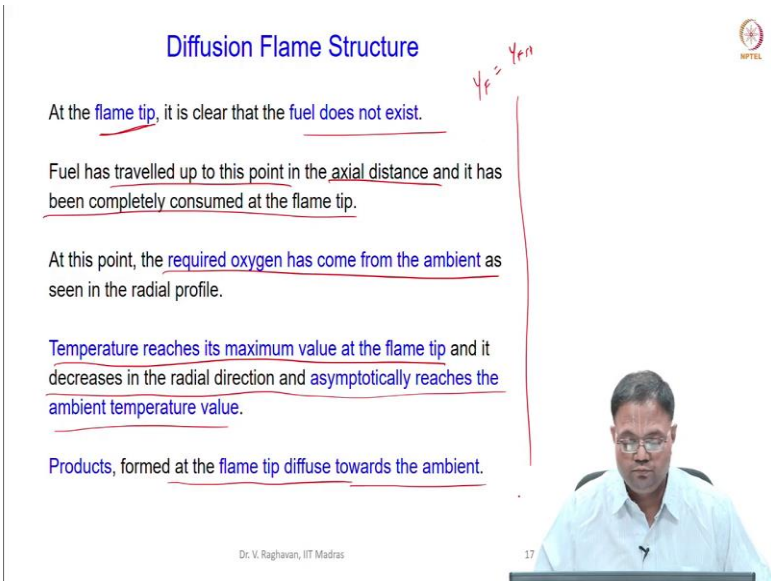

Now at the flame tip, what happens? A fuel does not exist because all the fuel is now consumed. When that happens the particular flame tip is actually characterized by Y_F equal to $Y_{F,stoichiometric}$ that means when you ignite this, whatever fuel left there its stoichiometric proportion has to be consumed for the flame to be formed there, so, fuel will not be there. It means that fuel has travelled up to this point in the axial direction that has been completely consumed at the flame tip.

So, here you can see that when you draw profile at this flame tip in the species side, you will not have fuel. Products are formed and they are the maximum at the center line and they decay. Similarly, oxygen which is required for the combustion to take place at the flame tip comes in goes to 0 at the axis. So, oxygen from the ambient diffuses and goes to 0 at the radius equal to 0 that is the axis.

Temperature is maximum at the flame tip and decreases towards the ambient. So, the profile is actually different. So, you can see that this is the profile what you get. So, low local maximum at non-zero radius and reduction after that. So, in the profile which exhibit for the products and temperature, but the temperature here has maximum at the axis and decreases towards the ambient temperature. So, the profiles are little bit different.

Even in the products you can see products are maximum at the flame tip, at the axis, but the products are not maximum at the axis, they are maximum for non-zero radius. So, that is the thing. So, again the oxygen going to 0 is not occurring at r = 0 here, within the flame. But here it is exactly at r = 0. So, this is the structure.

So, within the flame you can plot structure. A representative structure at any axial location is enough, but you have to understand that this is not going to be the same at all the axial locations there will be variations in the maximum values as well as the location at which the maximum occurs.

And the flame tip is exactly different, actually at the flame tip we can see the maximum of temperature, maximum of product, mass fractions occurring at the axial line itself. So, these are the aspect of the diffusion flame structure. Now, at the flame tip, required oxygen has come from the ambient as seen from the radial profile and it goes to 0 at the axial location, that is the axis.

Then, temperature reaches its maximum value at the flame tip, at the axis it is maximum and decreases in the radial direction. Asymptotically reaches the ambient temperature value. Products are formed at the flame tip diffuses towards the oxygen. There is no flame like, so, inner zone at the flame tip. So, these are the important aspects of the structure at the flame tip. So, we have seen the structure within the flame and at the flame tip.

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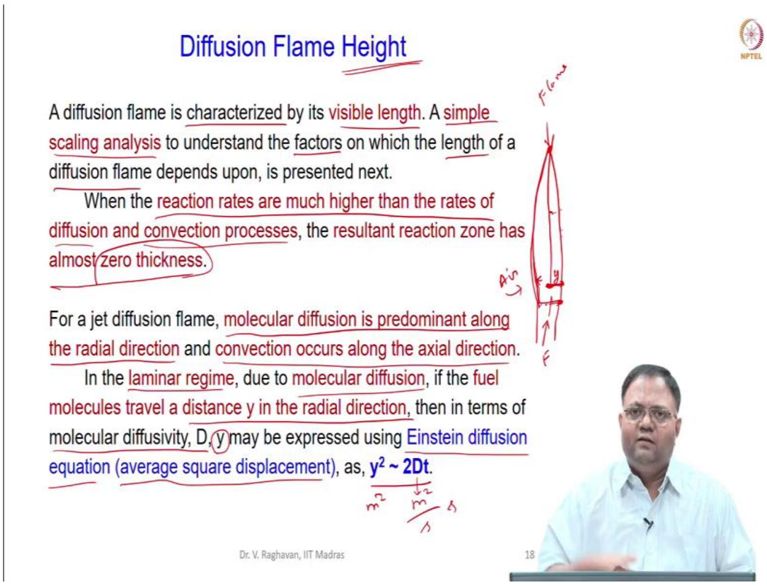

Now, as I told you very important characteristic of a diffusion flame is the visible length or the height of the diffusion flame. So, how to calculate that?

Now, we will try to do a simple scaling analysis. Please understand that it is not going to reveal the exact value of the flame height, but it will give us an understanding of the factors which are going to affect the length of the diffusion flame that is what we are going to see now.

Now, in this analysis, we have to understand that predominantly in any diffusion flame, the reactor, the reaction rates are much higher than the rates of diffusion or the convection. So, they leave alone the turbulent regime, some complexities are there.

In the laminar regime basically, the convection process is not due to very high velocities, so, convection time scales and diffusion time scales if you take chemical time scales are much smaller than that. That means, the reaction rates are much higher than the transport processes.

So, that we have already discussed several times to emphasize, I am again writing this. So, as a result, the reaction zone will have almost zero thickness. So, the finite thickness of the reaction zone is not considered here. When you go for the premixed flame, the flame speed and the flame thickness are important characteristics what we saw. So, the flame thickness was a characteristic.

So, here, we need not worry about the flame thickness, take the flame thickness as zero thickness because the reaction rates are much fast, infinitely fast that is the important point you want to have here.

Now, that means that we do not really care about the reaction rates at all, even you do not need a single step reaction also. Just do it with normal non-reacting flow or simply simple chemical reaction system and so on. Just solve the equations without any source terms.

Now, again another point which I am stressing here is diffusion is predominant in the radial direction because there is no convection in this direction. Convection is present, the convection time scales are basically lower. So, convection occurs in the axial direction because there is an initiation from the port exit. So, convection occurs in the axial direction and in the radial direction, it is predominantly molecular diffusion.

Now, let us understand how we are going to do the analysis. So, let us take some port from which fuel is supplied. Now, there is a flame which is formed. So, this is a flame which is formed. So, only fuel is coming out and air entrains from the atmosphere and you have reaction zone which is formed which we have discussed, this is the flame zone which is formed.

Now, at the axis, let us take a molecule. The fuel molecule goes to the radius here and it consumes. So, the fuel from the center line has to travel a distance in the radial direction after which it is consumed. Similarly, the fuel molecule in this position has to travel like this and go to the tip where it is consumed correct. So, fuel has to travel by diffusion in the radial direction from the center line and reach the flame surface where it is consumed.

In the axial direction, from the nozzle exit, it has to go to the flame tip, and it is to be consumed. The flame has to be steady. Please understand that the flame has to be steady. So, if the molecule which is traveling in the radial direction is slower than the molecule which is convected in the axial direction, then there will be unsteadiness here.

Basically, you can see that the length is higher and the radius is shorter because of the scales of the diffusion and convection. Convective timescale is lesser so, within a shorter time, the molecule travels the longer distance in the axial direction, but in a radial direction, no diffusion and it has to travel only a shorter distance.

So, we get the shape which is like this. So, in the flame, radius is much shorter than the length because of the diffusion dominated transport in the radial direction and convection dominated transport in the axial direction. Now, let us take a molecule.

Laminar regime molecular diffusion alone is considered. Now, fuel molecule from the axial travels a distance y in the radial direction before it reaches the flame. From the axis, the fuel molecule travels a distance y, before it reaches the flame where it is consumed ok.

Now, what is this y? In the terms of molecular diffusivity here only binary diffusivity is used. For example, we can say fuel and air. So, how the rate at which the fuel goes into air also we can take, some diffusivity you take D. In terms of diffusivity, what is the distance it has traveled can be written using Einstein diffusion equation which is also called average square displacement which is y square is approximately equal to 2 into the diffusivity into time.

So, this is actually m^2, and this will be you can see that m^2/s and second. So, Einstein diffusion equation or the average square displacement says that y square is proportional to or it is equal to 2Dt. $Y^2 \alpha 2Dt$

So, if this is the y it has traveled, y is the distance traveled by the molecule from the center line to the flame radius that will be equal to 2 times the diffusivity into time what it takes. We are interested in finding time again. Now, if you see this, what will be the order of distance the molecule has to travel from the axis to the flame? For example, it may be higher here, it may be equal to radius at this exit. It may be higher here in the middle somewhere and it may be lower here.

So, what we can say is on an average, this the distance which is travelled by the molecule from the centerline to the flame sheet or the flame surface will be of the order of the radius of the pipe or the port.

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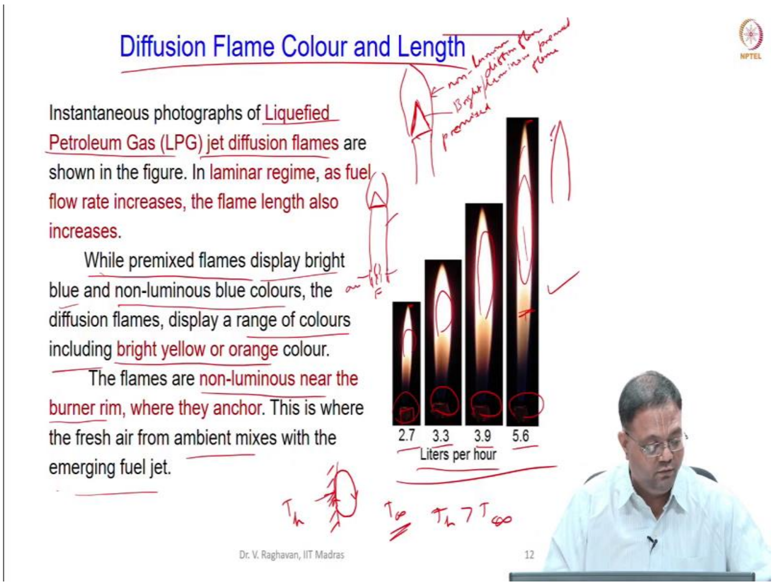

So, if you see all the flames what we have depicted in these figures, we can see that this is the radius so, the flame radius is almost of order of, it is not exactly equal to the radius, but of order of the radius of the port. If you have a bigger pipe, then the flame also will be bigger, the flame radius will be at least equal to the radius of the pipe.

So, the molecule at the centerline to the surface has to travel at least a distance which is equal to radius. So, that means, y will be of order of the radius. So, I do not want to take arbitrary distance y here, the known value is radius, so, I will take that.

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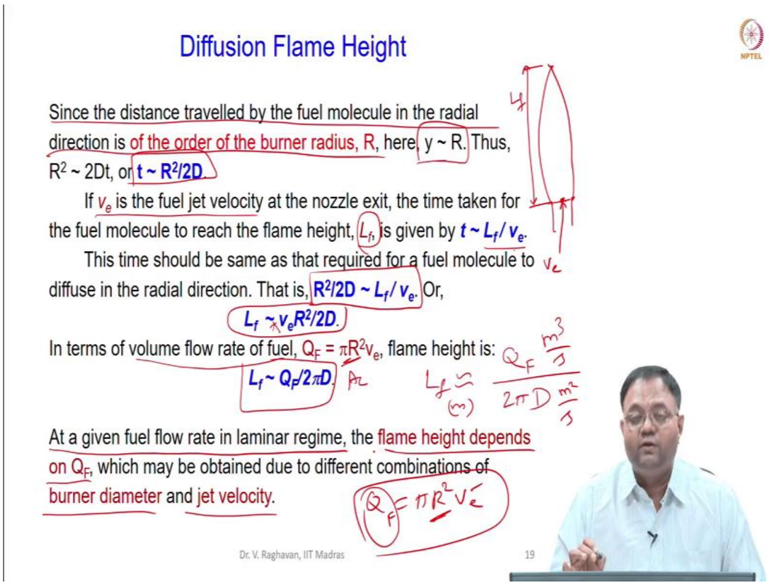

The distance traveled by the fuel molecule in the radial direction is of the order of the burner radius. So, I can say y is approximately equal to R, then use the diffusion equation, instead of y^2 I put R^2. So, $R^2 = 2Dt$, or I am interested in time, $t = R^2/2D$. So, that is the time taken by a molecule from the centerline to reach the flame surface.

Now, we will see the convective time scale. So, at nozzle exit, the velocity is v_e and the flame height is L_f. So, for a molecule here to convectively reach this flame height what is the time scale required?

So, v_e is the jet exit velocity, then time taken for the fuel molecule from this point to reach the flame height L_f will be distance by velocity so, L_f/v_e so, that is the time it takes. But for that time, the molecule reaches from this point here to the flame sheet in the radial direction or this point at the flame tip will be the same because the flame is intact there.

So, you can say that $R^2/2D = L_f/v_e$ because the convective transport is there, the length is much higher than the radius. But the time taken should be the same, you equate this. So, $R^2/2D = L_f/v_e$ or we can say scaling analysis. Order of magnitude, if it is same that it is enough for us.

Now, L_f, the flame length is v_e $R^2/2D$, D is diffusivity. Now, what is the volumetric flow rate of the fuel? That is nothing, but $\pi R^2 v_e$, area of cross section into velocity. So, $\pi R^2 v_e = Q_F$. So, $Q_F/2\pi D$ that will be the length of the flame.

So, length of the flame L_f is approximately equal to, because it is scaling analysis, volumetric flow rate of the fuel / ($2\pi \times$ binary diffusivity). So, this will be the m. So, L_f is in m. Now, this means when the volumetric flow rate is increased, the flame rate will increase. Diffusivity will not change much if I fix the fuel and air the diffusivity, the average diffusivity also you can take, that will not change much.

So, the denominator is predominantly constant. The fuel flow rate, if it is increased, the flame length has to increase in the laminar regime. So, at a given flow rate in a laminar regime, the flame height depends on Q_F, which may be obtained due to the different combinations of burner diameter and jet velocity.

So Q_F as I told you it is $\pi R^2 v_e$ so, that means, I can vary the diameter of the burner or the velocity by combination of this.

So, actually speaking, this is the only factor which is seem to be affecting the flame length. That is what you also see here in these pictures, you can see that from 2.7 lph, when you increase the flow rates to 3.3, 3.9 etcetera you can see a significant increase in this.

It is almost a linear increase also; you can see this. So, this is what the laminar flame length of a jet diffusion flame.

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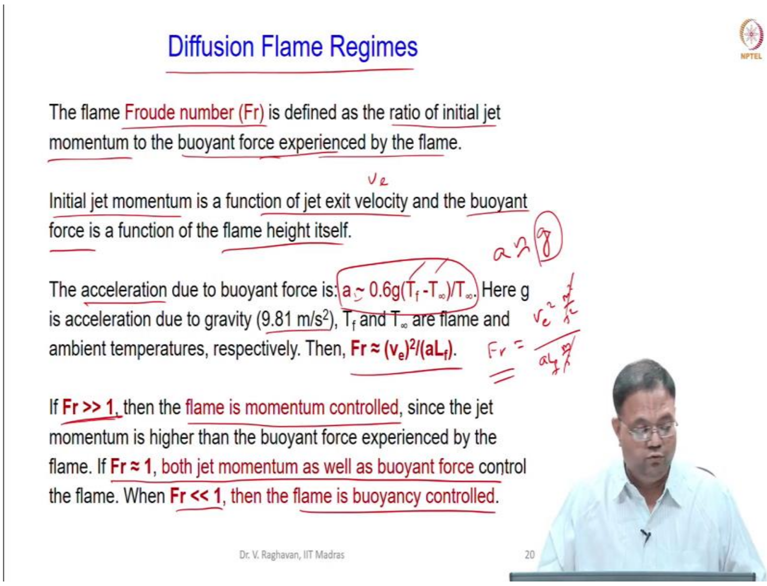

Now, let us go to the next topic here. So, how it is controlled? See for example, these flames are formed under normal gravity. We have to discuss this also. For example, you can see this, the flame shape etcetera, this is due to experiments done in the normal gravity condition.

But if you go to say for example, space and do the experiment without gravity say micro gravity or zero gravity environment, then the flame shape will be entirely different. So, this type of flame shape is important to this not only because of the convection, it is also because of the buoyancy force which is there.

For example, if you have a hot surface so, this is at T_h and we have a cold ambient so, $T_h > T_c$, you can see that the particles which are in contact with this, will have a motion like this, So, you have a natural convection which is occurring.

So, this is the surface which is at a hotter temperature T_h and say this T_∞ is cold, then you have a natural convection driven flow, so, that also we will aid here. See, the flow rates are lower here, based upon the strength of the convection the natural convection induced flow also will be there. So, in the normal gravity conditions both the convection, forced convection and the natural convection will also play a role.

But which is going to be dominant? Whether the momentum of the jet is going to be dominant or the buoyancy driven flow? Because the flame is like a hot surface and when you go away from the flame you can see this.

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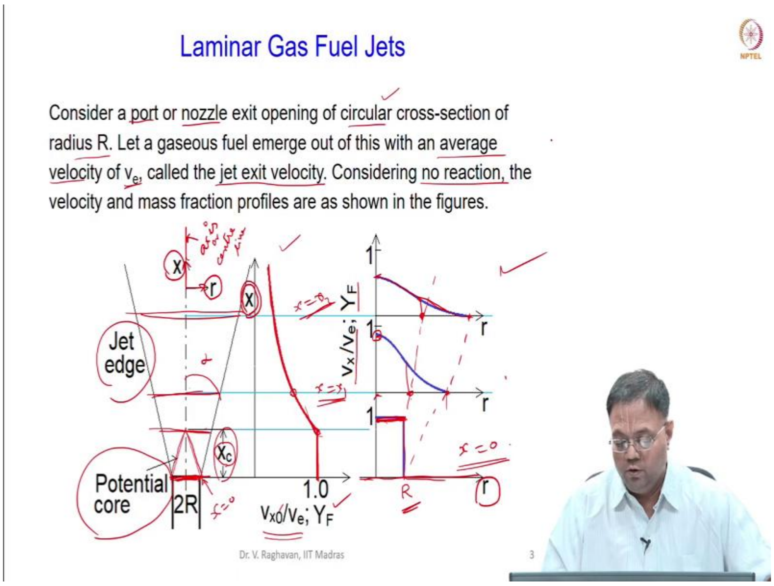

Here when you go away, you can see the temperature etcetera dropping. So, here in the structure, you can see that temperature drops from the hot condition, hot surface here temperature drops very rapidly to a very low value.

So, we can see this; the density here will be very low, density here will be very high. So, there will be a buoyancy driven acceleration. So, the buoyancy will also be there to impart this particular shape to the flame. So, in general, which is going to dominate? Whether the momentum itself is going to dominate or the buoyancy is going to dominate or both?

So, if the velocity, see we can literally just guess. So, if velocity of the fuel jet is very low, then the buoyancy force will be higher than this or it will be comparable or higher than the velocity. If the jet velocity is increased, then the buoyancy force may be negligible. So, the regimes of the diffusion flame, jet diffusion flame is what we are going to discuss here in this diffusion flame regimes.

So, just to give a preamble, which is going to control, we have to define a non-dimensional number for this called Froude number, flame Froude number which is defined as the ratio of initial jet momentum that will be the convective strength of the fuel jet and the buoyant force experienced by a flame which is due the temperature gradient and the gravity. It is actually the temperature gradient which is inducing a density gradient.

So, the density gradient driven flow is the buoyant flow, natural convective flow. Now, initial jet momentum is a function of exit velocity v_e and the buoyancy force is flame height itself that is the hot surface what we have and very near to that, a cold region is there. So, due to this, along the entire length of the flame, you will have a buoyancy force.

So, what is acceleration? When there is a force there is a mass and acceleration what is acceleration due to the buoyancy force? Acceleration created on the hot gases and the hot gases raise up, accelerate up, what is that acceleration? Typically, if you calculate the acceleration, again as I told you it depends upon the temperature gradient and the acceleration due to gravity. If T_f is the flame temperature, T_∞ is the ambient temperature, due to this ΔT only this is driven.

So, 0.6, some factor before g, it is approximate please understand. Acceleration due to gravity which is 9.81 m^2/s, $\Delta T/T_\infty$, simply just normalizing this. So, this will be the strength of the acceleration due to buoyancy.

Now, if we know this value of a, so, we can say that this may be just taken as seen in many cases you can also approximately take the buoyancy driven acceleration as just the acceleration due to gravity itself is not a problem. So, in this case, Froude number will be v^2/a or $g \times L_f$.

So, Froude number is a non-dimensional number which is equal to $(v_e)^2$ m^2/s^2 divided by $a \times L_f$ which is nothing but $m/s^2 \times m$. So, that will cancel, that is non-dimensional number.

So, if convection is dominated, then we will see the momentum controlled regime; that means, if Froude number is much greater than 1, that means either the buoyancy driven acceleration is low or the velocity of the jet is high, then the flame is momentum controlled.

Because the momentum is going to control the entire flame length etcetera. But on the other hand, if Froude number is less than, much less than 1 that means, what happens here v is very less or acceleration due to buoyancy force is very high, in that case, flame is buoyancy controlled. In several cases, we will get both momentum as well as buoyancy force which is controlling the flame.

So, let me stop here. We will proceed in the next class.