Spray Theory and Applications
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Lecture - 04
Steady vs unsteady spray

We are going to discuss a concept related to sprays that has applications to applications or more specifically causes problems in [FL] sorry, sorry. We are going to discuss a concept related to unsteadiness in sprays and we will see that there are two kinds of unsteadiness that we need to be careful about, you need to be concerned about, because unsteadiness in sprays causes unsteady heat release if it was spray combustion application and unsteady heat release as we will see later on is a cost of concern especially, if the unsteadiness frequency is close to one of the resonant frequencies of your combustion cavity.

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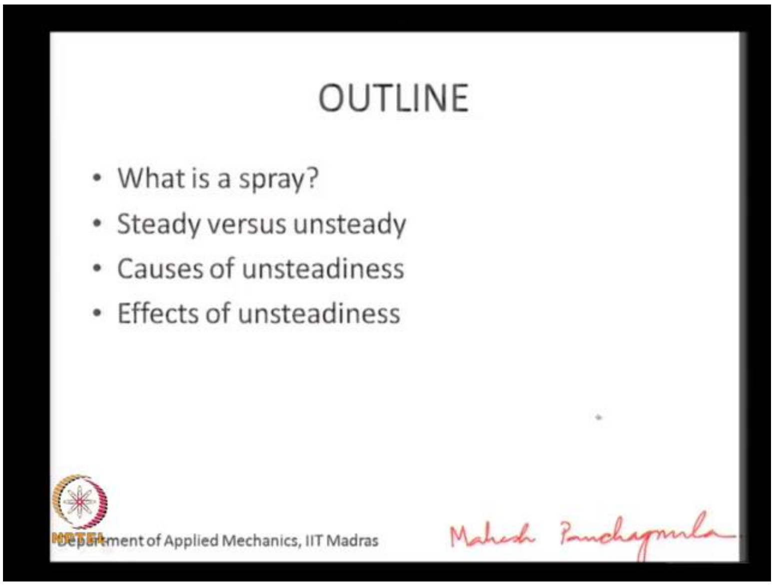

So, that sought of the motivation for why we need to understand unsteady sprays. So, we will quickly start by recapping some of our earlier discussion on what is a spray and what we mean by steady versus unsteady we did discuss this very early on, but I do want to bring in definition of unsteadiness working definition and then we look at some effects.

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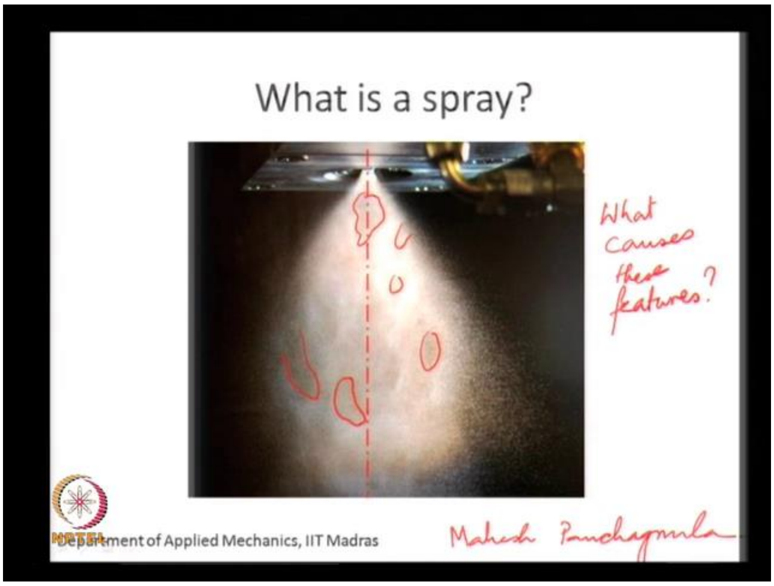

What is a spray? We have dealt with this quite a bit, we have seen an image like this what we have here is a an image from a pre-filming air blast atomizer, operating at a certain air typical ratio this is an what you see here is an instantaneous snap shot.

So, as you can see there are regions where there is a slide reduction in the fuel you can see these kinds of features. Our goal today is going to be to understand what causes these features? And as we will see what is the result? What is the effect of having these kinds of features in an instantaneous snap shot?

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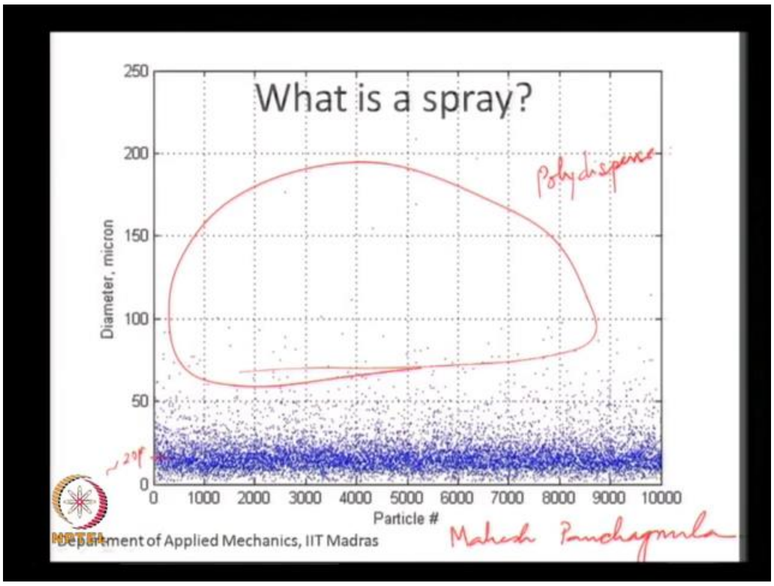

Now, I do want to mention a couple of things, first as to what a spray is and some of the reasons for this unsteadiness as we will see later on. One a spray by definition is very poly disperse, this is an example of drop size distribution in a spray, as we can see there are drops that are mostly somewhere between 10-20 microns, but there are also lots of there are also a few drops that are very large.

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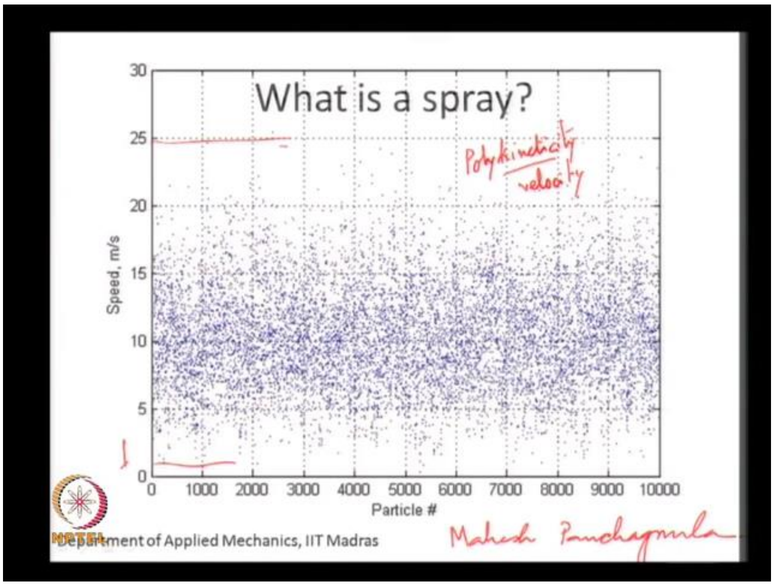

So, you are going to have a very polydisperse collection and that is by definition and also the speeds of the droplets as you will see vary from all most like 1 meter per second up to nearly 25. So, a factor of 20 variations in the speeds of the droplets is also something that is a feature of most sprays this is what we will call Poly Kinetic, although poly kinetic has to do with velocity we are looking at speeds in this plot, but it still is a representation of the poly kineticity in a spray.

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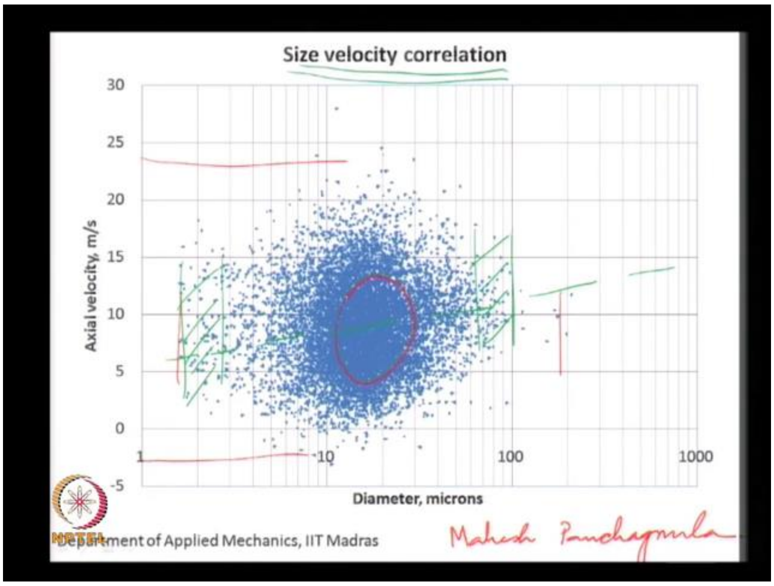

And then finally, when I plot the axial velocity of every drop at you know sample that a given point versus the diameter. You will see that the diameters like we said vary about two orders of magnitude, speeds vary by a factor of 20 and by enlarge there is a large group of drops right here in the middle, but you can also notice that there is a general visible trend that can be picked up. There is a general visible trend and this trend becomes more obvious when we look at, when we fit linear profile to this data set that the smaller drops tend to move with the smaller axial velocity then the larger drops.

So, there is a small discrepancy on the order of about 15 to 20 percent between the mean velocity of a group of drops here and the mean velocity of a group of drops here, this is what we call size velocity correlation. These three features of the point statistics in a given spray, if I generate drop size and velocity statistics at one point using some kind of measurement instrument. At one point in the spray these are the features I can observe at any given point in the spray and these features in turn cause unsteadiness as we will see a little later on. So, we have polydispersity in size, poly kineticity in velocity and size velocity correlation that the larger drops are moving with the larger velocity, slightly greater velocity than the smaller drops.

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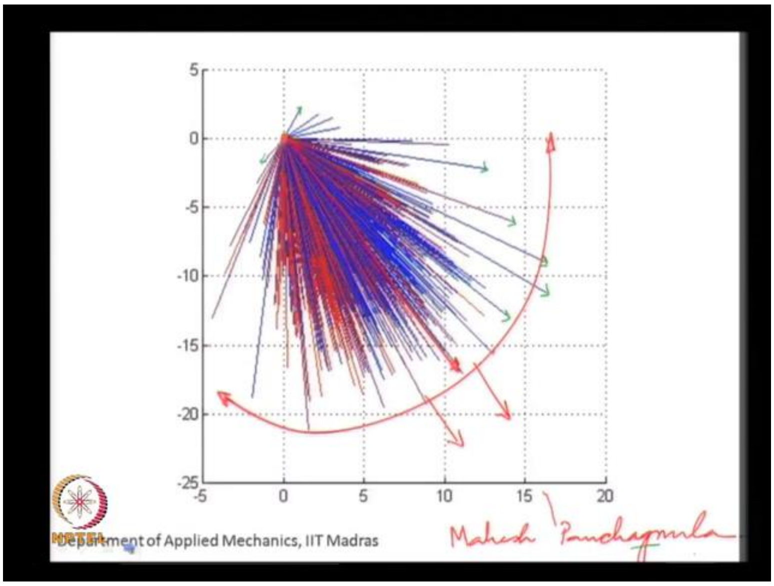

Now, I can represent this in a slightly different way here is a line plot where each vector, each line here represents a velocity vector of one drop. The length of the velocity vector is an indication of the magnitude of the velocity and the direction of course, is indicated by the direction of this vector. So, if I have points, if I have drops originating at a given point, let us say here I have drops going in all these different directions, but by enlarge there is a mean flow direction, but there is a big spread in the angle in the direction chosen by the drops and this variation in the angle of the direction chosen by the drops is represented as size velocity correlation.

Because, what we had there is like an axial velocity so even if they were moving with similar axial velocities or similar magnitude, similar speeds because they were moving in slightly different directions you tend to get a different axial velocity. So, this plot here shows you that what we call our mean velocity of the droplet phase; we talked about droplet phase in the context of multi phase flows. The mean velocity in the context of a droplet phase is this one arrow you can see how there is a large variation in the velocity field at one point, this is like turbulent flows basically, that the instantaneous velocity vectors of a given fluid flow at a point in the turbulent flow would look something like this. Although that, this the spread in the theta coordinate or the angular, the angle made by the velocity vector to some vertical axis is much larger here in comparison to most turbulent flows. So, this idea of poly kineticity is I think best represented in a graph like this.

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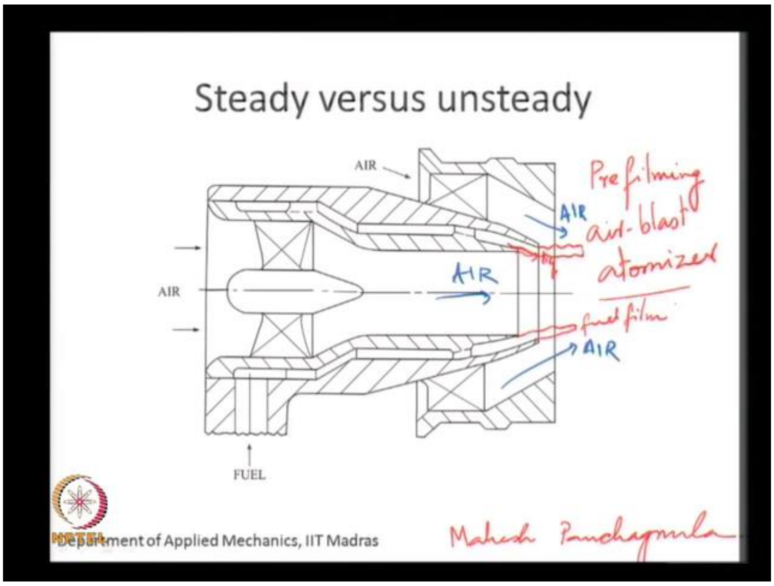

Now, let see what unsteady versus steady means and we will take the example of what called a Pre Filming air blast atomizer, we have seen a design of this, in the context of the various nozzle types you have liquid coming out of here and air moving through both an inner passage and an outer passage. So, you essentially have a liquid film that dribbles out of this annular passage and that is impacted by air on both sides, so this is my fuel film.

So, what we are going to see today is causes of unsteadiness in a spray caused, in a spray emanating from a pre filming air blast atomizer now before I go in to discussion of the pre filming air blast atomizer, really speaking let us say there are two kinds of unsteadiness. One that is intended unsteadiness and second that is un-intended unsteadiness. So, if I think of a diesel spray, a diesel injector typically sprays into the combustion chamber very close to the point the phase angle where the piston is close to the top dead center and that causes ignition auto ignition and you start to get combustion and the piston goes through its driven stroke.

This process is repeated over and over again, so you have a start and a stop to every injection cycle and this is repeated, you know whatever, repeated as frequently as your rpm requires the injected to perform. So, in the context of a diesel injector unsteadiness is intended because I do need the injected to start and stop in a very very short period of time. So, in most cases steady state models are not very applicable to the real diesel injector. So, work in the diesel community focuses on pulsed injection. So, you have every pulse causing you know combustion reaction and you have a power stroke at the combustion followed by power stroke and this in some sense is intended unsteadiness. What we are going to discuss today is unintended unsteadiness which is sought of driven by fluid mechanics and we want to develop and understanding for the causes of this unintended unsteadiness so we can try to mitigate some of those causes.

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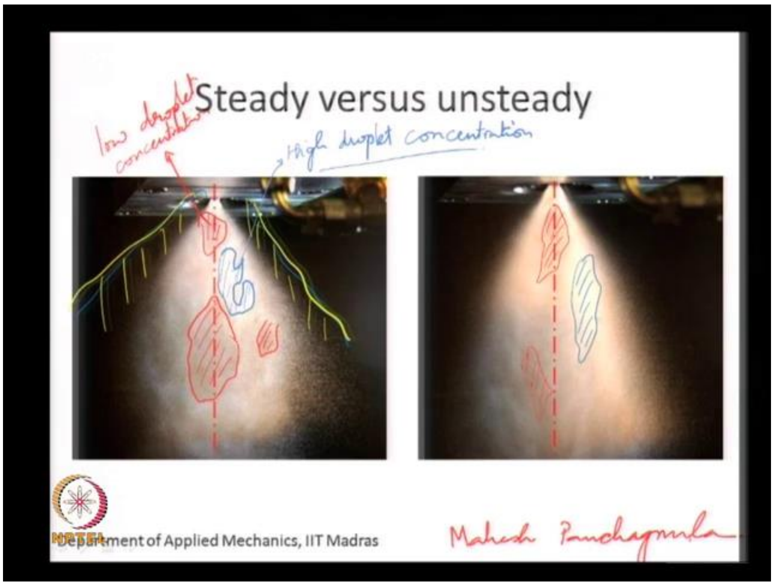

So, let see what are the, so like we said, let us look at a very simple working definition of steady versus unsteady I have two examples spray shown here both of these have these features in the instantaneous snap shots that we can see. Now I have to tell you that both of these sprays are axis symmetric sprays, what we are seeing is essentially the droplet in the light being scattered by the droplets on the periphery of this conical spray. So, when I see a region where there is sought of where which is sought of dark in comparison to another region that is more bright which is let say, so that is more bright. If I look at this red hatched region versus a blue hatched region I am just, this is a region of high droplet concentration on the surface and this in turn is a region of low droplet concentration.

So, this rich and lean regions in terms of fuel droplet concentration is a cause for concern we want to see how to eliminate that and the reason we call these, call this unsteady is because, if I took two snap shots one immediately following the other - two instantaneous pictures those two would look different in terms of these red and blue features. Whereas, if I took the second spray which is relatively speaking more steady as you can see there are still pockets which are sought of lean and rich as you can see from here, but for the most part this would be in some sense more steady in comparison to this. So, the steadiness or the time variance from image to image is lower with the second image than the first. So, I cannot tell that from just looking at one snap shot, I have to look at a series of these snap shots from each spray, compare the whole series.

So, develop an average picture of the whole spray and then look at what the variability of each of the instantaneous images is from that averaged picture. So, this process is there is a lot of very nice math that can going to this two quantify the level of uncertainty, we are not going to quantify the level of variability, we are not going into that this morning, and we are only going to look at what causes this unsteadiness.

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So, let see what the first cause of this unsteadiness is and to understand the first cause of unsteadiness we are going to look at a video I think that we played very early on, this is a high speed video of a spray emanating from a regular pressure swale or a simplex atomizer the video has been capture a 10000 frames a second and it is going to be played back to you at 30 frames a second. So, it is mean slope down by a factor of 30 by a factor of all most 300 not 30.

So, the first cause of unsteadiness as you will see is right here, I have a liquid sheet that is coming out of this atomizer as you can see in the form of this gray cone and that cone is flapping. So, there is sought of a movement up and down in this direction and that flapping motion is due to our own linear instabilities that grow on this liquid sheet that we are able to understand using our linear instability analysis. So, I have created a flapping conical liquid sheet coming out of the atomizer and this flapping conical liquid sheet breaks up in to rings, these rings in turn as we saw from our analyses these rings in turn our responsible for our, are unstable and they break up into drops.

So, that is our primary atomization process and this primary atomization process is somewhat discretized because, every time I have this flapping motion every time the liquid sheet goes up and comes down I am going to break of a ring. So, I have a sequence of rings formed from every one of these flopping motions and that time frequency of formation of rings is going to cause a spatially varying droplet size distribution, droplet size concentration especially near the nozzle. So, if I look at even this sought of instantaneous picture I can see that there is a region where I have a large number of drops or surely I can tell that the mass concentration of the fuel is high followed by a proceeding region where there is linear concentration of fuel and I can see that there is going to be another fuel rich packet that is right behind it.

So, this spatial variability of fuel concentration is a result of the primary atomization process. So, this temporal variation of causation of drop, temporal variation of production of drops is going to cause a spatial variation in the spray itself, now this is unsteadiness originating from my primary atomization process.

Now, but this happens very close to the nozzle why is this important? In a real spray capacitor there is not enough time for these drops to undergo, for a non uniform field created from a primary atomization process to completely become uniform. So, this unsteadiness may still have some remnant effect on the downstream process. So, this is one cause of unsteadiness in a spray that is the primary atomization and the wave length associated with, the wave length and time temporal frequency associated with the most unstable mode of breakup this is the first cause of instability. You can see this sort of progress forward as you look at the process. Now any sort of variation in the mass flow rate coming into the atomizer as you can see when there is a sudden increase in the mass flow rate that causes a change in the temporal characteristics of this spray.

So, the first cause as we discussed is anything that happens just inside the nozzle or just outside the nozzle our primary processes. The second cause of unsteadiness is what we want to discuss in some detail today and that has to do with the particle vertex interaction.

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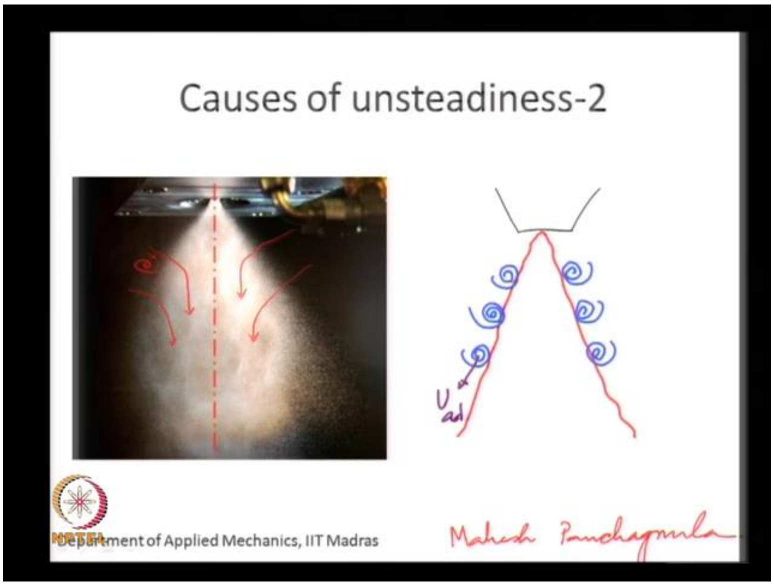

So, if I take a typical spray like I have shown in a cartoon here, at the edge on the edge of the spray we have essentially air that is outside being entering in. So, these are representative stream lines and these representative stream lines cause a vertical roll up, I mean the entrainment process causes what is to be formed on the edge of this spray it is just like, edge of any turbulent jet. When you have these vertical structures the drops on the vicinity of the spray are going to interact with these vertical structures and like we said we already have a polydisperse collection of drops. So, if there is some kind of size dependence of the nature of interaction between a vertex and a drop then different sized drops are going to react differently to the vertex and that in turn could cause other non-linear effects.

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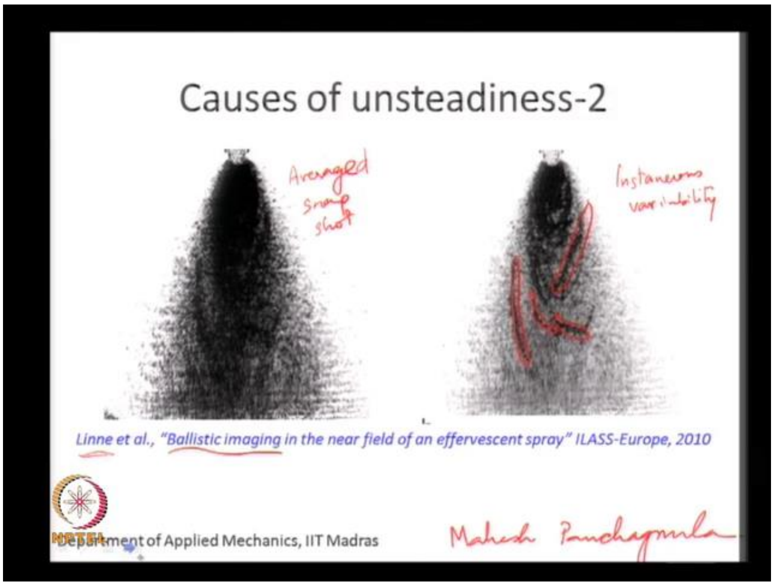

So, we will see what this means in just a moment this is another way to quantify what I was talking about in terms of this non-linear effect is using the technique called Ballistic Imaging. This is recently finding use in looking at dense sprays where the number density of droplets is very high and where this group was able to make ballistic images of an effervescent spray and if the left hand side is sort of an average picture we are able to separate out the average picture from the instantaneous snap shot and quantify instantaneous variability, this instantaneous variability as you can see causes these kinds of agglomerated structures of drops. So, these are regions where droplets are agglomerated together they are collected together.

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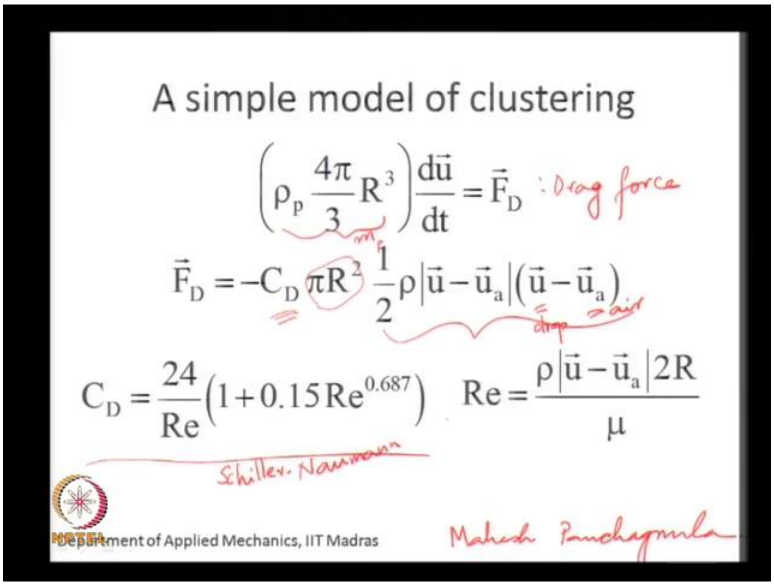

So, we want to understand what is the cause of this collection of drops? A simple model we are going to try and understand a very simple model for this clustering which is based on drag. So, when I have a droplet in a cope flowing air stream that if the drop let is initially addressed, the air stream is going to drag this drop to some terminal velocity ideally the same velocity as the air itself, and this process is very simple model for this process is based on our Newton second law - that says that the mass of the particle times the acceleration of the particle equals any external force that acts on it. In this case the external force is my drag force, the drag itself has got two components - one the fact that drag is proportional to the mean velocity between the drop this is the drop velocity and this is the air velocity, and a drag coefficient. So, essentially the drag force is equal to some drag coefficient times half rho u squared where u would be the relative velocity between the instantaneous relative velocity between the drop and the air and the cross sectional area over which the drag force acts.

The drag coefficient itself we are going to assume a very simple model for the drag coefficient which is based on drag on a sphere of radius R over range of Reynolds numbers. So, if the Reynolds number is very low then for Re tending towards 0 you have C D which is equal to 24 over Re which is our stokes drag. For Re greater than 0 laminar or turbulent this coefficient this drag correlation due to Schiller and Neumann is pretty useful. So, we just want to understand the effect of the air around this around this ploy-dispersed collection of drops on the drops themselves.

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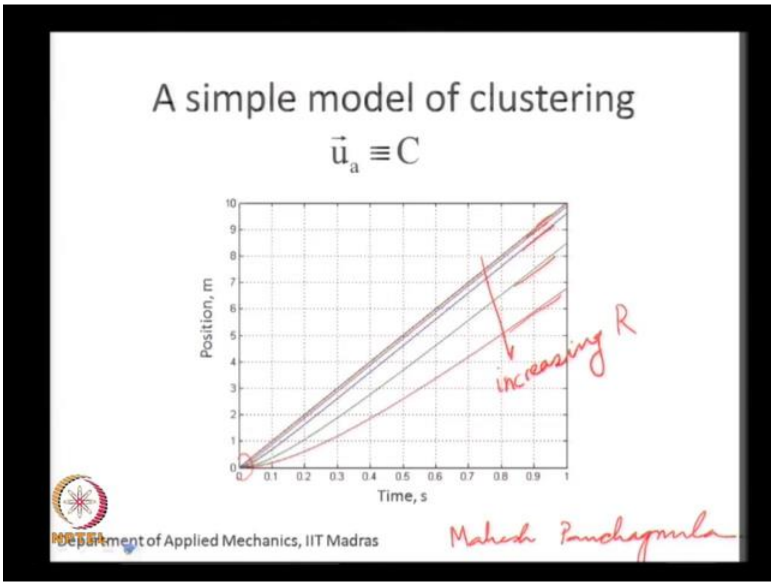

So, I think we have completed our model now. So, I have the mass I know the radius of the drop I know mass times acceleration is a drag force and assuming I know everything else in this I am going to solve for u for the of the drop as a function of time and from there get the position of the drop as a function of time. We will start with the very simple model now these are increasing drop size. So, increasing R in the previous model as R increases if the air velocity is constant, first of all I do get the position increases linearly with time.

So, in other words this transient over which the drop accelerates to the air velocity is very small whereas R increases you can see the region where the droplet is still continuing to accelerate until it reaches the terminal velocity which is the equal to this value C what we have plotted here is position versus time. So, when the slope reaches a constant value it is equal to the velocity of the air stream around it.

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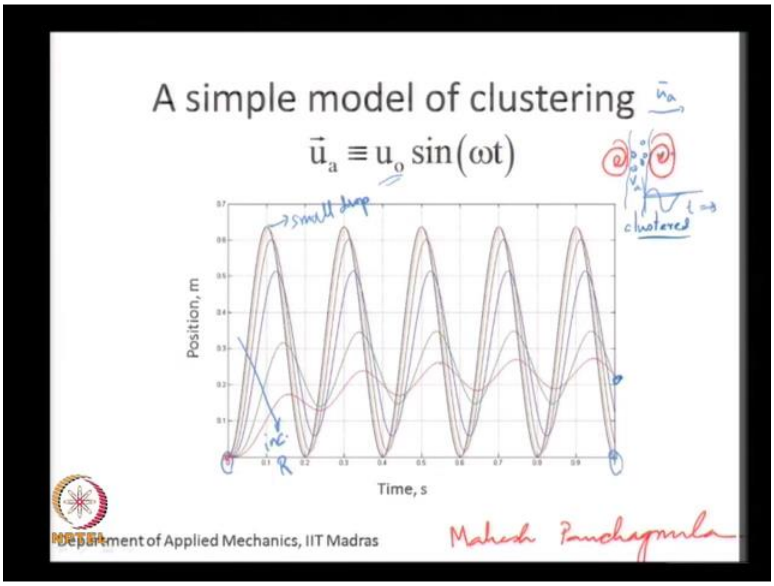

If the air has an oscillatory nature to it what do we find is that if all the drops started at position x equal to 0. So, I have a vertex essentially that is stationary and in the middle of the vertex I have introduce a drop.

Now, as far as the field experienced by the vertex, a field experienced by the drop the velocity field experienced by the drop it is going to be an oscillatory velocity field because as the vertex. So, for example, instead of the drop being at the middle if I take the drop over here instantaneously it is going to look at a velocity field that is of an oscillatory nature and two oscillatory fields one in the x direction and another in the y direction, superpose to form how vertical field. So, that is like our field that is causing some kind of a rotation.

We will only consider one dimensional flow field for a moment. So, if I have air flow in this direction except that air flow is got an oscillatory component. So, it is mean velocity is 0, over some time average, but it is got an oscillatory component the magnitude of which is this u 0. Now if I put drops at x equal to 0 in this oscillatory flow field the smaller drops are just going to go back and forth. So, you see this is for a small drop the blue line for example, is for a small drop and it is simply going to ride the wave back and forth along with the air stream.

The larger drops as you can see this is now increasing R; the red line is for the largest drop, the largest drop tends to actually move. So, it is center of mass moves to let us say in this case 0.2 meters from 0, even if the mean velocity of the air is 0. So, I am able to if I look at their instantaneous positions of 4 or 5 different sizes of drops some time later, let say one second after I started this process at time 0 all the drops were at x equal to 0. I subject this poly-disperse collections, so I have 5 discrete sizes in this particular simulation.

I take the 5 discrete sizes they are all at x equal to 0, but they are subjected to this oscillating air field over one second of time the larger drops have moved preferentially outward in relation to the smaller drops. So, if this was to happen due to two neighboring vertical structures. So, I have one here and another here each of these would preferentially move the larger drops outward. So, over time I would have a region here of clustered drops because the oscillating air field is able to move the larger drop preferentially in relation to the smaller drop, this is entirely due to the non-linearity in the drag law that we discussed.

So, this Schiller Neumann drag law has a non-linear dependence of C D with an on R e and this non-linearity in the drag is responsible for this kind of a variability or size dependence of the response characteristics of a drop to an oscillating flow. So, any time I have size dependence that non-linearity is going to result in size separation. So, it is like the larger drops are going to move in one direction preferentially in relation to the smaller drops and if I do the same thing in two dimensions and if I have a line of vertices in between two success in between a pair of vertices I could create a fuel rich region. So, right on the edge of the spray where I have these vertical structures entraining air from the outside into the spray I have region that could result in a cluster of drops especially large drops.

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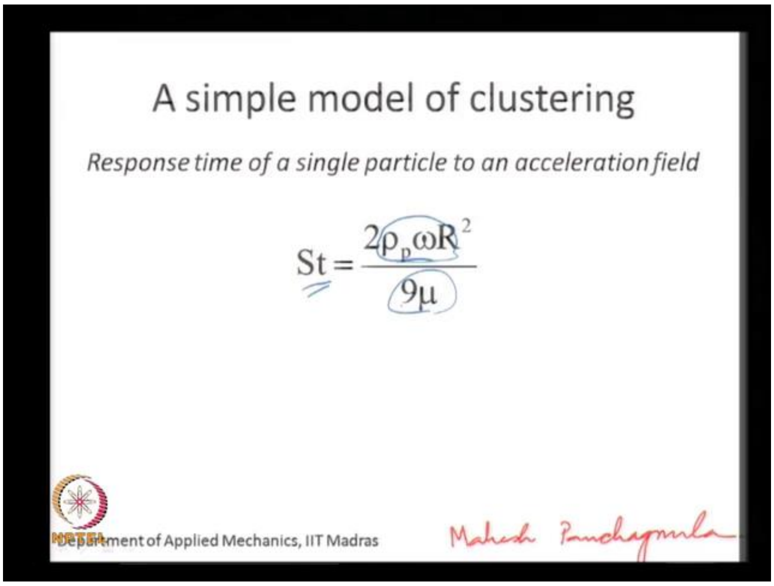

Now, the way to understand whether I will get clustering or not we just showed how size dependence in the drag log causes clustering. So, the way to understand whether I get clustering is based on stokes number. So, if I take the inertia so essentially a part of this is the inertial effect, the inertial force on the drop itself and the drag force from the neighboring air. So, if I quantify the relationship between these two then this response this gives me a response time of a single particle to an acceleration field. So, if the response time of the largest particle to the smallest particle is comparable then I am likely to not get size separation.

Another way to look at this is if the range of frequencies time frequencies associated with these vertical structures are such that the response times of the largest drop to the smallest drop are similar then I will not get size separation and clustering resulting from size separation. If the response times are vastly different then I am likely to get clustering due to the size separation this is a very simple model that helps us understand why you see a picture like this.

So, let us come back to this image, now like we said this is a pre-filming air blast atomizer spray. So, I have a spray and outside the spray it is invisible in this photograph, but I have air it is a swirling stream of air that is coming from this outer air, this outer air is like a sheet covering the outside of my spray. So, right around here I have a co-flowing stream of swirling air and this swirling stream of air interacts with the drops that are formed on the periphery of the spray and this interaction between the swirling air stream and the drops is responsible for these lean and rich spots.

So, if this same spray was inserted into; let us say a gas turbine combustor these richer lean spots would cause fuel vapour rich regions and fuel vapour lean regions in the combustion zone and that in turn if the spatial distribution or temporal distribution in, if I was sampling at one point in time, one time in space the temporal distribution of these fuel and lean packets had a frequency close to the resident frequency of the cavity then I am going to get, I am going to create a situation for combustion oscillations which is a form of instability. So, unsteadiness in spays is very important form the context of understanding and mitigating combustion instability and also we what we are. So, this fluid mechanic driven instabilities need to be understood through these kinds of non-linearities arising from the drag law. Now turbulence droplet interaction can also be understood in a similar sense.

So, if I we looked at the effect of a mean flow structure a vertex is like a mean flow structure if I have a coherence structure a coherence turbulent structure. So, which is just turbulent fluctuations that are in phase over some region and space those turbulent fluctuations have a temporal frequency and has a model similar to what we discussed. We will also help to understand how droplets a poly-disperse collection of droplets interacts with turbulent coherent structures. So, whether you have a mean flow structure or turbulent coherent structure these interactions can be studied using a simple model like that and the primary cause for this clustering in both those is essentially this responsible time difference. We will stop here, we will continue in the next class.