Indian Institute of Technology Madras

NPTEL

National Programme on Technology Enhanced Learning

COMBUSTION

Lecture 43
Droplet Burning

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Today we will start looking at droplet burning now the context of droplet burning comes up in many liquid fuel applications many of the popular liquid or commonly encountered liquid fuel combustion applications is in automobile engines where we inject either petrol or gasoline as it is called in different countries or diesel in piston engines or for examples from some form of kerosene in aircraft engines and soon in all these things the fuel is essentially the essentially in the liquid form and it is atomized into a spray.

And the spray is essentially composed of a ensemble of lots of different droplets of different sizes another application of droplet combustion is in liquid rockets where you typically are injecting a liquid fuel as well as liquid oxidizer and you try to atomize both of them and to try to burn them so in this situation then in general what basically happens is whichever is in liquid form has to evaporate and burn in the gas phase and the combustion that is occurring in the GAT gas phase has to feed back heat to the liquid fuel or oxidizer in order for it to vaporize in the case of liquid rockets where you have both liquid fuel.

And liquid oxidizer having to be atomized in two sprays and this phrase have to mix and vaporize and a burn together you have a problem of multiple droplets of different species which are trying to vaporize based on flames that are existing while the gas phase products of these are gas phase vapors of these are mixing and burning and that is a little bit more difficult problem think, think about an easier problem is where you are looking at a fuel being in liquid phase and being atomized into spray and burning in a gaseous oxidizing ambient right.

So first of all we will try to limit ourselves to this situation where only one of the reactants namely the fuel is in liquid phase and yet it vaporizes and it is vapors mixed with a gaseous oxidizing ambience so that that is the first limitation that we will set for ourselves the second thing is we will not deal with sprays now we will deal with a single droplet so out of the spray and whatever is the fate of the single droplet is something that we should expect for all the droplets to face in a in a in a ensemble of them that is considering this spray if the spray is a dilute what is called as a dilute spray?

So what is meant by a dilute spray is that the spray droplets are not interacting with each other in other words the combustion that is occurring in this in one droplet does not influence the vaporization of another droplet that is nearby and so on this is typically what is called as a dilute spray and many times you do not necessarily have a dilute spray at all you have typically what is called as dense phrase where most of the combustion happens in droplet clouds as opposed to happening on sin dell droplets but for the sake of convenience at the moment we will try to analyze a single fuel droplet burning in a gaseous oxidizing.

So this is the framework to in which we want to do this having said that then we want to look at this essentially in the context of diffusion flames basically a droplet combustion essentially is fundamentally a diffusion flame because you are talking about a fuel that is vaporizing and the vapors are mixing into the gaseous ambience just add the flame therefore there is no way you could have actually pre-mixed the oxidizing vapor into the liquid droplet okay the liquid droplet is originally separate.

And then the land as it vaporizes its fuel vapors mix at the flame so it is essentially a diffusion flame however there are in certain liquid rockets typically smaller once we use something called mono propellant liquid or liquid monopropellant whichever way you want to call it where the mono propellant for example is a hydrogen peroxide which can actually burn by itself because it had it contains both hydrogen.

And oxygen within itself and as it thermally decomposes because of heating from aflame it gives rise to both fuel and oxidizer a few species that can that can react he add the flame and that would be premix thing right so except for this particular situation we are essentially going to be looking at a liquid fuel droplet that is vaporizing and mixing with a gaseous oxidizing ambience add the flame forming essentially a diffusion flame.

And since we are going to be looking at a diffusion flame we will actually look at what is happening at the buck Sherman limit which is where the fuel and oxidizer vapors meet each other in the mixing field at stoichiometric proportions. And therefore locate the flame corresponding to where the stoichiometric surface is in the mixing field similar to what we did for the book Sherman flame the general problem with most droplet combustion is to examine what is called as the DC or is popularly called the d squared law.

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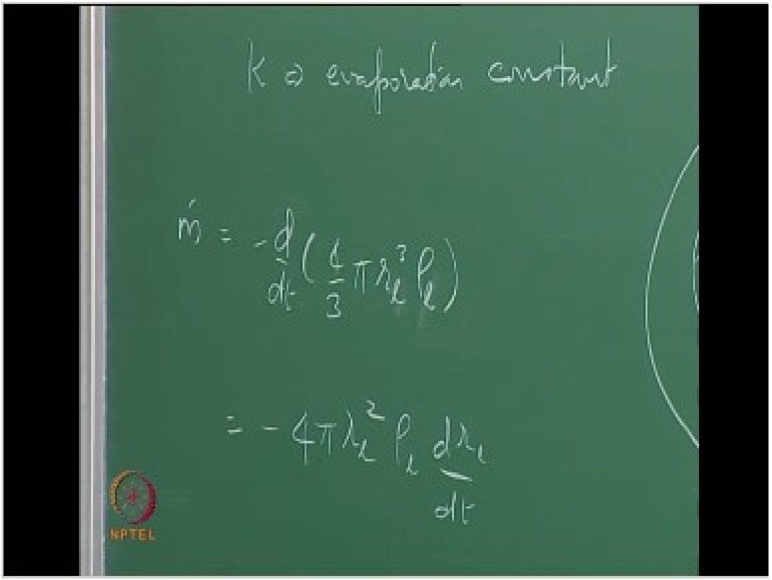

K → evaporation constant

$$\dot{m} = -\frac{d}{dt}\left(\frac{4}{3}\pi r_l^3 \rho_l\right)$$

$$= -4\pi r_l^2 \rho_l \frac{dr_l}{dt}$$

So the starting point for us to actually look at is what is called as the disquiet law what did what this really means is that there is a certain rate of evaporation or combustion of this droplet dictated by how the droplet diameter changes with time okay so you now take a certain droplet of certain diameter at a particular time an ignited and get it to combust or let us say it starts evaporating at about time t0 then what this really means is if you now start with a original diameter for the liquid droplet DL0 ^{2} and then the diameter decreases two deals quite at any time T this is simply given by K times t-T0 this is what is called as a d squared law now this is an empirical observation to begin with.

And certainly for many different droplets you do not necessarily have to have a d squared law it could be D to the some power which is approximately around two okay there are some situations where it could be as low as one sometimes and many times you do not necessarily fit in a integer for the power it could be a non integral number like let us say one point five one point eight and so on now on the face of it what it really means is lead when you say D^2 it essentially refers to surface area okay so what we can understand is more the surface area of the droplet greater is the evaporation right or and evaporation leads to combustion in the you know in a combusting environment but whatever we are talking about will also be valid for evaporation when you have a hot Amiens.

So what we are talking about could be thought of even in a non reacting sense where you have a hot Indians okay so like for example you want to draw as pray for example or dry droplets like for example if you get hired by a washing machine company and you want to figure out how to design a dryer like for example droplets that are actually trapped in a cloth how they get dried depending upon of course you allow you not to bring in conductive heat transfer and so on so you do not think about all those all the issues that we are talking about in a in that context so whatever we are talking about now will also be valid for evaporation in a in a harder ambience than the liquid droplet temperature.

So and we say D^2 it robotically refers to a surface area and as a matter of fact the goal of atomization is to actually try to enormously increase the surface area of the liquid from originally like let us say a flow of bulk liquid you do not want to actually spread it spread the surface area for the given same the same volume and essentially then increase the surface area so that you will now increase the evaporation and therefore the combustion rate and so on so the goal of the theory here is to see if we can look at the governing equations and deduce the D^2 law by applying the governing equations to this particular geometry and this problem so obviously here DL0 is essentially DL at time T =T 0 and T0 could be thought of first like a ignition delay beyond which the combustion begins and case what is called as the evaporation constant your operation constant.

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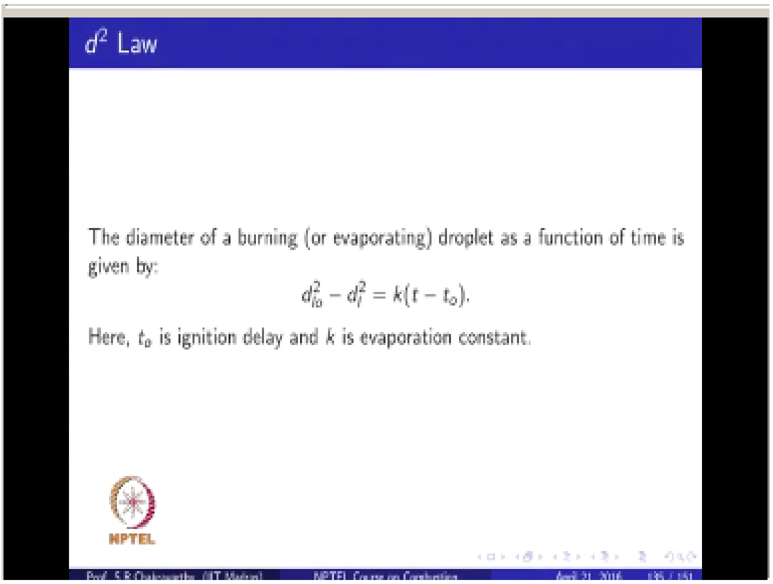

d^2 Law

The diameter of a burning (or evaporating) droplet as a function of time is given by:

$$d_{l_0}^2 - d_l^2 = k(t - t_o).$$

Here, t_o is ignition delay and k is evaporation constant.

So the framework here is we now assume that the droplet is finical it is not a bad assumption considering surface tension effects that try to keep the droplet spherical beyond below should say below a certain, certain size for it for a given droplet given liquid so this is not a very bad assumption at all like for example if you are looking at droplets that are of the order of 10 microns or even hundred microns they are reasonably spherical even in a gravitational field like what we face on earth.

And then so this is the fuel and then what we expect is in diamonds be a concentric flame around it now this is a questionable assumption in a gravitational field because buoyancy effects will induce a vertical convection upward and also distort the flame shape in a way that is pointed upwards all right and of course what we are looking at is a is a droplet to be stationary in aqueous and oxidizing k was in gaseous oxidizing ambient therefore we could now assume the spherical a spherical flame concentric to the droplet if the droplet were to be moving right so there is a motion for the droplet then the motion can correspondingly induce a distortion and the flame shape relative to the spherical shape that we have assumed.

So that is that is not to be considered in what we are assuming what would we what we are taking up because we are saying it is quiet and ambience so if you know how a concentric flame and this is the droplet right then we can we can say that the mass flow rate of the fuel that is coming out of the surface of the droplet is minus D over DT for over 3πR ϱ D where RL is the liquid should I should probably use different subscripts here but, but I think it is a mix up of subscript 12 just keep it as RL okay or L^3 and L where RL is the liquid radius and ρ L is the liquid density.

And now in this of course the liquid density is not expected to change with time and 404 by 3 π is it is constant therefore we can pull them out and then differentiate our L cube with respect to time and that is going to give you- 4 πR l^2 ϱ L D RL/ DT the negative sign is because as time increases or decreases okay so and then we want to have a positive mass flux that is coming out before you throw in a negative sign to make them make that out so now what we now assume of course here we have already mentioned assume spherical symmetry not a not a great assumption for moving droplets or

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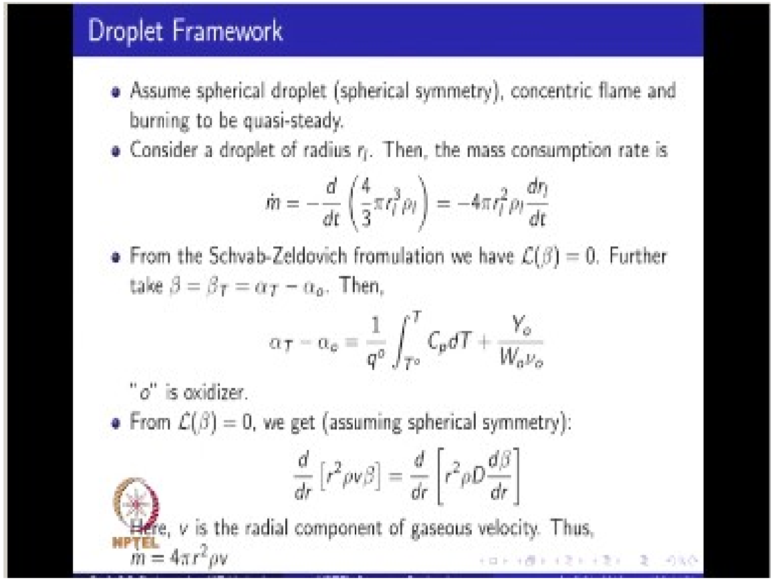

Droplet Framework

- Assume spherical droplet (spherical symmetry), concentric flame and burning to be quasi-steady.
- Consider a droplet of radius r_l. Then, the mass consumption rate is

$$\dot{m} = -\frac{d}{dt}\left(\frac{4}{3}\pi r_l^3 \rho_l\right) = -4\pi r_l^2 \rho_l \frac{dr_l}{dt}$$

- From the Schvab-Zeldovich fromulation we have $\mathcal{L}(\beta) = 0$. Further take $\beta = \beta_T = \alpha_T - \alpha_o$. Then,

$$\alpha_T - \alpha_o = \frac{1}{q^o}\int_{T^o}^{T} C_p dT + \frac{Y_o}{W_o \nu_o}$$

"o" is oxidizer.

- From $\mathcal{L}(\beta) = 0$, we get (assuming spherical symmetry):

$$\frac{d}{dr}\left[r^2 \rho v \beta\right] = \frac{d}{dr}\left[r^2 \rho D \frac{d\beta}{dr}\right]$$

Here, v is the radial component of gaseous velocity. Thus, $\dot{m} = 4\pi r^2 \rho v$

In a gravitational field or both the other assumption that is going to be quite important and needs to be elaborated upon is what is called as aquasi steady assumption what that means is the droplet diameter does not significantly change when the droplet evaporates and the gaseous vapor moves away from the droplet up to the flame and mixes with the ambience to form the form the reaction in other words the typical timescale of convection and diffusion of the gaseous species is much smaller when compared to the typical time scale of production of the droplet size appreciably all right so how do I understand that the answer is essentially coming from the fact that the ρ L could be significantly larger than the gaseous density okay.

So you can have a factor of about two or three assertions a factor sorry order of magnitude by about two or three but like the gauge is density is like of the order of one kilogram per meter cube the liquid density could be off the order of thousand kilogram per meter cube right so, so what the answer is we need to look at mass conservation across the interface right so for a unit mass per volume of liquid to evaporate will now give rise to a much lower density which means as the as the surface recedes inward it is now going to put outgas that is that has to actually move radically outward at a significantly larger rate.

So to give you an idea correspondingly if you now say that the gaseous velocity that is going to go out relative to our frame of reference centered around says centered at the droplet Center if that is off the order of let us say a few meters per second right then correspondingly the droplet rate of motion is going to be only a few millimeters per second right so because you know how to have this three orders magnitude to the three orders magnitude disparity between the rate of progression of this droplet surface inward to the rate at which the gases would be will evolve out of the droplet what this really means is a couple of things one first of all the droplet regression sets epic convection.

So why will why while we would like to think that it is purely a diffusion problem right in fact when you think about it as a diffusion flame in the book Schuman limit where we now adopt an infinite chemistry mix just burnt approach same sheet assumption and so on where we do not have to worry about the chemistry and we will have to worry about the mixing so we would like to think that this is purely a mixing problem wherein the liquid vaporizes and the fuel vapor steps out of the liquid surface after the vaporization and is just sitting there to diffuse no it is not sitting there it is actually flowing out because you have this regression right.

But the second point that is actually being made is this which is the regression is so slow when compared to the rate at which the gases move away from the center with away the velocity such that we can now think of a droplet of a given radius at any particular instant as a snapshot that means you freeze frame your droplet and, and then say for this particular droplet diameter the gases are rather instantaneously moving out and diffusing with the oxidizing ambient forming the stoichiometric surface and hence the flame and, and then the heat is rather instantaneously moving back to droplet of this particular size.

So all this balance happening in the gaseous phase is rather instantaneous when compared to the droplet motion that we can freeze this picture right that is what is meant by quasi steady assumption that means as far as the gaseous equilibrium is concerned the mass balance and the energy balance the species balance and energy balance is concerned we can essentially say it is steady state we do not have to worry about any unsteady months so we now stop with the short seller which formulation the short seller which formulation has 11 assumptions including a steady state right which, which we just try to out the articulate now.

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So the shrubs earlier which formulation is the operator L of β=0where β is the coupling function and of course for n species the behavior supposed to have n+1 beaters of course sorry for 4n species to be a VF NV does and 1 α so we have n +1equations but if you notice what we did earlier with the premix flame as well as the workroom and diffusion flame where we adopted the shrubs formulation earlier in this course we now try to choose this particular α and β in the shrubs elevate formulation that is the most pertinent to what we are what we are doing so we do not necessarily have to worry about n+ 1 equations right.

So here what we want to do and this is actually the art of solving the problem so take here β equals the energy β which is should say identically β T which is equal to α t-α o now I could have used α F to subtract from any of the other α including α T or some other α some other species α right so the choice of actually using α T and α o is because I want to actually keep track of the oxidizing ambient species which is purely gaseous alright and then the temperature because that temperature is very important because the energy balance is the one that is actually giving rise to a heat feedback that vaporizes the droplet.

So if you did not factor in the heat feedback you are not going to be able to vaporize the droplet so you need to you need to have the energy balance number one and the oxidizing species is taken because it is purely gaseous I do not have any problem with it vaporizes so αt- αo is a is a good combination that I can think about which will now translate to a T superscript not to T integral CP DT/Q that is based on the heat of heats of formation plus y o / wo ρ o where of course oh I should I should mention here o refers to oxidizer in the ambience right and tell of β is basically divergence of ρ Velocity β-ρD divergence β=0 right there is something that we have written about two or three times.

Now in solving different problems in fact for the for the premix flame problem we had a one dimensional formulation so did not quite really matter but the it is virtually one dimensional Cartesian in the individual problem and we adopted the web Zelda which formulation we voted for a two-dimensional cylindrical polar coordinate system it is now going to be back to a one-dimensional situation because the only variation is going to be along the radius right so well but we are going to adopt a spherical polar that system alright in a one-dimensional sense where the radio, radio variation is the only thing that is considered then and in a spherical polar coordinate system of all θ and π we are we are going to how to get rid of ρ and θ variations but still the or variation the one dimensional variation in R is going to be in a spherical polar coordinate framework.

Therefore insulin in spherical polar coordinates this can be written as we get d by $d/dr(r\rho v\beta)=d/dr(r^2\rho d\beta/dr)$ okay the r^2 as a coefficient is special to the spherical polar coordinates here and notice that we have a double derivative here whereas we have only a single derivative here okay and you are using ordinary derivative because R is the only independent variable now so it is not necessarily a partial differential equation now we want to try to bring in this m dot which will RL which is the radius of the droplet at any particular point to any radius so R is going to vary from RL to ∞ all right and m dot is going to be then that can be a better way and that can be defined for any or for the mass flux of the gas but at the surface it is it has to match the liquid mass flux right so MDOT is essentially ρ V times four PI R squared small V of course is the radial component of gaseous velocity right.

And ρ is the gaseous density right or the density of the gaseous mixture in your in your in your domain the domain is now for the gas and so it starts from $R= L$ to $R=\infty$ that is how it is going and m dot is for any radius and that is let us be a constant in steady state okay what is it that is really what we do not know what we are basically looking for is what is the rate at which the droplet is evaporating if I knew what is the rate at which the droplet is evaporating I would know what is a lead at which the mass is coming out of the droplet surface and I would know what is the rate at which mass is flowing at any point R in the geishas field and up to the flame and Beyond.

And so on but that is what I do not know in that sense this is actually similar to the premix flame problem where what we are actually trying to find out is the rate at which the flame was propagating right we did not we did not know what the rate at which the flame was propagating at and that is what was setting up the convection right here again they m dot the mass flux which is it is a constant right from the droplet radius to any other location or in the gaseous field is the unknown and that is related to the velocity V which is setting up the convection convective feel for the gaseous flow right.

So we want to make use of this and therefore what we want to do is so the point basically is you know whenever you see a $R^2 \rho v$ right immediately what you want to think can I throw in a full pie and then make it look like M. and then utilize it to be a constant and then I can pull it out and then take it to the other side flip it into the derivative you can do all these kinds of things so this can now be written as $D \beta / dr = d/dr$ of $4 \pi R^2 \rho D / m.$ times $d\beta/dr$ okay that looks better.

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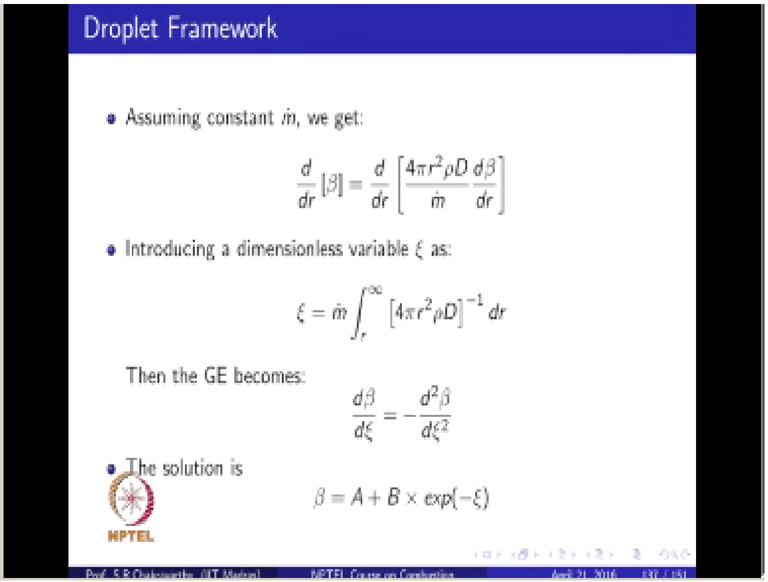

Droplet Framework

- Assuming constant $\dot{m}$, we get:

$$\frac{d}{dr}[\beta] = \frac{d}{dr}\left[\frac{4\pi r^2 \rho D}{\dot{m}}\frac{d\beta}{dr}\right]$$

- Introducing a dimensionless variable ξ as:

$$\xi = \dot{m}\int_r^\infty \left[4\pi r^2 \rho D\right]^{-1} dr$$

Then the GE becomes:

$$\frac{d\beta}{d\xi} = -\frac{d^2\beta}{d\xi^2}$$

- The solution is

$$\beta = A + B \times exp(-\xi)$$

And we will try to make a deal look even better.

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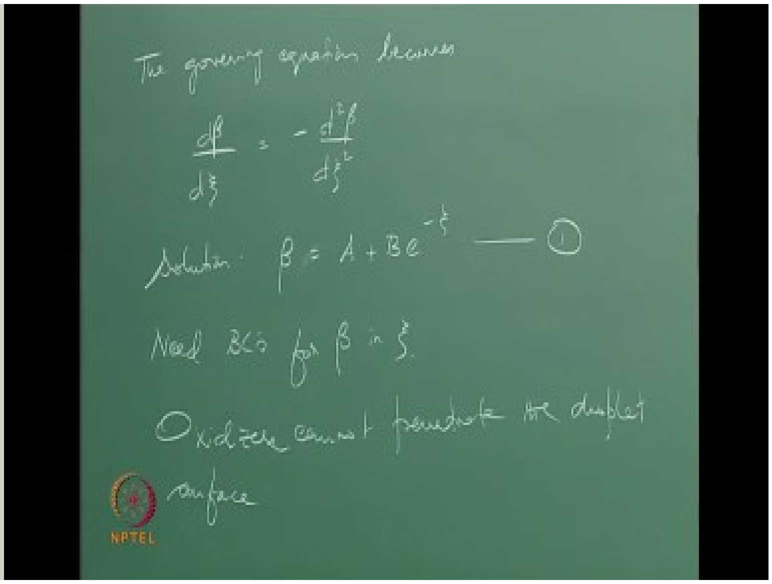

The governing equation becomes

$$\frac{d\beta}{d\xi} = -\frac{d^2\beta}{d\xi^2}$$

Solution: $\beta = A + Be^{-\xi}$ —— ①

Need BCs for β in ξ.

Oxidizer cannot penetrate the droplet surface

By introducing a new dimensionless independent variable so introduce dimension less independent variable X I = m. times R to∞4 π^2 ρd to the negative D R to the negative 1 d R now what does that mean you look at here you have a force 4PI R^2 ρ d /m. so strictly speaking of course you could take this m dot inside the integral because it is a constant and what you are looking at is m./4 PI R^2 ρ d hey since R squared is actually showing up in the denominator right we now have to end up integrating from R to ∞ and that is the reason why we are taking up an α Oh or you can put it the other way I took an α oh therefore I want to actually look at the region.

Between any R and ∞ as a measure of our okay so this is a inverse thing as our keeps growing my X I is going to decrease because that ∞ X I is going to go to 0 okay so this is actually trying to invert or because are showing up in the denominator here $R^2$1 over R^2 right now this is these are some of the things that are puzzling about combustion theory which is you come up with these what should I say innovative ways of non dimensionalization which are which are which is not very apparent to a student who is not really well-versed with mathematics but that is the game the DS this mathematics is typically.

So complicated that we will have to come up with these innovative non dimensionalization methods that will try to simplify the governing equation significantly so if you know adopt this if this particular independent variable then you now transform your equations in terms of ξ as opposed to R and the governing equation becomes the governing equation becomes D β developed by DXi =- d^2 β / DXi ^{2} so simple because essentially all the well this is the only term that has a coefficient within the derivative and that is simply being robbed off by the definition of ξ therefore that dead vanishes and you simply have d^2 β/ dXi ^{2} with a negative sign and so essentially this is d^2β /dxi ^{2}+ D β/ dxi =0 right so this is a linear second order ordinary differential equation for which we know how to saw how to write the solution the solution is the solution is β=- B e t X I.

Now let us call this one in fact this is where we are going to start doing the problem as of now we have not really done anything because the problem is always defined by the boundary conditions all right so strictly speaking I have not really said from here on when the mathematics started that I am working on the droplet problem okay so the droplet problem is going to show up only when we start applying the boundary conditions right and the boundary conditions need to be applied in order to evaluate the constants of integration A and B which are coming up because fears we have solved we have just solved a second-order equation.

So we have two we have two boundary conditions that need to be provided in order to solve for this and keep in mind we do not quite know why as well it involves m dot that is the unknown okay so in that sense this is kind of like an Eigen value problem and as I said it is are it is very similar to the pre-mixed flame problem where we do not know the propagation speed and that was an Eigen value in that problem and in order to evaluate that besides applying boundary conditions there we also applied an interface condition between two regions the preheat zone and II and the reaction zone.

And the interface condition was the one that actually fetched as the Eigen value namely the flame speed here we will also have to have an interface condition add this at the liquid surface which is now trying to say so much of evaporation is happening for so much heat that is being sent right so in addition to applying boundary conditions in the gaseous phase that R=R or L which is the liquid surface and r=∞ we will also have to supply an interface condition in order to evaluate the m dot this is what we will try to do so need boundary conditions for β and sigh great so the first boundary condition.

So here to go back and see what, what this board is β is αt - αo α t is this which proteins to with energy balance right and α o is this which proteins to Y o which is the mass fraction of oxidizer right so if you are now able to actually generate boundary conditions at R= R L and R= ∞ for you and temperature or energy balance then we subtract the one from the other in order to find the boundary condition for beta so this is the process that we are going to do.

So as far as the species is concerned what we know is that the oxidizer cannot penetrate the liquid surface all right now this is something that need not necessarily be true but the moment you now are able to suppose that you have a liquid droplet which is intact and it is going to produce gaseous fuel means that the oxidizer does not really the gaseous oxidized that does not penetrate the liquid okay now there are more complicated situations where typically one of the products of combustion so what is going to happen to the products of combustion so you are going to have the products being formed at the flame right and just like how we thought about flame as a frame sheet in the book Shuman problem.

And we tried to actually locate how the temperature profile and the product concentration profile were very away from the flame on either side and of course the fuel concentration oxidizer contras concentration plunging in at the flame and so on we could think about it like that so what we would expect is the products are being formed at this flame they are at a high concentration relative to the neighborhood and therefore they would have a tendency to diffuse right so they would diffuse inward against the current in this case as well as outward right when they diffuse in and of course the temperature is also going to be at it speak at the flame.

And it is going to come down so it comes down on both sides and well that goes out there it is going to match the oxidizer temperature in the far field but it is going to match the surface temperature of the liquid which could be like the boiling point of the liquid right and then of course inside the droplet you could have a constant temperature if the droplet is too small so thermal equilibrium has happened significantly considering the liquid thermal conductivities are an order more than the gaseous thermal conductivity and so on or let us say if you have is still a profile that is going in but at the temperatures of boiling point of the liquid the product could also condense into a liquid okay.

So examples of this are for example if you now think about aluminum which is used widely in solid rockets where you have a molten liquid aluminum droplet that is burning vaporizing into vapor phase aluminum or aluminum vapor and mixing with oxidizing species course in the solid rocket you do not really have atmospheric oxygen kind of thing you have oxidizing species in the form of water and carbon dioxide and so on which carry oxygen atoms in them and they mix and then form a flame and the product of combustion is alright and in gaseous state because the temperatures are so high that it would-be even higher than the vaporization temperature of all so you form aluminum oxide vapor had the flame which now tries to diffuse out from the flame radically inward.

And very early outward and a little bit further out the temperatures are now lower enough for the all 2o3 vapor to condense in tail to both three liquids the, the vaporization temperature of all 2o3 is significantly higher than the melting point of aluminum therefore as the L 2 O 3 is diffusing backwards or inwards it is now going to begin to condense and then as it comes down closer it now starts reaching the aluminum droplet surface keep it aside look at another example let us think about things like methanol or ethanol droplets right and in this case you can even easily think about an oxidizing Indians made of this atmospheric oxygen right or pure oxygen or air whatever and then you have a flame.

And the products of combustion or carbon dioxide and water which try to diffuse but as the water one of the products comes back diffusing in it now condenses because when methanol exists is methanol it is quite volatile right so it can vaporize but the temperatures for the combustion of so high somewhere in here as the as the well reaper diffuses back in it can it can condense right and then further in it now finds the surface of methanol now the difference between these two situations of aluminum combustion and methanol combustion is in one case the product liquid that is condensed is immiscible with the parent molten aluminum fuel droplet whereas in the case of methanol the product water that is got condensed is miscible with the reactant fuel in liquid form.

So as the water actually comes back in it starts mixing with water in liquid phase and effectively dilutes the fuel so as the combustion continued to progress you get to a point where you are less and less rich in methanol and therefore as the and so what effectively the flame is trying to do is not only vaporize the methanol but also tries to vaporize the water that is mixed with it beyond a point it is God not getting enough methanol to burn and so the flame is going to extinguish at a certain, certain size of this droplet including having a certain amount of methanol as a residue along with water right as opposed to that if you now look at aluminum since the aluminum oxide is immiscible in aluminum.

Because of interface tension forces similar to surface tension effects all the aluminum oxide that is coming in cannot really stick at different points so they tend to actually accumulate to one side and they form what is called as a oxide labor on one side it could be any side because we are not looking we are not really necessarily looking at effect of gravity here right so for we have already tiny droplets so it could be on one side and this is going to first of all spoil your spherical symmetry right but it could still assume cylindrical symmetry about the lobe center right so there is an axis and then the flame is now going to assume a shape that is cylindrical asymmetric or axis symmetric.

And then as no more combustion happens the aluminum pod shrinks and the oxide lib goes and so you know how they towards later part of combustion of the droplet you have a smaller aluminum droplet and a larger lobe and ultimately then all of the aluminum is burnt the lid closes and becomes a oxide droplet right so that is the final product so in both the cases you get a liquid draw liquid product alright but in one case it is contaminated by some of the field that has got quenched without the flame being able to sustain in the other case you get this and of course when you have an oxide and, and if you are not beginning to think about a flow field it becomes unstable and then it can stop wobbling.

And soon so this is actually in reality a lot more complicated problem the point I am trying to make is there are these problems where we would expect either the oxide to come and collect to one side or penetrate in, in liquid form they penetrate the surface in liquid form and mix whereas that is not necessarily the case with ox oxygen okay if that were the case then even as the liquid exists lipid fluid existed the, the oxygen would begin to actually get dissolved in it right so the first thing that we have to adopt is that oxidizer cannot penetrate the liquid the droplet surface oxidizer cannot pen it for the droplet surface there is Ruby why not – woody the why not by the are that Oracle's are L=0 this is to say that the oxygen or the oxidizer the engages oxidizer can diffuse only up to the point that the droplet surface vacates by convection.

So ρv times 4 PI R ^{2}M. and that would be the same as this m dot right so as far as sagacious convective effect is concerned this is because of the space vacated by the droplet trying to regress in its surface so the diffusion is trying to match the droplet regression right so the droplet regression in terms of convection of the oxidizing gaseous species is this and this is the diffusion so this basically states that the diffusion can happen just as much as the convection can allow it do with the droplet surface regression so this is essentially the boundary condition here and this is in terms of our but we have adopted a non dimensionless independent variable ξ.

So basically means that this is similar to the flux boundary condition that we had we have seen when we were considering axial diffusion of the election in problem by the way right quite similar and (dy0/d ξ) ξ = ξ l=-yo at ξ = ξ l which can simply be called –yol.

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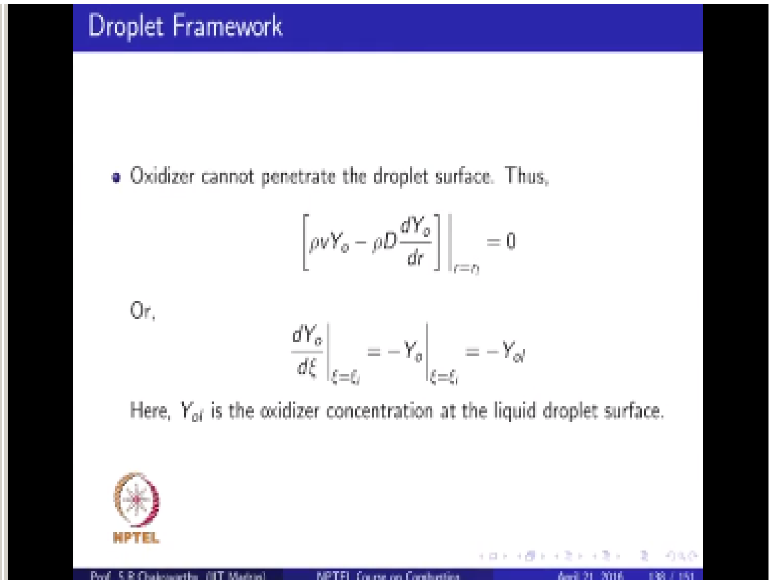

Droplet Framework

- Oxidizer cannot penetrate the droplet surface. Thus,

$$\left[\rho v Y_o - \rho D \frac{dY_o}{dr}\right]\Bigg|_{r=r_l} = 0$$

Or,

$$\frac{dY_o}{d\xi}\Bigg|_{\xi=\xi_l} = -Y_o\Big|_{\xi=\xi_l} = -Y_{ol}$$

Here, Y_{ol} is the oxidizer concentration at the liquid droplet surface.

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Where Yol is the oxidizer concentration at the drop at the liquid droplet surface what we expect is the oxidizer concentration to be in storchiometric proportions with the field concentration at the flame all right and further decrease to a value you L in combustion you will have the situation where the oxalate is getting, getting consumed in the fame in evaporation you do not worry about aflame it is this the heating from the outside that there is that is causing the evaporation and you will still have a ambient gas trying to diffuse up to the droplet surface and hold the certain concentration there right.

So this essentially is the oxidizer concentration at the liquid droplet surface we do not know it quite but we may have to make an estimate we will worry about these things as we try to plug in some numbers or typical values for these things as we go along but right now the boundary condition needs to be formulated to describe the droplet combustion problem so that is as far as one boundary of one component of α all right then we cannot worry about what happens to αT at R= R L corresponding ones at ∞ and so on we construct these boundary conditions and the interface condition plug them in into the solution in order to find out m. that is essentially what we want to do we will do it tomorrow.

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