Heat Transfer And Combustion in Multiphase Systems
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Lecture 31
Introduction to atomization

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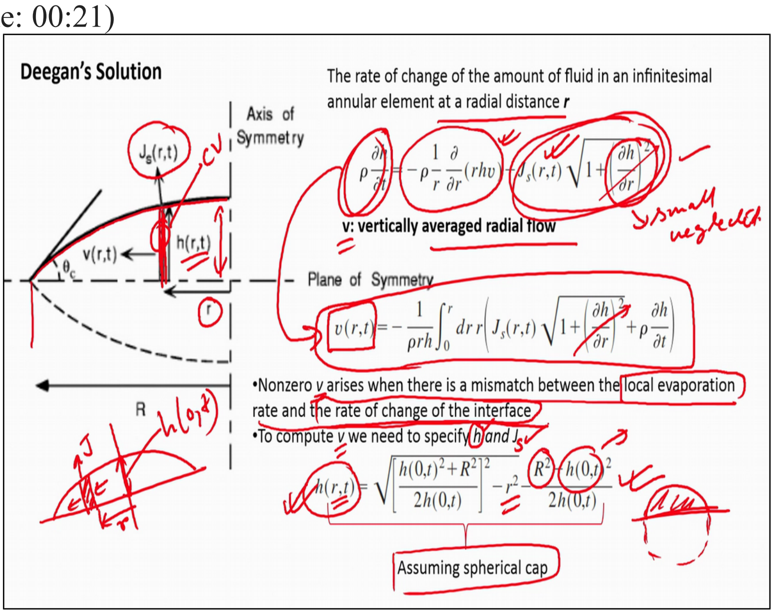

Deegan's Solution

The rate of change of the amount of fluid in an infinitesimal annular element at a radial distance ***r***

$$\rho\frac{\partial h}{\partial t} = -\rho\frac{1}{r}\frac{\partial}{\partial r}(rhv) - J_s(r,t)\sqrt{1+\left(\frac{\partial h}{\partial r}\right)^2}$$

small neglected

v: vertically averaged radial flow

$$v(r,t) = -\frac{1}{\rho r h}\int_0^r dr\, r\left(J_s(r,t)\sqrt{1+\left(\frac{\partial h}{\partial r}\right)^2} + \rho\frac{\partial h}{\partial t}\right)$$

- Nonzero *v* arises when there is a mismatch between the local evaporation rate and the rate of change of the interface
- To compute *v* we need to specify *h and J_s*

$$\underbrace{h(r,t) = \sqrt{\left[\frac{h(0,t)^2+R^2}{2h(0,t)}\right]^2 - r^2} - \frac{R^2 - h(0,t)^2}{2h(0,t)}}_{\text{Assuming spherical cap}}$$

So, in the last class what we did if you look at the presentation slide we have found out that in the case of hydrophilic droplet on a hydrophilic substrate which exhibits pinned contact line. You get expressions for you can write a mass conservation equation, you can find out what is the radial capillary flow.

And for calculating that radial capillary flow you need to know h and you need to know Js. So, that is what we are trying to find out h is written approximating it as a spherical cap in terms of the other quantities.

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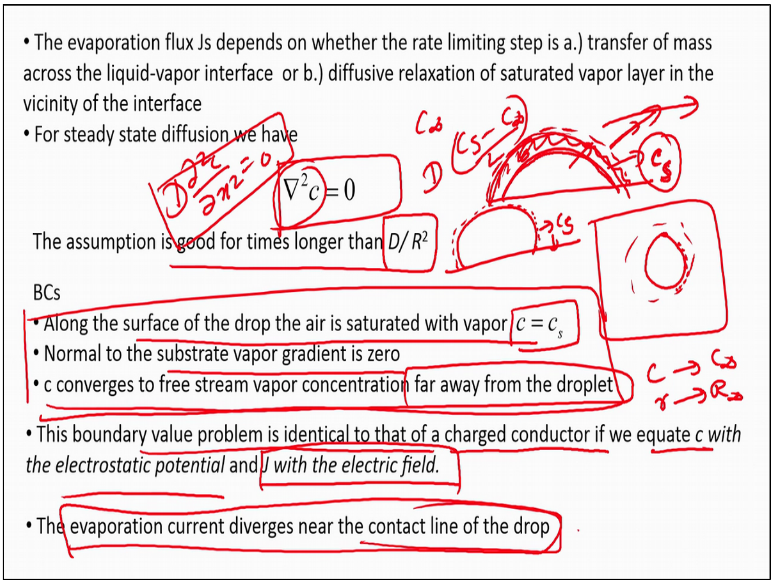

- The evaporation flux Js depends on whether the rate limiting step is a.) transfer of mass across the liquid-vapor interface or b.) diffusive relaxation of saturated vapor layer in the vicinity of the interface
- For steady state diffusion we have

$$\nabla^2 c = 0$$

The assumption is good for times longer than D/R^2

BCs

- Along the surface of the drop the air is saturated with vapor $c = c_s$
- Normal to the substrate vapor gradient is zero
- c converges to free stream vapor concentration far away from the droplet
- This boundary value problem is identical to that of a charged conductor if we equate *c with the electrostatic potential* and *J with the electric field.*
- The evaporation current diverges near the contact line of the drop

Now the evaporation flux Js now we next mix me to calculate the evaporation flux and this is very similar to the contact free droplet that we had right. It depends on whether they are to make limiting step over here. One is the transfer of mass across the liquid vapour interface. The other one is the diffusive relaxation of the saturated vapour layer in the vicinity of the interface.

So, it is like this so one is the transfer of mass from there the other one as it vaporizes there is a layer that forms okay we are that the concentration can be as high as the saturation vapour concentration right. As soon as the concentration of whatever the solvent is right reaches the saturation vapour concentration.

This evaporation rate will go down this is the same thing that happens in the case of your spherical droplets right. If you have a spherical droplet and you enclose it in a container right what will happen that after some time this entire container will be filled up with a saturated vapour. So, this droplet will stop to evaporate.

Similar thing happens in the case of a sessile droplet also. What happens is that the fissile droplet the vapour field that is around the sessile drop that gets saturated. So, unless this gets relaxed right relaxed means this has to be diffused out to the ambient right. How the diffusion happens exactly how it; how we say that it is going to happen in the case of a spherical droplets right.

There is more concentration here there is less concentration there so there will be the CS - C infinity by whatever is the length scale of the problem into D that will be the vapour flux right. Typically speaking that is what is going to happen. So, as this vapour relaxes this area around the droplet is going to become now under saturated okay unsaturated.

As a result of that motive opposition will happen so that is one of the rate limiting steps right. So, in most of the cases the diffusive relaxation is the rate-limiting step right. So, you want the vapour that is saturated vapour layer that is situated around the droplet around the vicinity of the droplet surface to basically relax out that means to basically diffuse out so that you can evaporate more right.

This is the same reason why for example if you put a pot of water or if you wash your clothes and put it to dry in on a rainy day, rainy day means on a humid day right. Do you know that it takes a lot of time for it to basically dry right. Why does this thing happen that is because the air that is outside right is very humid, it is already at full capacity of water vapour it cannot absorb anymore.

So, it takes a very, very long time for that to happen that means there is no diffusive relaxation of the saturated vapour layer near your cloth. In this case also near the droplet surface that vapour layer has to relax right. Now in order for the vapour layer to the relax we can always write it like a simple Laplace equation right.

It is a simple Laplace equation; it is basically this, if we write it in one dimension to be equal to 0, right. It is a steady state diffusion problem it is like a steady state conduction problem also. You can assume it to be like a conduction problem right okay, so that is equal to 0, this is good. When you have time which is more than the diffusive time scale right D by R squared you understood the problem.

So, this problem assumes that it can be 3d because it is a Laplace operator even if it is 1d you can write it simply in that particular fashion right. But there will be boundary conditions which will match it to the interface like we saw in the case of your spherical droplets right. So, what happens is that along the surface of the drop the vapour has to be equal to the saturation vapour concentration.

So, near the vicinity of the drop or in this case this is the droplet us say in the vicinity of the droplet okay this is always that CS right on the other side of the interface right. Normal to the substrate the vapour gradient is 0, the vapour gradient is 0 normal to the substrate because of no penetration right.

We are assuming that this vapour do not get adsorbed on the surface okay. And C converges to the free stream concentration far away that means C goes to C infinity okay when R approaches R infinity something like that okay. So, these are the cases that we have right.

Now this boundary value problem Deegan found that this is identical to a charged conductor if we equate C with the electrostatic potential and J which is the evaporation flux with the electric field that is how Deegan solve this particular problem. So, what he took, he identified any equivalence of this problem.

He took that this is a charged conductor okay and it is like a charged conductor okay where C is like the electrostatic potential J is like the electric field. The evaporation current in such a solution diverges near the conduction line contact line of the droplet. That means near this contact line this value becomes very high leave operations last value becomes very high okay.

So, if you go to the contact line is just kind of asymptotes like that got it, very near to the contact line okay leave opposition current diverges.

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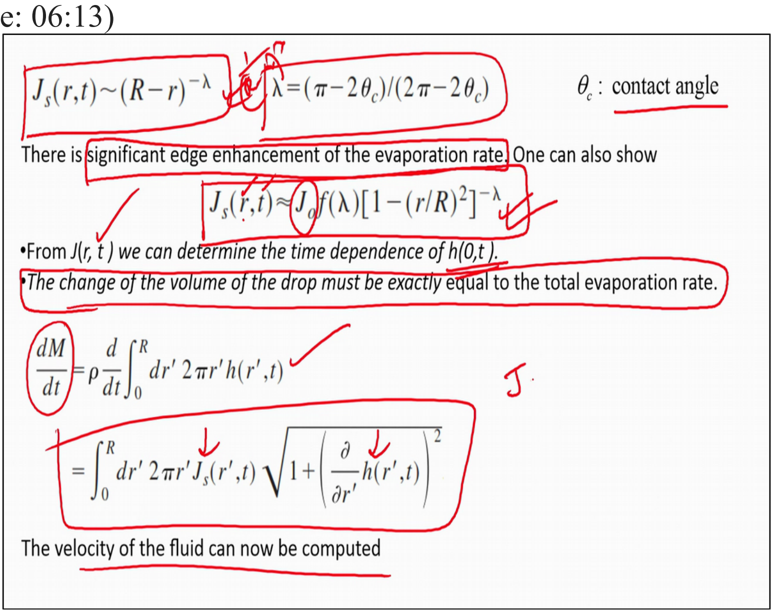

$J_s(r,t) \sim (R-r)^{-\lambda}$ $\lambda = (\pi - 2\theta_c)/(2\pi - 2\theta_c)$ θ_c : contact angle

There is significant edge enhancement of the evaporation rate. One can also show

$$J_s(r,t) \approx J_0 f(\lambda)[1-(r/R)^2]^{-\lambda}$$

- *From J(r, t) we can determine the time dependence of h(0,t).*
- *The change of the volume of the drop must be exactly* equal to the total evaporation rate.

$$\frac{dM}{dt} = \rho \frac{d}{dt}\int_0^R dr'\, 2\pi r' h(r',t)$$

$$= \int_0^R dr'\, 2\pi r' J_s(r',t)\sqrt{1+\left(\frac{\partial}{\partial r'}h(r',t)\right)^2}$$

The velocity of the fluid can now be computed

So, these are the expressions that Deegan found, he found that Js which is the evaporation flux is given by this particular form where alpha is related to the contact angle. Now you can imagine over here that when r becomes equal to capital R right small r becomes be equal to capital R this actually basically blows up okay.

This diverges completely right because it is one over, it is basically 1 over R minus small r lambda right. So, it basically blows up when our approaches capital R okay. So, there is significant edge enhancement due to the evaporation that makes sense because we say that the evaporation rate will be very high.

One, he also showed that this is given in terms of the of the flux, normal flux multiplied by this additional factor okay. So, this is a solution that he found for the Js there is map you can do algebra if you want but this is basically the expression that you would have. Now from J we can determine the time dependence.

Now that we know J okay and it is given in terms of R and t, so this is the local evaporation rate we can determine the time dependence of h naught t that means the height of the apex right the height of the apex comes over here if you look at it the height of the apex is right there right okay. So, the change in volume of the drop must be exactly equal to the evaporation rate right that is kind of given.

So, if we write the rate of change of mass of the drop in terms of this integral formulation okay. You get this expression Js and correspondingly h the velocity of the fluid can now be computed and from using the values of Js and h you can calculate this particular thing.

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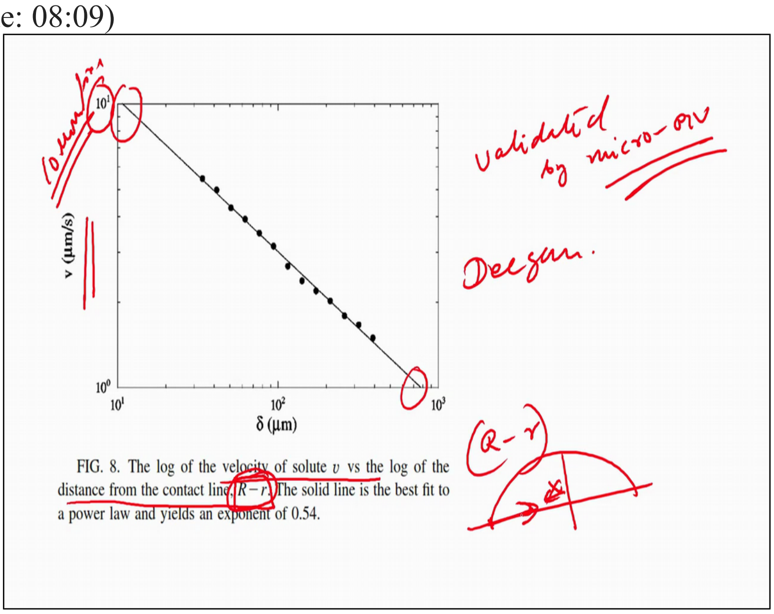

FIG. 8. The log of the velocity of solute v vs the log of the distance from the contact line, $R-r$. The solid line is the best fit to a power law and yields an exponent of 0.54.

And if you actually from Deegan showed that if you show that this is the velocity so it varies from 10 okay this is the log of the velocity of the of the solute that is the particles in this case versus the distance from the interface that is r, capital R. So, as you can see when this R, R - r okay that means when it goes to a very low values right, R - r goes to very low values okay.

You have a very high velocity that will try to happen and I did and this will come progressively go down okay. So, you can see that the velocity order is of the other order of 10 to the power of actually 10 microns per second. This is also has been validated by numerous groups including ours right validated by micro PIV a micro particle image velocity measurements have confirmed that this is what actually happens okay.

So, you get that this is the variation with respect to the distance from the contact line. So, it is the other way around actually so it is the distance from here rather than from here okay. It is the away from the contact line that is what we have tried to plot over here okay. So, you understood that this is that this is how you should actually work out the math of the problem right.

So you find out J and J is diverging and from J and h you can find out what will be the velocity right.

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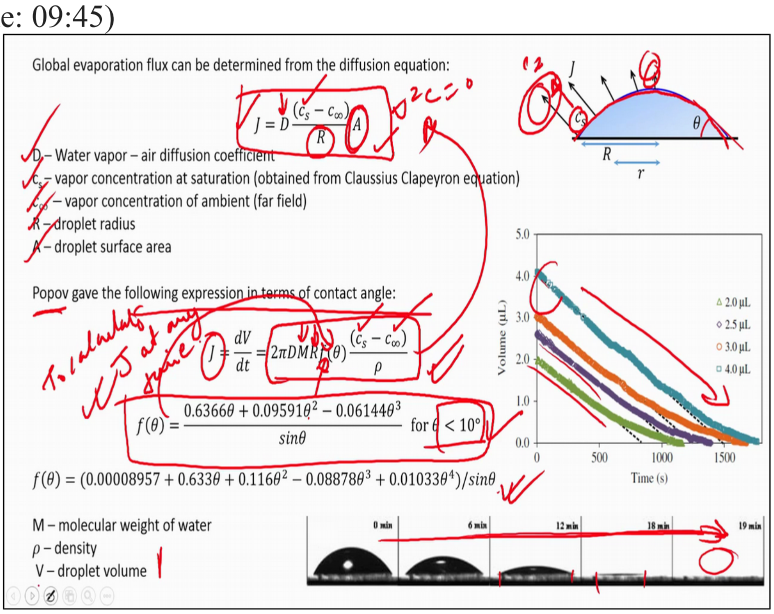

Global evaporation flux can be determined from the diffusion equation:

$$\boxed{J = D\frac{(c_s - c_\infty)}{R}A} \quad \nabla^2 C = 0$$

D – Water vapor – air diffusion coefficient

c_s – vapor concentration at saturation (obtained from Claussius Clapeyron equation)

c_∞ – vapor concentration of ambient (far field)

R – droplet radius

A – droplet surface area

Popov gave the following expression in terms of contact angle:

To calculate J at any space

$$J = \frac{dV}{dt} = 2\pi DMRf(\theta)\frac{(c_s - c_\infty)}{\rho}$$

$$f(\theta) = \frac{0.6366\theta + 0.09591\theta^2 - 0.06144\theta^3}{sin\theta} \quad \text{for } \theta < 10°$$

$$f(\theta) = (0.00008957 + 0.633\theta + 0.116\theta^2 - 0.08878\theta^3 + 0.01033\theta^4)/sin\theta$$

M – molecular weight of water

ρ – density

V – droplet volume

Now in many other cases one may not be; so you can now see that the evaporation flux, is highly non uniform across the surface right. It is very high at edge very low at the apex right so it is very unlike the spherical contact free droplets that we dealt with so far right where it was very isotropic correct.

And the flow was also diverging it was going radially outward right. So, these are the few things that you can get from your hydrophilic droplet. But in many of the cases people were interested look I do not want to know that what is the spatial variation of the evaporation flux okay.

Just let me know, what is a global evaporation plug that means what is the total rate of wave opposition? I am not interested in knowing that whether evaporation happens more on this side and less from this side. I want an average value right that could be the demand of several applications. And that is easy to solve because this evaporation flux we already said it was something like this right.

So, it is very easy that CS - C infinity, this is CS near the surface C infinity in the part stream right and you use the length scale of the droplet as your length scale of the problem here. This is the diffusive flux and this is the diffusion coefficient mass diffusion coefficient and or the mass diffusivity and this is the total area right.

So, just by using this relationship this is a simple diffusion problem right. There is vapour over here, this vapour has to diffuse out and that will control what will be the evaporation rate. Because we as we said earlier that is the rate-limiting step that we are looking at in this particular problem, got it, okay.

So what is that so D is the water diffusion coefficient Cs infinity we already said R is the droplet radius, A is the droplet surface area right. So, in so this is the most generic form that you can ever hope to get. However Popov okay gave the following expressions in terms of the contact angle.

So these are kind of like as the contact angle changes like the contact angle changes right because of the evaporation the contact angle, will change right because if it is happening in a CCR mode the contact angle will change quite a bit right. So, what he did was that he proposed essential an expression which is very similar to this okay.

Except that now it has a contact angle factor which is f theta, f theta is given by this for contact angle less than 10 okay, so that is what you have over here. So, for contact angle less than 10, so this is Cs -C infinity okay that is the same expression that you had before, this is the molecular weight, this is the corresponding radius of the droplet, this is the droplet volume right, okay.

So, he proposed two regimes one is for less than 10 degree contact angle. This is more than 10 degree contact angle not this is what Popov actually proposed for a wide range of contact angle you can apply this expression okay. You can just compute the instantaneous contact angle, plug that instantaneous contact angle here, calculate what is the global evaporation rate.

Remember this is a global evaporation rate this does not take into account that whether evaporation is happening more here and less there. This is a global factor that people have actually assumed okay. So, if you can see so this is a time marching of the droplet, so you can see that this is the droplet virtually remains in that constant contact radius kind of a situation.

And you see that it slowly evaporates and ultimately goes down, so there is no drops at there anymore right. So, this is the evaporation of a particular droplet which exhibits more the CCR mode in this case right. And if you plot the volume curves you will find that these are the volume curves for the different droplets okay.

Obviously higher volumes and lower volumes are actually there okay. So, you can see that these are the kind of volumes that you have. So 4 micro litre volume; you start that takes the longest time which is very common sense right okay. But this expression allows us with the tools to calculate J at any time during the evaporation process provided you know the contact angle which in most cases you can measure experimentally or things like that okay.

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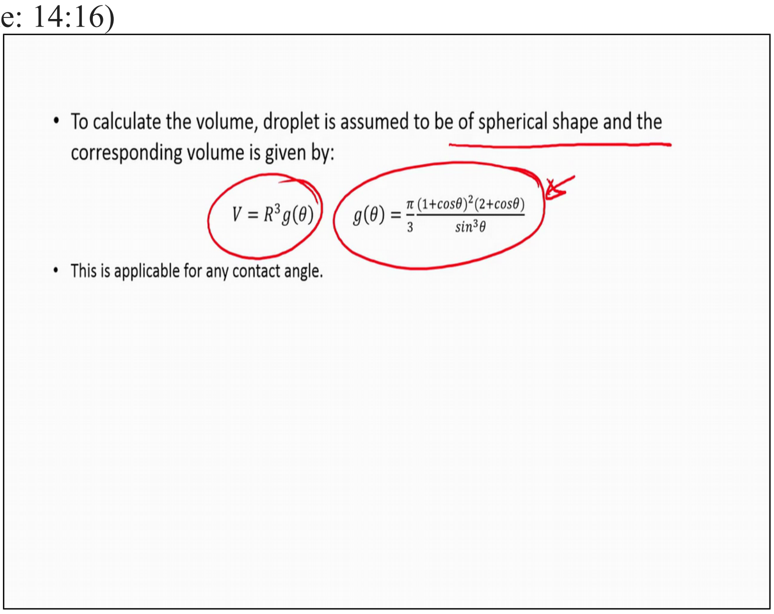

- To calculate the volume, droplet is assumed to be of spherical shape and the corresponding volume is given by:

$$V = R^3 g(\theta) \qquad g(\theta) = \frac{\pi}{3}\frac{(1+cos\theta)^2(2+cos\theta)}{sin^3\theta}$$

- This is applicable for any contact angle.

To calculate the volume if you see that there is a volume of the drop that is there okay. The volume of the drop is there okay in order to calculate the droplet volume okay you assume to be a spherical shape and the corresponding volume is given like this. These are all expressions I am not going to go into the details you can just do the math and find it out.

And this is applicable for any contact angle not just hydrophobic. It is applicable for hydrophilic and hydrophobic because these are the two ranges that we gave in this particular problem okay.

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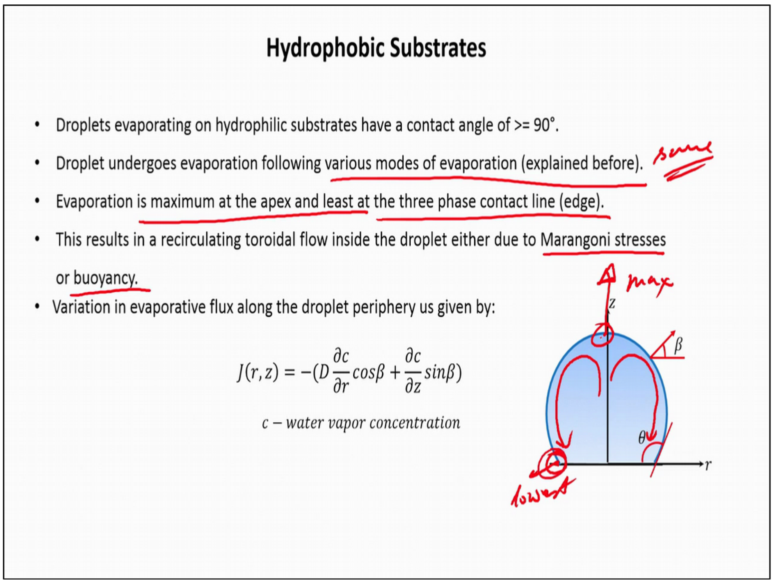

Hydrophobic Substrates

- Droplets evaporating on hydrophilic substrates have a contact angle of >= 90°.
- Droplet undergoes evaporation following various modes of evaporation (explained before). same
- Evaporation is maximum at the apex and least at the three phase contact line (edge).
- This results in a recirculating toroidal flow inside the droplet either due to Marangoni stresses or buoyancy.
- Variation in evaporative flux along the droplet periphery us given by:

$$J(r,z) = -(D\frac{\partial c}{\partial r}cos\beta + \frac{\partial c}{\partial z}sin\beta)$$

$c -$ *water vapor concentration*

Now only dedicated to hydrophobic substrates is interesting to see a few more things. Hydrophilic we said that the flow was very nice it was radially diverging outward right okay and we saw the various modes of evaporation. And we saw that the evaporation is maximum at the three-phase contact line okay.

And low at the epics however for hydrophobic droplets situation is very different right. So, it also undergoes the various modes of evaporation that is common, same okay. The incorporation however is maximum at the apex and least at the three-phase contact line. So, it is maximum here least here.

So, it is a lowest here this is a maximum here is completely reverse right. In the case of hydrophilic droplets what we had was that this was the maximum this was a minimum in this case this is the maximum and this is the minimum got it, okay. So, instead of radially outward flow okay you can guess what kind of a flow this will create.

This will create a toroidal flow a re-circulating toroidal flow like this okay. Due to either due to Marangoni stresses or due to buoyancy, let us assume that how each of this thing actually happens. So, understood this is completely different from the hydrophilic droplet, got it. In a hydrophilic droplet this was maximum that was minimum in this case it is just inverted. And it also creates a very different flow pattern that you have okay.

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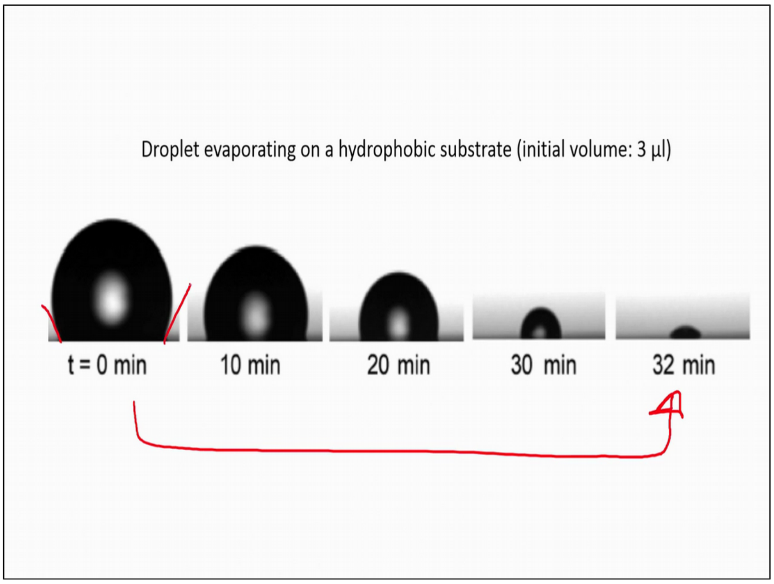

Droplet evaporating on a hydrophobic substrate (initial volume: 3 µl)

See if this is for example a sample image of a hydrophobic droplet evaporating in a hydrophobic substrate. You can see the contact angle is much greater than 90. At one point of time it does become 90 in this particular case and then it actually evaporates okay.

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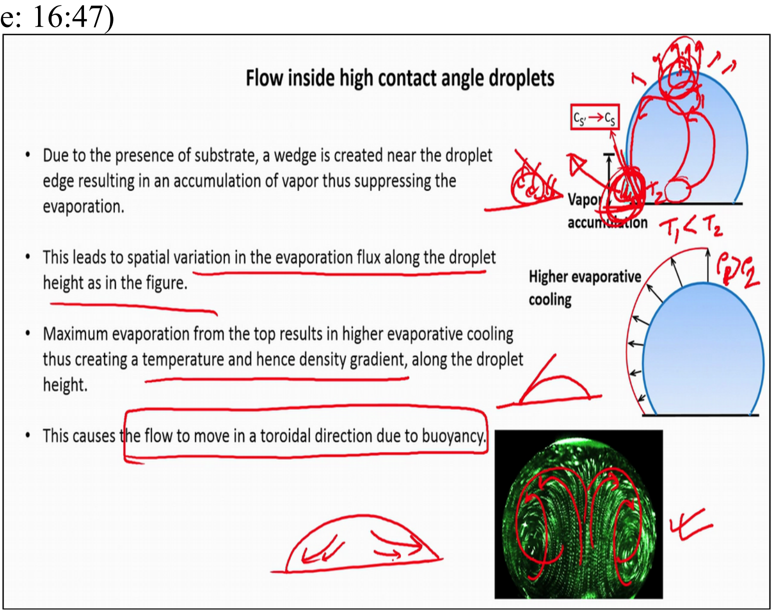

Flow inside high contact angle droplets

- Due to the presence of substrate, a wedge is created near the droplet edge resulting in an accumulation of vapor thus suppressing the evaporation.
- This leads to spatial variation in the evaporation flux along the droplet height as in the figure.
- Maximum evaporation from the top results in higher evaporative cooling thus creating a temperature and hence density gradient, along the droplet height.
- This causes the flow to move in a toroidal direction due to buoyancy.

Now why does this thing happens flow inside this high contact angle droplets okay. So, due to the presence of this substrate okay what you can see that there is a wedge-like structure acute angle wedge that is formed near the droplet three phase contact line. This is not present in the case of a hydrophilic droplet; there is no edge it is like an obtuse right.

It is basically like open, this is actually like a wedge if exactly like this it is like a wedge that is created right. What happens is that in this wedge you actually evaporate and fill this space up with water vapour right. There is a lot of water vapour at saturated condition that actually gets stored in that wedge right.

So, this water vapour is very hard to remove by diffusion, got it. So, this water vapour in this particular region this region that you see in this wedge region is due to accumulation and this accumulation is very hard to relax. As a result of that what happens is that evaporation is locally suppressed in this region right.

However evaporation in this particular region goes on because it has got no problem in actually diffusing out its vapour. Closer to the interface as you move closer to the three-phase contact line if you move there is an accumulation of vapour. There is an accumulation length scale and this accumulation lens scale prevents further evaporation from happening, got it.

So, there is a local suppression of his operation this also leads to a spatial variation and the evaporation flux with the droplet height. So, the maximum evaporation occurs from here okay and the lowest evaporation happens from here. As a result of that you create a temperature and density gradient along the droplet. Because here it is evaporating very fast here it is evaporating slowly.

So, naturally locally the temperature will be different right in both the cases right a substrate which is a droplet which is undergoing very fast evaporation goes under those local cooling right. It is locally the temperature comes down correct. Were on the other hand this is not undergoing that kind of an evaporation. So locally the temperature will be a little higher, got it, okay.

And as we know that moment this happens okay you create a density gradient of some sort which this one being a little lighter this one being a little heavier right. Because this is a little hotter this is a little cooler right. So, as a result of that you immediately create a circulating current like a buoyancy right. Buoyancy is stable; buoyancy is not there if you have hot on the top cold at the bottom right.

Here in this case what happens because there is a lot of evaporation happening over here? Locally this temperature is let us say it is T1 and this is T2, so T1 is basically marginally lower than T2, marginally right. As a result of that what happens is that if you talk about Rho2, Rho2 is marginally higher than Rho1.

Sorry Rho1 is marginally higher than Rho2 correct because of that the here it is a lighter fluid here it is a denser fluid immediately it goes and follows that recirculation pattern right. This causes the flow to go into a toroidal direction due to buoyancy as you can see in this picture it is very clearly evident that, that is what happened okay.

Now if the temperature distribution is too high for example there could be also buoyancy there can be also Marangoni related to stress okay. Marangoni related stress means that higher surface tension will actually pull the fluid right towards itself, so that can also happen in this particular case.

So, fluid can be pulled towards the top okay but in this particular case it is mostly due to the buoyancy effect that is created automatically right because of this wet structure because here the evaporation flux is low compared to that case and if you heat the droplet then situations will be very different as well okay.

So, this is a very typically very different type of flow compared to the flow that we got in the case of a hydrophilic droplet, do you see that that this is more of a re-circulating kind of a flow, this is more of a radially outward kind of a slow you see that. So, that should actually ring a bell and that should actually say that how hydrophobic droplets are very different from hydrophilic droplet and the evaporation rates are totally different okay.
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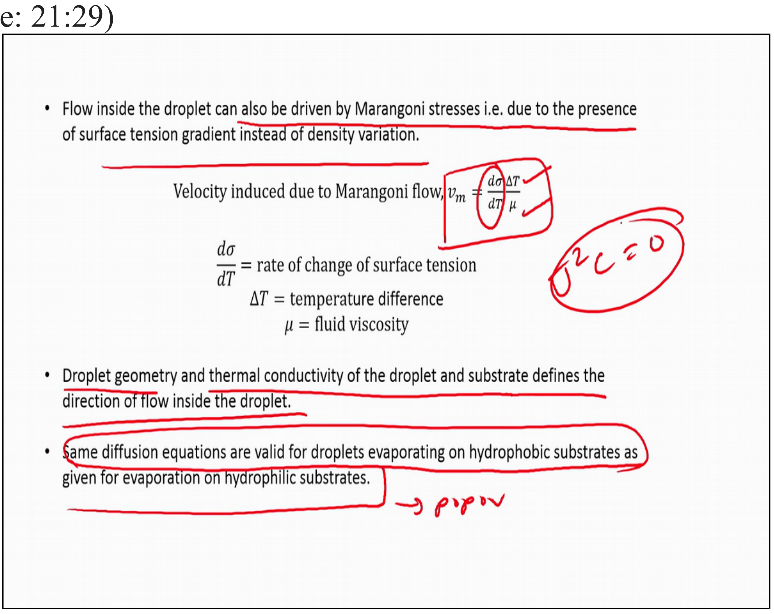

- Flow inside the droplet can also be driven by Marangoni stresses i.e. due to the presence of surface tension gradient instead of density variation.

Velocity induced due to Marangoni flow, $v_m = \frac{d\sigma}{dT}\frac{\Delta T}{\mu}$

$\frac{d\sigma}{dT}$ = rate of change of surface tension
ΔT = temperature difference
μ = fluid viscosity

$\nabla^2 c = 0$

- Droplet geometry and thermal conductivity of the droplet and substrate defines the direction of flow inside the droplet.
- Same diffusion equations are valid for droplets evaporating on hydrophobic substrates as given for evaporation on hydrophilic substrates.

→ popov

Now as I said flow inside the droplet can be also driven by Marangoni stress due to the presence of surface tension gradient instead of density variation that can also happen. For example if you heat the droplet from underneath things like that can happen okay. So, Marangoni stress that the velocity that is introduced is given by the radiation or the gradient of the surface tension with temperature into the total temperature.

And the fluid viscosity okay so the droplet geometry the thermal conductivity of the drop and the substrate defines the direction of flow, the same diffusion equations are valid for hydrophobic as well as for hydrophilic droplet. There are no changes in that and the solution is given by Popov.

But if you are interested in knowing the insight of what happens within the droplet regarding the flow. This flow field is more re-circulating and this flow field is more radially outward moving okay. So, this is the big change okay.

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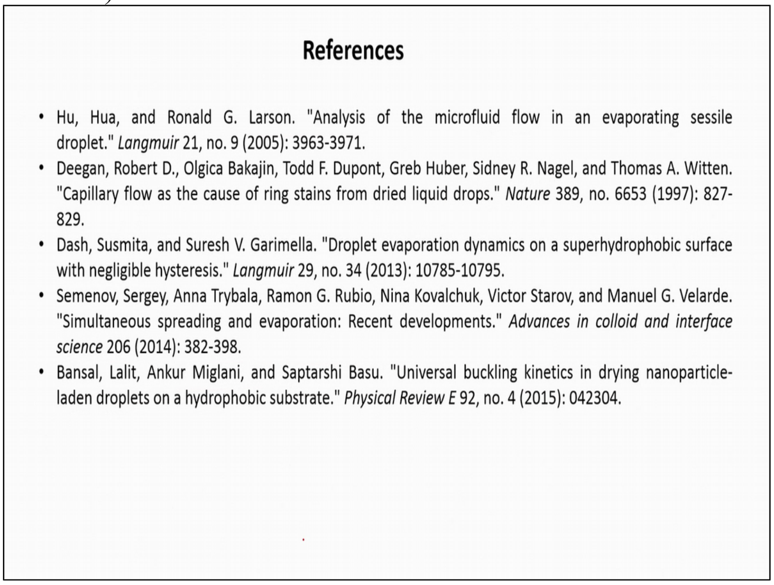

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And this is like you can study a few the papers if you have the time so including our own work there are work the seminal work that is done by Deegan which was published in nature and there has been some work done by Professor Suresh Garimella and then the Semenov's paper okay and Popov's paper you can read all those papers okay to get more insight okay into the evaporation dynamics.

So here we have what we have done we have differentiated between a hydrophobic and hydrophilic droplet. We have looked at how to find out for example the flow inside the hydrophobic droplet and the flow inside the hydrophilic droplet. Why hydrophilic droplet leads to this coffee strain type of patterns that we see.

What are the different if operational modes what are the equations that you can write for local evaporation as well as for global evaporation flux. What will be the typical velocity skcaled inside the hydrophilic droplets okay? We have also done measurements where the flow velocity inside hydrophobic droplets have been also measured is of the same order is about 10 to 12 microns per second okay.

And we have seen that how the evaporation flux varies specially along the length of the interface. So, these things are very important and this is different from a spherical droplet analysis okay. So, spherical droplet analysis though there are some similarities like for example the diffusion dominated thing if you recall.

This equation it was the same okay so it was like a steady state kind of a problem there also we said the gas phase was quasi steady and things like that. So, there are some similarities in terms of the basic governing equations. But because of the presence of the substrate there are some additional problems that it creates.

So, the modes of evaporation becomes very important the evaporation flux becomes highly anisotropic in nature okay. And that affects your particle transport your blood that blood example that we showed your coffee strain and varieties of other things mainly happens to you to this spatially inhomogeneous in opposition flux okay.

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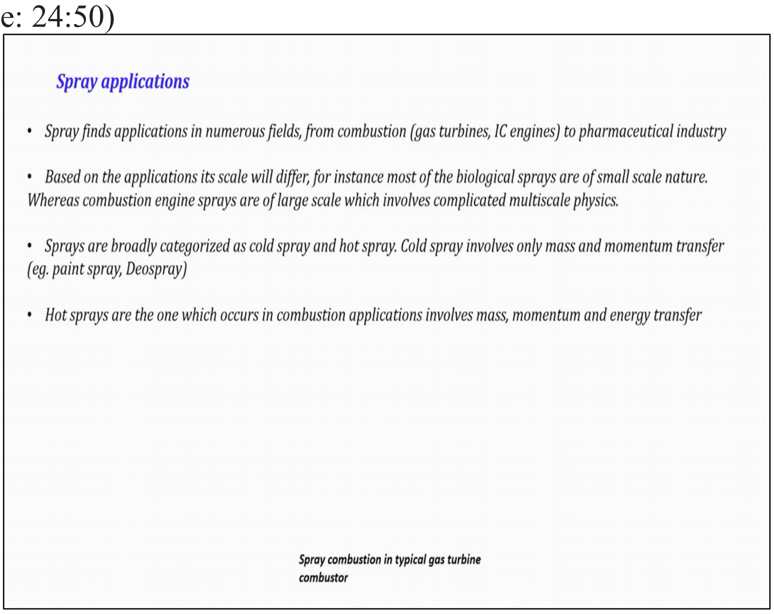

Spray applications

- *Spray finds applications in numerous fields, from combustion (gas turbines, IC engines) to pharmaceutical industry*
- *Based on the applications its scale will differ, for instance most of the biological sprays are of small scale nature. Whereas combustion engine sprays are of large scale which involves complicated multiscale physics.*
- *Sprays are broadly categorized as cold spray and hot spray. Cold spray involves only mass and momentum transfer (eg. paint spray, Deospray)*
- *Hot sprays are the one which occurs in combustion applications involves mass, momentum and energy transfer*

Spray combustion in typical gas turbine combustor

So, what so; we this is the so we will keep this. So, we have done what we are supposed to do in the case of sessile droplet of operation. Now we are going to start into one of the important topics in the case of this droplet okay. And we are going to look at now the droplets and look at how their shapes actually change okay.

So, this was all evaporation and flow where we assume that the droplet shape does not change okay drastically. It is just a shape change that happens due to evaporation. Like for example in evaporation sessile droplets is either comes down in CCR or CCA mode there is no corrugation of the interface okay.

There is no breakup of the droplet right, in the case of spherical droplet analysis also the work that we Sirignano and others. We also showed there that the droplet remains spherical nothing happens to the droplet right. It is all about the evaporation and the flow within such spherical droplets.

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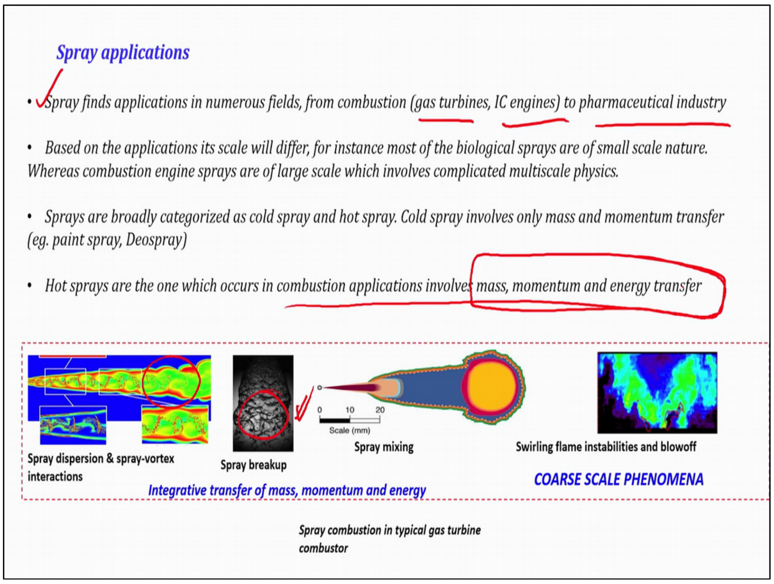

Spray applications

- Spray finds applications in numerous fields, from combustion (gas turbines, IC engines) to pharmaceutical industry
- Based on the applications its scale will differ, for instance most of the biological sprays are of small scale nature. Whereas combustion engine sprays are of large scale which involves complicated multiscale physics.
- Sprays are broadly categorized as cold spray and hot spray. Cold spray involves only mass and momentum transfer (eg. paint spray, Deospray)
- Hot sprays are the one which occurs in combustion applications involves mass, momentum and energy transfer

Spray dispersion & spray-vortex interactions

Spray breakup

Spray mixing

Swirling flame instabilities and blowoff

Integrative transfer of mass, momentum and energy

COARSE SCALE PHENOMENA

Spray combustion in typical gas turbine combustor

Now in most of the applications it is not the same anymore right. In many of the spray applications like from combustion to pharmaceutical industries once again like gas turbines combustion is gas sorry combustion is gas turbine and IC engines. We find gas turbines, IC engines to pharmaceutical industries.

We find that spray finds applications in numerous of these processes right. So in numerous processes sprays are there, sprays are basically droplets of different kind's right. So, interesting feature of a spray is that they are the droplets are not all this are spherical okay. They actually break the shattered to form smaller droplets.

They can displace the droplets can be the form of ligaments also. So, there are all kinds of dynamics that you can see if you look at closely this picture over there you can see that there are ligaments and sheets all around right okay. If you look at for example the dispersion studies of a spray if you can see that these droplets need not be spherical all the time right okay.

So, sprays are useful and we need to know, how they actually break up? How they actually atomized. So, when you put a spray inside a flow, the spray not only evaporates and evaporates as we have shown, it also breaks up into smaller pieces okay. So, it is common in the case of biological application where the sprays are usually like small scale structures that means it is more quiescent kind of spray okay.

Whereas the combustion involves sprays which are very large flow rate kind of spray which are very complicated as this diagram over here will show right. And it can be hot spray and cold spray. Cold spray is basically that you have just sprayed a fluid okay and there is mass and momentum transfer.

There can be also energy transfer but it happens at a very low temperature conditions okay. Whereas hot sprays are in combustion applications say for example where we have both mass momentum, energy transfer at a very high temperature. So, that is what hot sprays are. Combustion is mostly hot spray applications; spray drying is also a hot spray application.

So, some are cold sprays are like sprays which normally dry, naturally try like the problems that we did earlier and there can be examples where the sprays do not dry okay and I mean they do not dry at room temperature they are actually injected into a hot ambient.

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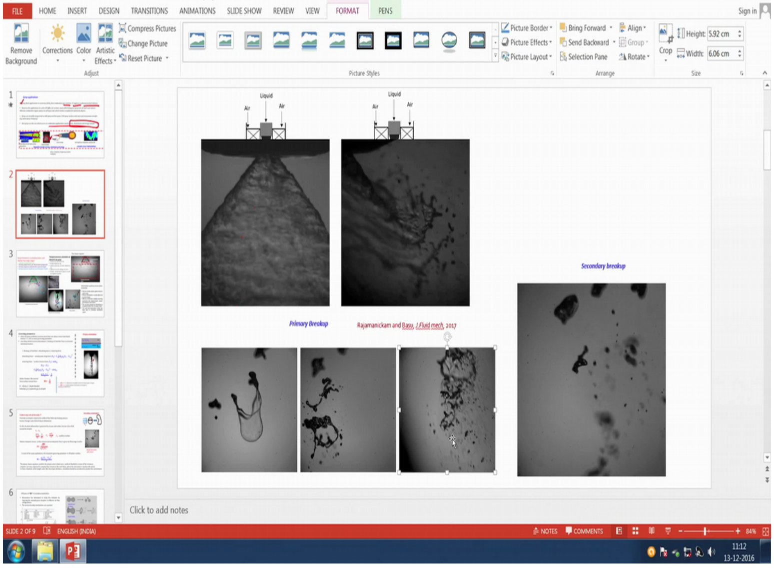

So let us look at some of the videos, if these videos play properly does not seem to play. Let us see if it if I can play it from there okay. So, this is for example a straight okay which is coming out and what we are looking at is basically not droplets anymore these are basically what we call liquid sheets.

We will come to that what is the liquid sheet okay. So, this liquid sheet is actually atomizing as we can see there are bits and pieces which are coming out of that liquid see those are basically droplets of different kind’s right. Now if we look at this particular application say for example from the liquid sheet you can see those tiny, tiny fragments that are coming out flattering and all those things.

You can see those fragments better coming out, there are, they are, these are ligaments as well as droplet. These droplets need not be of the same spherical size right okay. So, that is one thing and so if you look at those droplets very carefully you can see, does they look spherical no, right.

They are liquid there they are blobs of liquid right which actually are breaking up okay into very, very small fragments right but they are not spherical right. So, all this work that we say that it has to have spherical shape and other things. There is some inherent assumptions inside that because these are real life applications.

These are coming from the experimental data and you can clearly see that they are not spherical anymore. The smaller droplets may be spherical what we are coming out those bits and pieces that you are coming out over there, they may be spherical okay. But these major blobs of fluid they are not spherical.

You can clearly see they come in different shapes and sizes right. And there are some images like this that you see over there right where you can see this small droplets over here say for example. These droplets if you look at the cursor these droplets maybe still spherical but you can see these are ligaments okay this maybe these are long ligament okay.

And this is like a bag; it is like a bag of liquid which is actually bursting okay. These are like different shape okay. So, all I am wanting to emphasize over here is that spherical shape of a droplet it is not a given thing okay it is not given okay. So, the spherical shape of the droplet as we saw over there or in this particular application. You can clearly see from the example for the valence shading.

That they cannot be need not be spherical there are a lot of ligaments that you see right if you watch the video very close in like a movie okay you can see clearly that this is what is happening right. And this happens when you actually put it in a high-speed flow and if you look at the close up you can really clearly see that they all this droplets are no no way they are spherical.

They are doing this bag and all these types of break up right correct okay. So, that is becomes then a very important parameter over here okay so hot sprays as we saw are due to that and these are the some images which shows the displays need not be spherical.
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So, and this will be the last slide for this particular lecture. What we will show over here is that the spray formation is basically a complex process right. So, as we showed that there is usually there is a liquid sheet or a jet and this liquid sheet then breaks up and forms all these ligaments that we showed in the previous video okay.

And the big ligament then breaks up and forms numerous droplets. This parent droplet once again deforms and breaks up into dotted droplets right at a far downstream location right. So, first one where the sheet breakup happens is called the primary atomization zone right over there. This is the primary atomization zone right where the sheet is actually breaking up.

And this is called the secondary atomization zone where the droplets actually break up and droplets cannot break up without changing their shape right. They cannot remain spherical right. So, this is secondary atomization, this is primary atomization zone and there are basically; it usually involves liquid sheet, ligaments formation of parent droplets and formation of dotted droplets okay.

So, there are numerous examples like this like for example here you can clearly see a ligament that is breaking up do you see that, this is a ligament that is actually breaking on correct okay. There are all these ligaments of different kinds that you think right they are actually breaking up okay.

And once this ligament you can also see ligaments like that over here, ligaments like that over there right okay. And individual droplets can also break up okay due to this bag mode this droplet can actually break up into further droplets which will be more in the secondary atomization kind of a zone.

Whatever it is my point is very simple is that the droplet actually breaks up okay and they cannot break up without exhibiting say without exhibiting a non-spherical kind of a shape okay. And there are there are different parameters of interest over here. The droplet size the drop the dispersion the spatial uniformity the nozzle through which these droplets are coming out.

The droplet effect that means one droplet sees another droplet in its neighbourhood what does it do okay. So, primary break up will define the global structure, the primary atomization is influenced by the nozzle and there are other parameters not just the nozzles the flow field and other parameters.

Secondary atomization involves basically the flow and the droplet interaction so these are like droplets which interacts with the flow field like. This is a droplet there is a high velocity flow over it and this droplet deforms and breaks up, so that will be like secondary atomization okay.

And then this would then these droplets will undergo evaporation mixing etcetera normally the atomization process is very fast very quick compared to the evaporation process. So, you can take that evaporation only starts to happen after the drop that has substantially reduced in size. There is evaporation that continues to happen always but if you talk about the dominance of the scales atomization happens in a matter much, much earlier time okay.

For what we are going to talk about in the next hour or so in the next two lectures is basically the precursor events basically to evaporation. Evaporation would not be important we are not going to consider evaporation that much. But we are going to consider that this is the give opposition that actually the evaporation only happens after atomization is complete and you get droplets of sufficiently small sizes right.

And there this is of course a field in its own there are a lot of interaction parameters, there are a lot of evaporation mixing and all of these things happens makes it an extremely complicated subject. But we have shown some examples where it is very clear that why droplet atomization is important okay because that is what happens in real life in each and every process that we look at.

You cannot just consider the droplets which are here which are very stable does not undergo any breakup. You have to know what is happening there, there, there before you can understand what is happening here okay. So, that is very important so in the next class what we are going to do is that we are going to look at the atomization process in a little bit more details.

And study a couple of models which is basically called the tab model and the wave breakup model. And we will see that how the droplets actually deforms, atomises. We are not going to do primary atomization that much we will you do a little bit but we are not going to do because that itself is very complicated and it is not properly resolved but we are going to give you a heuristic understanding of what is going on, thank you.