Fluidization Engineering
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Lecture – 21
Entrainment Characteristics (Part 2): Elutriation Characteristics

So welcome to massive open online course some fluidization engineering. This lecture will be on elutriation characteristics in the fluidized bed. We have discussed the entrainment characteristics in the bubbling as well as a first fluidization condition.

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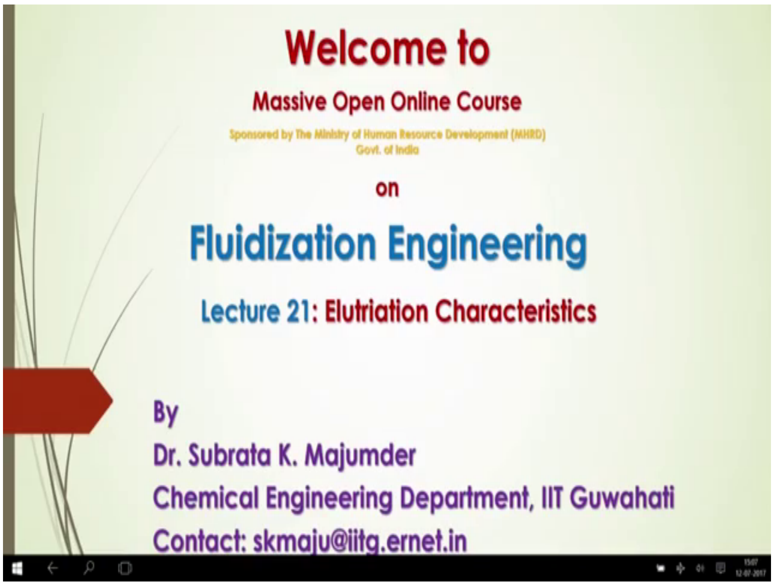

So, this elutriation characteristics also is the same way to discuss how to actually the particle is separating along the axis of the bed. Here also that mechanism is the same way that, the fine particles will be just segregating from the fluidized bed along the axis and the entrainment mechanism also will be some extent it will be useful to analyze this.

So, what is that actually elutriation? Elutriation that defined as the classifying effect of the fluidized bed entrainment it characterizes the selective removal of the particles of individual size from the fluidized bed. So, this is the definition and this elutriation way it is generally being denoted by notation W s.

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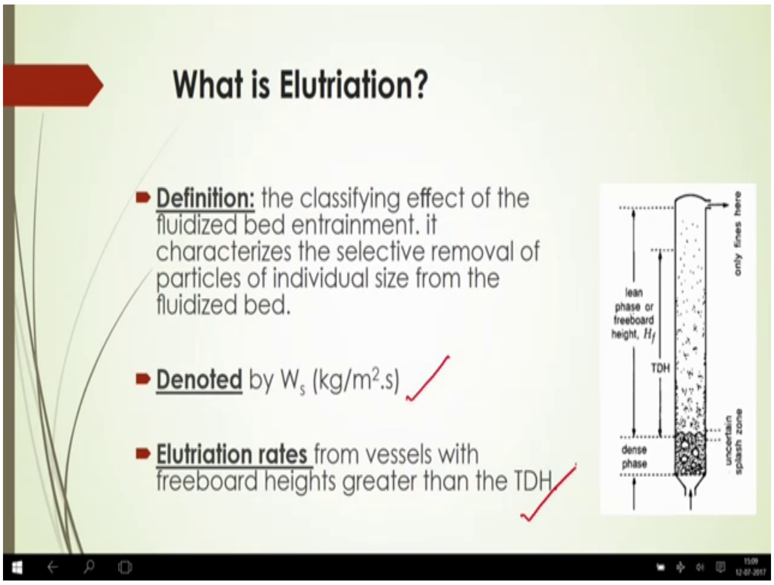

Which is exactly the unit for that solid flux here; W s unit is the; that means, kg per meter square second. And this elutriation rates from the vessel with freeboard height is greater than the TDH that will be should be remember.

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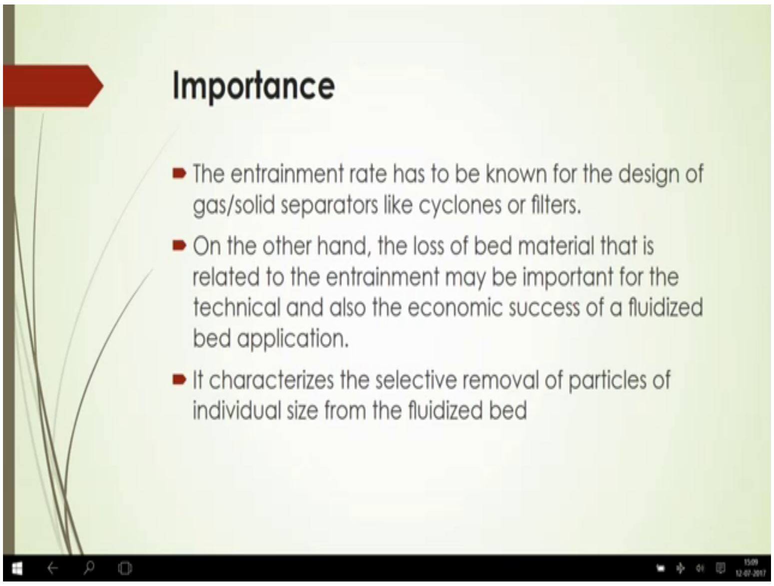

Now, what is the importance that for which you have to know that elutriation characteristics in the fluidized bed. Now you know that entrainment rate that has to be known for the design of gas solid separators like cyclones or filters, in the same way elutriation is also important because this give you the classification of the solid particles which particles will be go up, which particles will go down what should be the interaction of the larger particles or coaster particles with the smaller particles and because of that interactions, how the solid particles will be segregating by the entrainment mechanism there.

On the other hand, you can say the less amount of a solid particles will be coming down, relative to the finer particles if there is high interaction inside the bed and there will be a formation of the fine particles because of the interaction. And in that case, the very fine particles will be coming out easily relative to the coaster one. But if coaster one particles the strength of the particles actually in main factor if the strength of the particle is not that much enough. So, that the coaster particle sometimes by their individual interactions may be forming finer particles and then it will go up.

So, based on which that you can say, how the solid particles also will be segregating from these two classes of the particles there. So, the loss of bed material that is related to the entrainment may be important for the technical and also the economic success of a fluidized bed applications there. Sometimes you have to operate the fluidized bed in such a way that, there is no enough elutriation or there is no attrition of the solid particles because of which that, entrainment characteristics will go down. So, sometimes this fine particles the internal circulation of the fine particles is required for the better transport operation and in that way, sometimes the a economic operation of the fluidized bed can be done in such a way by designing without considering and those entrainment and elutriation characteristics of the particles inside the bed.

And it characterizes the selective removal of particles of the individual size from the fluidized bed. If you are going to segregate the particles from this bed, then there will be a certain selection or selective removal of the particles of the individual size from the fluidized bed by this elutriation mechanism.

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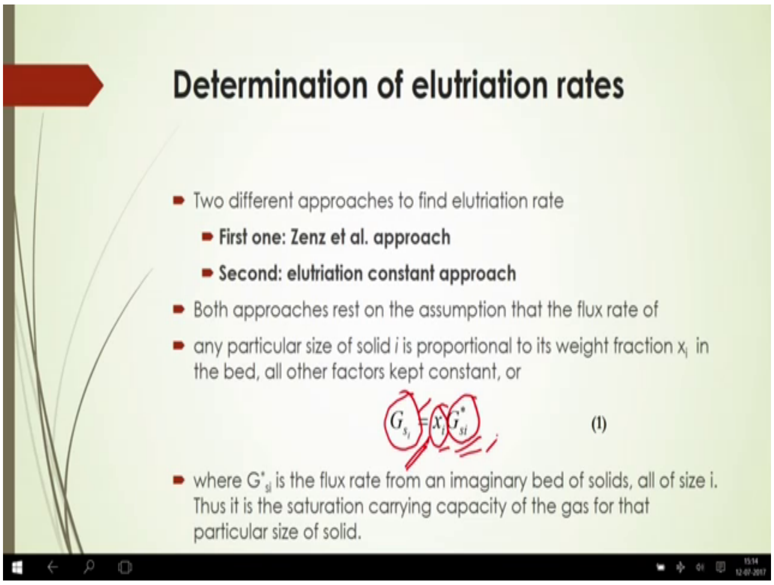

Determination of the elutriation rates you have to know, how to actually estimate the elutriation rate. Two different approaches actually you will get to find the elutriation rate, one is called that is Zenz et al approach, another is elutriation constant approach.

Now, both the approaches actually based on the assumption that the flux rate of any particular size of solids i is proportional to its weight fraction x, in the bed, and all other factors kept constant. So, this is very important that you have to know the elutriation rate. Generally in the literature it is given two types, one is Zenz et al model another is the elutriation constant model there; in that case, for both the cases you have to actually assume that the flux rate of any particular size of the solid that should be proportional to the weight fraction of that particular classes solid in the bed.

All other factors if you are keeping constant and G s i is equal to xi Gsi star in that case, Gsi star is the flux rate from an imaginary bed of solids all of size i thus it is saturated carrying capacity of the gas or that you can say that the exit concentration dilute exit concentration at a fixed rate there and for that the particular size of solids will be coming out from the bed.

So, in this case the rate of the elutriation you have to calculate by this denoting by G s i for this particular class of particles, that will be is equal to xi into Gsi star. So, i means here class of particles, at a particular class of particles here i. So, Gsi means here, the solid entrainment of that particular class; that means, if the particle size is suppose d p i;

that means, that class then it will be represented that finer or coaster of that particular classes that will be is equal to, what should be the weight fraction of that particular classes i particle? And also, what should be the carrying capacity or saturated carrying capacity of that particular gas for those solid particles of plus i?

So, from this equation we will be able to calculate the elutriation rate.

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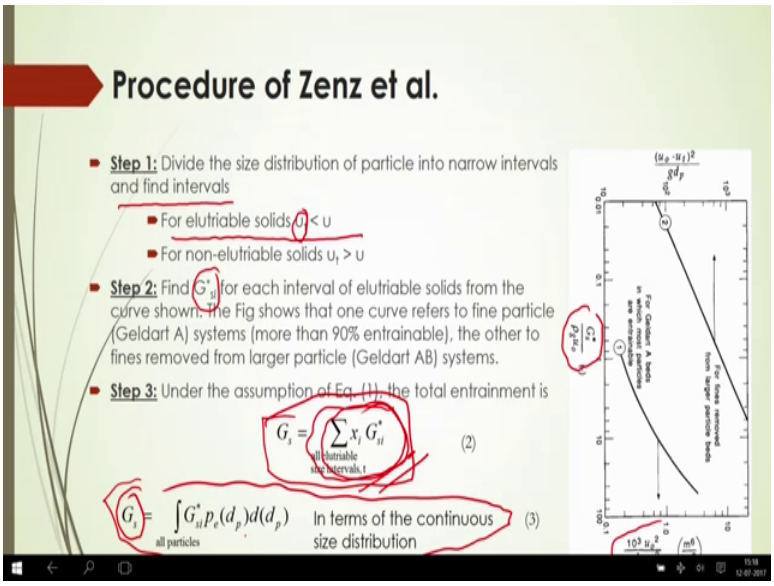

Now, Zenz et al model, as per that Zenz et al model you will get the different step to calculate that elutriation rate here. Now as a step 1, you can say that this distribution of the particle that will actually role enough there. So, you have to divide the size distribution of the particle into narrow intervals and then you have to find the intervals in such a way that, for elutriate for elutriable solids; that means, U f is less than u; that means, here or Ut here.

So, this U t elutriable solid in that case, the terminal velocity should be is less than a fluid velocity, then only those solids will be elutriable. And for a non elutriable solids, the terminal velocity of the solids will be is greater than fluid velocity of course, the coaster particles those are all those a terminal velocity is higher than the fluid velocity those particles will not be entrained at all.

So, it cannot be actually elutriable or cannot be segregated from the fine particles there. And if it is less than suppose terminal velocity then only it will be elutriable and then those particles will be segregated from the coaster particles whose terminal velocity will be higher than the fluid velocity there. And in the step 2, coined then G si star for each interval of the elutriable solids. So, first you have to find out which one is the elutriable, just from the terminal velocity of the solids and what will be the fluid velocity, whether it is greater or less than then you can find out, which one will be the elutriable.

Once you know the elutriable solids and then find the, what is the G si star for each individual of elutriable solids from the curve shown here in this case. And this is this curve actually this figure is representing the, this saturated carrying capacity versus this what is that some parameters here. So, then from which you will be able to calculate, what should be the? So, this figure you can get it from that Kunil and Levenspiel also there it is given.

So, once you know this G si star from this figure and then you have to calculate the G s here from this equation like this here. So, for each class of particles you have to get the respective G s star. So, once you know that you have to sum up all this parameter here in this case. So, G s to be calculated by this equation 2. Here again, for this continuous size distribution you can calculate this elutriation rate by this equation, by this equation 3 here.

So, here G s will be is equal to integration, for all particles it will be G si star into p e into d p into function of p e as a function of particle diameter into d d p. So, in this case, you will be able to calculate, what should be the, that means, elutriation rate. This here p d p is nothing, but the particle size distribution function.

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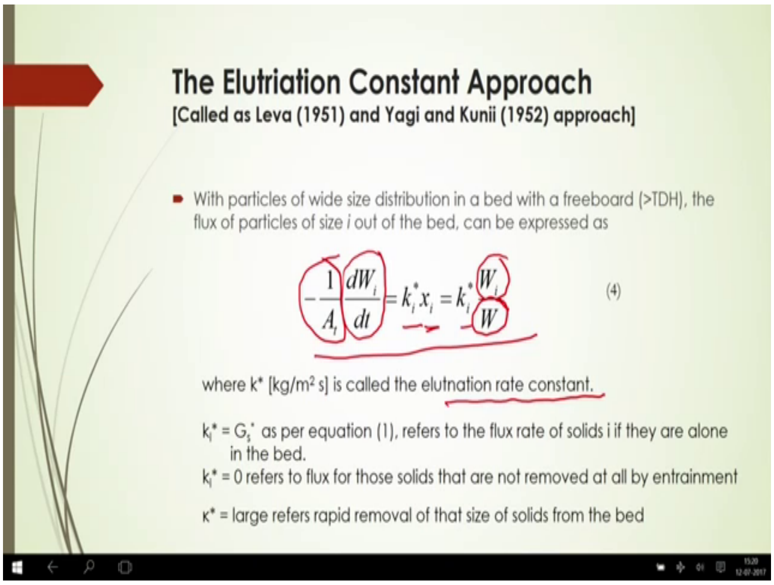

$$-\frac{1}{A_t}\frac{dW_i}{dt} = k_i^* x_i = k_i^* \frac{W_i}{W} \quad (4)$$

The elutriation constant approach here, it is called something is a Leva 1951 and Yagi and Kunli approach also. So, now, with particles of wide size distribution in a bed with a freeboard, which transport disengagement height is actually less than these a freeboard. The flux of particles of size i out of the bed can be expressed as by equation 4 here.

See here, this is the 1 minus 1 by A t, A t is the cross sectional area of the bed and here dW is the what would be the amount; that means, mass of a solids of size i, which is changing with respect to time, that the rate of that mass of this elutriation that will be is equal to k i star into x i or is equal to k i star into W i by W here. This x i is the mass fraction. So, this is W i of the W weight of the or mass of the i th size particles and W is the total mass of the bed here all for all classes.

Where k star is called the electrician rate constant, this k i star it will be is equal to G s star as per equation 1, which refers to the flux rate of solids I, if they are alone in the bed. And k i star will be is equal to 0 which refers to the flux for those solids that are that are not removed at all by entrainment. And k star that will be very large, which refers to the rapid removal of that size of the solid from the bed.

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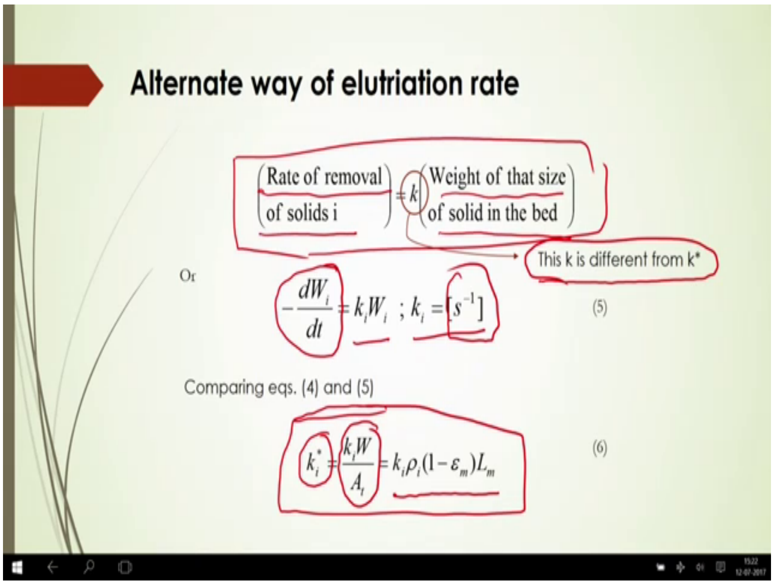

Now is there any other alternative way or not that there is one alternate way of elutriation rate that can be calculated, now if we represent this rate of removal of the solid of class i which is proportional to the weight of that size i of the solids in the bed, then what should be the proportionality constant that will be is k. So, this k is different from here k star.

So, if we represent this elutriation rate by this simple equation and this rate which is directly proportional to the weight of that size not weight fraction there. So, by in that case, this proportionality constant will not be the same as whatever in the previous equation it is represented. So, or you can say that minus dW i by dt will be is equal to k i W i, k i the unit will be a second inverse here. So, comparing this 4 and 5 equation number, then k i star what will be is equal to k i W by A t, it means cross sectional of the bed and then it will be is equal to k i rho i into 1 minus epsilon m m into L m.

So, from this what should be the relation between k i star and k i you can get it. So, k i is simple that it is that elutriation directly proportional to the weight of the solids whereas, k i star it will be represented by that the rate equation will be actually proportional to the mole fraction or you can say that is are the weight fraction of the solids of class high there.

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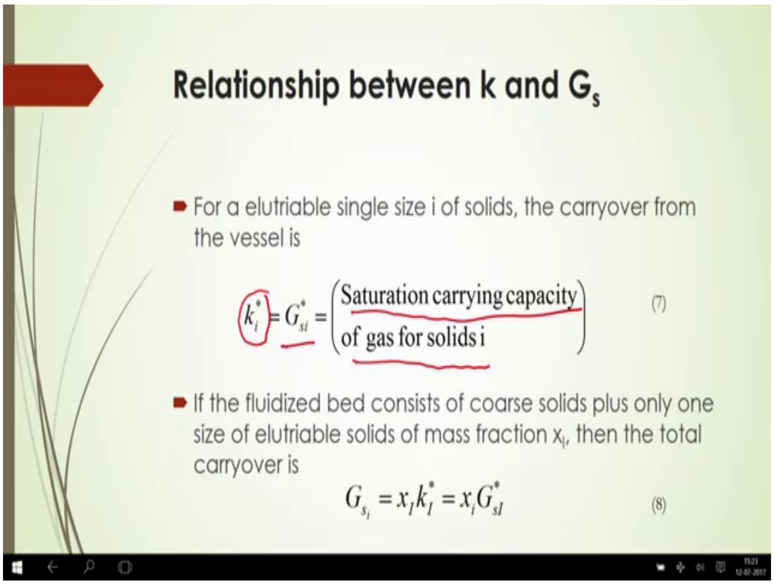

Now, significance of this k i and k i star, that is the elutriation rate constant. Now k i star is equal to G s star as per equation 1 which refers to the flux rate of solids, if they are along in the bed. And k i star is equal to 0 which refers to the flux for those solids that are not actually removed at all by the entrainment. And this elutriation rate will be very large if the rapid removal of that size of the solids from the bid bed is happen and k i varies inversely with a bed height. In batch or unsteady state in experiments it is seen that, k i should change during a run as the bed weight W is changed.

On the contrary, you can say that k i star is unaffected by these changes. It is the true rate constant and is the quantity to use when reporting data and presenting correlations there and relationship between k and Gs. For a elutriable single size i of solids, you can say the carryover from the vessel is represented as this k i star, that will be is equal to G s star are is equal to saturation carrying capacity of gas for solids i. If the fluidized bed that consists of a coarse solids plus only one size of elutriable solids of mass fraction x i, then the total carry over will be is equal to x i into k i star.

So, that will be is equal to x i into that means, G si star.

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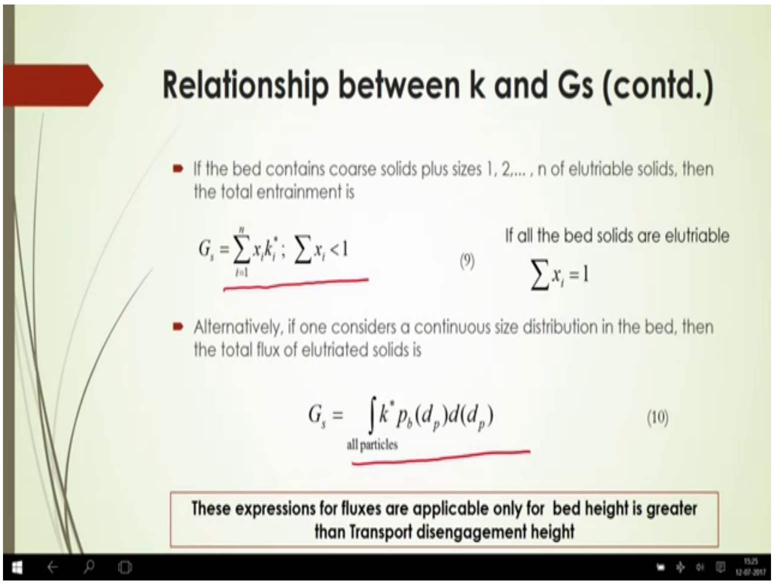

Now, here if the bed contains coarse solids plus sizes like 1, 2, 3 dot dot dot n; that means, n different size of a of solids which are elutriable and then, the total entrainment will be is equal to G s that will be is equal to their summation of i is equal to i to n, x i into k i star; that means, you have for all solid are classified a particles are there you have to sum up all those things.

Now, summation of xi should be less than 1 there, and if all the bed solids are elutriable then only you can say that summation of this mass fraction of all classified will be is equal to 1. Now alternatively, if one considers a continuous size distribution in the bed, then the total flux of elutriated solids will be calculated as these G s will be is equal to here k star into p b d p into d of d p here. Now these expressions for fluxes are applicable only for the bed height that is greater than the transport disengagement height. So, it is to be noted down.

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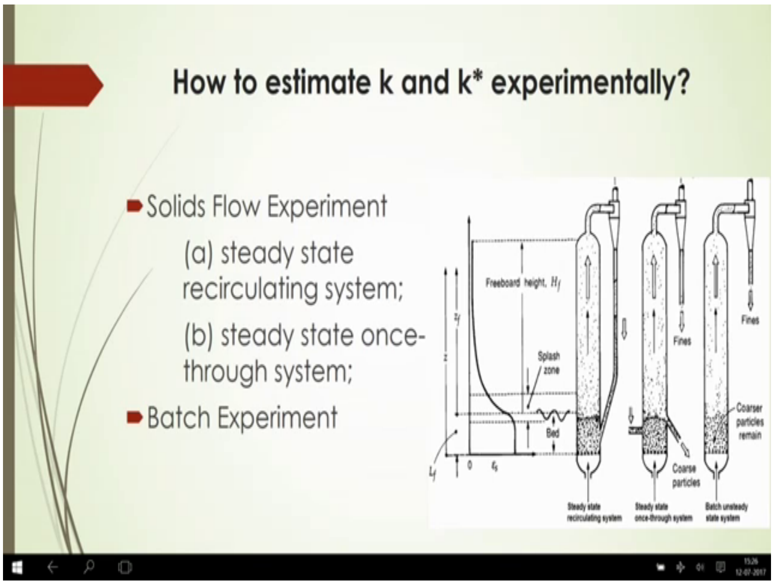

Now how to estimate k and k star experimentally? Now, solids flow experiments here you will see that one is steady state operation and steady state re circulating system and there will be a steady state once through system and another important experiment that as experiment. You can estimate this, this elutriation rate by this two types of a experiment there.

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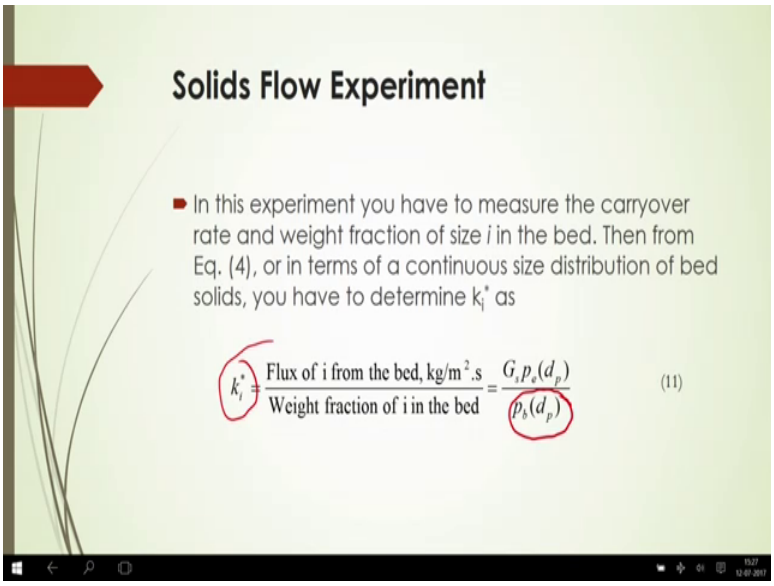

So, solid flow experiment as per solid flow experiment, you will see that you have to measure, the carry over rate and the weight fraction of the size in on the bed and then from equation 4 or in terms of a continuous size distribution, if it is given to you of the bed solids, then you have to determine k star as here this k i star that will be is equal to flux of i from the bed in kg per meter square second upon weight fraction of a weight solid particles in the bed.

And that mathematically you can say that G s into that means, p into d p; that means, a solid particle size distribution and divided by p b into d p here. This again this void fraction of the bed; that means, represented by this distribution.

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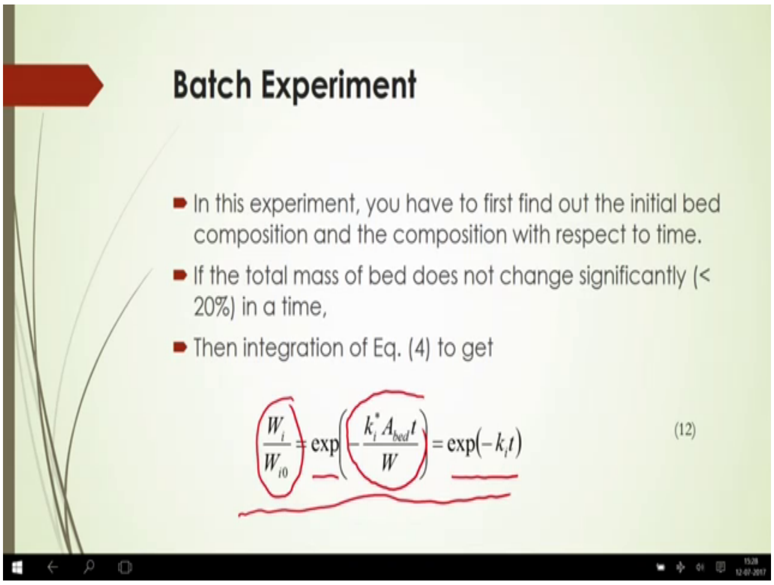

Now as per batch experiment, this experiment you have to first find out the initial bed composition and the composition with respect to time. Now, if the total mass of bed does not change significantly; that means, less than it is 20 percent in a time then integration of the equation 4 will give you that W i by W i0 that will be is equal to exponent of; that means, here minus k i star into a bed into t by W and; that means, your exponent of minus k i it.

So, from this equation 12, you can get what should be the actually a elutriation amount of solids of class i from this equation.

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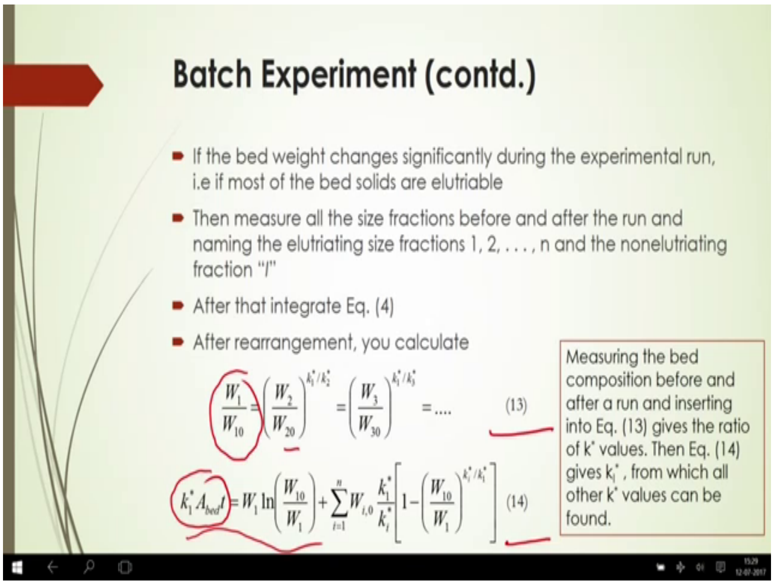

Now, if the bed weight changes significantly during the experimental run that is if most of the bed solids are elutriable. Then measure all the size fractions before and after the run. And rooming sorry and naming the elutriating size fractions 1, 2, to n and the nonelutriating fraction of i.

After that you have to integrate the equation 4, and then rearrangement you can calculate W 1 by W; W 1 by W i 0, that will be is equal to W 2 by W 2 0 and to the power k 1 star by k star is equal to this as per equation 13. And from which you can calculate that k i star, or that will be is equal to this as per equation 14, you can calculate this k i star.

Now, measuring the bed composition before and after a run, and inserting into equation 13 that will give you the ratio of k star values. Then equation 14 gives k i star here and from which all other k star values can be found here.

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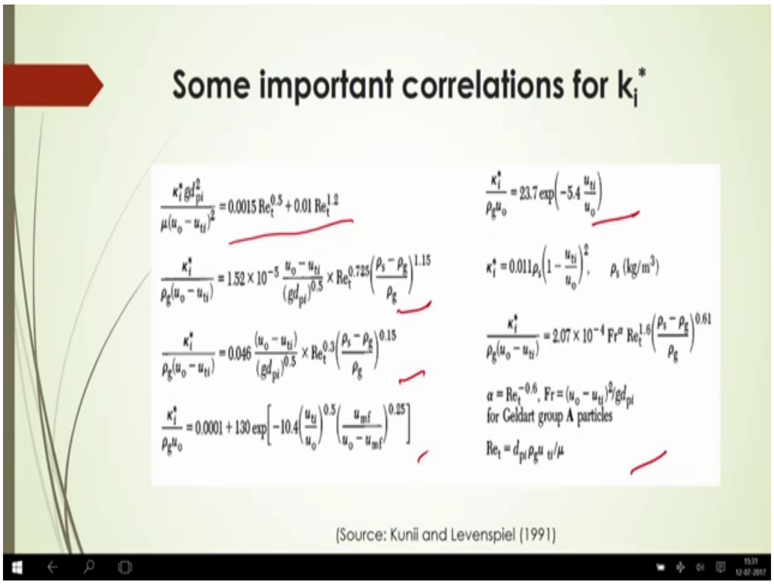

Now, some important correlations for k i star as per different investigators from the experimental results, it is given in Kunil and Levenspiel textbook and you can get. So, these are the different correlations from which you can get this k i star. So, this correlations will be helpful to know this k i star for designing any fluidized bed, and all this things they have all this k star k star given by different investigators. They have correlated this with the experimental condition like here terminal velocity of the fluid particle diameter and velocity of the fluid particle size, density of the gas, and density of the solid and minimum fluidization velocity, and also the terminal velocity for that particular classes of solids.

And also what will be the significant group, as per that is given this terminal reynolds number based on terminal velocity and a proud number based on that particle diameter, and also relative velocity of the fluid, relative to that terminal velocity of the particle and also based on different type of solids. They have also got the different correlations you can get more information from the Kunil and Levenspiel book for more correlations also. So, these correlations very important to calculate how to calculate the a k i star and from which, what should be the elutriation elutriable amount of solids in the fluidized bed for that particular operating condition you will be able to calculate.

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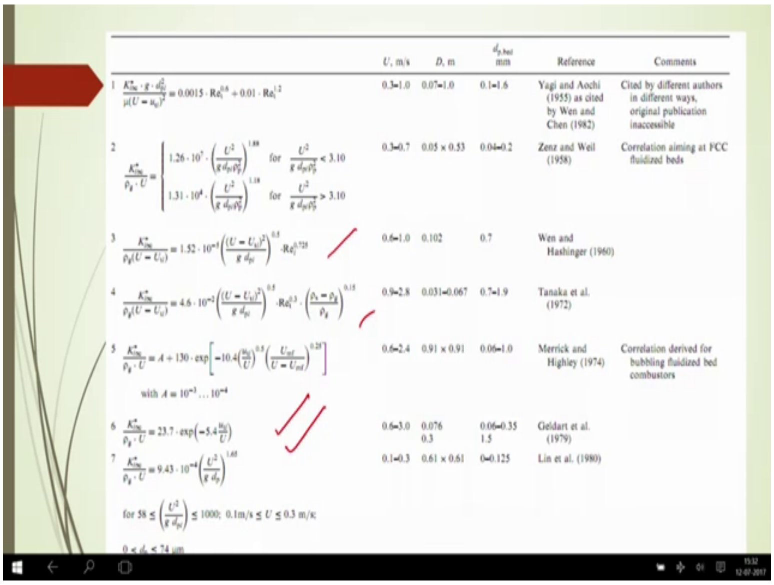

Some other correlations also given here, see in this table, there are different correlations also given for predicting the k i star in the fluidized bed from their different experiment and within a certain range of their particular experimental condition. As per different investigators, they have suggested different correlations and they also obtain that experimental results of this k star, based on their by using different operating condition and solid particles there.

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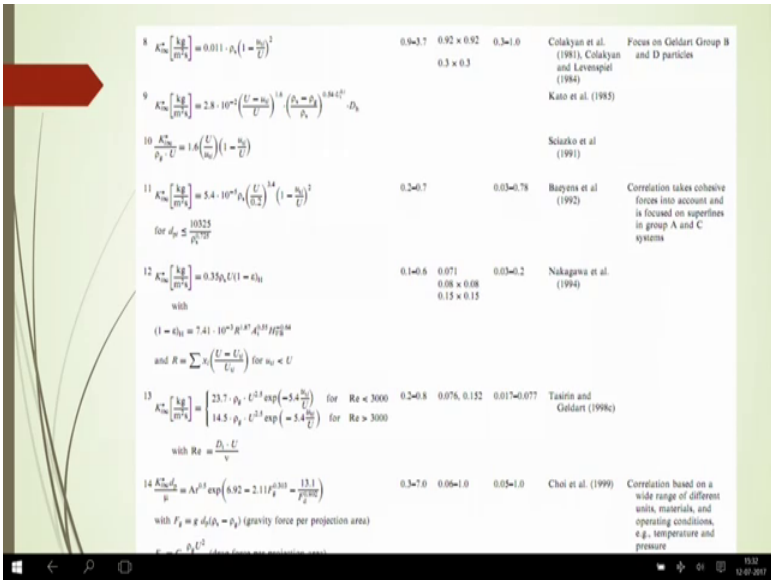

So, these are some other correlations by which you can calculate the k i star elutriation rate constant.

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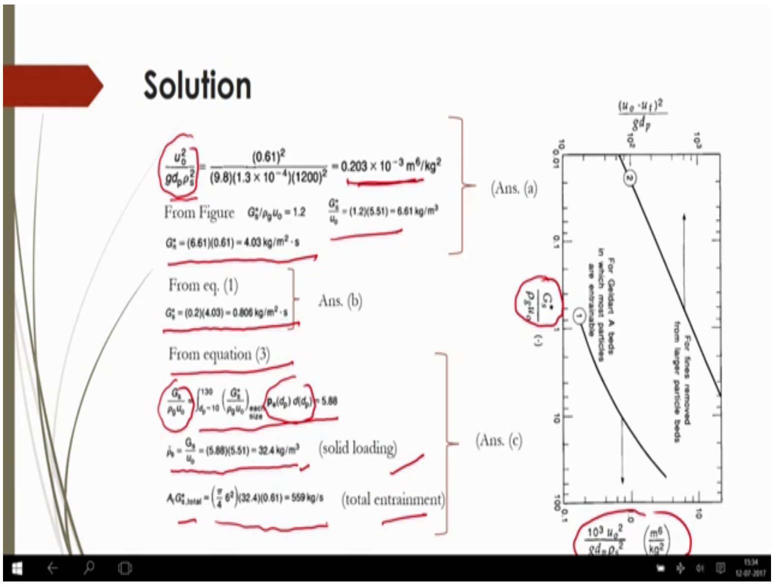

Now, let us see one example to calculate this elutriation rate there. Now a fluidized bed of 6 meter diameter is operating with catalyst particle under the following operating conditions. Here the gas density is given here, density of the solids and the fluid velocity is given, particle size is given, and the freeboard height is a considered is greater than transport disengagement height. So, in this case you have to calculate, what should be the saturation carrying capacity? Calculate the saturation carrying capacity for a bed in which, the fines constitute just a 20 percent of the bed solid. Calculate the total entrainment and the solid loading at the exit port of a bed of fine catalyst here.

And it is given that; this particle size distribution is that for different particle size here in the table, this function is obtained from this table for this P dp here. Now, just calculate the u this group u o square by g dp rho s square and once you know this value. So, from this figure, you just calculate what should be the group G s star by rho G ug for that particular value of this u square by g dp rho s square here and from which, you will be able to calculate, what should be the G s star?; that means, saturated carrying capacity.

And then from equation 1, then G s star will be is equal to this once and from equation 3, then G s by rho su 0 will be calculated as per this here. After substitution of this, what is that size distribution, and integrating with a size range obtained to 130 micrometer here.

And what should be the density of the rho s here, it is burg density of the solids here, it is given here, solid loading you can calculate from which. Then after that total entrainment amount you can calculate from this equation.

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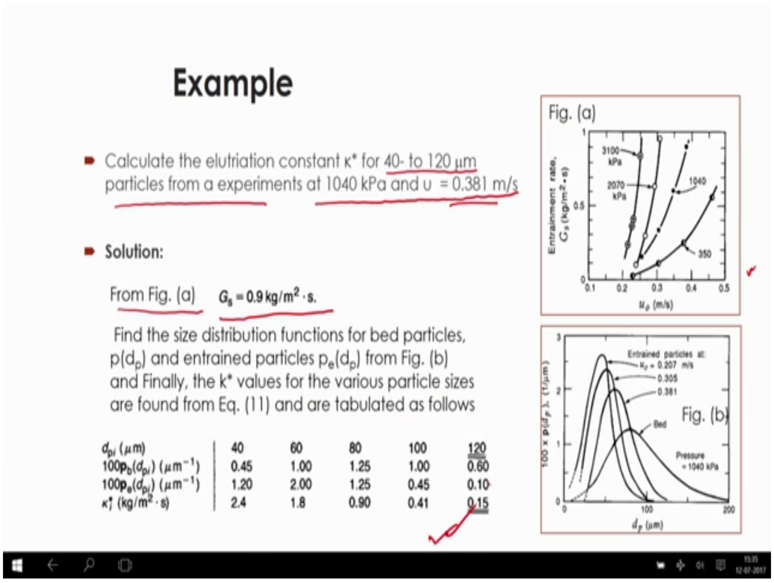

Now, what should the elutriation rate constant k star for 40 to 120 micrometer particles from a experiment at 1040 kilo Pascal and the fluid velocity is 0.381 meter per second. Now in this case, what is the G s? That it is very simple to calculate from this figure a, what should be the G s you can calculate with respect to this velocity of fluid here. And after that, find the size distribution function for bed particles, here p d p and entrained particles pe dp from figure b here. And Finally, then k star values for the various particle size are found from equation number 11 and are tabulated as follows here.

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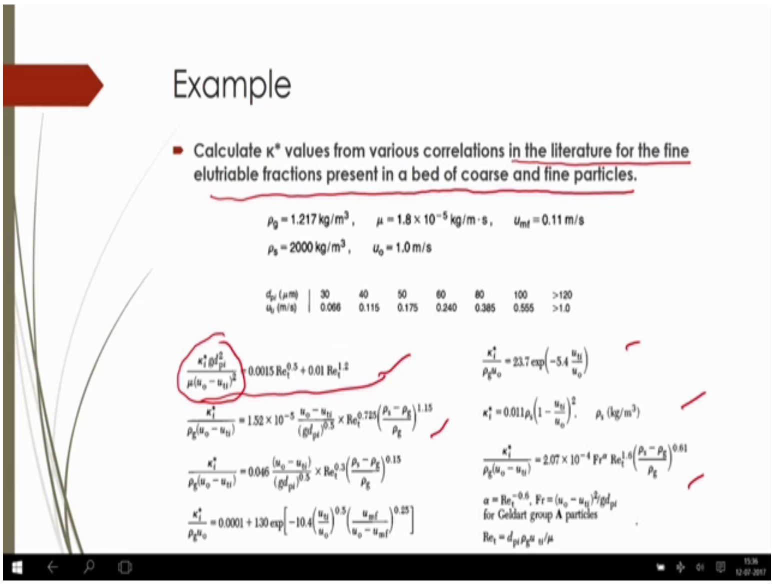

So, in this way, you can calculated the elutriation rate. Another example for calculate this k star values from various correlations in the literature for the fine elutriable fractions present in a bed of coarse and fine particles there.

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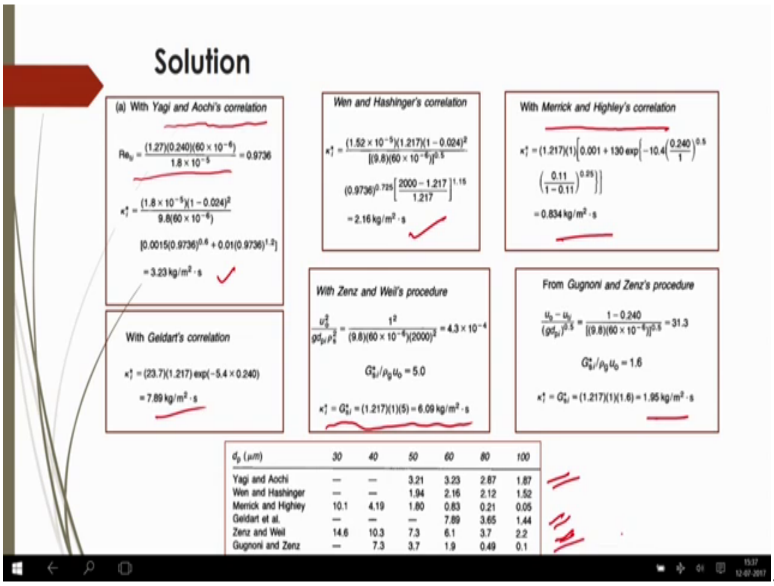

So, in this case, again you can calculate here this correlation value in this case and then different correlations you just use, these correlations you can use from this table and based on which, just you can get that with Yagi and Aochi's correlations this you can get this k i star as this. And here Wen and Hashinger's correlations you can get k star is equal to 2.16 whereas, with Merrick and Highley correlations 00.834 and other correlations will give you the different value like this here.

So, as a sum as a summary, you can get that if you increase the particle diameter, you will see Yagi and Aochi, it will decrease the constant for this elutriation and for Wen and Hashinger, it is seen that also here it will increase and then decrease. And Merrick and Highley, as per that, it will decrease decrease and decrease very it is substantially decreasing that with respect to particle size. Geldart et al it is seen that, also the particle size will decrease the elutriation rate. Zenz and Weil it is seen that, that as per the particle size again this elutriation rate will decrease, but Gugnoni and Zenz et al as per their calculation purpose the correlation to seen that also this d p will decrease the that is rate constant there.

So, very interesting that, we can then calculate what will be the elutriation rate from this lecture, and what is the elutriation rate? What are the different methods to calculate or estimate the elutriation rate and what is the elutriation rate constant and based on the different experimental condition how, how this elutriation rate can be estimated by different correlations that we can get from this. So, this will be helpful for the design further information and further understanding of the fluidization phenomena inside the bed ok. So, next class on what will be our next lecture will be will be something else on that fluidized bed we will be discussing later on.

Thank you.