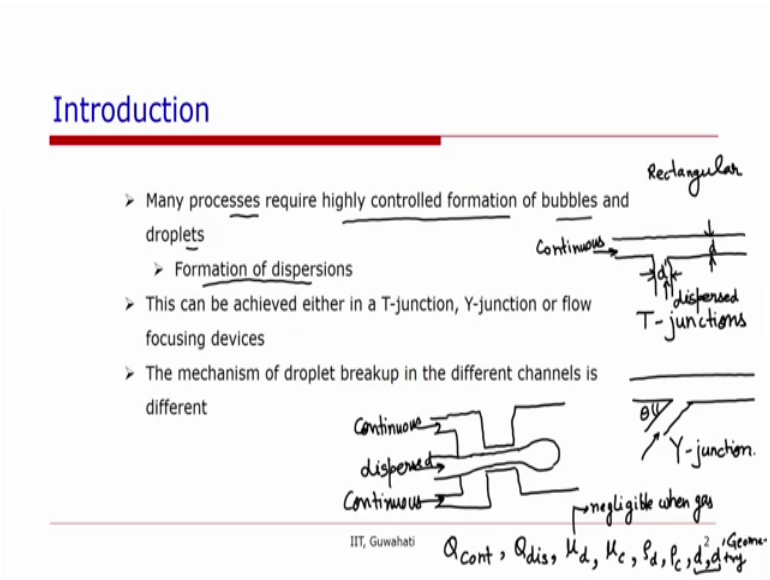
Multiphase Microfluidics
Dr. Raghvendra Gupta
Department of Chemical Engineering
Indian Institute of Technology, Guwahati

Lecture – 02
Bubble and droplet generation

Hello, so the main advantage of microfluidics specially, for applications in analytical chemistry, biotechnology and um chemical processing. It is stems from the fact, that one can control the size of bubbles or droplets precisely so, as to be able to create mono dispersed bubbles or mono dispersed droplets, emulsion etcetera for a number of applications and they can have a very precise control over the processes and can control and manipulate the interfaces.

So, in order to be able to do that one needs to understand the mechanisms of the formation of the droplets or bubbles. So, if one look at the literature the experiments that have been performed in micro fluidics or the applications that have been developed, there is lot of work that has gone through in understanding the formation of bubble and droplets. So, in this lecture we will try to review some of the droplet formation and bubble formation mechanisms and what are the factors that may affect? Them what are the different regimes that may exist during the formation of droplets?

(Refer Slide Time: 02:09)



So, as I said that many a processes that are relevant to micro fluidics They required very highly controlled formation of interfaces that is bubbles and droplets one example is formation of dispersions. Now, this can be achieved or this has been achieved by the design of the channels. So, as you will see that number of channels that are of relevance in micro fluidics. They are rectangular in nature and this is achieved by say T junctions.

So, in the T junctions the continuous phase which is generally a liquid comes from the steady stream. And the dispersed phase enters from the um and the size of these 2 channels d. And let us say d does they may or may not be same; the channel depth may or may not be a same.

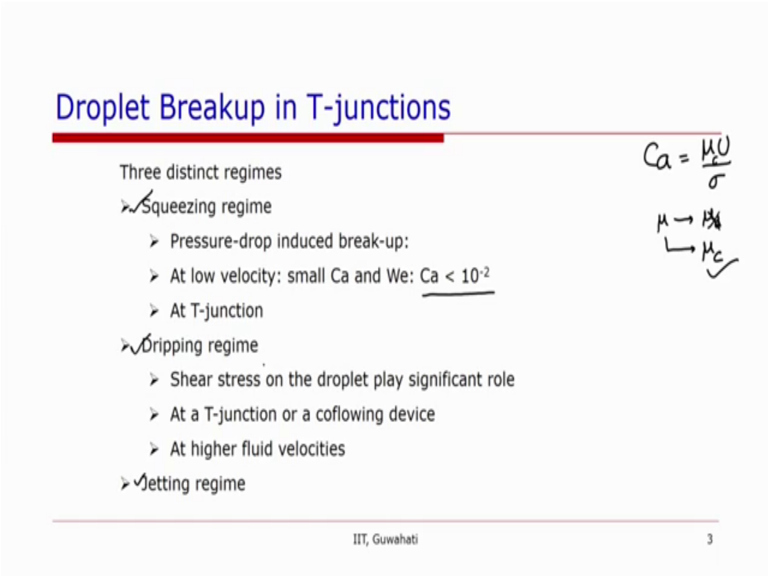
As you might have seen or might realize that a number of applications especially, because of the each in manufacturing number of applications in microfluidics the channels are rectangular or square in nature. So, most of these channels are rectangular or square. So, one of the configuration that is often used is T junction a variation of T junction is say Y junctions and this angle theta between the 2 channels might vary. So, this is Y junction.

And another approach that has been used to generate flow is known as flow focusing device. So, for example, dispersed phase comes from the center and the continuous phase from the two sides and a neck formation can happen in that will may the bubble may generate. So, these are 2 different configurations, there are actually 3. But, we can consider Y junction to be a variation of T junction where the angle between the 2 channels is not 90 degree, but an angle theta. So, the mechanism of droplet break up or the bubble break up in different channels which expected to different on it has been observed to be different.

Now, there are a number of factors that may affect the process the droplet may break up. First of all, that it may depend on the flow rates in the Q of continuous phase and Q of dispersed phase. It may also depend upon the viscosity of the dispersed phase and viscosity of the continuous phase. Now, viscosity of the dispersed phase if it is gas bubbles then, the viscosity of the dispersed phase can be negligible. So, it when gas right; negligible, it may also depend rho d and rho c, but generally not observed to depend on such parameters it may also depend on d, d dash and other geometrical parameters channel geometry. So, we can say.

Now, let us look at the droplet breakup in these different channels.

(Refer Slide Time: 07:44)

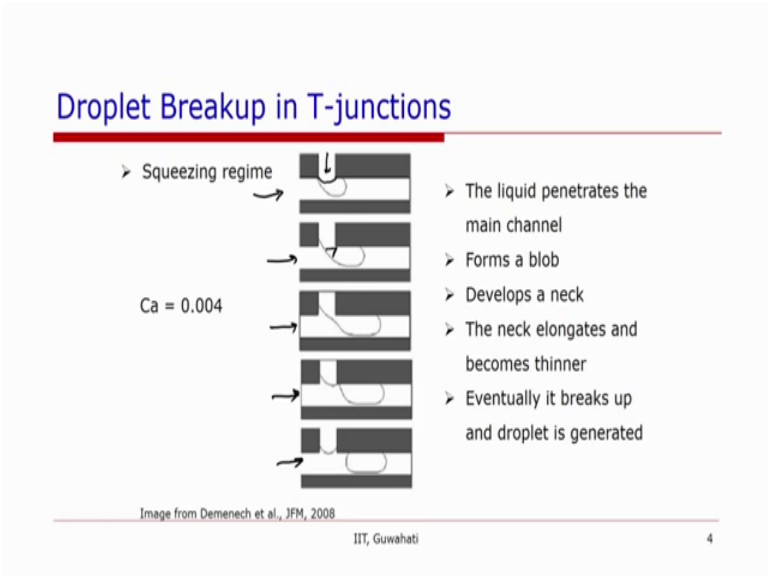


First we will look at droplet breakup in T junctions and in T junctions, it has been observed that depending on the velocity of the liquid or the viscosity of liquid different flow regimes or different mechanisms are observed. For example, so, this can be grouped together in capillary number, the capillary number is mu U over sigma. So, the at low velocities the capillary number is expected to be small for water, for very highly viscous fluids one might see that the capillary number is large for highly viscous liquids.

So, there are 3 distinct regimes that has been observed one is squeezing regime, then the dripping regime and then jetting regime. So, in this squeezing regime it is observed at the smallest capillary numbers. So, the capillary number less than 0.01 or 10 to the power minus 2; you might want to clarify what is this mu? Mu is mu dispersed or mu continuous. So, the mu dispersed is not so significant here. It is mu continuous which is used in the definition of capillary number.

So, at low values of capillary number the squeezing regime is observed; the dripping regime, it is determined by the shear stress or by the interplay of the shear stress and the interfacial junction, the balance of these 2 force will determine the size of the bubble. And in the jetting regime, what one gets is a long jet of the 2-continuous fluid. So, the thickness of jet or thickness of this thread is determined by the viscosity ratio of the 2 fluids.

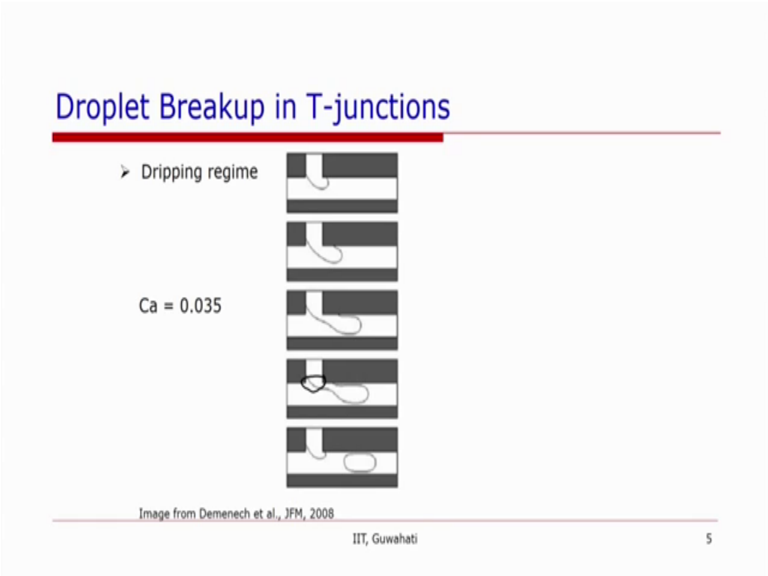
(Refer Slide Time: 10:23)



So, let us look at the squeezing regime the squeezing regime, it can be described in a number of the steps. So, in the first step, as the liquid enters from the T junction and it starts forming a neck or slowly this develops because the flow is from left to right in these cases. And as the droplet enters, it grows in size. Once it grows in size, the necking occurs or this interface the size of this interface or this distance keep decreasing and eventually the droplet break up occurs. So, this regime is squeezed.

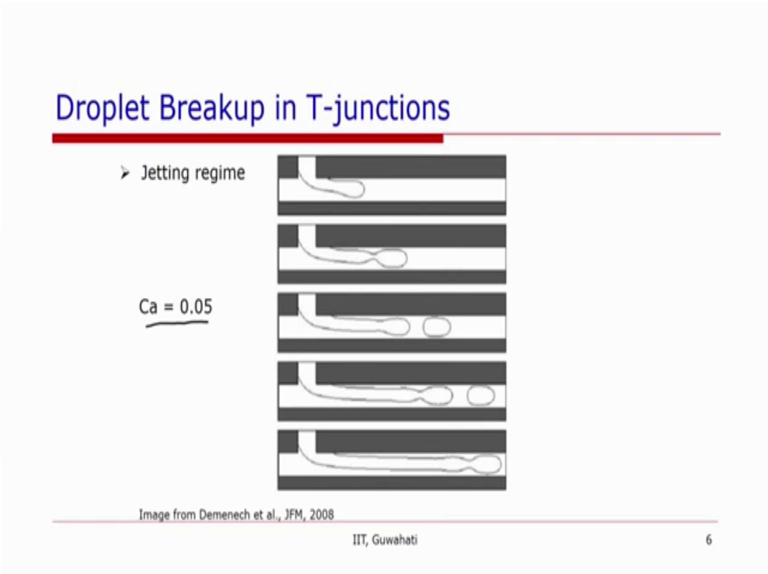
So, the 4 steps that we have listed here that first, the liquid penetrates the main channel and then forms a blob. because, the flow of the continuous liquid or the continuous phase is happening in this direction. So, this deforms or this moves the interface towards the downstream direction and this block moves to us or downstream direction. Then slowly a neck is developed and this neck will depend on the on the flow rates of the 2 fluids. and then eventually this neck elongates the bubble or the blob becomes longer and the neck becomes thinner and thinner and then it break up breaks up and the droplet or the bubble is generated.

(Refer Slide Time: 12:14)



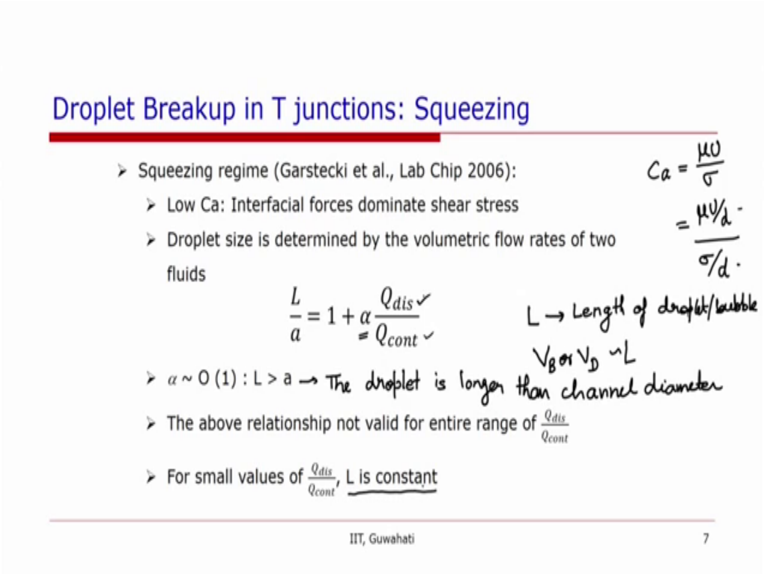
Now, in the dripping regime the process is same ah, but the one can see that necking does not occur at the junction itself, but further downstream. So, this is not determined as we will see that the breaking or the necking process is not because of the flow rates of the 2 liquids or the 2 fluids ah, but rather the shear stress balance ok. So, this is a typical picture of the dripping regime and then.

(Refer Slide Time: 12:57)



The third one is chatting regime, so in the jetting regime what one observes that this the thread the liquid thread becomes longer and longer and eventually. This the necking on the droplet generation happens because of the capillary instability. So, this particular experiment has had been observed higher capillary number Ca is equal to 0.05 and the previous 1 at Ca is equal to 0.35.

(Refer Slide Time: 13:35)



So, most of the applications where the viscosity of the liquid or the dispersed phase is not very high. So far of the gaseous for all the applications of the water and so on at low flow velocity which is generally that is in micro fluidics. The capillary number is small so it is important or the squeezing regime is the most important flow regime. So, low capillary number as one can see the capillary number is ratio of mu U over sigma or the ratio of mu U by length scale.

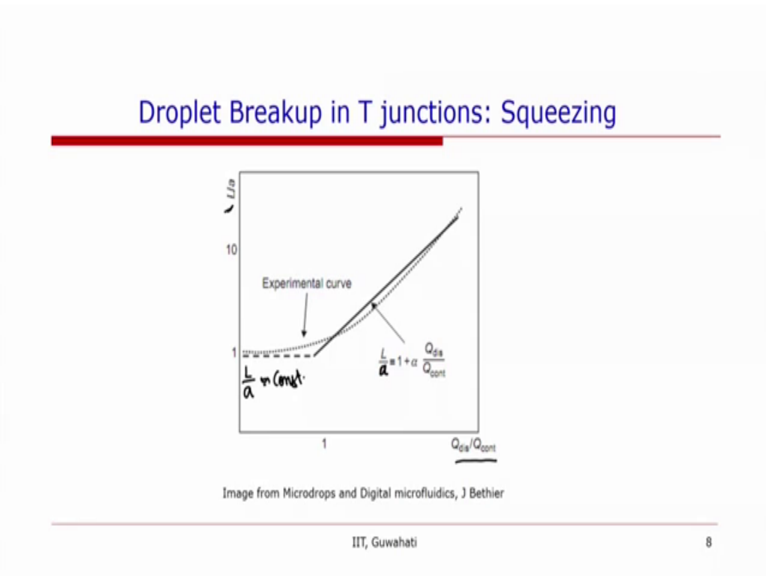
So, mu U over d divided by sigma over d. So, it ratio of viscous stresses or viscous forces to interfacial stresses. and one can see that the at low capillary number the interfacial stresses will be dominant and the shear stress will be relatively lower or smaller than the interfacial stresses.

So, it has been observed experimentally that l where l is the length of the droplet or bubble as the case may be. And so, volume of bubble or volume of the droplet that is proportional to the L. because, the there will be a constant thickness liquid film surrounding it as we have seen in Taylor flow examples of Taylor flow.

So now, it has been observed experimentally, that the length of this bubble of l by a is proportional to or equal to 1 plus alpha the ratio of the flow rates of 2 phases. The volumetric flow rate of discontinuous phase and the volume of flow rate of continuous phase. The alpha is a constant which is of the order of 1. So, that means, that l by a is greater than 1. So, the droplet; that means, the droplet is longer than channel diameter.

Now, this relationship has not been observed that it is always true for the entire range of the ratio of the flow rates. It has been seen that for small values of flow rates or say for this ratio. When this ratio is 1 L is observed to be a constant.

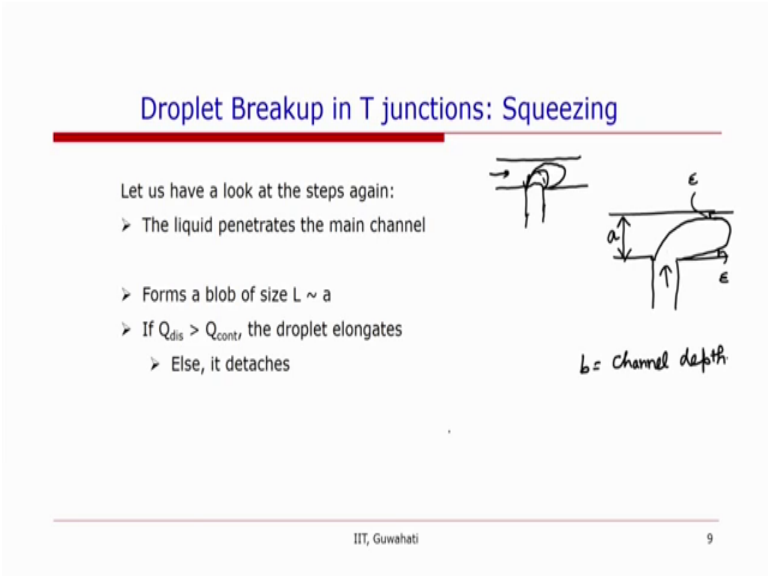
(Refer Slide Time: 17:07)



So, if we plot this picture on a graph, where x axis is the ratio of the 2 flow rates and the y axis is the non-dimensional droplet or bubble. Then 1 observe from experiments the a a this kind of curve where we can have 2 asymptotes. So, at low values less than 1 observes that L by alpha or L by a is equal to constant. And at high values of flow rate ratios L by a is l by a is linearly varying with the ratio of the flow rates ok.

So, now let us look at this in.

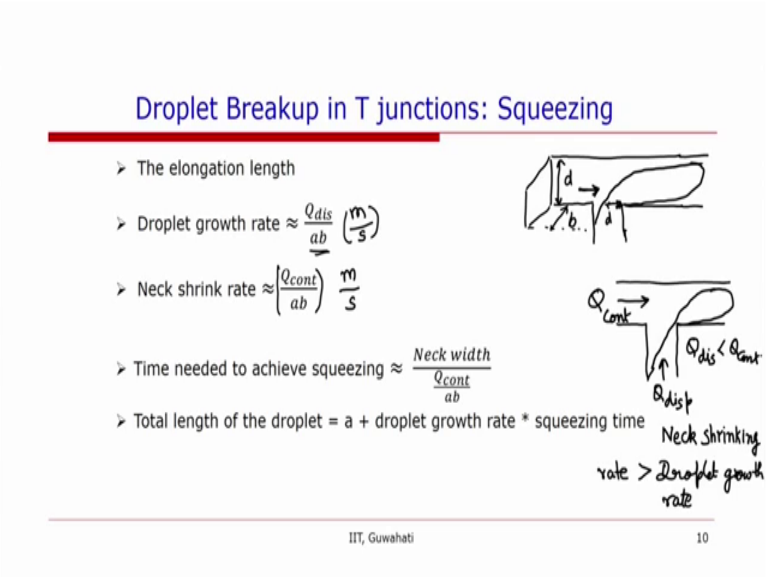
(Refer Slide Time: 18:09)



Further details; so, if we look at the steps of the bubble formation again, in the squeezing regime or the droplet formation what happens? That the discontinuous or the dispersed phase enters from here. And because of the flow it will if there is no flow, then it might grow this way, but because of the flow to starts moving in this direction and then eventually it envelops the main channel; when it envelops the main channel, one of the things that happens is that there is always a there is a small opening between the wall and the interface. Let us say this is small opening as thickness epsilon and because this restricts the flow of the continuous phase so the phase are builds up upstream.

Now, this forms this a blog blob this blob is of typical sizes a. Where a, is the size of the channel. and let us say b is the depth, the channel of rectangular and cross section. So, b is the channel depth and if the dispersed phase flow rate or the discontinuous phase flow rate is more than the continuous flow rate, then the droplet keeps elongating otherwise it detaches.

(Refer Slide Time: 20:11)



So, this has been given that the elongation length the droplet will grow. So, in a case where this is let us say, this is the neck be or a clear picture of neck will be. So, the droplet growth rate will be determined by the dispersed phase flow rate, which is and divided by the cross sectional area. So, the cross-sectional area is a is this dimension and b is the depth of the channel.

So, the rate at which the droplet growth is Q displacement over a b. and the neck shrinking rate the rate at which once this neck forms and the let us say that this thickness of the neck is d and this shrinks with a when the dispersed of an the continuous phase pushes this neck then the neck shrinking rate is continuous phase flow rate divided by the channel cross sectional area. So, Q continuous divided by ab now, the time needed to achieve this squeezing.

When the neck will shrink, when the neck shrinking rate is the velocity or the detention say it has units of meter per second and it also has units of meter per second.

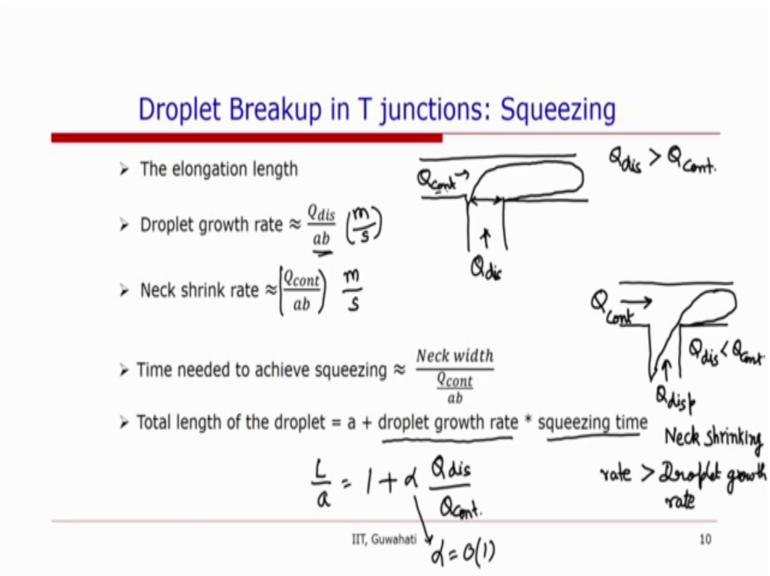
Now, if the continuous phase flow rate is more than the dispersed flow rate dispersed phase flow rate, then as soon as it develops the neck develops the dispersion happens actually this neck will never be able to grow and what one will have is a picture like this.

So, this neck will be very thin because the rate at which it grows it is shrinking faster than that. So, this will be the picture when Q dispersed phase is less than Q continuous.

So, this is Q continuous and the flow rate here is Q dispersed. And in this case the neck shrinking rate which is proportional to PQ continuous is greater than the droplet growth rate. So, the neck never develops there is never a um a neck which is enveloping the this mouth of the or the junction of the channel of T junction.

whereas, for the other case, when we have the dispersed phase flow rate is higher than the continuous phase, then.

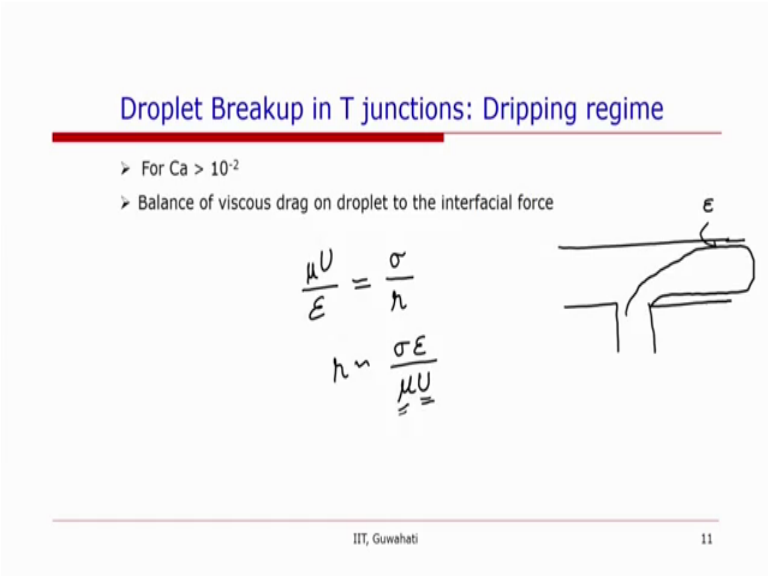
(Refer Slide Time: 25:05)



We will see a neck forming which may look something like this. So, in this case, Q continuous and Q dispersed , but dispersed phase flow rate is more than the continuous phase flow rate. So, neck will develop and then once this neck has developed reach a steady state, there will be continuous supply of the liquid or the gas in this blob.

At the same time, because of the continuous phase flow rate the neck will start sinking. and eventually, when this the time based on which the squeezing time based on the squeezing time, the length of the droplet will be determines. So, the total length of the droplet will be when it is or when it is envelop the channel plus the rate of the droplet growth rate into squeezing time. Now, this is squeezing time is neck width divided by the Q continuous by a b; which is the neck shrinking rate. So, from this get the relationship L by a is equal to 1 plus alpha Q. This continuous phase divided by the Q continuous phase ok. and this alpha will be of the order of 1 k.

(Refer Slide Time: 27:20)



Now, coming to the other regime the dripping regime in the dripping regime, the balance of 2 forces. So, the viscous drag that is applied by the continuous phase on the dispersed droplet and the interfacial force that will determine the size of the droplets. So, if we write that the order of magnitude. So, the viscous drag will be mu U by epsilon.

So, in this case, as we have seen in the so this epsilon is the distance between the interface and the droplet. So, that is the order of magnitude of the dispersed drag mu U by sigma and that will be equal to sigma over r. R is the radius of curvature and from this one can have an order of magnitude of that r is equal to sigma epsilon over mu U. from this relationship, one can calculate the volume of the bubble.

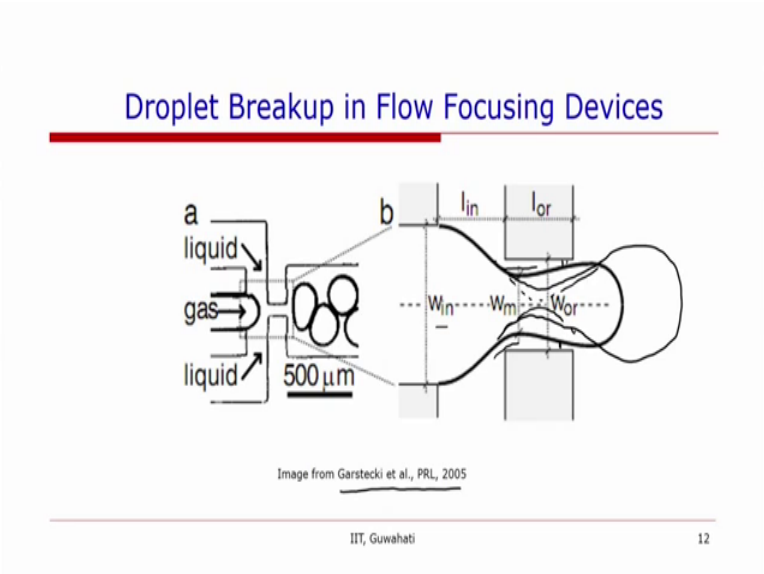
This; so this is the dripping regime ok we do not have further relationships for the droplet volume in the jetting regime. Even in the dripping regime, but we have is the scaling law and the dependence of the of the bubble volume on the velocity or the flow rate of the phases and the viscosity.

Now, it has been observed that in the squeezing regime, what is important to note here that in the squeezing regime, the volume of the droplet does not depend anything else except Q of dispersed phase and the q or the flow rate of the continuous phase. So, it depends only on the flow rate ratio of the 2 phases.

And that is a very important and significant result, because it does not depend it respective of it is gas or liquid it does not depend on the viscosities or either the continuous phase or the dispersed phase and. So, this flow regime it is possible to achieve such a capillary number then, it can be used by manipulating the flow rates of the 2 phases. It can be used to generate the droplet us or the bubbles of a desired size.

Now, at higher flow rates, one can have the effect of viscosity, may be effect of the viscosity of the disperse phase this especially seen in the jetting regime where we have discussed rates and so on and so, forth ok. So, that was about the T junctions and one can develop similar relationships for a Y junction.

(Refer Slide Time: 31:14)



Now, for flow focusing devices; so, in the flow focusing device, a typical flow focusing device that had been taken by taken from article by the Garstecki et all. And the discussion we have is based around the article or the discussion in the article here.

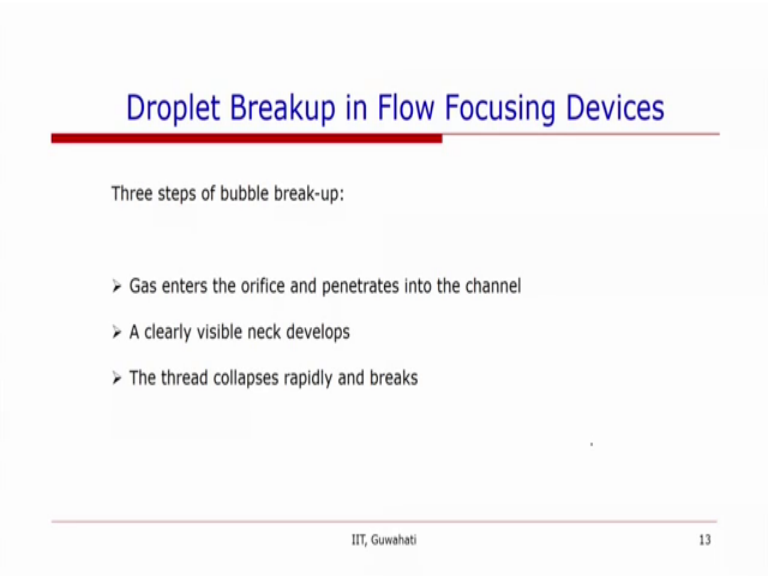
So, in the flow focusing device, the dispersed phase comes from a channel in the middle and the 2 from the 2 sides, the liquid phase comes in. So, what happens in this case? that the this is a particular case, we have the emulsions of the droplet formation is happening and the polydispersity is less than one percent.

So, polydispersity means, the size of the bubbles or the size of the droplet is not dispersed one get mono dispersed problem; that means, the size of all the droplet us around the bubbles is same. This particular case for a gas liquid combination where, the gas is coming at the center and which is the dispersed phase.

Now, if you look at this configuration, what they have given is the this is the W in and Wm is varying that is the neck radius or neck diameter one can say. And there is another parameter on the orifice diameter which is a geometrical parameter and these are the lengths of the different. So, this is of the flow focusing device is very commonly used to generate polygous from the mono dispersed emulsions on the droplet us of bubbles are same size.

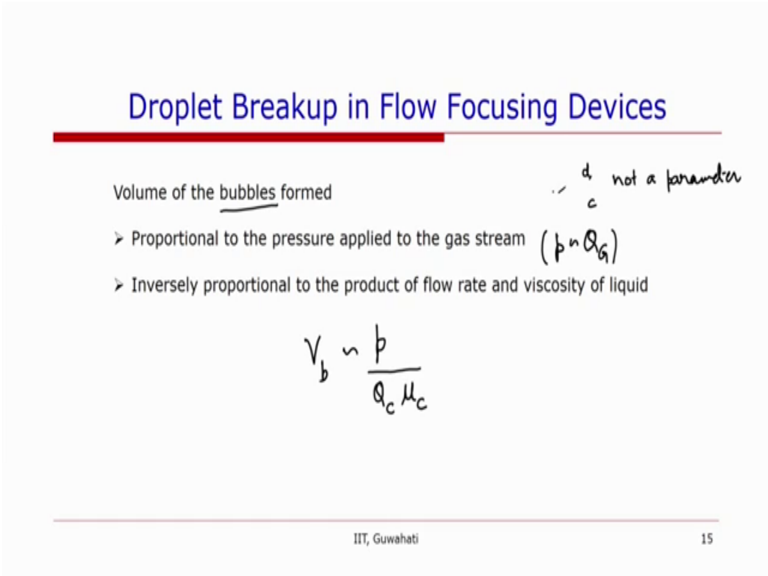
Now, there are 3 steps that have been identified in this. The gas enters the orifice and penetrates into the channel as can be seen here the gas comes in, and it enters the orifice it squeezes in the orifice there is a film surrounding it of liquid. And then it grows and there is very thin film surrounding it here. and then as the this grows in here, the neck formation happens. So, eventually the neck will be become neck will become thinner and thinner as this grows and then finally, the neck will form.

(Refer Slide Time: 34:05)



Now, then when the neck is thinning; finally, at one particular time and the thread collapses rapidly and breaks. So, the process of thinning of the neck and the then the collapsing in that gives rise to that um droplet breaker.

(Refer Slide Time: 34:40)



Now, what had been observed experimentally that the volume of the bubbles. So, this is for the bubbles and they so one need not worry about viscosity ratios of dispersed and continuous phase not a parameter right. Because the dispersion continuous phase ratio is almost 0; so, one do not need to take into account it this into account in the bubble formation.

So, one c or what they have observed that the experiment from the experiments the volume of the bubbles is proportional to the pressure of the gas stream. and at this at these flow rates the pressure or the gas Reynolds number is one calculates then it be in the laminar flow regime and one can say that this pressure will be proportional to the gas flow rate from the Eigen (Refer Time: 34:50) equation.

So, anyway the volume of bubbles is proportional to the pressure in the gas stream. and it is inversely proportional to the product of the flow rate so, the Q continuous phase in the viscosity of the continuous phase. So, it is proportional to the 2 it is proportional to the pressure and inversely proportional to the continuous phase and dispersed phase. Flow rate it is inversely proportional to the flow rate and the viscosity of the continuous phase which is liquid. So, that is a relationship or scaling between the bubble volume and the pressure flow rate and the viscosity.

So, in summary, in this lecture, what we have looked at? Is the mechanism of the bubble formation in at a T junction and what we observed is there are 3 different droplet breakup regime where different physical phenomena govern; or determine the droplet or mobile type of process. These 3 flow regimes are dripping flow regime, ok by smallest capillary number what we have is squeezing flow regime, at capillary number. More than 10 to the power minus 2 one has the dripping flow regime and at further higher capillary numbers one has the jetting regime.

So, the most relevant and most useful flow regime is the squeezing regime, because bubble length or the droplet length in the squeezing regime depends on the ratio of the flow rates of the true phases. in the dripping regime, the bubble size is governed by the shear stress or the shear stress that develops on the droplet or the bubble that is responsible for the breakup of the bubbles. In the jetting regime, the gas or the liquid it elongates as a continuous jet and eventually the breakup happens from the capillary instability or relay play to instability.

The mechanism of bubbling droplet formation in the flow focusing devices is not so well understood there ah; however, what we have seen based on few articles that the droplet volume is proportional to the gas flow rate or the gas pressure. And it is inversely proportional to the continuous phase flow rate and the viscosity of the continuous phase. And it depends on the 2 times scales the time scale the; at which the gas is filled up in the continuous core or in the blob that grows. and the time scale at which the necking occurs and the neck break up happens, so.

Thank you.