Heat Transfer And Combustion in Multiphase Systems
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Lecture 32
Atomization principles and governing parameters

Welcome to today's lecture, last time what we said we started discussing about sprays and dropped it breakup model.

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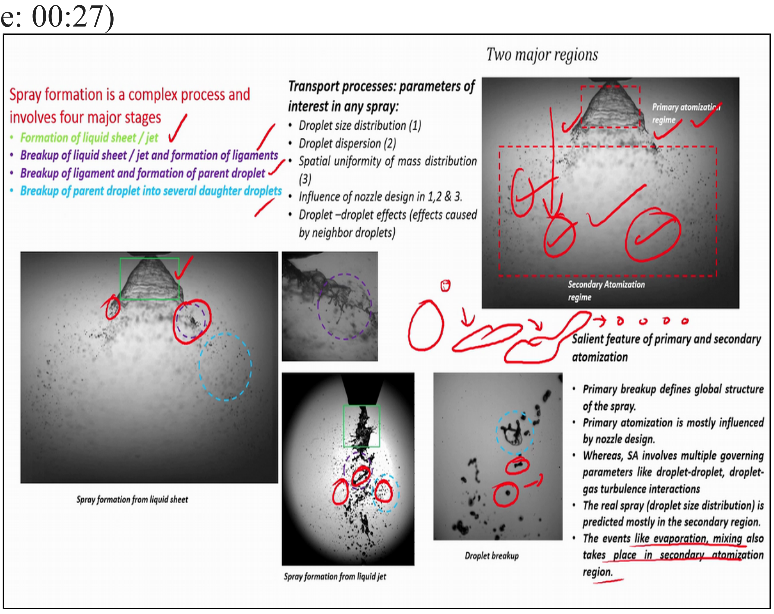

Two major regions

Spray formation is a complex process and involves four major stages
- Formation of liquid sheet / jet
- Breakup of liquid sheet / jet and formation of ligaments
- Breakup of ligament and formation of parent droplet
- Breakup of parent droplet into several daughter droplets

Transport processes: parameters of interest in any spray:
- *Droplet size distribution (1)*
- *Droplet dispersion (2)*
- *Spatial uniformity of mass distribution (3)*
- *Influence of nozzle design in 1,2 & 3.*
- *Droplet –droplet effects (effects caused by neighbor droplets)*

Salient feature of primary and secondary atomization
- ***Primary breakup defines global structure of the spray.***
- ***Primary atomization is mostly influenced by nozzle design.***
- ***Whereas, SA involves multiple governing parameters like droplet-droplet, droplet-gas turbulence interactions***
- ***The real spray (droplet size distribution) is predicted mostly in the secondary region.***
- ***The events like evaporation, mixing also takes place in secondary atomization region.***

So, in this particular presentation we are going to show that we already covered a little bit of this. We said that usually it is a complex process there is usually a liquid sheet which is very much like that, that you see over there. This liquid sheet subsequently breaks up okay and forms ligaments. Ligaments like structures we can see there right.

These would be kind of ligamentish kind of structures right there will be also ligament structures there if you zoom in right. So, this ligaments first form and then these ligaments what happens is that this ligament then further undergoes further break up and form smaller droplets okay.

So, the smaller droplets will be like that those kind of droplets that easy right these. Now these droplets depending on their on the load that means depending on the aerodynamic breakup like aerodynamic forces or the force or whatever forces that you are applying this can undergoes further break up into even smaller droplets okay.

So, usually the spray zone is divided into a primary atomization zone which is very close to a nozzle where the liquid sheet breaks up into ligaments and some things like that. Then there is a secondary atomization zone which is further downstream of the nozzle right where we actually get these smaller droplets undergoing further break up okay.

So, that is the; I mean that those are the processes. Now in between these droplets starts to interact with the flow, the flow has an effect on the droplet dispersion. How the droplets are actually spread? How much the droplets actually operate also. So, all those things start to happen okay when you actually have a spray injected into a high velocity fluid high velocity gas phase flow field usually.

Now events like evaporation and mixing happens, a little later okay that is in this zone it starts to happen it does not really happen there because this process is very fast. It starts to happen in this zone, starts to become important in this zone because evaporation as we already learnt is a very slow process right.

And these processes are very fast they can be microseconds and that order right the break-up process can be very, very fast itself okay. So, these nice pictures actually shows that how the droplets actually break up and they are not spherical that is what we told that, they are like this or they are like that all kinds of shapes okay.

Obviously all these shapes are unstable right because as you know the droplet a liquid glob always tries to be spherical no matter what right. So, in that process it starts to split okay it generates two smaller and smaller droplets. As it becomes very small surface tension starts to become very, very important and those droplets becomes very stable okay.

So, when in operation and mixing takes place the droplet can be considered spherical. So, the analysis all those analysis that we did earlier on droplet evaporation holds but not for very large droplets right because large droplets are unstable inherently okay especially in a high-speed flow it depends on the flow conditions it is not like that they are unstable by nature okay it is like it depends on the flow okay.

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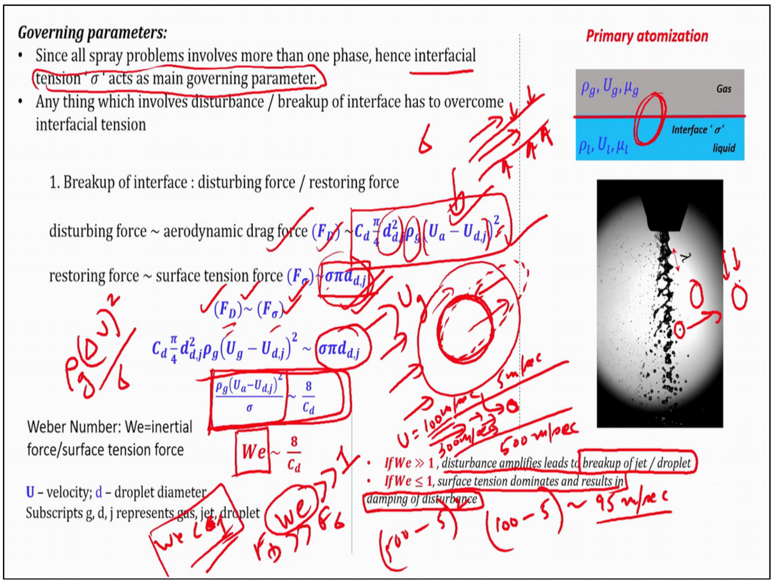

Governing parameters:

- Since all spray problems involves more than one phase, hence interfacial tension ' σ ' acts as main governing parameter.
- Any thing which involves disturbance / breakup of interface has to overcome interfacial tension

1. Breakup of interface : disturbing force / restoring force

disturbing force ~ aerodynamic drag force $(F_D) \sim C_d \frac{\pi}{4} d_{d,j}^2 \rho_g (U_a - U_{d,j})^2$

restoring force ~ surface tension force $(F_\sigma) \sim \sigma \pi d_{d,j}$

$$(F_D) \sim (F_\sigma)$$

$$C_d \frac{\pi}{4} d_{d,j}^2 \rho_g (U_g - U_{d,j})^2 \sim \sigma \pi d_{d,j}$$

$$\frac{\rho_g (U_a - U_{d,j})^2}{\sigma} \sim \frac{8}{C_d}$$

Weber Number: We=inertial force/surface tension force

$$We \sim \frac{8}{C_d}$$

U – velocity; d – droplet diameter
Subscripts g, d, j represents gas, jet, droplet

Primary atomization

- *If $We \gg 1$, disturbance amplifies leads to breakup of jet / droplet*
- *If $We \leq 1$, surface tension dominates and results in damping of disturbance*

So, let us look at a governing parameter since you see that all the spray problems actually involves interfacial tension right. So, that should be the main governing parameter. So, Sigma which is the surface tension has to come in some way right. So, let us look when you actually have a droplet or an interface okay there are two types of forces that usually acts on an interface right.

So, if this is a droplet let us take the example of a droplet there is a very high velocity fluid gas phase flow heat that is coming and hitting the droplet. So, what will happen is that this will give rise to a force around the droplet right. So, that force is nothing but the aerodynamic drag. Now aerodynamic drag is given by Cd.

Cd is the drag coefficient, this is the diameter of the droplet, this is the gas phase density and this is a relative velocity between the droplet and the gas phase right. So, this is the relative velocity so the droplet maybe also moving the gas is also moving right. It is a relative velocity between the two that actually determines that what is the drag force?

As you can see if say for example we have this duct in which there is a very high-speed flow. So, this U is of the order of 100 meter per second it can be much higher than this okay. And the droplets are say injected at say five meter per second right. So, this is a droplet which all of a sudden sees a 100 - 5 something like a 95 meter per second flow filed right.

If I am a droplet all of a sudden I see that I am hit by a 95 meter per second and 95 meters per second is very high okay velocity stream okay. So, it is almost like you are in your home you finally go out understand there is a hurricane going on and you suddenly feel that there is a blast of wind that is hitting you right.

Now that is nothing but the aerodynamic force that the droplet experience as it gets exposed to a high velocity fluid flow right. So, as you can see larger the value of this, this is square you remember, so if larger the value of this more is aerodynamic force simple right. So, if you inject, if this flow velocity instead of 100;

Now it becomes like say 300 meter per second okay sonic condition or if it goes to say 500 meters per second hypersonics or supersonic conditions okay what you will have this droplet now we will feel 500 - 5 square okay that will be the value of this guy right. So, that is an abnormal flow velocity.

Now what is the restoring force that is for this force tries to deform the droplet. If you are a droplet you will now start to be deformed in that particular fashion right. You will no longer remain spherical okay. But the droplet has got alai is basically its surface tension right. Surface tension always tries to restore you want to stretch it.

It tries to restore you back right. So, what will be the surface tension force that is given by Sigma into the perimeter of the droplet, right. So, that is the surface tension force that because remember perfect tension is per Newton per meter right. So, that is a surface tension force that is essentially restoring in nature.

That means the air tries to or the aerodynamics tries to deform the droplet, surface tension tries to restore it back into this particular shape into this spherical shape as we know spherical shape is the most stable shape we already did that okay. Now in the limiting case when both these forces are the same right okay.

You can equate the two that is the drag force is equal to the surface tension force. So, basically you equate the two and you can get an expression like this right. Now this expression if you look on the left hand side of the expression and the right hand side both are non dimensional in nature right okay.

So, if we look at the left hand side of this particular expression you will find that it is our quantity it is a peculiar quantity right. It is a peculiar quantity which is basically given as a Rho of the gas phase then this is a relative velocity square right divided the surface tension. So, this quantity actually implies that this is a ratio of the inertial force.

Inertial force is basically the aerodynamic force divided by the surface tension force that is exactly what it is because we have equated these two right. So, divide one by the other basically gives you the inertial force divided by surface tension force right. So, this particular quantity has got a name it is called the Weber number or we write it as We, right.

So, what is the Weber number actually designate, so if the Weber number value is very high okay say it is much, much greater than 1, what does that imply that implies that your inertial forces that means the aerodynamic forces are much, much more than your surface tension forces right okay.

So, that means your FD is basically much, much greater than your F Sigma right. As a result the droplet will distort, it will distort it will no longer remain spherical. Whereas if your Weber number is much, much less than 1 or less than 1 let us not say much, much less than 1, let us say that it is less than 1 okay.

In that particular case you imply that your surface tension force okay is actually winning over the aerodynamic force this can happen when you are injecting the droplets say into a very low speed, low Speed say cross flow okay. In that particular case okay we imply that the droplet will not be deformed okay.

The deformation of the droplet will not take place. So, this quantity Weber number basically becomes a very interesting parameter. It says when Weber number is greater than one disturbance amplified basically leading to breakup of the droplet or in other cases if this says this is a jet. So, we have done it for a droplet it could be also a jet right which is moving at a velocity there is a difference in velocity between the two.

So, there will be shared at this created at this interface right okay and that will also need to break up in a very similar way. So, they are also you can define Weber number okay. If Weber number is less than equal to one surface tension dominate and result in the damping of the disturbance that means the droplet will not break up or the jet will not break up.

So, Weber number becomes a very important parameter it is basically the ratio of the inertial force by the surface tension force like Reynolds number was inertial by viscous Weber number is inertial by surface tension because these are the two quantities that are relevant in the current situation right okay.

So, that is an interesting observation as you can see so the Weber number can come here in this kind of a situation or it can come in the case of a droplet. So, you take one of these droplet out and you can see what is the flow field around it right, okay.

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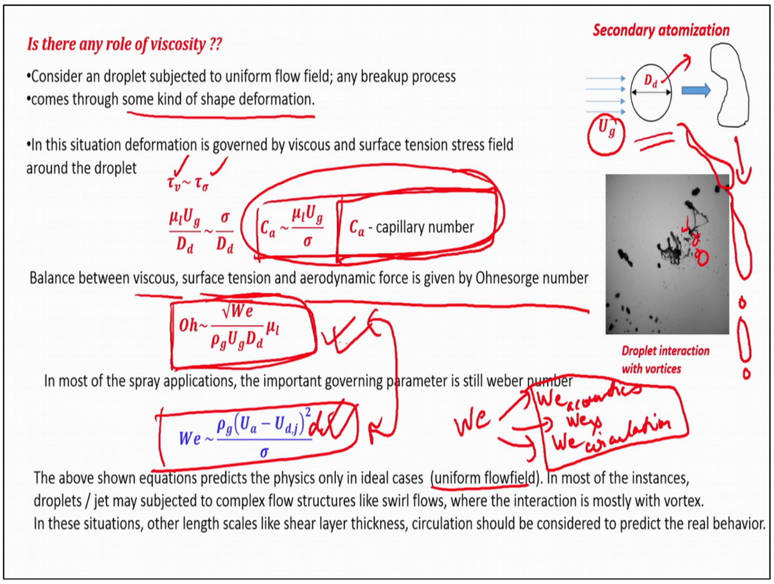

Is there any role of viscosity ??

Secondary atomization

- Consider an droplet subjected to uniform flow field; any breakup process
- comes through some kind of shape deformation.

- In this situation deformation is governed by viscous and surface tension stress field around the droplet

$\tau_v \sim \tau_\sigma$

$$\frac{\mu_l U_g}{D_d} \sim \frac{\sigma}{D_d} \qquad C_a \sim \frac{\mu_l U_g}{\sigma} \qquad C_a \text{ - capillary number}$$

Balance between viscous, surface tension and aerodynamic force is given by Ohnesorge number

$$Oh \sim \frac{\sqrt{We}}{\rho_g U_g D_d}\mu_l$$

In most of the spray applications, the important governing parameter is still weber number

$$We \sim \frac{\rho_g (U_a - U_{d,j})^2 dl}{\sigma}$$

$We \rightarrow We_{acoustics},\ We_{exp},\ We_{circulation}$

The above shown equations predicts the physics only in ideal cases (uniform flowfield). In most of the instances, droplets / jet may subjected to complex flow structures like swirl flows, where the interaction is mostly with vortex.
In these situations, other length scales like shear layer thickness, circulation should be considered to predict the real behavior.

So, what is role of viscosity now we have said that it is inertial by surface tension, right, essential, right. We have not said anything about the viscous force at all. Now you know that the break-up process is not an instantaneous process right. So, you have a droplet which is facing this gas phase flow field right that is what we covered.

This first deforms right the droplet will first deform it will deform more and more and then it will break up right. So, it will it will be several stages may next stage it will be like this, after that it will be like this, then after that small droplet may come out from both sides right there is a process right. It is not like that this immediately breaks up okay.

There is a finite time that is required it may be short time, very short time. But that time is actually legally required. So, if we look at this cartoon over here this will also tell you the same story that there is stretching a lot of stretching that happens right. Then there is end from the endpoints the droplet starts to they basically be ejected right.

So, my point of view over here is very simple that there is for this kind of secondary atomization process because it deals with a droplet right. There is a finite time that is required and that invariably involves some kind of a shape deformation right. Now whenever there is a deformation of shape okay. See both the viscosity as well as the surface tension tries to restore it back okay.

Viscosity tries to damp out that effect okay tries to damp out that effect okay. So, when we compare say for example the viscous and the surface tension role okay. We get something like a capillary number; it is called a capillary number once again a non-dimensional number okay. It is a ratio of basically nothing but the viscous force to the surface tension right okay.

So, the capillary number is very, very low right, if the capillary number for porous media and other things okay the capillary number becomes very important it also becomes important you have to know the relative dominance between viscous and surface tension forces right, okay. Capillary number much, much greater than 1 and much, much less than 1 this kind of scenarios can happen right.

Normally they are very small number to begin with okay but if you want to not I mean this is between the family essentially right. It between viscosity and surface tension what they are actually doing to restore the droplet back. But balance between viscous, surface tension and aerodynamic force all three combined is given by a number called the Ohnesorge.

Ohnesorge number includes the effect of surface tension, viscosity as well as aerodynamic force okay. So, this is the number and this is one of the most important number that you will ever get right. So, Ohnesorge number determines whether viscous dissipation or viscous effect on the break-up process is dominant or not.

In many of the cases we will find it is not but okay in some cases there will be a lot of roll this Ohnesorge a number will actually play okay. Now this is for a uniform flow field the Weber number. The Weber number is very difficult to define when you actually have a fluctuating flow field or you have a flow field which is more complicated.

So, there can be variations of Weber number for example when acoustics is important you can define something like a Weber number acoustics okay. You can define something like a Weber number based on circulation okay. You can define a Weber number based on some other parameters whatever is it can be if there are other types of forces that are present.

So, you can define a Weber number based on that I would call that Weber number X right. So, Weber number in itself okay just means a quantity which says what is the relative importance of? What about the force that you are dealing with? Whether it is aerodynamic? What is the driven? Whatever it is right compared to the surface tension.

So, the lower part that is the denominator always remains surface tension okay it is a force which actually changes right. So, do not think that Weber number is just this. This is the most common definition of Weber number okay or there can be other definitions also right, okay. Ohnesorge number and Weber number are the two main parameters that you will ever be concerned within in your, in the course of this particular study and beyond right.

Sorry, so, in a the Weber number I am sorry here of course there is a d which was missing right because this one of the d cancels the other day actually remains okay. So, the Weber number comes here with a d okay. So, there is; that is the length scale I am sorry about that. So the Weber number here is where d that is the definition of what about number okay.

So, that makes me non dimensional, d basically, whatever is a length scale here is the length scale of the droplet okay. So, that is the Weber number definition but anyway it is a non dimensional number that is the Ohnesorge number and this is Weber number okay.

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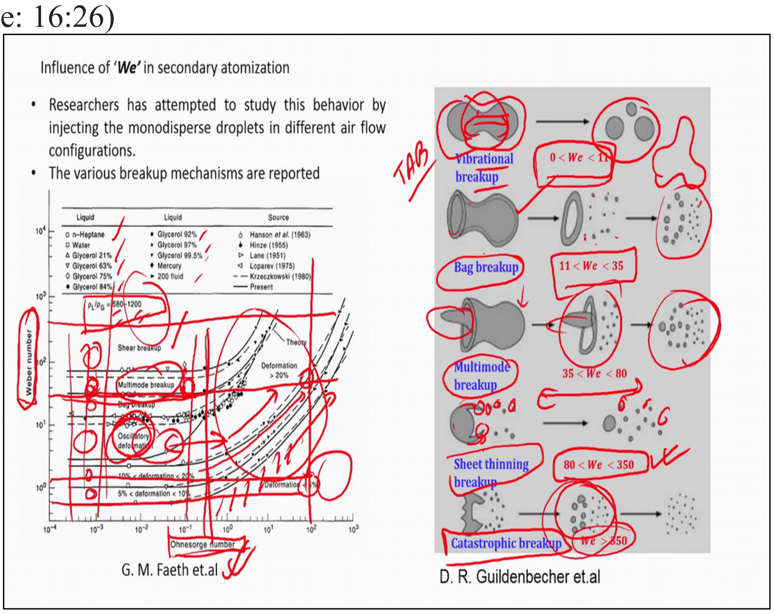

Influence of '***We***' in secondary atomization

- Researchers has attempted to study this behavior by injecting the monodisperse droplets in different air flow configurations.
- The various breakup mechanisms are reported

G. M. Faeth et.al

D. R. Guildenbecher et.al

Now the influence of Weber number on secondary atomization has been a well-studied problem okay and there has been some phenomenally great work that has been done. One of the great papers has been by Jerry Faeth okay and there he actually showed that if you plot the Weber number versus the Ohnesorge number.

Remember look at the values Ohnesorge number is usually starts very low and goes very high that will discuss effects when it becomes very important okay. You see that there are several zones and this is the density ratio has been maintained between 580 to 1200 okay. So, 1000 will be like for water there are fluides which can go a little below and a little higher right.

So, that is the density ratios that we are dealing with and they have done it for all kinds of liquids like n-heptane, water or glycerol as you know is very viscous fluid okay, very, very viscous okay, then there are all other kinds of fluids that has been attempted okay, glycerol 92% makes the fluid very viscous basically okay.

Now if you look at this particular problem now this Weber number versus Ohnesorge number space okay there are several regimes that are available in this particular space. Say for example when you actually have a very low Ohnesorge number okay you say in this zone, let me draw a line through it like that right, okay.

What you go is that you go from this domain which is like deformation is very small that means a droplet deformation is very small progressively goes higher. Because you know that the Weber number is increasing right so naturally it will go high. Then there is oscillatory deformation that means the droplet will start to oscillate and shows shape deformations.

Then we would see some varieties of breakup things like bag, multi mode and shear. So, this is across this line right. As you progressively go through some a little bit higher Ohnesorge number you basically get the same thing because you see that this space is not changing that much right. Across the board you see the same thing right.

So, for that for two orders higher Ohnesorge number you do not see a difference in the breakup mode right for the same Weber number, if I just cross the same Weber number and that is very high, this is not very high it is about fifty okay. You see that you still fall within that multimode kind of a breakup right.

But however this curve starts to move upward if you look at the slope as we go to very high Ohnesorge number right. So, that means now if I go to this particular line what do you see over here. If I now take the same Weber number okay you will find that the deformation will fall somewhere here right that means there is a smaller amount of deformation.

Because this is that less than 20% deformation line right, okay. So, you can see that progressively it becomes harder to break the droplets. If a droplet is undergoing multimode breakup right it is very difficult to achieve multimode break up okay when the viscosity is very high when Ohnesorge number is very high, got it, clear.

So, Ohnesorge e number as you can see rightly its scales with the Mu l right okay. There is a Weber number component over here as well okay. But what it generally implies is that this zone as you can see this gets expanded right. So, for the same whether number you where you are getting like less than 2; greater than 10% deformation.

Now you are getting less than 5% deformation understood it becomes progressively harder to basically is the same thing okay in a particular mode, so this curve. But the interesting part is that up to a certain regime up to here say for example right which is very close to something like .5 okay.

It does not matter whatever is Ohnesorge number value it still shows break up in the same way okay because those lines are absolutely flat right. Of course there is some oscillatory response curve which actually varies a little bit but you can see that there is this zone, big zone where this Ohnesorge number does n ot seem to have much of an influence.

But it starts to have a lot of influence in the later part from the upward swing of the curve that you see you over there okay. Now we have said that there are different modes of breakup like multi more oscillatory this and that okay. So, one of the modes that we are going to look at is the vibrational or the oscillatory mode of the break up this happens for a Weber number range of about 10 to actually 11 okay.

So, 10 to 11 it is basically falls in this particular range so to say right. So, in that particular range what happens is that the droplet undergoes this almost single mode of breakup. You know what a single mode of breakup is; I mean the droplet can show this kind of modes also right. Single mode it like that it is like across one degree of freedom.

It is basically oscillatory in a particular direction. It is like one degree of freedom spring-mass system. So, it is basically being stretched and so it just basically goes that way and then it comes back to form the spherical shape right. So, this mode of breakup is basically called vibrational breakup and we are going to see when we do the tab model that what does vibrational mode of breakup is.

There is something called a bag breakup that means you can see that the droplet becomes like a pouch right and then it is basically inflates like a spau, like a pouch okay like a balloon right. And then it kind of atomisers from the rim and you get all this smaller droplet sizes this happens that the progressively higher Weber number okay.

And then this multimode break up that you see over there is this okay. So, you have a protrusion coming out, it is similar like a bag then you have a protrusion and then it breaks up into this smaller droplets okay. Then shear thinning type of a breakup, shear thinning breakup means from the side of the sheet okay from the deformed sheet okay.

This is like a sheet okay it is like a sheet if you stretch a balloon it is like that; like the stretched balloon and from this edge you start having this multiple droplets being injected okay. So, that is like a shear thinning type of a breakup happens for very large values of Weber number.

Then catastrophic atomization happens when there is like no random order. It is a randomized kind of a process the breakup is so valid right that it basically breaks up. There is no fixed pattern in that like this has got a particular sequence of events first it inflates then there is this protruding ligament and then it breaks up okay.

Here it first thin’s along the sides and then the side starts to atomize, so there is a process. There is a certain time a sequence history right. This actually atomisers like it is all so sudden it is like violent atomization happens for very high Weber number values over there right, very high Weber number values is corresponds to actually this kind of region right over there, like about 350 okay.

So, this is about 100 that is about 1000, so 350 will be anywhere up this of this line okay. But once again viscous if you have a lot of viscosity in your system right that mode may be very hard to achieve right. You try to atomize honey, honey is highly viscous right try to atomize it and see what happens okay.

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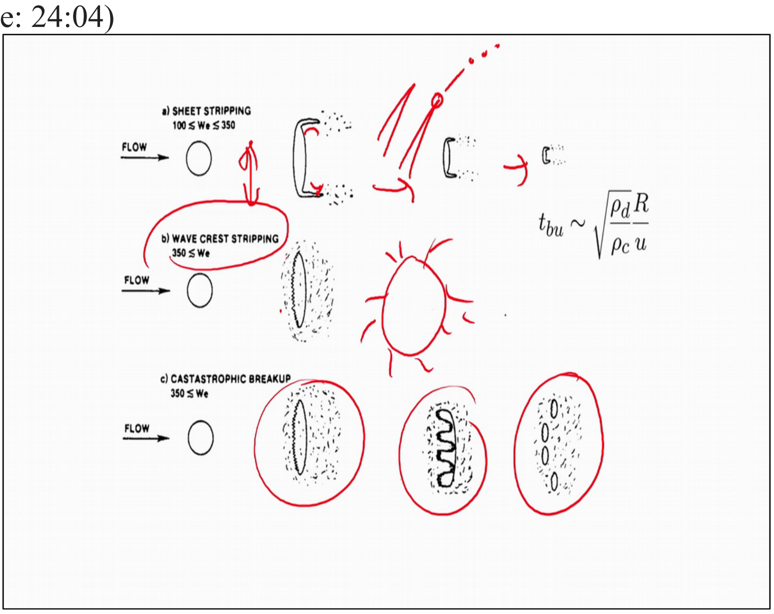

$$t_{bu} \sim \sqrt{\frac{\rho_d}{\rho_c}}\frac{R}{u}$$

So, just to finish before we finish this particular part of the lecture, we see that vibrational mode of breakup happens like this. So, there is a nice spherical droplet, it just deforms like this. It is a single mode and then it used to generate two dotters. And this might undergo this cascade once again okay.

So, this might undergo the same thing and break up into two more right this can continue okay till you get the Weber number actually less than about 5 or 6 okay once you get that in that range then this droplet becomes very stable right. Then the back type of break up you can see that this is the back growth.

So initially it becomes like a disc okay. So, at the center of the disc there is a lot of pressure right. So, if you have a disc right it is like a liquid disc remember and at the center if there is a lot of pressure then this liquid disc actually inflates like a balloon okay. So, this is the balloon made of water or whatever fluid that you are concerned with okay.

This sheet actually gets stretched and stretched and stretched and stretched till it becomes very thin at the top right and they did burst. It is like a balloon bursting, if you inflate it too much you try inflating a balloon and pumping lot and lot and lot and lot of air. What will happen at the end but the balloon just burst right.

We get this very fine droplets that are coming out of this okay. And the time scale of this breakup is given where we will come to that but what that actually means okay. You would not have any idea that one would means exactly okay. This is also very similar but there is that protrusion that is that protrusion of the ligament like that actually creates this kind of small sheet this kind of small droplets okay.

As we already talked about shear stripping we saw that this also becomes like a flat disk kind of a thing with two protruding ligaments which is very through. These are very sharp okay, so from these points the droplet starts to come out okay. So, there are mechanisms and this continues you can see this is like a cascade this continues okay.

So, catastrophic as you could see the catastrophic is like that there can be a lot of events like this. There are something like web crest stripping which is very much similar to this okay but it does not happen exactly in that way. But you do have a disc which basically perforates which would be basically strips from the sides okay.

So, that is also can happen, all this happens because the flow creates a lot of instabilities along the surface okay. So, these are the different break up this have got phenomenology of break up and then you see all this breakup times are also given there. So, in the next class what we are going to do, we are going to look at the first of the models okay and see that what that actually does okay, thank you.
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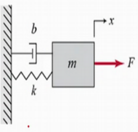
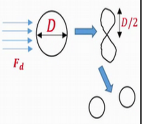
Taylor analogy breakup (TAB) model [PJ O'Rourke, AA Amsden – 1987]

- Relates oscillating and distorting droplet with ' *spring mas system* '; 1 DOF system
- Predicts when the aerodynamically disturbed droplet likely to breakup.
- The resulting droplet size can be computed from conservation of droplet energy
- Unlike wave model, TAB is widely used model in droplet level information (i.e. secondary atomization).





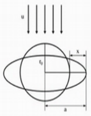
Analogy:

- ❖ *Spring restoring force → droplet surface tension force*
- ❖ *External force on spring → aerodynamic drag force*
- ❖ *Damping force → viscos force*

The general eqn. for damped harmonic oscillator can be written as,

$$m\ddot{x} = F - k_s x - d\dot{x}, \quad \rightarrow 1$$

$$\frac{F}{m} = C_F \frac{\rho_g u^2}{\rho_l r}, \quad \frac{k_s}{m} = C_k \frac{\sigma}{\rho_l r^3}, \quad \frac{d}{m} = C_d \frac{\mu_l}{\rho_l r^2} \quad \rightarrow 2$$



Min wook lee et.al

- k_s - *surface tension*
- d-*viscos force*
- F-*aerodynamic drag*
- C_F, C_k, C_d – *respective drag coefficients*
- r – initial droplet radius