Indian Institute of Technology Madras

NPTEL

National Programme on Technology Enhanced Learning

COMBUSTION

Lecture 45
Spray Combustion

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So today we will talk about spray combustion this is actually like a follow-up to the droplet combustion that we did where we were basically considering only a single droplet at a time, and at the time I pointed out that it may or may not be exactly the way it happens in reality because in reality you may have a cloud of droplets that burn or you may have all the droplets evaporate by the time they reach the gas phase flame and therefore we do not necessarily have a droplet combustion and so on.

So there are lots of different possibilities and it also depends on whether the spray is dense or dilute and typically we think about a single droplet combustion mode in a spray. In reality most of the droplet combustion happens only in space right, so spray is the more realistic situation that we need to think about and the single droplet combustion mode probably happens only in situations where you have dilute sprays and so on.

So let us now see if we can take the idea of the single droplet combustion further and see when that happens in a spray so basically we will now look at the spray combustion. Now there are a couple of ways by which you can think about spray combustion similar to the way we have been dealing with the gas phase flames, so in the case of gas phase flames we had on the one hand pre-mixed flames on the other hand we had the diffusion flames right, so we could think about these things this there are you could still think about like analogies to spray combustion similarly.

But however we have to think about in reality it is again in between it is not it is neither pre-mixed nor diffusion, so what is really meant by pre-mixed spray combustion or what is meant by a diffusion flame kind of spray combustion. On the one hand you could now think about droplets that are now Laden in an oxidizing gaseous flow, gaseous oxidizing flow so it is possible for us to mix liquid droplets of fuel in a gaseous oxidizing flow and of course the gaseous oxidizing flow could also have inert gases like for example if you are looking at a gasoline air mixture or something like that, right.

So air casts the oxidizing gaseous species as well as you know inert species and then you are now throwing in liquid droplets of gasoline and then let us suppose that you now have the flow up here a flow in a tube and then you now stabilize the flame in between or you could also think about more like a Bunsen burner where you have the approach flow is actually made of mixture of liquid droplets in a gaseous oxidizing flow, so that is one configuration that you can think about.

On the other hand let us suppose that you now just have an orifice in which through which you just issue a liquid fuel and because the orifice is so small or the pressure injection pressure is high or a combination of both you now have a spray that is coming out so what is basically coming out is essentially a liquid fuel spray and the oxygen has to get in the oxidizer is in the ambience and it has to get entrained into this and as it gets entrained it mixes vaporizes the liquid and burns the liquid fuel and so on.

So that that would be like a diffusion flame counterpart in reality as I said you would have a combination of these two things it is neither this nor that and of course you can think about like a partially premix flame that is established in what could be nominally an on-premise injection of liquid field but you since you have like a standoff distance it allows for some mixing and so on so many such possibilities exist in reality. So what we will first consider is a pre-mixed mixture for the sake of simplicity.

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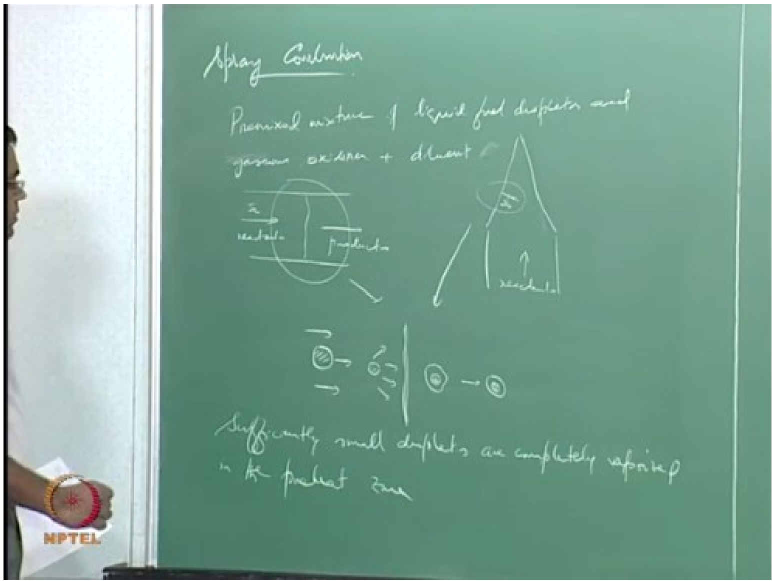

Spray Combustion

Premixed mixture of liquid fuel droplets and gaseous oxidizer + diluent

Sufficiently small droplets are completely vaporized in the preheat zone

Mixture of liquid fuel droplets and oxidizing gaseous oxidizing gaseous oxidizer plus inert or diluent right, so as I said it could have like a norm possibilities or let us say you have a cube and then you have now the reactants and then you have a flame and then you have products or you could have a burner and with your knobs in the reactants and then you have a flame and then of course you products downstream of the flame so these are different possibilities.

So in this case for example, you now can talk about a is S_L and what is really opposing it is the normal component of the flow right so that is equivalent to saying you know have a reactant flow at the speed of S_L that is approaching a stationary flame or in a flame fixed coordinate system. So in this case what we are basically talking about is let us suppose that in if you now look at this locally or in this region what this basically amounts to is if you now have a flame right.

What you are essentially saying is you now have a droplet that is approaching the flame along with oxidizing gas with inert and then it begins to evaporate because it is now in the influence of the flame as far as the heating is concerned and as the heating happens you know sorry, as the evaporating happens it not the fuel vapor is now evaporating out and then also flowing along with the oxidizing as and mixes and you now reach this is the flame and when this new liquid droplet goes past it you now still have a liquid droplet with a flame behind we have rounded as an envelope flame and this now decreases further into a smaller droplet and then flame and so on.

So this is typically the kind of picture that we are looking at in these situations alright, so if it is possible for us to now set up something like a Bunsen burner with liquid filled droplets we should now expect the larger ones particularly and that is what I am just next going to talk about the larger ones will actually get you start burning as the loop flow through the flame and then begin to go as individual droplets that are burning like an single droplet combustion that we have seen but the smaller ones will now have evaporated by the time they reach the flame.

Therefore you would not have a single droplet combustion right, so the question that we have to ask is what is the limiting droplet size be a below which you will not have a singledroplet combustion mode okay, so if this droplet is going to actually shrink to 0 size by the time it reaches the flame that means it is starting size should have been small enough, if it is large then it keeps on shrinking but when it gets fast it begins to burn in a single droplet mode right. So the question basically is what is the limiting size maybe a beyond blow which speed the droplets do not burn it burn in a single droplet mode.

The answer to that question can be answered done by a simple analysis so do you think that we look at is what is the residence time of the droplet in the flame right, so the so what we are basically saying is sufficiently small droplets or completely vaporized, vaporized in the preheat zone, the preheat zone of the flame is the is where the heat conduction is happening so the characteristic times.

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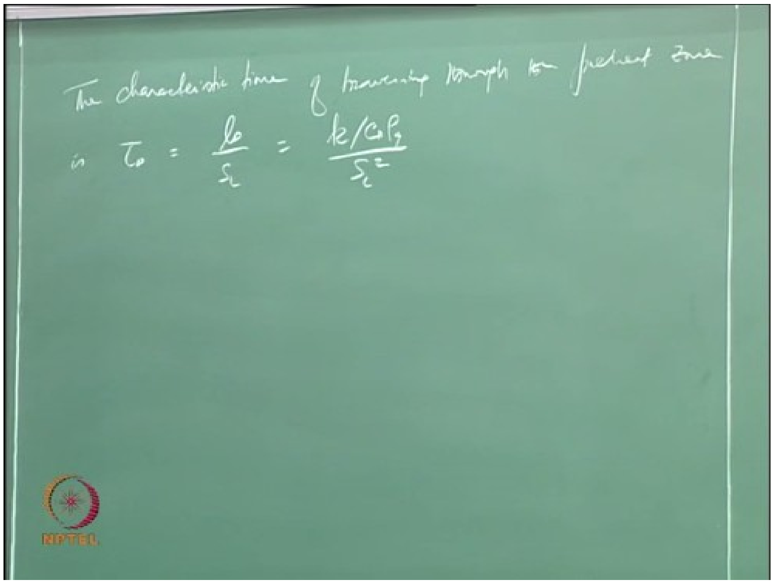

The characteristic time of traversing through the preheat zone

is $\tau_D = \frac{l_D}{S_L} = \frac{k/C_P\rho_g}{S_L^2}$

The characteristic times of traversing through the preheat zone preheat zone is let us say τ_D is l_D which is like the film thickness divided by S_L and that would be $k/C_P\rho_g$/ we should have actually a l_D is $k/C_P\rho_g$ S_L then we also have another S_L therefore you get in S_L^2 and then what we have to compare this time is with the droplet evaporation time how long does it take for the droplet to evaporate versus how long is it going to be within the preheat zone right.

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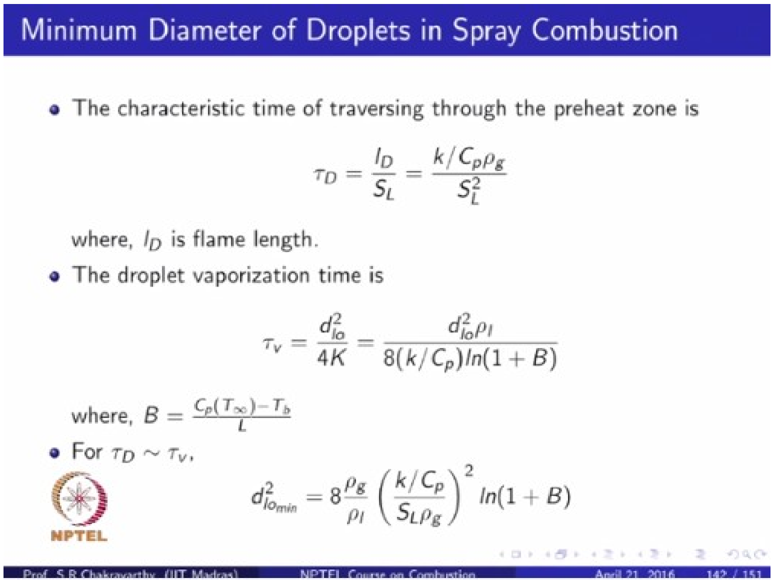

Minimum Diameter of Droplets in Spray Combustion

- The characteristic time of traversing through the preheat zone is

$$\tau_D = \frac{l_D}{S_L} = \frac{k/C_p\rho_g}{S_L^2}$$

where, l_D is flame length.

- The droplet vaporization time is

$$\tau_v = \frac{d_{lo}^2}{4K} = \frac{d_{lo}^2\rho_l}{8(k/C_p)ln(1+B)}$$

where, $B = \frac{C_p(T_\infty)-T_b}{L}$

- For $\tau_D \sim \tau_v$,

$$d_{lo_{min}}^2 = 8\frac{\rho_g}{\rho_l}\left(\frac{k/C_p}{S_L\rho_g}\right)^2 ln(1+B)$$

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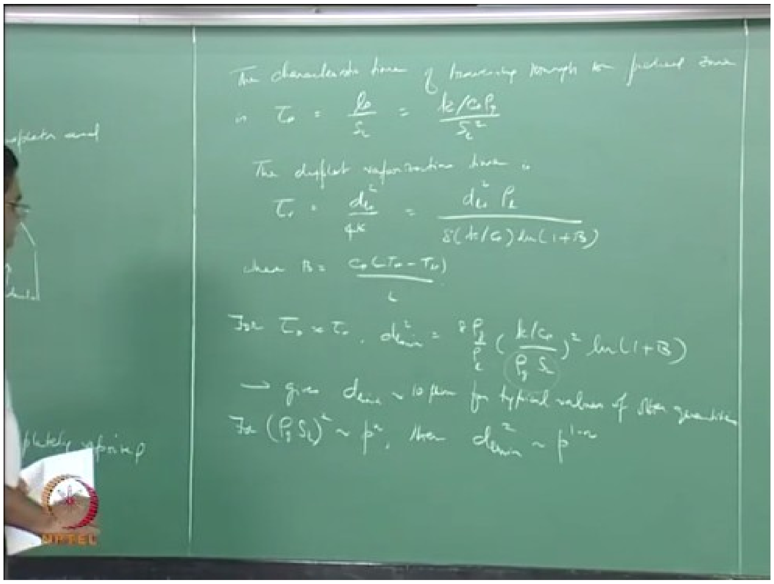

The characteristic time of traversing through the preheat zone is $\tau_D = \frac{l_D}{S_L} = \frac{k/C_p\rho_g}{S_L^2}$

The droplet vaporization time is

$$\tau_v = \frac{d_{l0}^2}{4K} = \frac{d_{l0}^2\,\rho_l}{8(k/C_p)\ln(1+B)}$$

where $B = \frac{C_p(T_\infty - T_b)}{L}$

For $\tau_D \approx \tau_v$, $d_{l0,min}^2 = 8\frac{\rho_g}{\rho_l}\left(\frac{k/C_p}{\rho_g S_L}\right)^2 \ln(1+B)$

→ gives $d_{min} \sim 10\,\mu m$ for typical values of other quantities

For $(\rho_g S_L)^2 \sim p^n$, then $d_{min}^2 \sim p^{1-n}$

So the droplet vaporization time is τv $dlo^2/4k$ that is essentially is not talking about the radius divided by the in terms of surface area divided by the evaporation constant it is essentially coming from the dlo^2 and so this is as if this is dlo^2 for evaporation we are not basically saying that it is going to burn in a single droplet node but we talked about when we did single droplets we also said that the same approach can hold good for evaporation so then we use the expression for the evaporation constant that we had that we had obtained to get natural log(1+B), where B is nor kC_P the ∞-T_b the boiling point divided by the latent heat of vaporization.

So if you now say that these two times are comparable then we begin to get a diameter of the droplet below which you would not have a single droplet combustion that means you would not have anything that is burning and coming out of the flame right. So for τ_D approximately equal to τ_v or the same order $dl0_{min}^2 = 8\rho g/\rho_l(k/C_P/\rho_g S_L)^2 = \ln(1+B)$ the reason why we write ρ_g S_L together is this is actually the mass burning rate or the burning mass flux okay.

So now for typical values of things like if you know the zoom approximately stoichiometric mixture for the fuel and air where the combustion happens and then you now throw in like ρ_l/ρ_g is of the order thousand and then and so on so, you do all these things then so this gives about ten microns so dl_{min} dl_0 the original droplet size the minimum original droplet size is of the order of ten microns 10 micrometers for typical values for other quantities right.

Now we can also see the dependency here so for $\rho_g S_L^2$of the all going as going as P^n you know it is coming from how the burning velocity depends on the pressure and we are looking at $\rho_g S_L^2$ so we do not remember that and we say it is going a speed at the end then the dl_{0min}^2goes this p^{1-n} right, and this is purely coming so what this means is the pressure dependence purely comes from the preheat zone length okay, and we do not have to worry about the dependence of the evaporation time on the pressure so the evaporation time is not dependent on pressure it is only the preheat same length that changes with pressure and therefore the residence time of the droplet within the preheat zone is going to change like this right.

So that is mainly the effect on pressure what we should actually look for and you now have these bunch of droplets here so we the picture that we drew is only for one droplet right but that is not that is not reality so this is assuming like a dilute spray essentially and then talking about a single droplet combustion event in the case of droplets of size larger than d_{min} right. So question is what is the interaction effect, okay.

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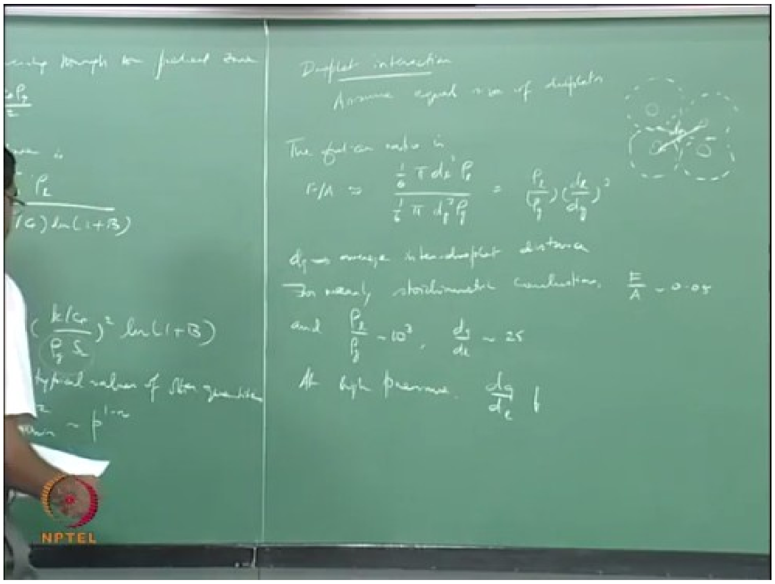

Droplet interaction

Assume equal size of droplets

The fuel-air ratio is

$$F/A \simeq \frac{\frac{1}{6}\pi d_\ell^3 \rho_\ell}{\frac{1}{6}\pi d_g^3 \rho_g} = \left(\frac{\rho_\ell}{\rho_g}\right)\left(\frac{d_\ell}{d_g}\right)^3$$

$d_g \rightarrow$ average inter-droplet distance

For nearly stoichiometric combustion, $\frac{F}{A} \sim 0.08$

and $\frac{\rho_\ell}{\rho_g} \sim 10^3$, $\frac{d_g}{d_\ell} \sim 25$

At high pressure, $\frac{d_g}{d_\ell} \downarrow$

So the droplet interaction now assume for this purpose equal size of droplets right, then what you are essentially saying is let us suppose that these droplets are located in space and at a particular time with some distance and what we would like to think is the distances are about the same okay, for the sake of what we are doing not very difficult we are basically looking for something like an average inter droplet distance, so what you could then do is now draw spheres around these right and so on.

And if you now say this is this the sphere around which you around the droplet that you have drawn is having a diameter that is equal to the that is approximately equal to the inter droplet distance okay, and then if you now take that sphere worth of mass of oxidizer neglecting the presence of the droplet okay, and then take the mass of the droplet you can now form a fuel-air mixture based on that alright.

Now we are there are voids here and those volumes of the oxidizer we are not considering so it kind of compensates between taking this volume and not taking that volume right. So approximately speaking the fueler ratio is F/A is approximately $1/6\pi d_l^3\rho_l$ it is essentially $4/3\pi\ R_l^3$ but RL d_lS_L $R_L/2$ sorry, R_L is $d_l/2$ so if you know plug that in there you get the $1/6\ dg^3\ \rho_g$ so there the d_g that we are talking about is the inter droplet distance average okay, so d_g average inter droplet distance right.

So what does that mean this is like $(\rho l/\rho g)(dl/dg)^3$ so what this means is of course if you have for nearly stoichiometric mixture stoichiometric combustion for typical hydrocarbons let us say typical liquid hydrocarbons your F/A should be around 0.05 alright, you can you can evaluate that for typical so you look at the stoichiometric chemical reaction and that means it is balanced and then you can liquidly mass ratios for that if you now plugged it in and ρ_l/ρ_g this about 10^3 right, then we can find that d_g/d_l is of the order of 25 right.

So 25 is like more than 10 so we can say that the inter droplet distance is about is quite larger when compared to the droplet diameter itself so this does not mean too much interaction, but if you now start thinking about the effective pressure okay, so at higher pressures ρg increases okay because as pressure increases ρg increases so if $\rho l/\rho g$ so if ρg increases $\rho l/\rho g$ decreases if $\rho l/\rho g$

the decreases then dl/dg will increase or dg will decrease effectively right, so dg/dl then decreases.

For example, in automobile engines if you now look at the typical kind of pressures you will find that those pressures dg/dl would be as low like about 15 or something it is still around again 10 but you are now hitting a limit where you have to consider the interactions. What we should then think about as we started looking at a pre-mixed mixture but let us now look at get a spray jet and a spray jet flame.

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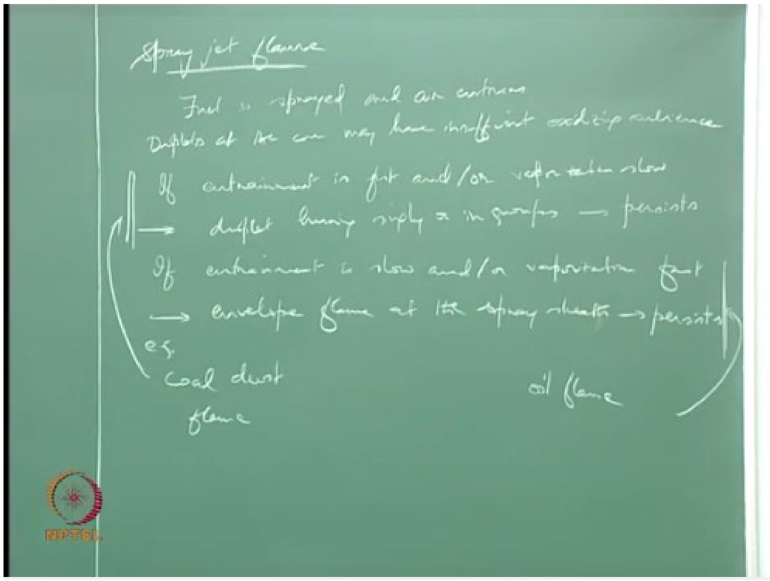

Spray jet flame

Fuel is sprayed and air entrains

Droplets at the core may have insufficient oxidizing ambience

If entrainment is fast and/or vaporization slow

→ droplet burning singly as in groups → persists

If entrainment is slow and/or vaporization fast

→ envelope flame at the spray sheath → persists

e.g.

Coal dust flame

oil flame

So this is now getting closer to reality so what is going on here is two things one as you now have a jet that is coming out this is jet of liquid fuel it is also beginning to entrain air and then of course we have ignited it then there is a flame the question is are we having individual droplets that are burning in this flame or is it like an envelope of the all the droplets that is burning together that is essentially the question that we have to ask right.

So the answer to that is of course the droplets are evaporating from the heat of the flames right, so the competition now is between how much is the entrainment right because you oxidizer for the flame to happen and so therefore you need to have the entrainment to happen so how fast is the entrainment versus how fast is the evaporation. So the evaporation is going to give rise to the fuel the gaseous fuel the entrainment is going to bring in the great gaseous oxidizer and you need to have both of these for the combustion that happen right.

So typically when you are now looking at entrainment the entrainment is happening from the sides and then it starts penetrating to the core so there is a there is a core of liquid which does not see the ambient air significantly right, for some distance maybe on which the ambience penetrates. So you could now think about the inner droplets not as exactly going through a single droplet combustion right, whereas the outer droplets are going through this because there is access to air.

So effectively fuel is sprayed and an entrains right, so droplet the core droplets may have insufficient oxidizing ambience. Now so what you have to look at is the competition between entrainment and evaporation right, so if entrainment is fast and or okay, it is a combination vaporization slow right, so entrainment is faster vaporization is slower then what do we expect, air is now beginning to get available to most droplets and therefore most droplets can burn by themselves they are harder to evaporate therefore there they are going to be waiting for the flame to come near them okay, oxidizer to come near them and the flame to happen near them.

So this actually leads to a single droplet burning more toward single droplet or so or droplet burning singly or in groups right. Now once you have a single droplet mode of combustion that is established then it is difficult for the flame to coagulate and then have a outer envelope flame, because once you have the flame you do not have fuel penetrating outside of the flame so the oxidizer has to come to this you get to the flame in order to consume the fuel right. So once you have this mode of burning this persists it is kind of like a stable solution that the system approaches.

On the other hand if entrainment is slow right, and or vaporization fast so this now leads to a flame that is actually enveloping a what is good for like a spreadsheet so now we can look at us pray you now have a cover around this and that is exactly why you expect the flame to happen so this is envelope flame at the spray sheet, right. Now once you have a envelope flame then that is not going to let the oxidizer get it okay, so the droplets will now be waiting for the oxidizer but no oxidative coming because it is all getting consumed in this flame so they just begin to get evaporated because of the heat from this flame and they will have to undergo continually and undergo combustion and the envelope flame.

So once you have an envelope combustion mode it is it sets in and it purses it is hard for it to transition into a droplet combustion mode right, so this persists. Now typical examples of these are for example if you are now looking at a situation where the vaporization is slow that means we have to look for materials that are less volatile okay. So a typical example of this would be I have in solids so example you look at coal particles okay, so if you if you now look at pulverized coal so cold or coal dust okay, example coal dust flame.

Now the example of this would be the second one where the evaporation is fast is essentially oils so oil flame right, where the oil is typically quite volatile and so the oxidizer spread there is a fuel the gaseous fuel spreads out and meets the oxidizer even before it can end entrain significantly. So then what we have to look for is how does how does this what we call as a cloud combustion or a dense spray combustion happen.

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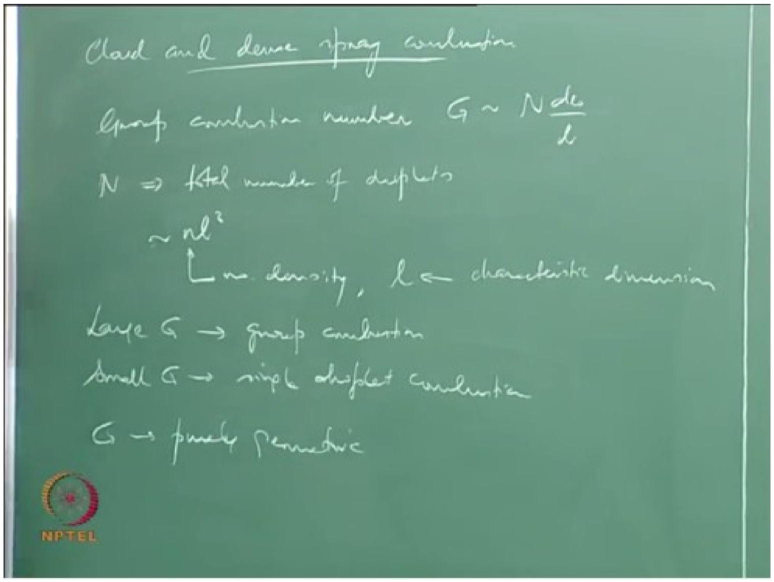

Cloud and dense spray combustion

Group combustion number $G \sim N \frac{d_0}{l}$

$N \Rightarrow$ total number of droplets

$\sim nl^3$

$\llcorner$ no. density, $l \leftarrow$ characteristic dimension

Large G → group combustion

Small G → single droplet combustion

G → purely parametric

We define something called a group combustion number or we can, you can call it a group combustion index or number this would be called G and this is defined as and Ndl0/l where N is the total number of droplets that can be now written as I should say goes as nl^3 where N is the number density that means number of droplets per unit volume and L is characteristic dimension right. So essentially what we are saying is if you now have a total number of droplets times the diameter divided by the characteristic dimensions let us say for example if you are looking at a spray flame or a swirl flame where you are sending in the liquid in a swirl flow and so on you have like a burner diameter.

So within this burner diameter or off the order of the burner diameter how many droplets can you space is essentially what is indicative of the group a combustion number and what it basically means is if you have a large G it indicates a group combustion if you have a small G it indicates single droplet combustion. Group combustion and small G single droplet combustion, now in reality you would have also things that are in between that means you have small clouds of droplets that are burning with the flame enveloping it but many such clouds separately right as opposed to when you say group combustion it is like all droplets that are there or having a single flame.

So there is a reality that is in between so it seems like these are extreme cases right, so what and then the other thing that you have to point out is this is purely a geometric parameter right, so we are talking about what is like the spacing between the droplets if you will so G is purely a geometric parameter and it does not take into account these things like we are not looking at how well is the entrainment happening versus how well the vaporization is happening okay.

So these two will keep this in mind but before we proceed with taking into count dose in a in a spray jet flame about what we will think about is it possible for us to think about like a spherical cloud of droplets right, what could happen if you now have a spherical cloud of droplets as a function of G. So if you now start from a large G towards a small G what happens to a spherical cloud of droplets. Now there are four possibilities that the can that can happen with a spherical cloud.

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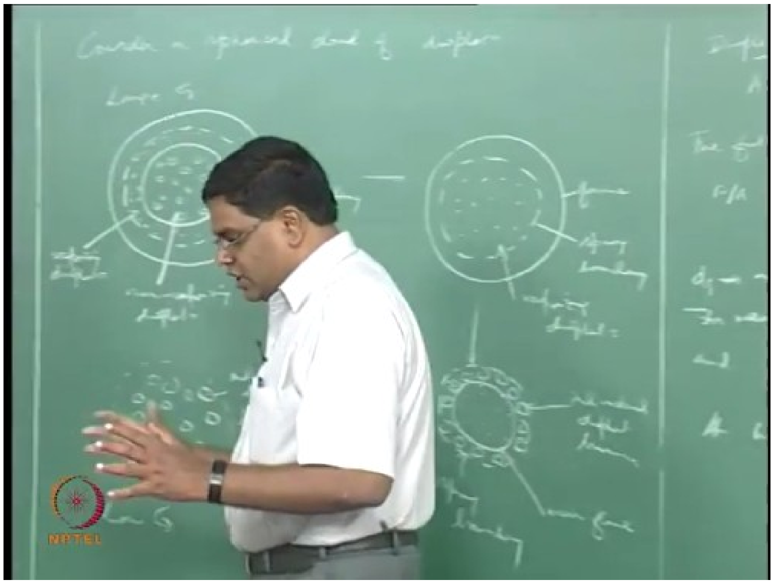

So consider a spherical cloud of droplets right, so what we are basically saying is can we have a large G situation where we are looking at a group combustion and what that means is you now have lots of droplets that are the core and they are non evaporating right, so if you now have like a slow vaporization situation. Then there is suppose that you now have a spherical boundary, imaginary boundary spherical imaginary spherical boundary of non-evaporating, non vaporizing droplets and out of which you now have let us say smaller ones which are evaporating droplets so they are obviously much smaller and I am just representing them by a dot.

And you can now talk about this as the spray boundary so in all the pictures that I am going to draw for the four possibilities the broken line refers to what is called as a spray boundary okay, so there is another way of thinking about this it is you can look at like a spray that is coming out of the board right in a cylindrical manner it does not have to be spherical but you can look at things happening in a circular manner as across-section right, so it is like you now have a non evaporating core and a evaporating surrounding that forms the spray.

So this is the broken line basically means this jet the spray boundary so this is vaporizing droplets and the broken line is a spray boundary and you now have the actual flame around this right. Now as you now increase your sorry, decrease your G as you now go in this direction of decreasing G the other possibility is you do not have a core of any non vaporizing droplets that means this diameter basically shrinks to 0 you are now beginning to think about droplets that can vaporize faster.

But still not fast enough for flame to eaten okay, so you know you now have a single spray boundary without having to distinguish between vaporizing and non-vaporizing droplets because all of them are vaporizing so that is reprising droplets and then you have a flame around right, now the next possibility is for the flame to move in okay into the spray so as I said the broken line is the spray boundary so the moment the flame moves into the spray boundary you are now begin to have single droplets in the periphery single droplet burning in the periphery and then you have group combustion in the middle.

So that gets us to a situation where let us suppose that you now have this picture of vaporizing droplets in the middle and still it is not the spray boundary you have to actually have the main flame now we have to distinguish between main flame and individual droplet flame lights for those that are burning outside this, so those are individual droplet burning right, and this is what constitutes your spray boundary.

And finally the flame now eats into each and every droplet there okay, so that means you now have a spray boundary in which all droplets are burning individually and so on right, so this is a limit of low G and this is individual burning and this is this is now low G right. The question is what happens so this is as if like you had these droplets kind of put together in isolation as if they were not part of a flow right, and then we were beginning to play with the G so if there is a high G then there is more group interaction when there is low G there is less group interaction you have more individual droplet burning and so on.

But what happens in reality for something like a spray jet flame the answer is this spray jet flame you now have a flow field with a variable G so you start with some things like a very dense spray that is just beginning to atomize and then spread out and then you now have more and more entrainment that allows for individual droplet burning further out so it is like a variable G that starts with a high value and then keeps proceeding along the low value. So this is where it is not just purely a geometric parameter that we can rely on we have to bring in the flow effects.

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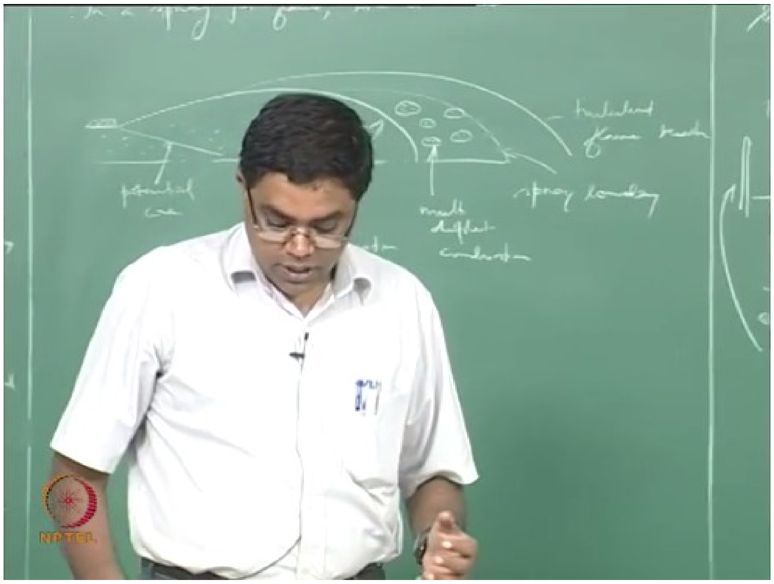

Therefore in a in a spray jet flame G is variable right, so you now get into a situation where it is supposed to be a center line and let us say you have got a lip of the nozzle and which issues out this spray and you can now think about like a potential core and you now have near the center line you have bigger droplets but away from the centerline let us say you have smaller droplets because they are evaporating and now you have a the main flame or the internal group combustion flame right, and outside of which as you now keep going the G actually decreases and you now have lots of cloud combustion going on right, forming the spray boundary so this is likely maybe keeping a de convection we should use broken line spray boundary and this is multi droplet combustion.

And there is a overall terms and flame brush that that we will have that encompasses the entire flame and so that is that is essentially turbulent flame brush we will be we might look at it when we do turbulent flame status it is an envelope of all the fluctuations, right so that is it is a determined flame brush. How do you formally this crowd this kind of problem right, so the way we you have to do with this obviously to deal with it in a statistical manner so we have to look at how to do spray statistics.

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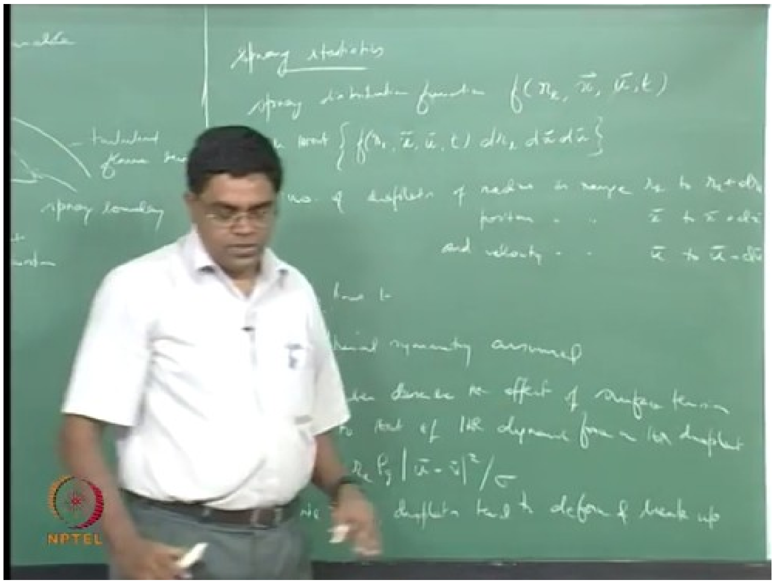

Spray statistics what you do is you now have what is called a spray distribution function f(rl) which is the droplet diameter position x velocity u vector and time such that this is a density distribution that means f(rl,u,x) should say x, u and t drl dx̄ dū so this is basically a seven dimensional space in 3D right, so you have three components of velocity and three directions of location and then the radius. So this quantity now right, indicates the number of droplets of radius between or let us say in range rl to rl+drl velocity position in range x to x+dx that is within this bin and velocity in range u to u+du right at anytime t it is time dependent alright.

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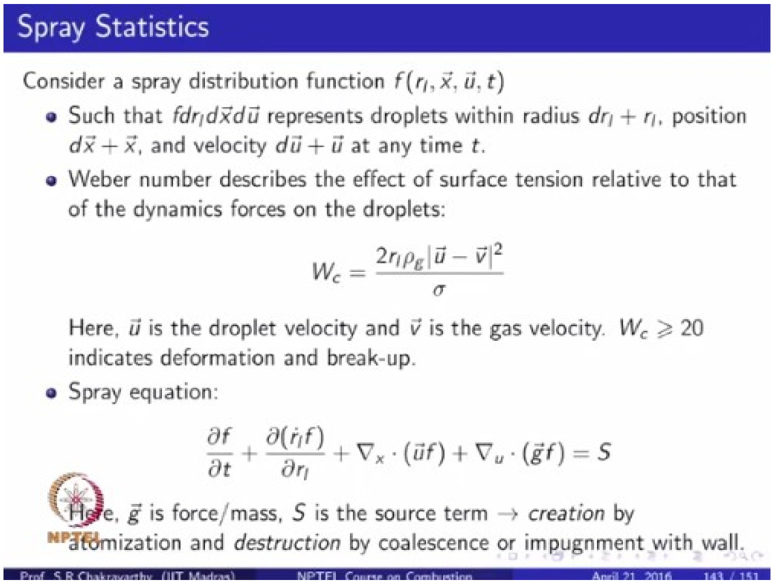

Spray Statistics

Consider a spray distribution function $f(r_l, \vec{x}, \vec{u}, t)$

- Such that $f dr_l d\vec{x} d\vec{u}$ represents droplets within radius $dr_l + r_l$, position $d\vec{x} + \vec{x}$, and velocity $d\vec{u} + \vec{u}$ at any time t.
- Weber number describes the effect of surface tension relative to that of the dynamics forces on the droplets:

$$W_c = \frac{2 r_l \rho_g |\vec{u} - \vec{v}|^2}{\sigma}$$

Here, $\vec{u}$ is the droplet velocity and $\vec{v}$ is the gas velocity. $W_c \geqslant 20$ indicates deformation and break-up.

- Spray equation:

$$\frac{\partial f}{\partial t} + \frac{\partial(\dot{r}_l f)}{\partial r_l} + \nabla_x \cdot (\vec{u} f) + \nabla_u \cdot (\vec{g} f) = S$$

Here, $\vec{g}$ is force/mass, S is the source term → *creation* by atomization and *destruction* by coalescence or impugnment with wall.

So we have to now let it like this fluctuate in time so when we now use the word rl so the quantity rl their implicitly assuming a spherical symmetry, so assumed there are ways in which we can relax this but we have to see when this is relax able so the now typically small droplets for example if you are looking at things like 10 microns and soon 10 to 100 microns like they will you look at that range for most typical fields you have a significant surface tension effect that sphere arises the droplet okay.

So the sphericity is maintained because of the surface tension therefore we have to actually look at what else is causing the adopted to be non spherical as competing against the surface tension, so what typically allows for the droplet be non spherical as when it now tries to flow you now have a shear that is happening at the surface as well as a hydrodynamic instability because you now have high density and low density interface which becomes unstable and so on these things are obviously proportional to the relative velocity between the two the droplet in the surroundings okay.

So the droplet were to be stationary you do not have these effects right, so therefore the Weber number, Weber number describes the effect of surface tension relative to that of or the dynamic force on the droplet so We that is a symbol for Weber number is 2RL that is for the diameter gaseous density times $|\bar{u}-\bar{v}|^2$ let us see a relative velocity between the between the droplets and the ambient gas divided by σ which is the surface tension, so U is the droplet velocity V is a gas velocity right.

Now for We greater than or equal to about 20 droplets tend to deform and break up, so if you are looking at atomization situation you are looking forward to deformation of liquid sheets into ligaments and ligaments to droplets so you are looking at a high Weber number situation okay, but once you get to fairly small droplets the Weber number becomes small and then the surface tension takes over. So for Weber number greater than 20 droplets tend to deform and break up right.

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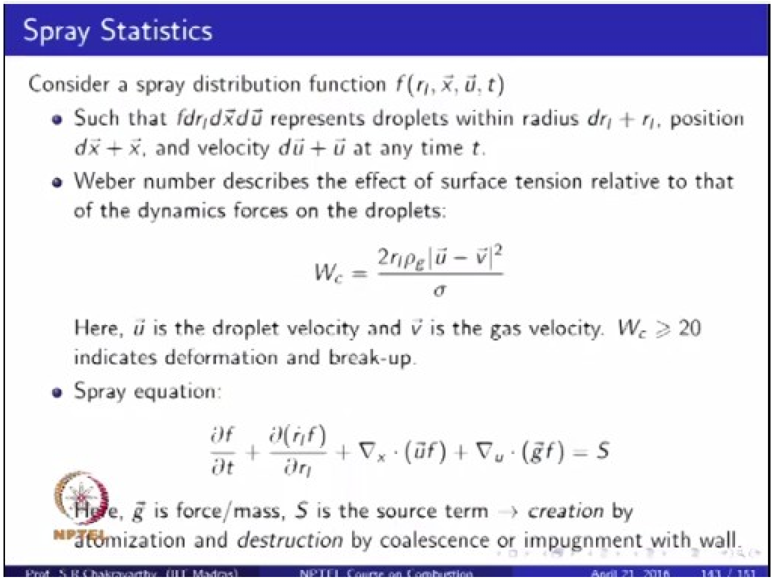

Spray Statistics

Consider a spray distribution function $f(r_l, \vec{x}, \vec{u}, t)$

- Such that $f dr_l d\vec{x} d\vec{u}$ represents droplets within radius $dr_l + r_l$, position $d\vec{x} + \vec{x}$, and velocity $d\vec{u} + \vec{u}$ at any time t.
- Weber number describes the effect of surface tension relative to that of the dynamics forces on the droplets:

$$W_c = \frac{2 r_l \rho_g |\vec{u} - \vec{v}|^2}{\sigma}$$

Here, $\vec{u}$ is the droplet velocity and $\vec{v}$ is the gas velocity. $W_c \geqslant 20$ indicates deformation and break-up.

- Spray equation:

$$\frac{\partial f}{\partial t} + \frac{\partial (\dot{r}_l f)}{\partial r_l} + \nabla_x \cdot (\vec{u} f) + \nabla_u \cdot (\vec{g} f) = S$$

Here, $\vec{g}$ is force/mass, S is the source term → *creation* by atomization and *destruction* by coalescence or impugnment with wall.

So given this we can now write what is called a spray equation for F on how this is actually going to go.

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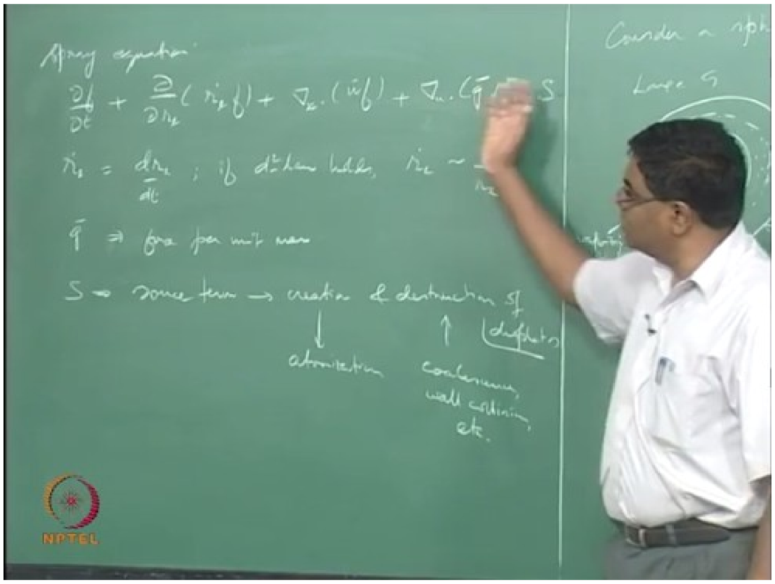

Spray equation is a dynamic equation for F $(\dot{r}lf)+ \nabla\dot{x}$ divergence with respect to x of the droplet velocity carrying the f and a the dynamic divergence with respect to u of the body force all equal to s, where now will now explain these charms $\dot{r}l$ there is something that we are familiar with which is drl/dt right, so this basically tells how this f is going to change because you are having a evaporation or burning that changes the or at a certain rate of it with respect to time.

And for example if d^2log holds that right, we know that $\dot{r}l$ is goes as 1/rl right that is something that we have seen before, G is as I said is a force per unit mass whatever forces are acting that that changed the droplet in the display the distribution function and s is actually the most important thing and also the most difficult thing is essentially the source term and essentially you not look at two sets of quantities one is creation and destruction, so creation and destruction so it is essentially a net source term or droplets right.

So creation is like for example by atomization and destruction is by qualities, and let us say impingement with the wall right, so wall collision etc so it is kind of like what is called as a population equation that that keeps track of the droplet population given by F and what you are looking for is how do the droplets get created and destroyed as a source of this that is getting dynamically going in a flow field. Now these are difficult to model and the fidelity of this equation is lies in actually how we model this and that is where all complexities I mean.

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