Fluidization Engineering
Dr. Subrata K Majumder
Chemical Engineering Department
Indian Institute of Technology, Guwahati

Lecture – 16
Bubbling Fluidization-Part 4:
Bubble breakup in 3-phase fluidization

Welcome to massive open online course on fluidization engineering, todays lecture will be on bubbling fluidization part 4, and here the bubble breakup in 3 phase fluidization system will be discussed.

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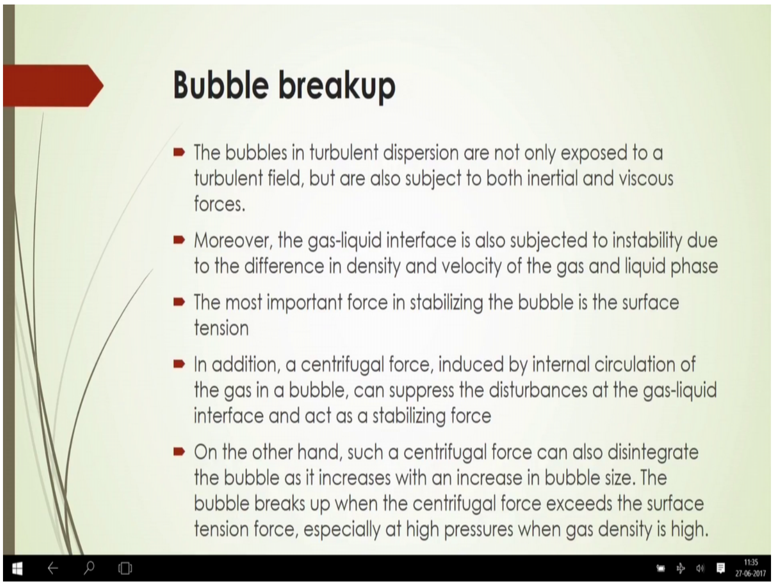

So, the bubble of course, the characteristics we have already learned in our previous lectures, and there are different aspects of bubble characteristics in the bubbling fluidized bed in 2 phase and 3 phase systems.

So, we have discussed about this bubble breakup, and coalescence in the gas solid fluidization system, whereas, in 3 phase fluidization system where gas liquid solid will be taking part and the breakup processes, and also coalescence processes and what are the different courses that actually influences this actually bubble characteristics inside the 3-phase fluidized bed, it will be discussed here. So, the bubble in turbulent dispersion in gas liquid solid fluidization, are mainly expected due to the different forces acting on it, is like here turbulent force like inertial and viscous force and other different acting forces like centrifugal course, and if any other forces externally supply to govern this dispersion of this fluid inside the bed.

Now, we will discuss here what is that bubble breakup. So, this in this fluidized bed, already you have discussed the fundamentals of this breakup for the mechanism of this, here in this case also we will try to discuss how that bubble breakup is happening because of this equivalence of the different forces acting on it surfaces, and also how this bubble will deform and also what are the different sizes of bubbles will be forming because of this forces acting on it, and what should be the stabilized form of the bubble, that also after breaking up will be actually effecting by this different forces.

Now, the bubbles in turbulent dispersion are not only exposed to a turbulent field, but are also subjected to the both inertia and viscous forces, of course, the gas liquid interface is subjected to instability due to the difference in density and velocity of the gas and liquid phase inside the fluidized bed, the most important force in in stabilizing the bubble in the fluidized bed is with the surface tension, surface tension is the most important factor here and which will govern the surface of the bubble or interfaces of the phases whether it will be stabilized or not.

Now, in addition a centrifugal force induced by internal circulation of the gas in a bubble can also suppress the disturbances at the gas liquid interface and as a stabilizing force, on the other hand you can say that such centrifugal force can also disintegrate the bubble, as it increases with an increasing bubble size. So, here of course, the centrifugal force disintegrate the bubble and this phenomena will increases when the size of course, change. So, if size is change if size is increased then, you will see that disintegration of the bubble will increases, and the bubble breaks up when the centrifugal force exceeds, this surface tension force specially at the at the high pressures when gas density is very high. So, in that cases the bubbles breakup will possibly happen because of this extent of centrifugal force beyond the surface tension.

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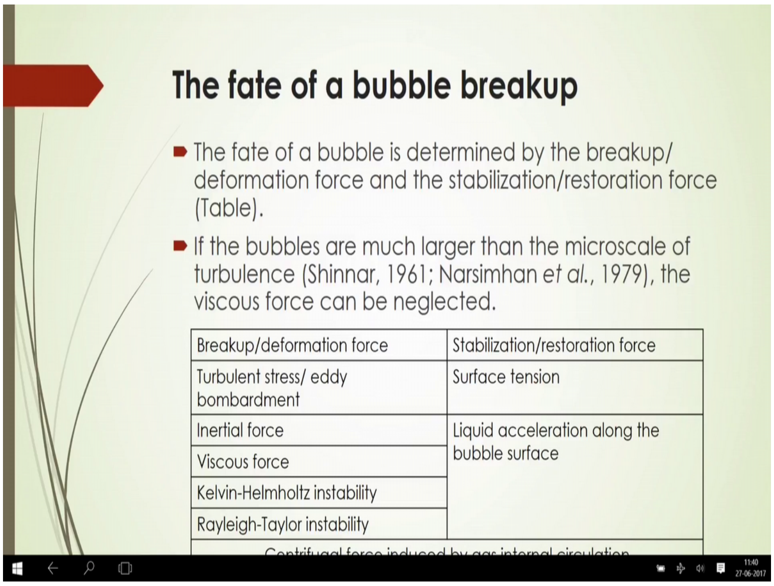

Now, what are the fate of a bubble breakup then, then the fate of a bubble is determined actually by the breakup or deformation force which is acting on this bubble and the stabilization or restoration forces of the bubble, now if the bubbles are much larger than the microscale of the turbulence, then you can say that the viscous force can be neglected. So, in that case there are different forces how it will be acting for this deformation of forces of course, we have to know.

Now, this turbulence stress or eddy bombardment is on mechanism for representing this bubble breakup fate, and also what will be that stabilization or restoration forces there. So, if the breakup of deformation forces turbulent or stress or eddy bombardment then you can say, this stabilization force will be as a surface tension whereas, inertia force viscous force and other like kelvin Helmholtz instability, Rayleigh Taylor instability in that case bubble liquid acceleration along the bubble surface is the main governing forces for the stabilization or restoration forces here.

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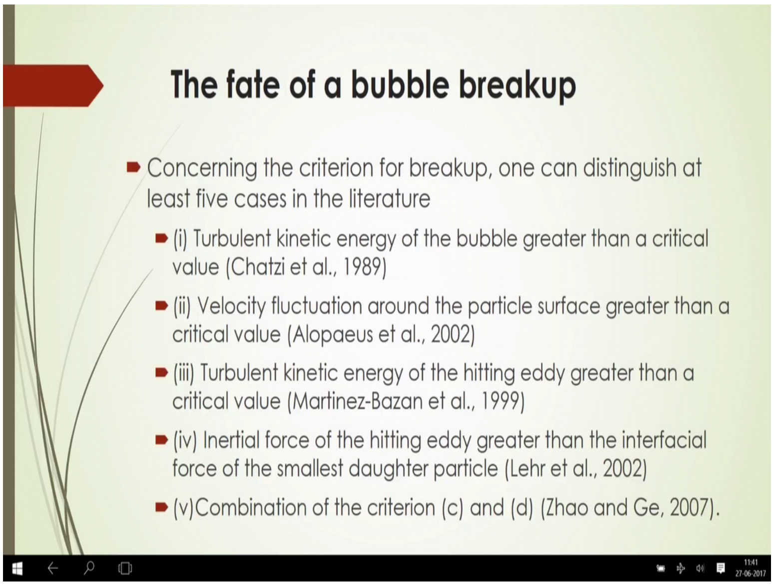

Now, if we consider the criteria for breakup, then one can distinguish at least 5 cases in the literature services available different investigators they have presented different actually, remarks or different they have actually stated different way, that what are the different actually criteria for breakup, in that case now turbulent kinetic energy of the bubble greater than a critical value that chatzi et al 1989, they have actually commented on that that if that turbulent kinetic energy greater than the critical value, then the bubbles will breakup also velocity fluctuation is also important factor for this breakup processes.

Now, velocity fluctuation around the particle surface greater than a critical value, in that case you will observe that breakup of the bubble, and the turbulent kinetic energy of the suppose if any eddy is hitting to the bubble, then what should be the kinetic energy that is that hits the bubble by which the eddy hots the bubble, if it is greater than a critical value according to the Martinez Bazan et al 1999, then there will be possibility of breakup of bubble.

Also another important factor that inertia force of the hitting eddy, if it is greater than the inertia force of the smallest daughter bubble, which is formed after breaking up then there will be a possibility that is the criteria for the bubble breakup, this is actually explained by that lehr et al 2002, now another important that if I consider this this combination of this that is criteria for turbulent kinetic energy, and the velocity fluctuation or that inertia force of the hitting eddy, if it is greater than the interfacial forces of the smallest daughter particle, in that case both the both the energy both the forces may be responsible for the breaking up bubble.

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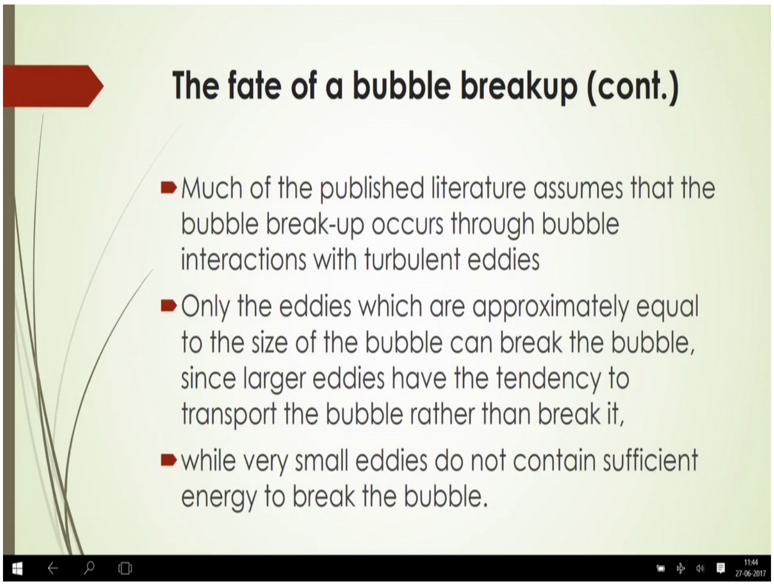

Now, there are several publications that in the literature and different investigators, they have assumes that that bubble breakup occurs through the bubble interactions with turbulence eddies, now only the eddies which are approximately equal to the size of the bubble can break the bubble, since larger eddy is have the frequency have the tendency to transport the bubble rather than break it.

So, that is why only the eddies which are approximately equal to the size of bubble can break the bubble, while very small eddies that is very small; that means, this is smaller than bubble do not contain sufficient energy to break this bigger bubbles, relatively bigger bubbles to this eddies. So, small eddies that is this energy kinetic energy or whatever energy carried by this eddy, to break the bubbles it should be sufficient of course, So, very small eddies do not contain that much energy to break the bubble. So, here important point is that the eddies responsible some eddy surrounding this bubbles, which is hitting the bubble there may be a possibility of the breakup of the bubble, now that eddy contains of energy that energy should be sufficient. So, that the bubble will breakup.

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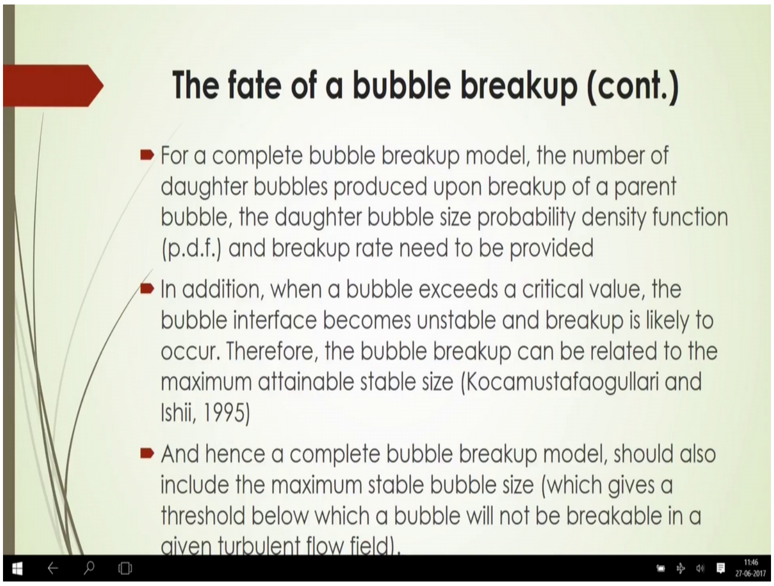

For a complete bubble breakup model the number of daughter bubbles of course, produced upon the breakup of a parent bubble, the daughter bubble size probability density function and the breakup rate need to be provided for expressing the bubble breakup efficiency. Now in addition when a bubble we are considering that exceeds a critical value, the bubble interface becomes unstable and breakup is likely to occur therefore, the bubble breakup can be related to the maximum attainable stable size, now hence a complete of course, bubble breakup model should also include the maximum stable bubble size, which gives a threshold below which a bubble will not breakup in a given turbulent flow field. So, what we know that of course, to know the bubble breakup efficiency, what is the frequency of the bubbles that is formed after breakup.

And also how many bubble will form, and what is the daughter bubble frequency all these things of course, depends on the collision between bubbles, and also what will be the probability density of that formation of bubble, and also what is the stability of the bubble; that means, at what size of the bubbles will be stable to form to it is final stage as a daughter bubble, and also if the bubble exceeds a critical value, the bubble interface becomes unstable in that case that breakup is likely to occur.

And this breakup of course, related to the maximum attainable stable size, now how to calculate or how to estimate that maximum stable bubble size, there will be some energy related this stability and by which we can say this much energy will give you this size of this bubbles that will be stable. So, will be calculating later and also how to calculate that stable bubble size. So, this breakup model; that means, here how to calculate the density function of the breakup and frequency, and also efficiency of the breakup that depends on the stable size of the bubble.

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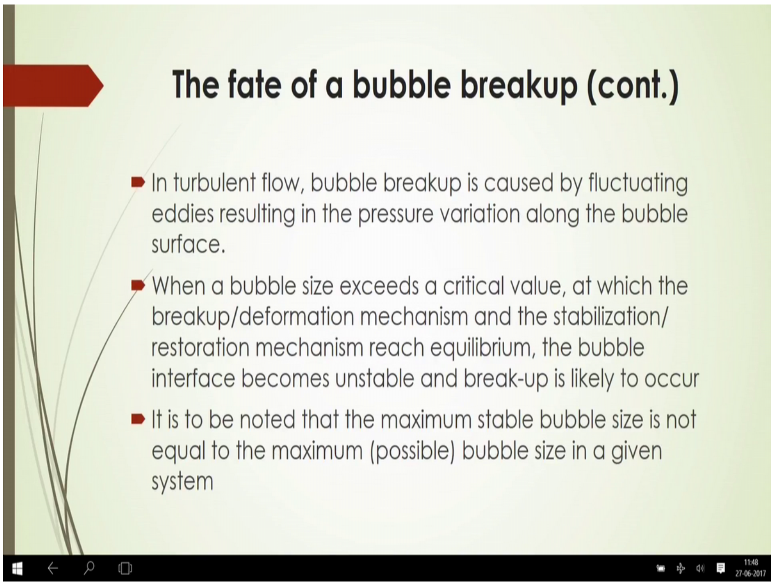

Now, in turbulent flow bubble breakup is cost by fluctuating eddies resulting in the pressure variation along the bubble surface, important thing is that maximum cases in gas liquid solid fluidized bed, generally the operation are in turbulent flow. So, in that case the bubble breakup is generally happen due to the fluctuating eddies, fluctuating eddies which is which govern the pressure variation along the bubble surface and which will give the breakup efficiency, when a bubble size exceeds a critical value at which that bubble breakup or deformation happens, and the stabilization or restoration mechanism reach it is equilibrium, the bubble interface becomes unstable and breakup is likely to occur. So, it is to be noted of course, that the maximum stable size is not equal to the maximum bubble size in a given system. So, this is important that this of course, the stable bubble size depends on the how much energy is supplied in the turbulent flow, and if the bubble size it is exceeds the critical value, then it will deform and loose it is equilibrium, and then interface become unstable and breaking up into a daughter or smaller bubbles.

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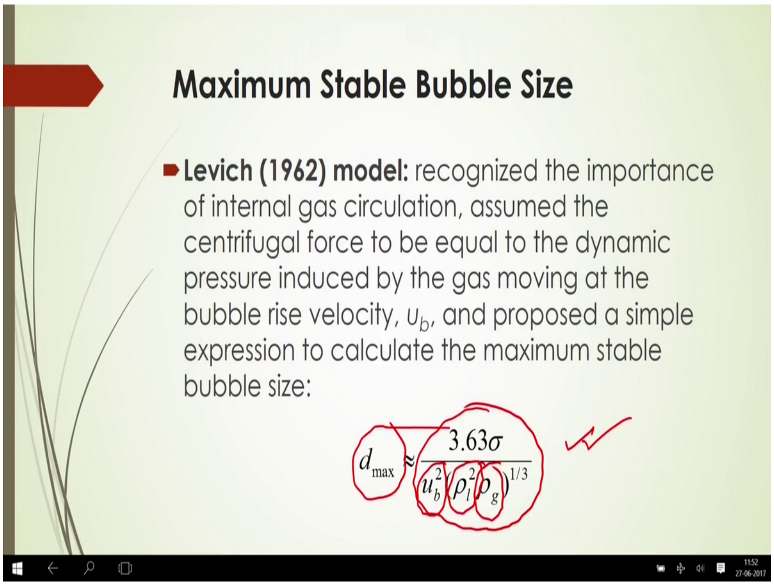

Now, how to estimate that bubble stable bubble size levich 1962, they have actually recognized the importance of this internal gas circulation, during their ha experimentation, and they have seen that there when bubble will be moving there will be internal gas circulation inside the bubble, and also there will be some force that is called centrifugal force acting on the surface of the bubble, and due to which if it is equal to the dynamic pressure induced by the gas moving at the bubble rise velocity, then they can actually then they have observed that this maximum bubble size actually depending on the physical properties of the system and also size and also bubble rise velocity.

They proposed a simple expression to calculate the maximum stable bubble size there. So, here this d max here in this case this d max is called maximum stable bubble size, they have proposed this correlations to calculate this d max as this here this 3.63 into sigma, this sigma is called surface tension divided by U b square this is called bubble rise velocity U b is the bubble rise velocity, and the density of the liquid square into rho g this gas density to the power 1 by 3. So, by this equation they have actually calculated this stable maximum size of the bubble, from their that is from their internal gas circulation phenomena of the bubble and also from the rise velocity of the bubble.

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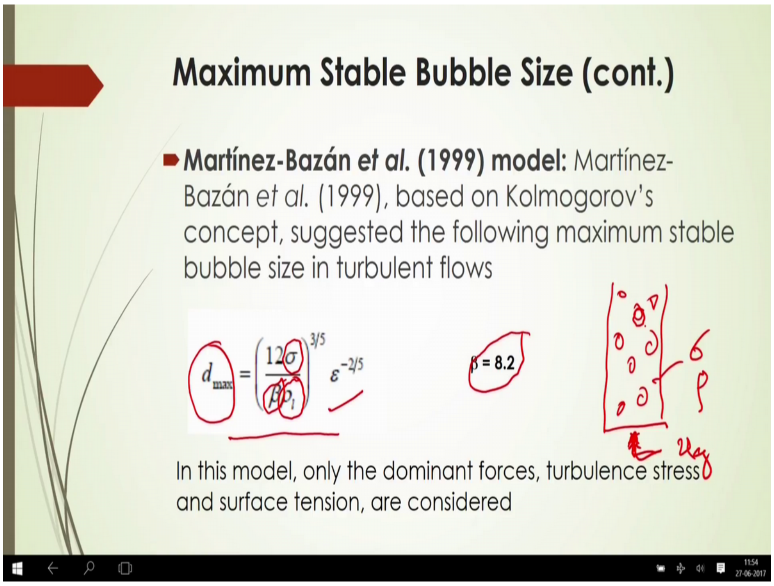

Martinez Bazan et al 1999, they have also given another model to calculate the maximum stable bubble size in turbulent flow, they have proposed the maximum stable bubble size by this correlations, they have calculated it is or they have suggested this correlations here as this 12 sigma by beta into rho l to the power 3 by 5 into epsilon to the power minus 2 by 5, here this sigma is called surface tension and beta is the parameter which value from their experiment they got beta is equal to 8.2, and rho l is the density of the liquid and epsilon is called the energy dissipation per unit much inside the bed.

So, in this model only the dominant forces, turbulent stress and the surface tension are considered. So, by this model also you can calculate what should be the maximum stable bubble size inside the bed. So, if it is a bed there 3 phase fluidized bed, and then you can calculate what should be the maximum bubble size. So, what is required to calculate here? What is the surface tension of the liquid? What is the density of the liquid? And what will be the energy is supplied for this turbulence inside the bed, this is if it is u g gas velocity then what will be the energy supplied to that it will be is equal to u g rho into u g, and also there will be some energy that you can calculate kinetic energy may be half of rho u square, u may be in the gas velocity there or if liquid is also moving then you have to calculate what will be the kinetic energy supplied there inside the bed. So, and what will be the unit per unit must what should be that turbulent kinetic energy then, from which you will be able to calculate what will be the maximum bubble size or stable bubble size that is formed inside the bed that can be calculated.

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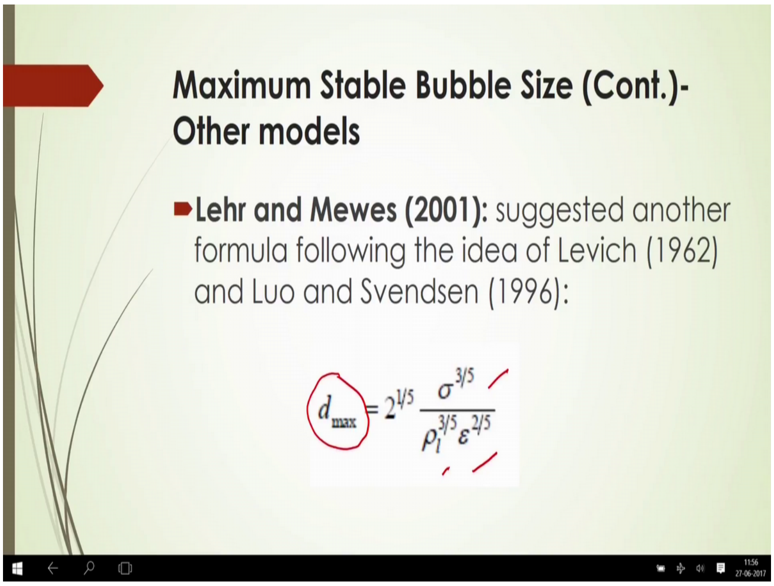

Now, Luo et al 1999 they have suggested another model based on the internal circulation of the gas in a bubble by rising by using the force balance between the centrifugal force and the surface tension force. So, from their model it is seen that this maximum stable bubble size will be approximately equals to, 2.53 into root over of sigma by g into gas density. So, from this relation you can calculate what should be the stable bubble size, from this Luo et al model lehr and mewes 2001 they have suggested another actually formula, following the idea of levich 1962 and Luo and Svendsen 1996, they have also correlated this stable bubble size in terms of surface tension of the liquid, and density of the liquid, and also the energy supplied per unit must to the bed. So, that here this d max will be is equal to 2 the power 1 by 5 into sigma to the power 3 by 5, rho l to the power 3 y 5 into epsilon to the power 2 by 5 into epsilon to the power 2 by 5, from this correlations you also will be able to calculate what should be the maximum bubble size that is form, inside the fluidized bed of 3 phase system.

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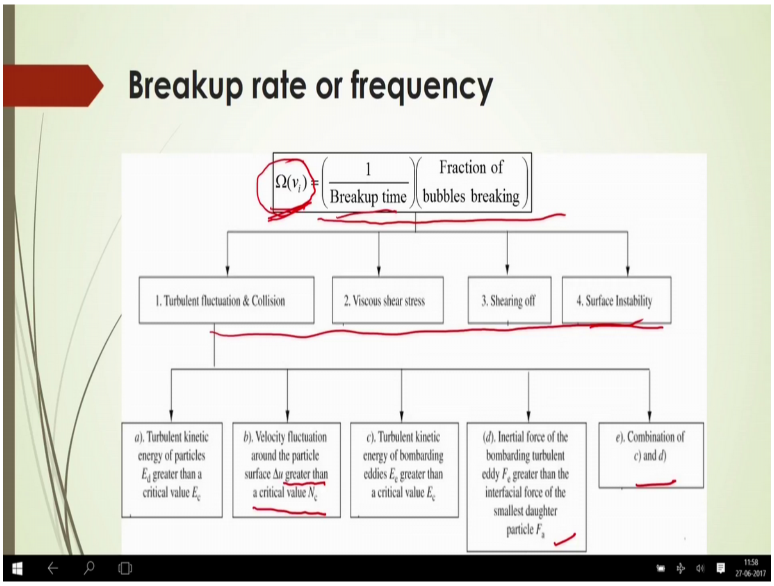

Now, what will be the breakup rate or frequency that, how to calculate, now we should know what are the different actually forces, what will be the different mechanism by which this breakup is happening, and what will be the rate for that. So, this bubble breakup rate or frequency you can calculate or you just denoted by this omega here, into v I v I is the this I is here the I th class of bubble if you consider that I j k classes of bubbles there in the fluidized bed, and particular classes of bubbles of diameter suppose that class or suppose I, then what should be the volume this is this bubble breakup depends on that volume of that particular class of bubbles, this class actually defined based on the differentiation of the size of the bubble.

Now, this bubble breakup rate that will be is equal to 1 by breakup time into fraction of bubbles breaking. So, from this definition you will be able to calculate this, now from this this breakup rate actually depending on that turbulent fluctuation and collision, viscous shear stress, acting on the bubble surface, and the shearing off at the surface, and the surface instability of the bubble. So, there are different mechanism for these 4 types of this forces acting on this bubble surfaces, and turbulent fluctuation and collision is the most important factor, and mostly they are considered by this mechanism of this bubble breakup this happened.

Now, in this case the turbulent kinetic energy of the particles this is denoted by E d sorry E d which is greater than the critical value of E c, and also the velocity fluctuation around the particle surface if it is denoted by delta u, and if it is greater than the critical value of n c, then you can say there will be a breakup also this turbulent kinetic energy of bombarding eddies, E g greater than the critical value E c, and inertia force of the bombarding turbulent eddy F c greater than the inertia interfacial force of the smaller daughter particle, and the combination of this c and d now this is the mechanism by, which that you can expect this bubble breakup? And what should be the breakup rate based on these mechanism? It will be calculated.

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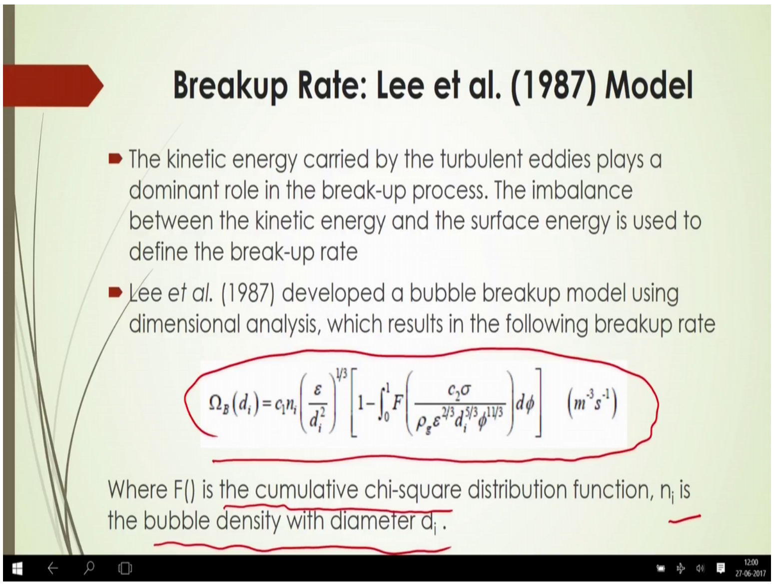

Now, this breakup rate as per this lee et al 1987 model, now as per this model this the kinetic energy is being carried out by the turbulent eddies which plays a dominant role in the breakup process, the imbalance between the kinetic energy and the surface energy actually will govern the breakup process, and this imbalance between this kinetic energy and the surface energy is cause to define the breakup rate.

Now, lee et al 1987, they have developed the bubble breakup model suing dimensional analysis which results the following breakup rate. So, from this equation you can calculate what should be the bubble breakup rate, where this here function of f, this function of f, is the cumulative chi square distribution function, and n I is the bubble density with diameter d I. So, here of course, you will see that bubble breakup rate by this lee et al model and depends on this, how many number of bubbles are produced at that particular classes of bubbles?

And what will be the energy supply if we know the diameter of that particular class, and also what will be the distribution of that particular bubbles that formed, and what should be the physical properties of the system, and because of which you will be able to calculate that what should be the breakup rate. So, based on this from this correlation you will be able to calculate. So, here very important point is that that you have to integrate this distribution cumulative distribution of that bubble breakup, and after that breakup what will be the number frequency of that bubble the distribution function that of course, you have to know and after integration then finally, you will be able to calculate from this.

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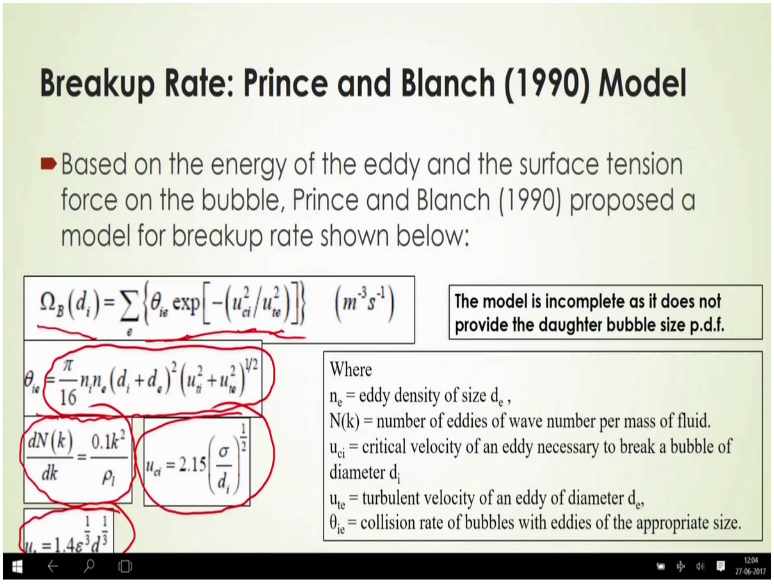

And then breakup rate as per prince and blanch 1990 model, based on the energy of the eddy and the surface tension force, on the bubble prince and blanch proposed a model for breakup rate which is shown below this omega b here this is a function of this values, which is theta I e and u c I, u t e and what is that this theta I e means here collision rate of bubbles with eddies of the appropriate size and of course, this collision depends on the number of eddies and also how many number of bubbles after collision it will form, and what should be the diameter of that particular class bubbles that are formed, and also what will be the size of the eddies.

Because of which this breakup is happening, and also what will be the velocity of that particular eddy and particular classes bubbles. So, this collision and of this bubble and l e actually can be calculated from this equation, and what will be the number of eddies of wave number of per mass of fluids that also important here to calculate the, to calculate here the eddy density of the size d e here, and also what will be the size velocity of the particular class bubbles there that will be important to calculate, and u ci is the critical velocity of an eddy necessary to break a bubble of the diameter d I, and u t e is the turbulent velocity of an eddy of diameter d e here it is it can be calculated as this one point 4 into epsilon to the power 1 by 3 into d to the power 1 by 3. So, from this relationship we will be able to calculate what should be the turbulent velocity of the eddy of diameter d e. So, d e is the size of the eddy, and also this collision between this eddy and bubble depends on this size, and also number of bubbles that are formed because of this collision.

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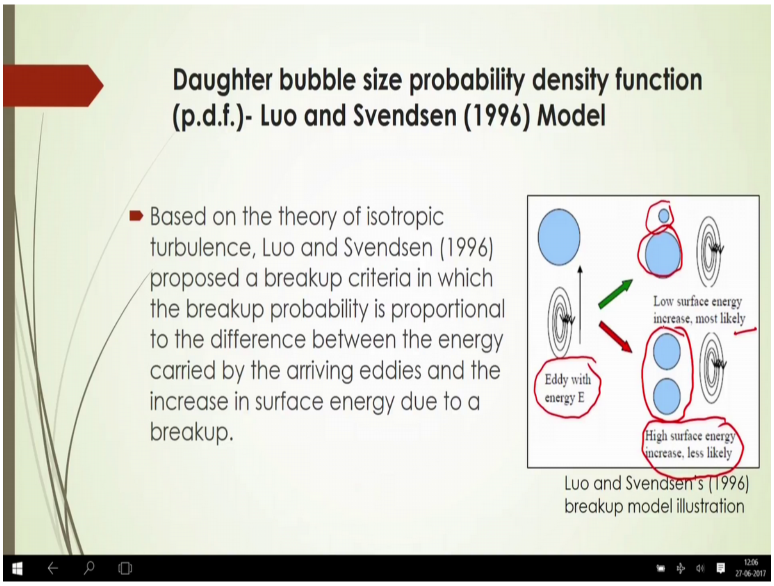

Now, daughter bubble size probability density function, how to calculate that after breaking up you will see that one bigger bubbles will form, number of a bubbles that bubbles that are form that may not be same as that that is source bubbles of course, and also that the size will be of course, different from that initial bubble, and those bubbles are formed after breaking those may not be the same may be same equal to each other.

But that depends on that energy supply or uniformity of the flow inside the bed, and also the what is that fluctuating velocity inside the bed, now based on the theory of isotropic turbulence Luo and Svendsen 1996 proposed breakup criteria, in which the breakup probability is proportional to the different between the energy criteria, energy between the energy that carried out by arriving eddies and the increase in surface energy due to a breakup. So, in this case of course, the eddy whenever is colliding with the bubbles with energy E, and breaking into the bubbles of this smaller and bigger bubble diameter that is unequal size bubbles, there will be low energy increases must likely to be, and high surface energy is increases less likely to be there and because of which there will be the equal size formation.

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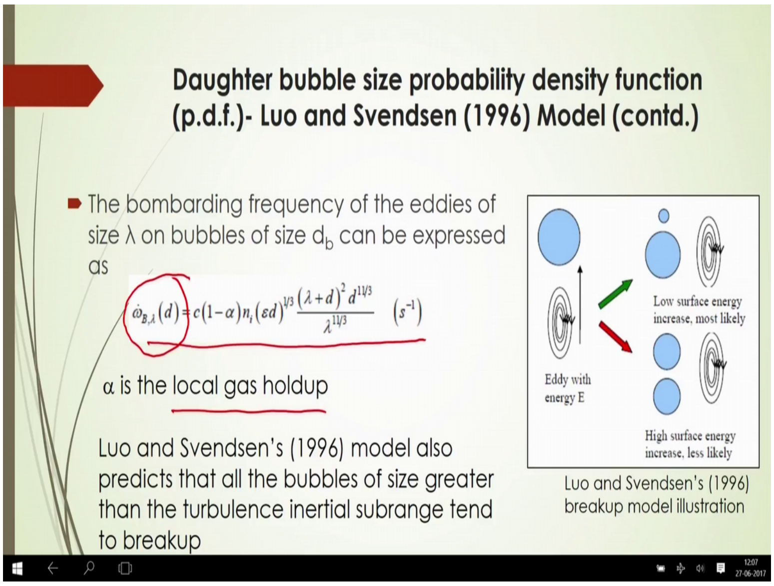

And the bombarding frequency this also another important, that when that colliding to each other there will be a frequency of eddies of size lambda on bubbles of size d b can be expressed as like this here, and then here in this case this daughter bubble size probability density function that is depends on this hold up, or the gas inside the 3 phase fluidized bed, that alpha is called here the local gas holdup if local gas holdup increases of course, the collision between the eddy and the bubble will increase and there of course, and number of bubbles will number of bubble formation will be higher than the higher than if.

That higher and of course, it depends on the size of the bubbles also. So, in that case if higher gas holdup it is seen that the number of bubbles will be higher, and then the size of the bubbles will reduce and then the frequency of the bubbles will increase, now Luo and Svendsen 1996 model also predicts that, all the bubbles of size greater than the turbulence inertial subrange that is tend to breakup.

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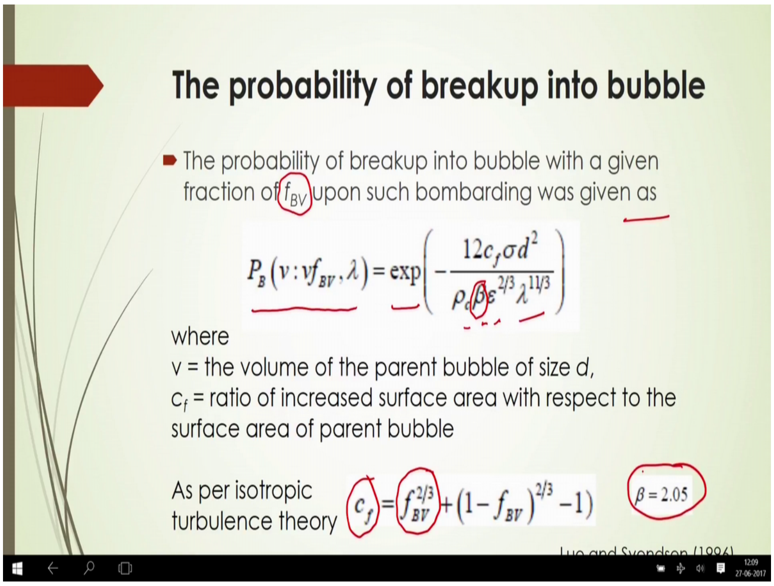

Now, what will be the probability of breakup into bubble, now the probability of breakup into bubble with a given fraction of f BV upon such bombarding was given, as this P B that will be is equal to exponent of minus 12 c f sigma d square by rho c beta epsilon to the power 2 by 3 lambda to the power 11 by 3 here. So, in this case what is c f? The c f is the ratio of increased surface area with respect to the surface area of parent bubble, and v is here the volume of the parent bubble of size d, as per isotropic turbulent theory this c f that is ratio of increase surface area with respect to the surface area of parent bubble, is a function of this this fraction of bubble volume inside the bed, this if here the fraction of this bubble volume increases it is seen that this c f will increase, but that depends on other factors of course, and there is one factor it is called beta, this beta is characterized the bombarding nature inside the bed and also it in in 3 phase flow it is seen that this beta will be is equal to 2.05 as per isotropic turbulence theory.

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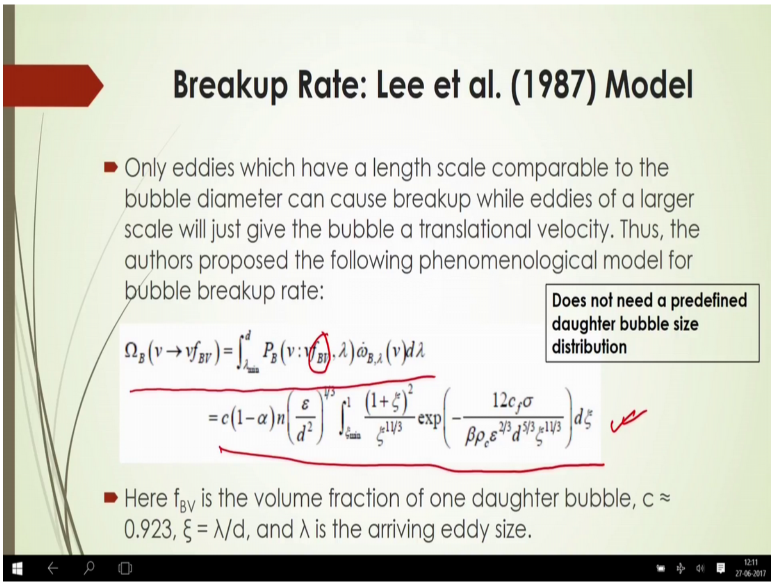

On the eddies which have a length scale, comparable to the bubble diameter can cause breakup, while eddies of a larger scale will just give the bubble a translational velocity. So, in this case lee et al 1987, they have proposed based on this concept the following phenomena logical model for bubble breakup rate here. So, this as per this phenomenology, this here this bubble breakup rate can be expressed by this equation, here this f B V this is f B V is the volume fraction of one daughter bubble, and c is equal to 0.923 chi is the parameter lambda by d, and lambda is the arriving eddy size here also eddy pushing that bubble to break the parent bubble into daughter bubbles.

And here only eddies which have length scale that is comparable to the bubble diameter will only cause this breakup, if the eddy size is larger than that bubble then there will be a actually translational velocity of the bubble, which may cause this bubble breakup and at a certain rate, and in that case this based on this is, equal to model bubble breakup will be calculated on this now does not here in this case this model does not need a predefined daughter bubble size distribution earlier one earlier model of course, you have to know that what should be the daughter bubble size distribution, in this case it is not required to know this daughter bubble size distribution.

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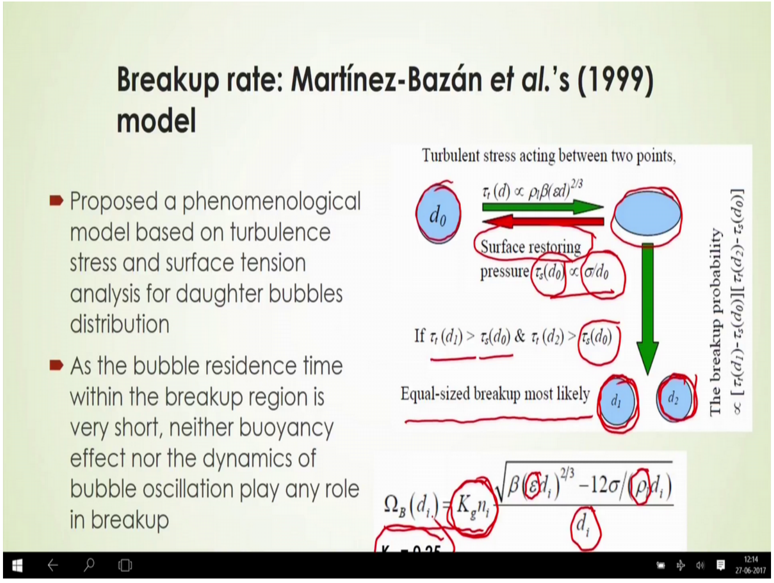

Martinez Bazan et als 1999 they have proposed a phenomenological model based on turbulence stress, and surface tension analysis for daughter bubble distribution, as the bubble residence time told within the breakup region is very short, neither buoyancy effect nor the dynamic of the bubble oscillation play any role in the breakup processes. So, in this case of course, this turbulence stress and the surface tensions, are very important factor for this breakup processes.

Now, that depends on that how long this bubbles will reside inside the bed, this if the bubble residence time within that breakup for region, and it is very short than buoyancy effect or the dynamic effect of the bubbles oscillation does actually effect this breakup processes, now turbulence stress see here in this figure this turbulence stress acting between 2 points here, this turbulence stress how this is the parent bubble and this another bubble here in this case there will be stress.

Now, surface restoring pressure here will be calculated here, tau is that will be proportional to the ratio of surface tension to the parent diameter of the bubble, now in this case this bubbles will be breaking up into 2 daughter bubbles of size d one and d 2.

Now, if this turbulent stress acting on the bubbles is greater than this turbulent stress, if the turbulent stress of this daughter bubble is greater than the turbulence stress of this parent bubble, and also if the turbulence stress of this daughter bubble of size d 2 is greater than tau s d 0, then there will be a actually tendency to breaking up this bubble, and here equal sized breakup most likely happen in almost all cases, and also based on this processes it is seen that this breakup probability, actually proportional to this this turbulence stress of this individual bubble s of size individual classes. So, in this case the bubble breakup rate can be calculated here this as K g into n I into root over beta into epsilon d I to the power 2 by 3, minus 12 into sigma by rho l d I by d t d I, here d I is the diameter of daughter bubble of class here I and rho l is the density of the liquid, and epsilon is the energy dissipation per unit much here, and this k is the factor which is generally taken as k is equal to 0.25 in this case.

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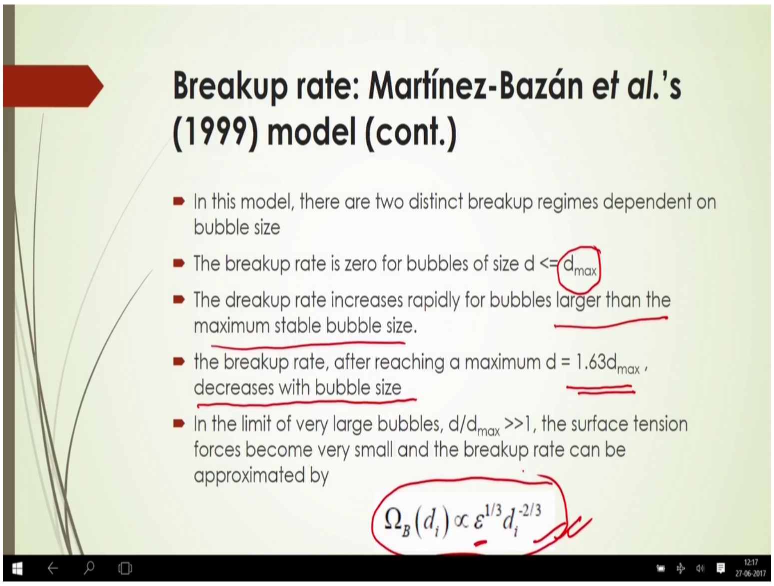

Now, in this model it is seen that there are 2 distinct breakup regimes are observed that depends on the bubble size, and the bubble rate is bubble breakup rate is 0 for bubble size if d is greater than is equal to d max, and the bubble breakup rate increases rapidly for bubbles if it is larger than the maximum stable bubble size, the breakup rate after reaching a maximum stable diameter if it is 1.63 times of diameter of maximum bubble stable bubble, and it is seen that this this breakup rate will decrease with the bubble size. So, this is very important for criteria that if your maximum bubble size is equal to this is 1.63 times of this maximum bubble size.

Then there will be a decrease of breakup rate with this bubble size, in the limit of very large bubbles if suppose d any bubble to the maximum bubble size is greater than greater than is equal to one; that means, if you are having that the diameter of any bubble, if it is greater than maximum stable bubble size, the surface tension force become very small, and the breakup rate can be approximated by in this equation here omega b will be is equal to this energy to the power this is 1 by 3, and the diameter of the class I to the power minus 2 by 3. So, this is very important criteria whether there will be a breakup will happen or not.

So, there are 2 distinct breakups regimes that we have observe here, one thing is that whether breakup rate will be 0 or not; that means, here breakup will not be there if the diameter is less than there the maximum stable size, and the breakup rate will increase if the bubble size bubble size is larger than the maximum stable size, if the bubble size is equals to the 1.63 times of maximum stable size, then it is seen that the bubble breakup rate will decreases with bubble size.

And if any bubble size is greater than, are greater than this maximum stable size, and it is seen that that the surface tension forces actually become very small and breakup rate can be approximate and approximated by this equation here.

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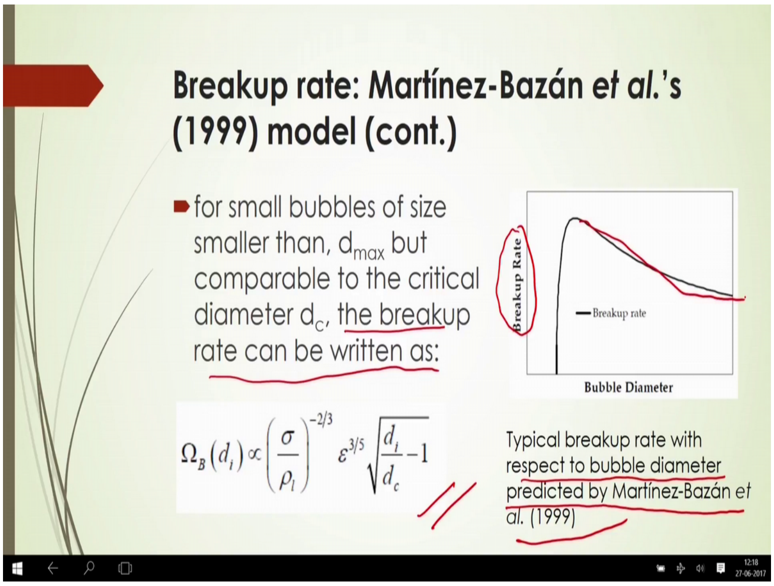

And for small bubbles of size if it is smaller than d max, but comparable to the critical diameter d c, then the breakup rate can be written as here by this equation, you can calculate the breakup rate from this equation now typical breakup rate with respect to the bubble diameter predicted y the Martinez Bazan et al 1999, they have given this bubble diameter if it is increases initially this breakup rate will be higher whereas, it is size is if it is decrease from it is maximum stable size the breakup rate will decreases here.

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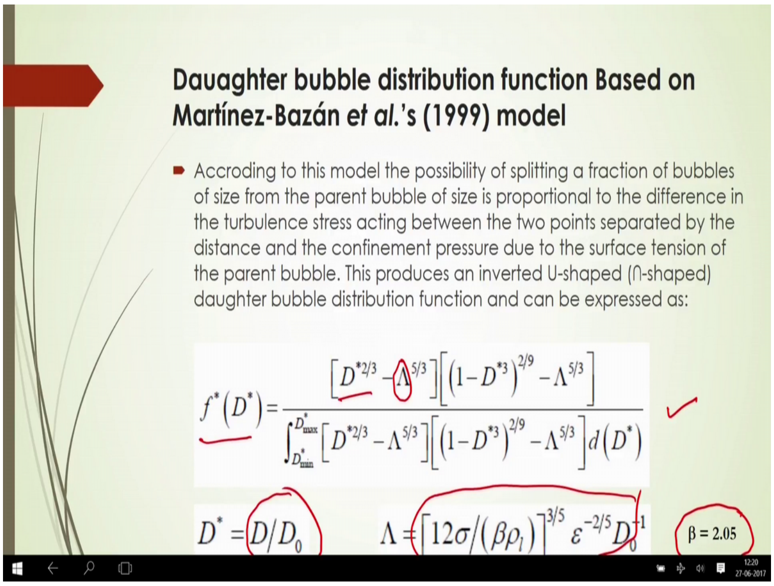

Now, daughter bubble decreases function based on Martinez Bazan et al model, how to calculate this daughter bubble distribution function, now according to this model the possibility of splitting a fraction of bubbles of size from the parent bubble of size is proportional, to the difference in the turbulence stress, that is acting between the 2 points that is separated by the distance and the confinement pressure, due to the surface tension of the parent bubble, this an inverted u shaped daughter bubble distribution function and can be expressed as this, this is f star D here this is a function of this bubble size critical bubble size or not critical this is called ratio of bubble size of D by D 0, D 0 is the initial bubble size and this is the lambda, this lambda is defined as this here this 12 sigma by beta rho l to the power 3 by 5 will be energy per mass to the power minus 2 by 5 into D 0, to the power minus 1, here this beta is a characteristic factor this is called 2.05 and from this then equation will be able to calculate what should be the daughter bubble size distribution function.

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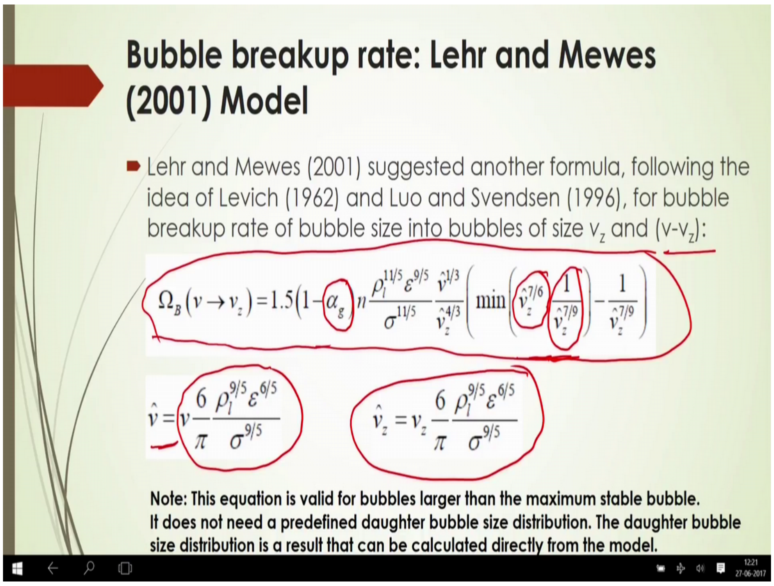

Now, lehr and mewes 2001 actually they have suggested another formula that following that idea of levich 1962, for bubble breakup rate of bubble size into bubble of size v z and v minus v z here. So, they have given this correlation to calculate this bubble breakup rate here as this. So, from this equation you will be able to calculate what will be the bubble breakup rate. So, in this case very important that there will be some criteria of this bubble size here, there will be this there will be 2 portions of this equation here, you have to calculate this minimum of this 2 from which you will be able to calculate the bubble breakup rate.

Of course all other factors that depends on that gas holdup inside the bed, and then v that is bubble size average bubble size to be calculated as this here, and this at a certain height of the column, now this equation is valid for bubbles larger than the maximum stable bubble size, if does not need a predefined daughter bubble size here and the daughter bubble size here, and the daughter bubble size distribution is a result that can be calculated directly from this model.

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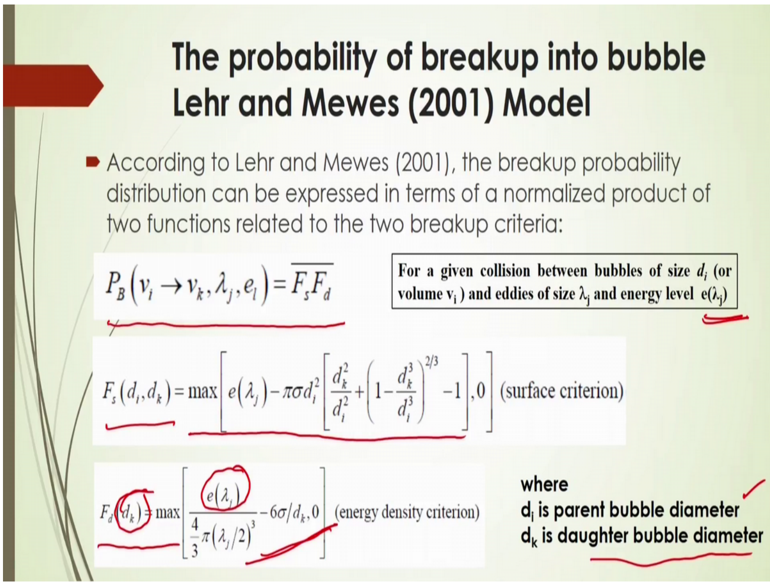

The probability of breakup into bubble as per lehr and mewes model, according to lehr and mewes the bubble breakup probability distribution can be expressed in terms of normalized product of 2 functions, that is related to the 2 breakup criteria. So, here for a given collision between bubbles of size d I, or volume v I and eddies of size lambda j and energy level epsilon lambda that is function of this lambda eddy size of j, then the probability function to be calculate as this P B that will be is equal to F s into F d bar, this F s F s this is called the surface forces and this surface forces is called this here this is depends on the size of the eddy, and the size of the bubbles and also of course, the surface tension of the solution.

And this F d this is called energy density criteria, or this energy function here in this case the kinetic energy of the eddy and it is size that is the main important factor because of which this breakup happens, and from this correlation you will be able to calculate what should be the F d, F d means the force due to the kinetic energy density, and this d I is the parent bubble diameter and d k is daughter bubble diameter. So, from this correlation you will be able to calculate what should be the probability of breakup into bubble.

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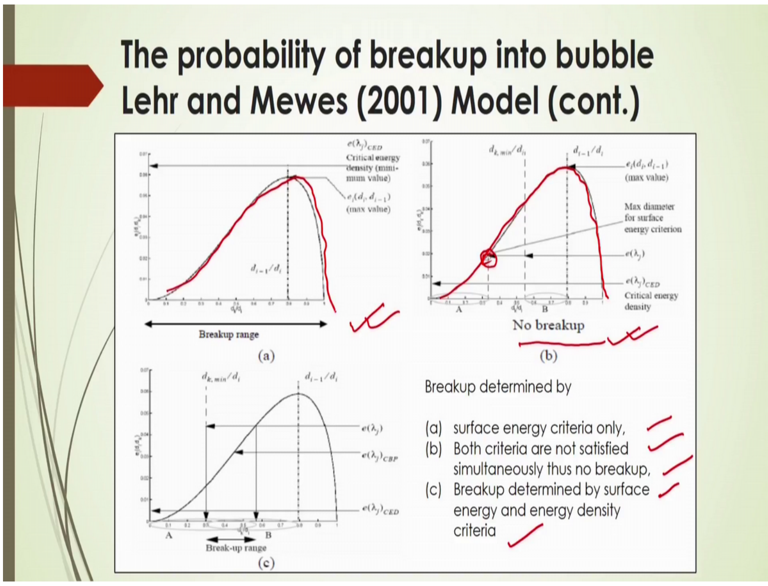

The probability of breakup into bubble as per lehr and mewes, they have presented this equation her it is seen that, this breakup range within this breakup range here how this probability function is there, if there is no breakup then this the profile for the bubble breakup and it will reset a critical energy density within this band and then maximum diameter for the surface energy criteria, here it will be there from this from this profile, and also this breakup determined by the surface energy criteria only both criteria are not satisfied simultaneously thus no breakup, and if the breakup determined by surface energy and energy density criteria then you will get this profile of this probability of the breakup into daughter bubble.

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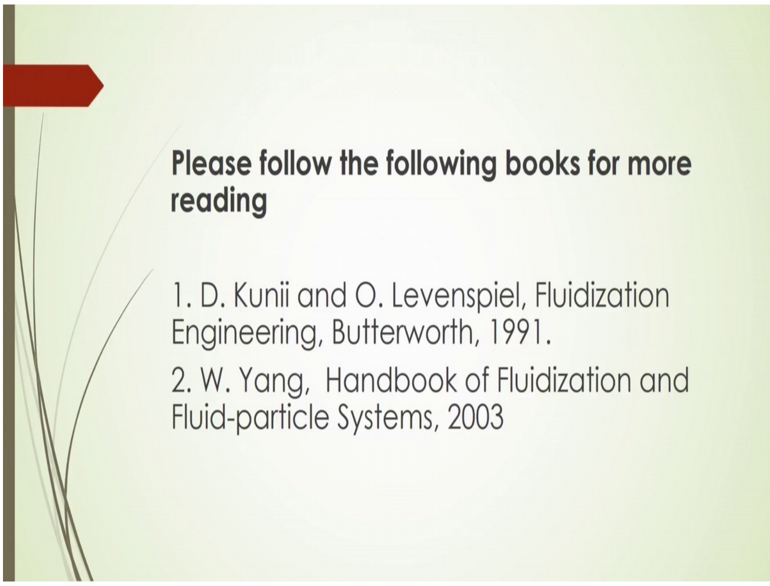

So, for this breakup criteria of the bubble in the gas liquid solid fluidized bed, more details you can obtain from this kunii and Leve spiel and also yang that is handbook of fluidization and fluid particle systems there for this. So, this reference of course, you have to follow for further reading and there are other research articles, by which you can get the more information about the breakup processes of the bubble in the gas liquid solid force.

So, from this lecture we obtain at least lesson of how this bubble breakup is possible what is the criteria of the bubble breakup inside the gas liquid solid, and of course, this 2 phase theories applied can be applied for 3 phase systems for breaking up the bubble, and mainly this turbulence and also surface tension force are governing to enhance the bubble breakup and also there will be some criteria, that whether this stable bubble size or not will be formed or not and based on the bubble stable bubble size if the bubble size is smaller or greater than the stable bubble size then, how to calculate the bubble breakup rate? How to calculate the probability density function? How to calculate the probability density function of the daughter bubbles?

What will be the breakup rate depending in the difference forces acting on the bubble? And, what will be the rate of bubbles that depend on the collision of the bubble? And also, what will be the deformation of the bubble and liquid surface. So, all those things are important to know to actually simulate the 3-phase fluidized bed, based on this hydrodynamics of the bubble breakup.

So, in the next class we will be calculating or how to actually the coalescence of the bubble will happen inside the bed, because of this turbulency and also surface tension forces and other if there is there another forces acting on that, that we will be able to know and also will be discussed in the coming lecture, and then after knowing this bubble breakup and coalescence of course, based on the coalescence bubble population balance equation will be applied to, calculate the phenomena of the bubble breakup and coalescence, and the distribution function of the bubble inside the fluidized bed. So, you can get the more information from this literature and the books that that is given here so.

Thank you.