Mass Transfer II

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Lecture No. # 34

In today's lecture, we take up this new topic adsorption in packed bed column. So, essentially it is a continuous adsorption column, what we had earlier class? In the earlier classes including the examples, which took those we are on a stage wise. So, we have when a packed bed absorber some a stirred vessel in which we brought a feed in a batch system. And contact we say charcoals adsorbents; we gave them enough time - equilibrium time. Then, we took out this stream, the treated stream brought to the second stage, where again we brought the fresh adsorbents gave them some contact. So, that is how we treated our influence.

So, that is a stage wise processes, and what we do today? In today's lecture is absorption in fixed bed column. So, we have a continuous packed bed column. So, certain length, column, horizontal or we can have a travel packed with molecular, sieves, zeolites, charcoals, alumina, silica etcetera., And then, whatever gas or liquid we want to treat which is contaminated we certain solutes is fed to the column, and then we can imagine that as the adsorption progresses. There is some wave or a front which moves from one end to the other end as certain regions of the bed is starts getting saturated. So, as to begin with it is a fresh column. So, when you bring in contact with the feed which has to treated, then first the region adjacent to the inlet we will get saturated.

Then the next region will get saturated. So, essentially are there is some wave which moves propagates from one end to the other end till the entire column gets saturated. So, it is a continuous packed bed column. Now, you also recall that first few lectures, we had we had setup a very extensive mathematical expressions.

So, first we started with a species balance, we took a differential elements in a packed bed column. We wrote in a expression for a species balance at what rate is species is brought by convection, by diffusion, by dispersion, so that is one balance; in the bulk phase liquid or on gas phase. Then, we had a balance in the solid phase. So, we have the porous adsorbents, so we have to write on a balance with in the spherical adsorbents.

Then, we had one more balance for rate adsorption, and desorption at the pore wall. So, essentially we had a very extensive mathematical set of partial differential equations or ordinate differential equations which have to be solve with certain initial conditions, boundary conditions. It is a very - very mathematical regress, but this course we said that we avoid the type of problem. Of course, we talked about mathematical approximations - one can make one D approximation, 2 D approximations.

We talked over LDF - linear driving force approximations. In today's lecture, we also talk about one of those approximations, except that we bring in two new parameters which is very handy, very - very good engineering parameters MTZ. So, mass transfer zone, and LUB - length of unused bed. So, these are the two new parameters which will be address in today's lecture, and we will see how we can use them to a scale up in a scaling of a packed bed column.

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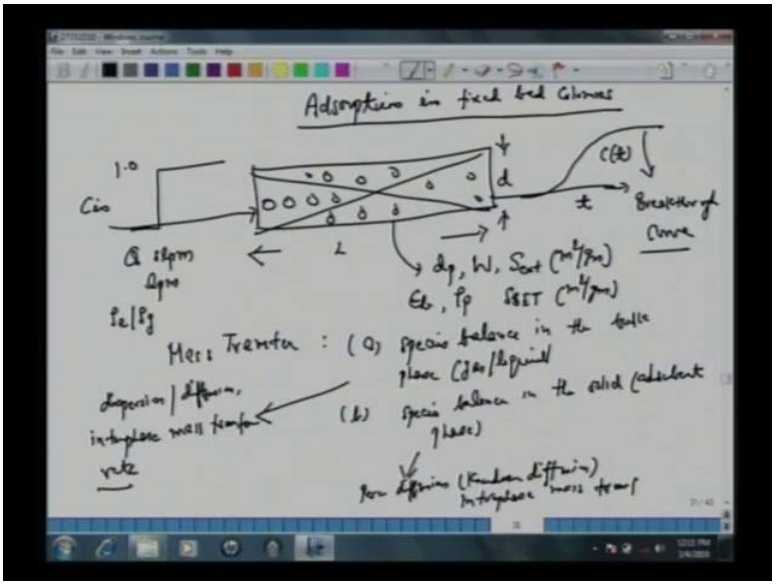

So, today's lecture it is on continuous packed bed. It is an approximations of a very regress mathematical; otherwise, you will have very regress mathematical expressions, but now we will address these two quantities next class. So, let us begin with this today's lecture adsorption in fixed beds or fixed bed columns. So, these are all packed bed columns.

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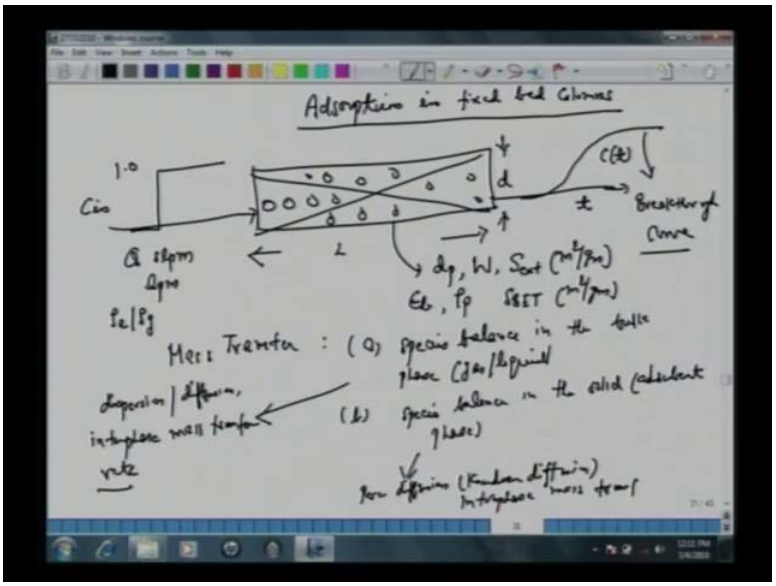

So, systematically may you have a tube or column could be vertical as well packed with the adsorbents. So, these are let say adsorbents packed in this column. It has length say one we have diameter d particle diameter. Let say, it is d p, let say total quantity is weight kg, we can have external area s external beta square per gram. We can have b t area, total area for adsorptions, meter square per gram weight porosity epsilon b, particle density rho p, and here we bring in contact or we challenge this packed bed which is initially clean fresh no solute inside which certain level let say one here or C in.

So, certain flow rates Q is standard liter per minute for the gas or for the liquid we have liter per minute; we know the density rho l and rho g. So, we bring in contact here, and we are interested in monitoring in this concentration profile C with time, what is it profile at the end outlet it changes of course, if you recall in our lectures we call this as a break through curve, and we had a very regress set of equations. So, break through curve or we have break through response here. So, in this case we will have to we want to address mass transfer. Then we have to make species balance in the bulk fluid in or in the bulk phase whether we have this gas or liquid. And then, we have to make this is species balance in the solid phase as well as, which is adsorbent.

And when we say species balance in the bulk phase then essentially we will have to put dispersion or diffusion, and what we call intraphase mass transfer by intraphase mass transfer rate here and when we write this is species balance in the solid phase then we are talking of pore diffusion. So, there is one (( )), because of pore diffusion our knudsen diffusion. So, were here we calling it intraphase mass transfer. So, we have intraphase

mass transfer, and we have the second setup equations, given by this intraphase mass transfer.

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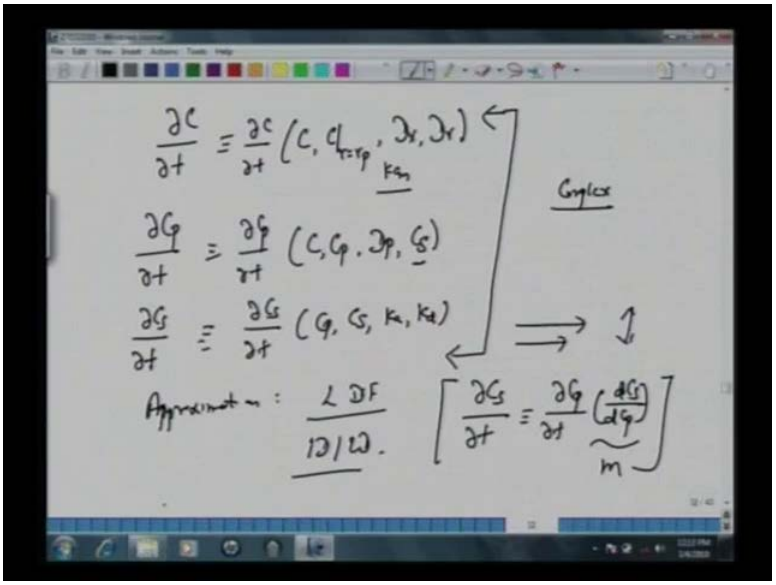

So, say for the first case if C is concentration we have del C over del t. this is as a function of bulk phase concentrations we also talking of concentration at the pore mouth we have dispersion in x direction, dispersion in r directions, mass transfer coefficient becomes another parameter here. Then one has to write the balance with in the pore of the solid. So, this is del C p over del t this will also be a function of say the gas phase or liquid phase; then inside the pores, we will have knudsen diffusivity or pore diffusivity then at the wall there is a rate at which species is getting absorb, desorb. So, C s is here is solid phase concentrations absorb phase. So, we have third set of equations which would be say function of gas phase concentration, solid phase concentrations, and maybe there is a rate of adsorption and a rate of desorption. So, all these three sets of equation have to be solve very regressly very mathematically is quite complex to solve.

Then we talked of approximations so, generally one makes approximations L D F is a very common approximation; linear driving force approximations 1 D, 2 D model etcetera; essentially, what we use here we assume the rate of change in the surface phase concentration is very fast; another words, one can write as rate of change in the gas phase or pore phase in the in the pores, and then we have d C s over d c p as slope of this isothermal. So, one very common example: is that we assume that all rates are quite fast everything is control by at the end rate of adsorption and desorption. So, they are similar, and different ways of approximations, we said that, you know we will for this course, we

will make only very simple calculations the one very common calculation here a simplified is concept of this MTZ.

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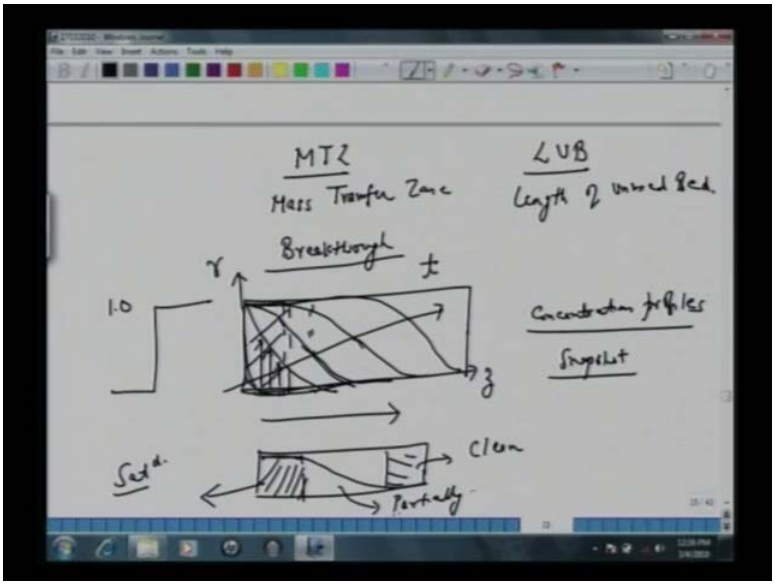

So, how about we are talking today's lecture approximations for a scale up scale up or a scale down or packed bed columns. So, here first let us introduce two terminology MTZ, which mass transfer zone, and here we have one more LUB length of unused bed unused bed. Let us, address first here before this breakthrough we just now, we talked about break through is nothing, but the response at the exits of the column. So, suppose we have this packed bed here which is t equal to 0 it is fresh, and we have challenge this which certain concentrations say let say make it 1, 0, 1.0, non dimensionalize. Then this is a z, and let us say that in the r direction concentration profile is negligible so to begin, you will expect that first certain this region will get saturated, and slowly, and slowly, this other reasons will get saturated, and there is wave or front is going to move from the left to right directions. In another words, if you want to plot concentration profile you will expect similar to this at different time different timing.

So, to begin with it was 0, now it moves in these directions now it moves in this directions. So, concentration profiles slowly, and slowly, it moves in this direction. So, this would be increasing time. So, that the bed is actually clean or very clean here. Then some more region gets challenge or gets income is come get saturated. So, concentration level raises then we have this another moment here. So, slowly this bed is now till here, if we talk about this profile, this now entire bed is now saturated here. So, essentially we have this concentration profiles. So, if you take some snapshot. So, depending upon

when you have taken the snapshot, you will expect that at anytime t arbitrary we have profile something like this.

This bed is now saturated and till here all these beds are now clean. So, it is a clean bed, and this is saturated bed here. Some zone is here some region where the bed is partially saturated you come back to this.

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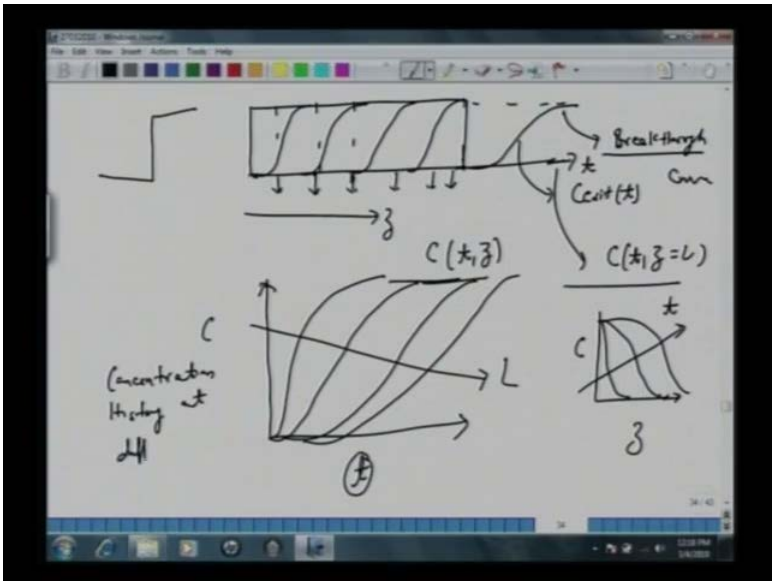

So, this is a concentration profiles or snapshot with time on the other hand. One can do some different type of experiments, if you have packed bed column, and we have challenge like this one can take let us say, one takes a sample from different locations. In other words, we want to monitor how a concentration profile changes here these locations, these locations or these locations. So, you will expect that as you go along this z length, then this length has got saturated earlier. If you take monitor the concentration here. Then this has taken off slightly longer time, it has taken a longer time like this, and at the exit we have a profile like this. So, this is what we call break through response in practically, what happens will cannot take the samples all the time for the different locations, because this will disturb or may disturb in the concentration profile insides. So very obtain, what we are interested in measuring concentration at the exit.

So, this is C exit with time; so, this called break through curve. So, we are saying their concentration is the function of time. It is a function of z as well, and what we are measured here. And what we are plotted here is c with different time at z equal to l. So, that is your break through curves, if you can plot all of this in one. So, we have profiles

like this like this like this. So, this is increasing length and this is timing. So, we are plotting it for different length, different times, and in the earlier, we had plotted C with along with z for different time where we got a profile like this so, you must understand. So, this is your increasing time, and this is increasing length, this way. So, this is your concentration history concentration history at different location. Now let us, come back to this exit concentration. So, we are monitoring the concentrations like this C over C exit.

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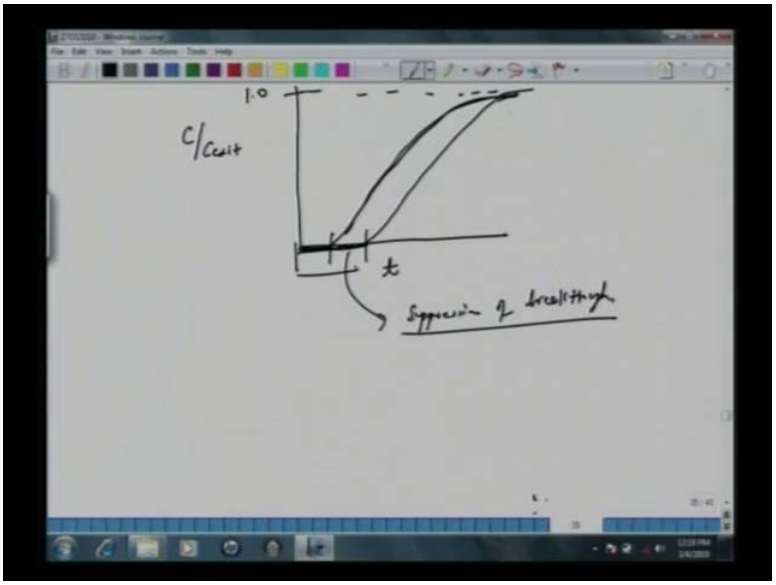

So, this is one this is time here when the bed become saturated then the concentration reaches same level as the inlet one unit, and what you will like in from the practical point of view. You will act to surprise this break through in other words, you will have to develop an absorbent which for the same conditions, which will increase this time. So, this called suppression of break through. So, this is what industrially point of view suppression of break through one has to optimize operating conditions or one has to choose a superior performance of absorbents which will increase the break through time from here to here. So, it is a suppression of break through.

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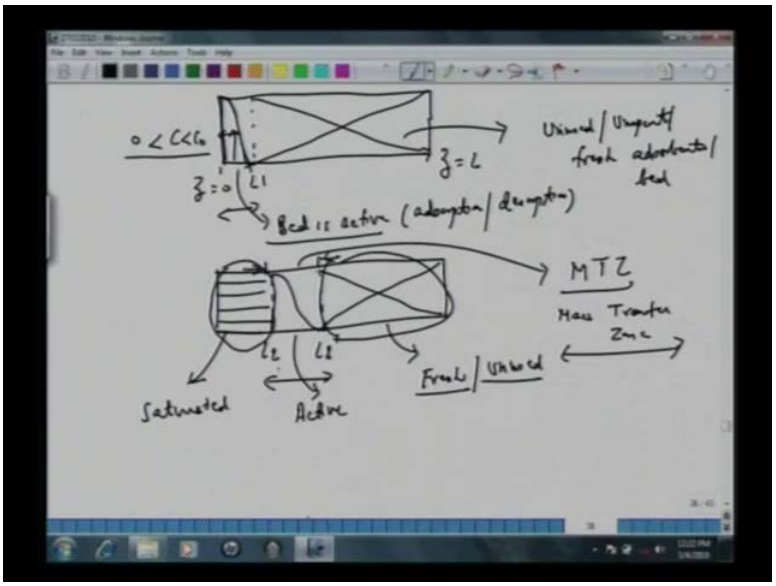

So, now, we will like to further discussion on this column - horizontal column, and let see at certain time the profile. So, this is increasing z here, this is z equal to 0, this is z equal to L, we have certain regions where the profile has gone like this. So, all it means that the end the entrance here is completely saturated, this level somewhere in between 0, and say L 1 concentration is in less than say C 0 , but its greater than 0.

So, this is a zone where the bed is active. So, when we say that the bed is active we are saying that there is absorption, and desorption, it is a reversal process. So, in this region there is an absorption and there is desorption; however, there is a region here where there is no activity. So, this is the region where we say that this is unused or unspent or it is a fresh absorbent bed. So, it is a fresh bed here.

Now, after sometime you will expect that now this column, this zone will further move. Now, some more bed region has been completely saturated. So, this is the region where the bed is now reason completely saturated and there is certain region here where there is an activity bed is active. So, look at this profile which was like this at the inlet now it has move like this and this is a region where the wave has not reach or the bed is still active. So, now let us mark this point let us call it L 2 prime, and L 2 here. So, this is the region where we are saying that the bed is saturated this is the region where the bed is active and this is the region where the bed is fresh or unused. So, this is what we call here is MTZ mass transfer zone.

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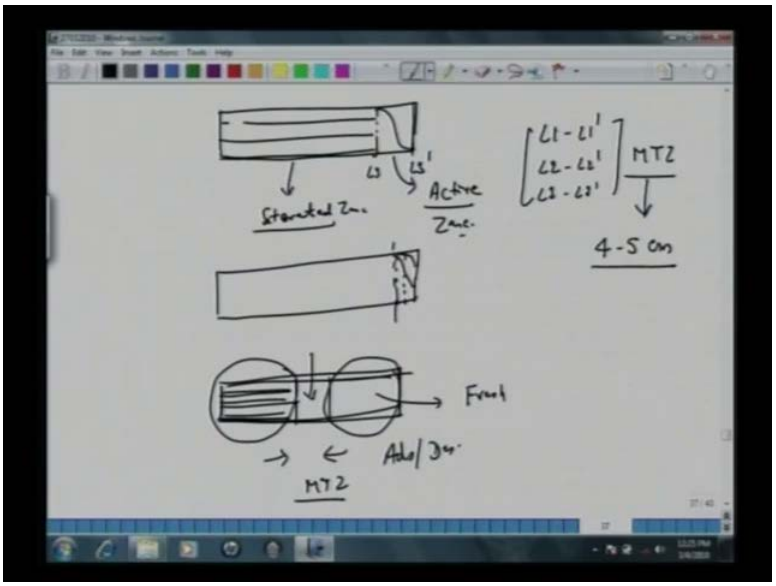

So, what is mass transfer zone it is a zone or certain region of this packed bed column which is dynamic in nature its moving its moving from here to here this locations it moves very thin region here and the reasons ahead of this is completely saturated and the region after this is fresh where the activity of absorption desorption has not yet arrived here. So, this is a region of mass transfer zone; we will see it is significance in you know in slightly. Now, if you plot further down. So, after sometime you will expect that now the bed this MTZ as arrived almost at the exit; that means, now the profile is like this, and this is a region which is now totally saturated.

So, this is a saturated zone, and this is a region where we say that there is an activity or it is an active zone here. So, now, we have region of l 3 and let say l 3 prime. if we further weight then of course, this MT which is going to go further smaller, and smaller. And this concentration profile will increase, and if increase, like this till the entire bed becomes saturated. So, as for our definitions we say that MTZ is say starting from beginning L 1 1 dash prime or L 2 L 2 prime or we have L 3 L 3 prime. So, that is a m mass transfer zone here, in reality it turns out to be that this mass transfer zone is very small or 4 to 5 centimeter. So, what is the significance of this number? If you have a column like this at anytime no matter how long is a column or how much is a quantity of absorbent here. There is only a small zone MTZ which is active this zone here is totally useless here it is totally spent. So, all its saturated this side here this zone it is not active it is a fresh absorbents; that means, is only region here where you have some activity or here you have absorption, and desorption. And this also brings this argument also brings

to another very important thing what we call is PI of process intensifications at so, without getting too much in details of these process intensifications. We are trying to say it here that since we realize that at anytime mass transfer zone is very small.

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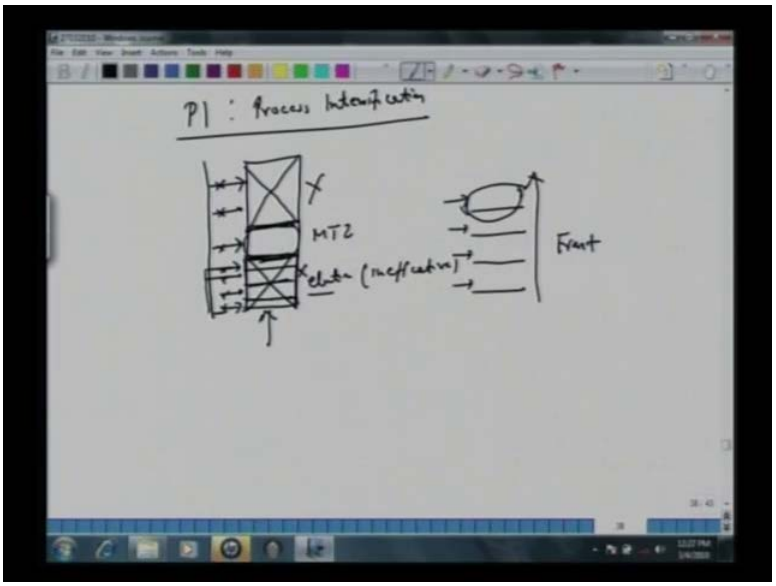

So, let say vertical column, we have this zone this MTZ, this is a region which is saturated, and this is a region which is unsaturated. So, to ensure that we make full use of this entire quantity at anytime one way of intensifying process is that one can bring this feed like this. So, this one example of process intensifications where we put some values in each of this stream, and as the wave propagates this feeds can also be moved upward up of this front. So, that at anytime whatever feed is brought it is in it is brought in contact with this mass transfers zone. In other words if you have the feed here then you will see that if this bed is saturated then entire this feed has to elute there is an illusions. So, essentially this is ineffective this zone, where nothing happens. So, it is a wastage of this spent regenerated a spent absorbent has to regenerate this. So, activated take place only here neither here nor here. So, there is one way of process intensifications which is quite interesting to note that.

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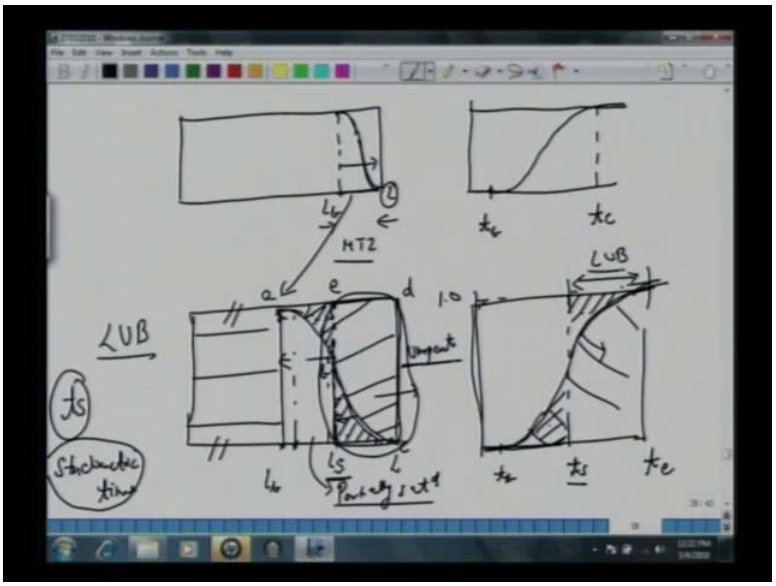

So, there is a wave which moves, which represents the front. So, there is a propagation of this front in these directions, and one has to make his feed move like this to ensure that in time, this feed comes in contact with this process. It is intensify essentially; one can show that we require a very small amount of absorbents in compression to this conventional process intensively not conventional process here. So, now let us go back to on this MTZ, we said that now we have a column, and let say no mass transfer zone has reach this level here at the exit. So, let us make a profile like this; this is MTZ mass transfer zone total length is l here, and let us mark this number as L b.

Now, when the wave reaches here or when the profile reaches that was the end, if you want to monitor the exit concentration; you will also expect that when it to reaches here we have certain time t b very 0 concentration or very small concentration obviously, and once this further moves this wave for the moves we will expect that this profile will also increase till this reaches one. So, if you call this as a t e this will correspond to this region l here. Now, let us expand this reasoning. So, let us take a larger view.

So, if you take a larger view here. So, now, we are saying that we have profile like this l b is a length where the break through obvious. So, the when the any observer he monitors when the wave has profile has reached here we will he still he monitor a very 0 a very small concentration, and as this moves here, he will monitor this concentration. So, this is l b this total length of the column let us put a break here we have all this region which is completely saturated. And when it becomes one, we have this t e with this time for equilibrium this is one we have plot in C exit over C in e. Now let see, what

this area represents here so, at if you choose this concerned level here just distance here then this is a level of concentration in, if you choose here, that means, this bed is partially active it is a partially saturated it has to reach one. So, one can say that this shaded region here represents the region which is unspent or fresh absorbents. This is a region which can say that this is partially region partially saturated.

Now, what we do we define 1 more quantity here is t s stoichiometric time. So, what is the stoichiometric time we are saying that lets draw another line here vertical line here at certain length l s corresponding to this will be another time here which is t s. So, that this area here is equal to this here. So, what is the meaning here, we are saying that this entire area of suppose we mark this is a, let say this is b, here c, d. So, a, b, c, d, this is the amount which represents are equivalent to the amount which is unspent. So, fresh, and now, I draw this line. So, that this area here a b c e is equivalent to l s b c or equal to l s b c. So, now, if I take this area and put it here as if I have now the entire region like this which is unspent.

So, all we have done we are saying that this area is partially spent partially saturated, because is this has not reached one, yet this is 0, here this is say 0.5 or 0.6 here. Now, all I do since this area is same as this area I can say that entire e t c l s b; this is the area which is unused and that we will call it as LUB. So, we have defined in length here L s. So, that this area is same as this, and we call it equivalent time on this exit concentration exit profile as t s is stoichiometry. Now, here also this area is now same as this area. So, if you define t e, when the concentration level has reached one, total area will be uptake will represent the amount of amount of solute which has been absorb, and this area will represent, and then this curve has a area which is totally unused. So, similarly here also the way we say that this area can we plot here this area can also be brought here. So, this will also represent very equivalent to this LUB length of utilize bed let us redraw this (( )).

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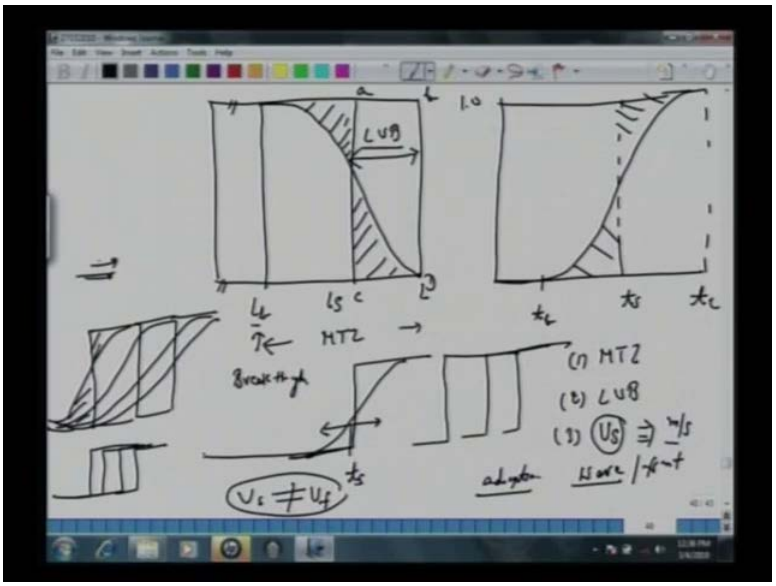

Now, we are talking of MTZ, and LUB. So, we will redraw this will take a let us make a break here. So, we have L b length corresponding to this b for break through. So, that we have a profile like this. This is MTZ this is a total length L e this area here is same as this area. So, that we can say that entire a b c d entire area is now fresh; it means, if the wave or the front is ideal or a stoichiometry we like this. So, break through curves, if you recall we said that profile propagates like this, why it happens like this. The another way of explaining that, if everything is ideal or there is no dispersions or all kinetics are fast here all rates are fast pore diffusion mass transfer coefficient, intraphase mass transfer, and everything decided by the rate of absorption, desorption, one will expect the front go like this. So, what we experience in you know particle sense we have the curve like this which is non-ideal kind of things had this when ideal our response of this break through curve would have been like this. So, there is a non ideality; what we see here is profile like this. So, there is certain region which become active ahead of this t s, and their certain region which is also active after this t s.

So, this all because of dispersion effect, at there we know dispersion effect you would have ideal situation like this front would have move like this, but now we have profiles like this. So, coming back to this we have defined, this L s length of a stoichiometric front we can call it an ideal front. So, that this area is here is like this, and we can say that the entire area here is unspent, and we call it l u b length of unutilizement. So, MTZ you can say that this approximately twice of this l u b equivalent to this, if you draw a response here. We have the front like this when the bed was here the when the profile

has reached in the last stage of this MTZ. There will be a t b break through time corresponding to this LUB there you will be t s. So, that this area is same as this area this is one here, and then finally, when the bed gets saturated we have t equilibrium. So, we are talking of this front we have introduce one MTZ. We have introduce the second quantity which is LUB, and we can also introduce another quantity U s, which is a speed of waves absorption wave or front say adsorption wave or adsorption front this also meter per second. Now, this u s is not equivalent do not equal to fluid velocity mind you this is absorption wave ideally the bed would wave would have been like this, but because of dispersion effect certain region in the bed gets active earlier, and certain region gets active greater than this t s.

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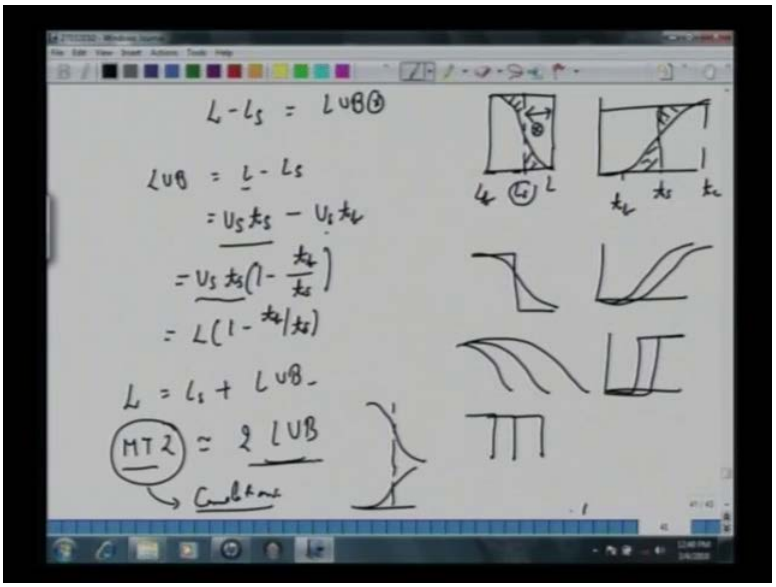

So, now we those introductions we can make some calculations here that one, if you look at minus L s is nothing, but LUB so, you should always keep these two figure in mind like this we have l we have L s sorry we have L b we have L s, and here we have. So, L minus L s so, l minus L s where is your L u b; this is star, and this is star and equivalent to this we have a stoichiometric time, where we have this t s where you have this t b, and now, you have this t equilibrium when the bed is completely saturated. So, LUB equals l minus L s, what is this length? Here at the wave would have been ideal at it reached here. So, we could have said, and since this area is same as this you could have said that the now the bed is completely saturated; that means, this L is nothing, but U s this speed of the wave into t s the time at which this area is same as this area. So, make a note here one is U s into t s minus L s. So, L s is here; that means, this is U s into t b.

So, let us try to understand this again the wave you have drawn like this ideally; the wave would have been like this the wave. It moves in the bed stoichiometrically, this should have moved like this would have been like this snapshot. Similarly, the break through profile is like this moves like this in the bed ideally would have moved like step functions. So, we define this quantity l s and we move this region from here to here or we move this region from here to here to make a note that we can write that these lengths get saturated, when the front has reached L s. So, that is u s at into t s, and then we have this L s which is would be U s into t b; the time at which the first break through takes place. So, that time the front is ideal front would have been writing.

So, we have U s t s minus U s t b length of unutilized bed, which is this you take common here U s t s we have one minus t b over t s U s t s is note down. Again it is l length total bed length is here 1 minus t b over t s or we can write L equal to L s plus LUB. We can also right MTZ as approximately twice of LUB why approximately, because generally, if the waves are symmetric like this or break through curve is like symmetric like this. It will be approximately, twice of length otherwise for to calculate MTZ; there are several co relations one has reported here. So, based on these arguments now we can taken example. So, before we take this example lets qualitatively discuss what we are said so far, we are talking of a non ideal response, because of dispersion effect, and we talked about this is a stoichiometric or ideal front in the weight moves. So, we define a quantity like t s or L s. So, when the wave reaches at L s has if entire bed is saturated. Because we choose the area accordingly. So, with this two quantities L s LUB, and MTZ .We will take this example also important to note here is that what is the uptake? Now this uptake also we have talk in our earlier class from the break through response, if we find the area above the curve that area should be equivalent to how much is the amount of solute which has been adsorbed. So, just for our own purpose lets go through that definition for this uptake or how do we calculate uptake from a break through curve before we take up this example here.

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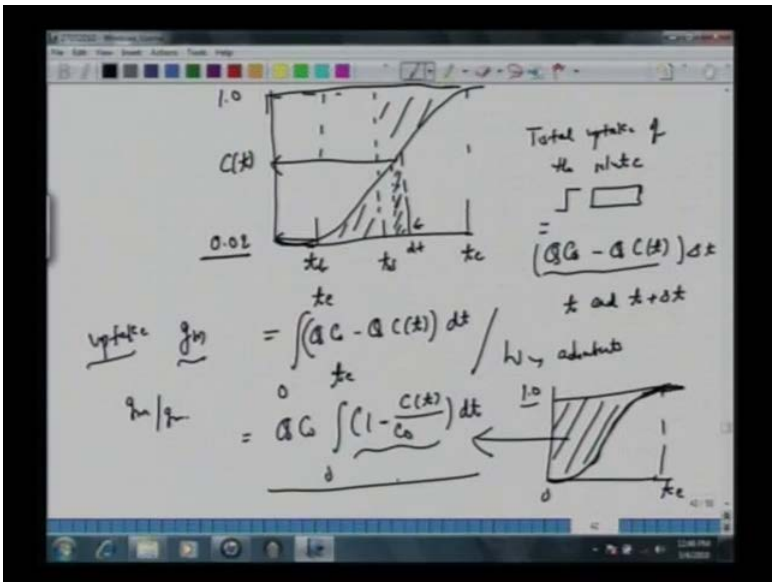

So, this is in the break through response here this is one, this is area if we say, it is very small t b. Now of course, break through is 0, and may be for our simplicity. We can say that, when this area when this response becomes 2 percent of the total response may be we can say that, now the bed has started breaking or the concentration or the bed has started becoming saturated one has to stop here. So, it is all will define here, whether it is a 10 percent, 20 percent for our purpose. We say that, it is 2 percent here; then we had drawn this t s stoichiometric time. So, that this area is same as this area. And then we had this t e now, if we want to measure how much is the total uptake takeoff this solute one has to make this balance across this column. So, Q is, if is the q is a flow rate C 0 say inlet concentrations, Q into C zero is species mass, which gets in for that solute minus Q C exit, which is a function of time here. So, this is the mass at the outlet multiplied by Del t.

So, essentially between here we have chosen time t arbitrary time, and we have this d t or del t. So, this is a concentrations c which is a function of time. So, we have in minus out. So, what happens to this area, this area is amount absorb between t, and t plus del t in minus out. So, that is the difference will give us how much amount has been absorbed between t, and t plus del t. So, if integrate this total amount absorb would be Q C minus Q C t d t from 0 to this t e. This will give us total amount of solute which has been absorb. So, this will give us, how much amount of give or uptake is called the uptake of this solute very often we express in terms of gram per gram; that means, total amount divide by the total amount of absorbents.

So, anyway coming back to this Q is a constant C 0 is a constant, one take out Q C is outside, and we have 0 to t e, 1 minus C t over C 0 d t. So, this a total amount of, and what is this number here 1 minus C t over C 0 look at this curve; this will give us, you should convince yourself. This is nothing, but the area above this curve. Let us, if we redraw here any break through curve, if you draw like this. If you measure this area, this area will corresponds to this starting from 0 to t e or for that matter it is t infinity. This all your first order this will take reach almost infinite time to reach one. Here approximately, may be it has reach 99 percent of 1 or exit concentrations. So, this is the total uptake now, if you know this total uptake on the same argument one can calculate how much is amount has been absorbed at the break through time.

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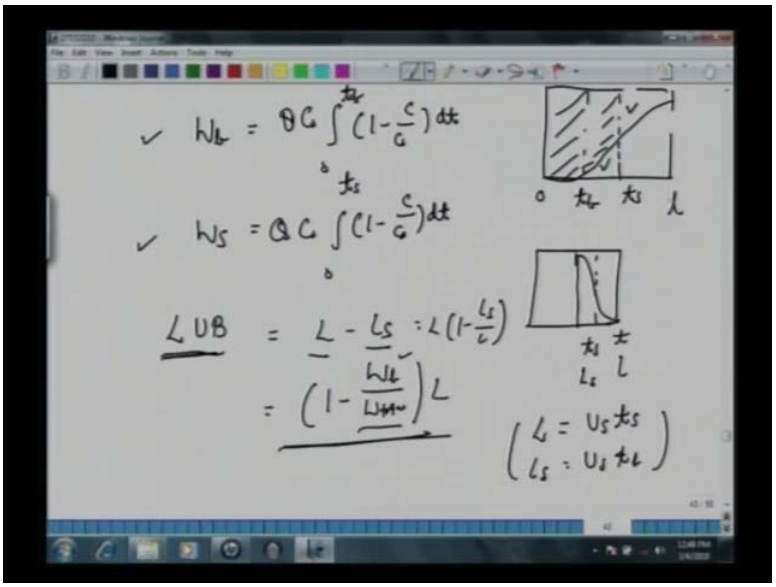

So, if we denote by w b this s should be same as say Q into C 0 to t b instead of t e 1 minus C over C 0 into d t. So, if we can draw the curve here. So, what is this represents the area till t to t b how much amount has been adsorbed so far starting from 0. So, this is your W b how much amount is adsorbed till W s, which we have define like t s here. So, that this area is same as this area is stoichiometry or ideal front this would be Q into C 0 to t s 1 minus C over C 0 d t. So, that would be the area till this t s above the curve, and then. So, once we are convince this W b, W s; one should go back and calculate LUB length of unused bed.

So, what was the length of unused bed we said this is a length of unused bed t s to this final t or this l s to final this LUB. So, L U B going from the same definitions; it was l minus L s total column minus L s same cross sectional area. That mean should be able to

convince yourself this nothing, but 1 minus W b over W total, which we have calculated into this length. So, if take one outside nothing, but L 1 minus L s over this l l s corresponds to this t b right. So, when we have total bed saturated you call L, we said that U s into t s, and this L s, was U s into t b. So, you should look at both the figures in this M T Z profile. In this M T Z, and this break through profile to convince yourself. That LUB can also be determined from here 1 minus total amount adsorbed till break through time, and the amount total not del this t e time; now, we can take this example. Let us say we have a packed column, we have certain concentration. It is a fresh packed bed let say the length is 15.2 centimeter, it is pack with charcoals.

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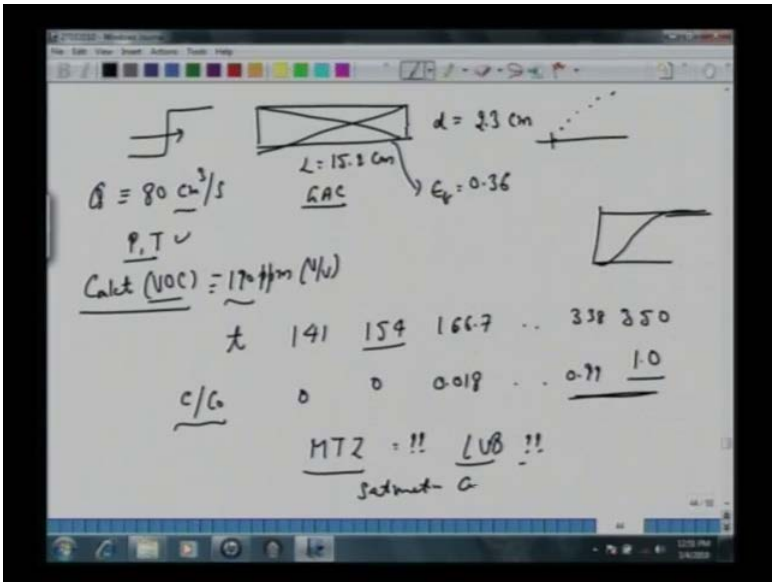

Let say, we have this granular activated carbon, bed porosity is 0.36 flow rate of this effluent say waste water Q or some gas. Let say it is 80 cubic centimeter per second. So, whenever you say this gas volume one has to specify this pressure, and temperature. Let say, this is at whatever p, and t b, have the flow rate of the gas is 80 cubic centimeter per second. This has the inlet concentrations C inlet; see let us say volatile organic compounds, undesirable compound. It contains at 190 p p m. So, what is p p m. So, all volume for the gas is volume by volume. It is one ninety 10 power minus 6 mole fraction. So, its 190 p p m diameter of this column is 2.3 centimeter, and for the system whatever use we have and whatever charcoals we have. So, this experiment was done at this flow rate, and then we got certain data.

So, this was the experimental data, and now, obtain like this; this data reads something like this let say 141 when at 154, 166.7 these are different minutes one has noted what

was the concentrations. So, this is different time, and we note here certain concentration, which has been non-dimensionalize with respect to this inlet concentrations. So, 0 0 all it means till 154 minutes; lets minutes it was no concentration monitor at this exit; after 166.7 minute very small concentration 0.018 is measure, and so, far and after 33 and 50 minutes may be its reached one 338 it reaches 0.99.

So, look at this it is a very - very slow when the bed start getting saturated response goes very slow here. It takes a very - very long time to come close to this one here, and the question ask here is that calculate mass transfer zone, what is this length of unutilized bed, what is the saturation capacity of this absorbent. So, these are three questions, one can answer here. So all we do, if first plot this response which we have.

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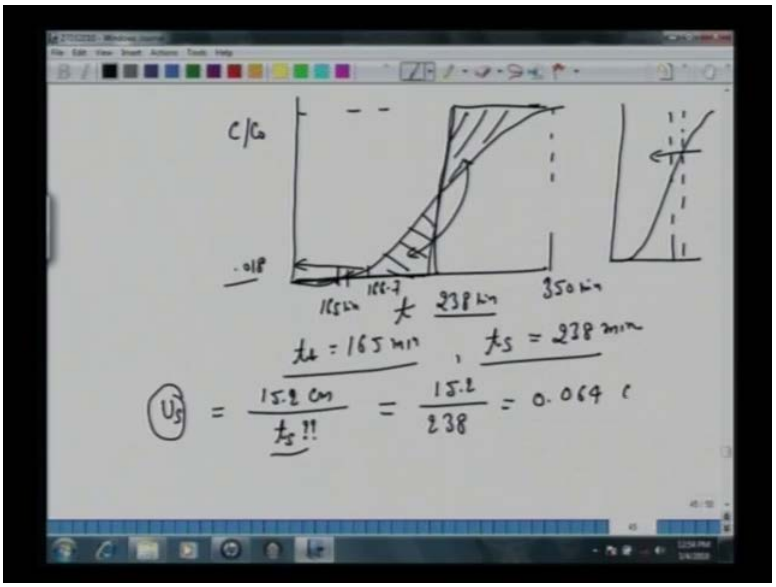

So, this is the time this is c by c 0; if you plot, and draw a very nice smooth curve, this like this. So, here tell t equal to 165 minutes as per the data there is no response 167, 165 there is no response, and 166.71 gets a concentration. Let say, 0.02 whatever we have 0.018. So, this 166.7 that means, as per our definition you know we can say that very close to this break through time t b is 165 minute. So, going back to the previous data 154 there was 0 response. Then 167.7 we have 0.0181 can do this interpolations to obtain thus break through time is around 165 minute here, and then 350 minutes 350 minutes the bed has become saturated.

So, the first thing is that what is this u s at what speed the way propagates mind your length column was 15.2 centimeter. So, what is this time, and what time you are talking

of we are talking of this t s. So, ideally the wave would have move like this one has to do this iteration to find that, how much length at what length or at what time actually. This area is same as this area. So, going back to this curve here or we are trying to do is by titrations. We are moving this line such a way that two area becomes same as this area, and if you do this one can show that this t s turns to be around 238 minute.

So, we have t b 165 minutes, and we have this t s stoichiometric time 238 minute. So, we got this u s 15.2 divide by 238 which is, if we calculate 0.04 centimeter per minute approximately. What is LUB length of unutilized bed which is L total length minus L s. So, we are talking of this length again. So, we have the wave like this, and we have drawn this L s. So, this area was same as this area equivalent break through profile.

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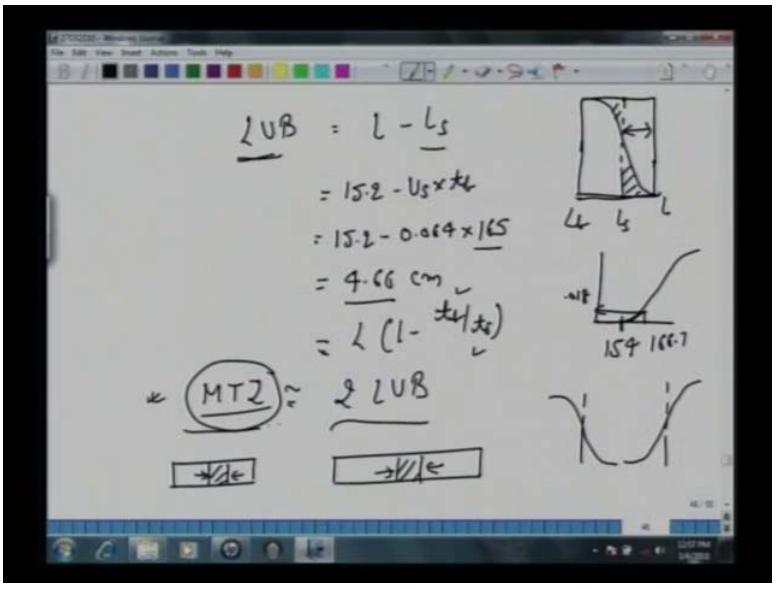

So, this is your LUB length minus L s. So, this is L b this is the total length here. So, we have l minus L s, L is 15.2, what is L s? U s into t b. So, essentially the wave front (( )) 65 reached here at this been ideal in the bed have to saturated had it reached here. Then the bed would have saturated till l s. So, minus u s into t b, and we know this two quantities 15.2 minus 0.064 into 165, you calculated from our break through profile.

We made some very small approximations data was given for 0 till 154 minute, and a 166.7 we had this data of 0.018. So, all you can do you can draw a smooth curve through this to find that at what time this is about to break. So, that is your165 minutes. So, we put this number, this number will be 4.66 centimeter mind you with this number. We will also be same as we calculate directly 1 minus t b over t s. We know the break through

time165 minutes, and we know this stoichiometric time t s which we calculated from there as 238 minutes both will give the same result to obtain this 4.66. So, what is this MTZ? MTZ is approximately twice LUB. If we plot, you will see that this is symmetric this symmetric response or the break through profile is like this. It is symmetric about this t s or L s. So, that is the way to calculate this MTZ mass transfer zone, what is the physical meaning of this mass transfer zone.

The idea here is that, if you take a small column or if you take a larger column as long as the operating conditions are the same. Then this mass transfer zone remains the same. So, one can do this experiment on a smaller scale to calculate this MTZ; one can scalar for this larger for a larger column. So, this becomes a very unique parameters for this course we remain confine our self to this level of discussions; otherwise, we can go through some different text book or higher level text book to get more comprehensive design of a absorption column based on this m t z or this length of unutilized bed column and the last column we have last answers question we have to answer what is this saturation capacity.

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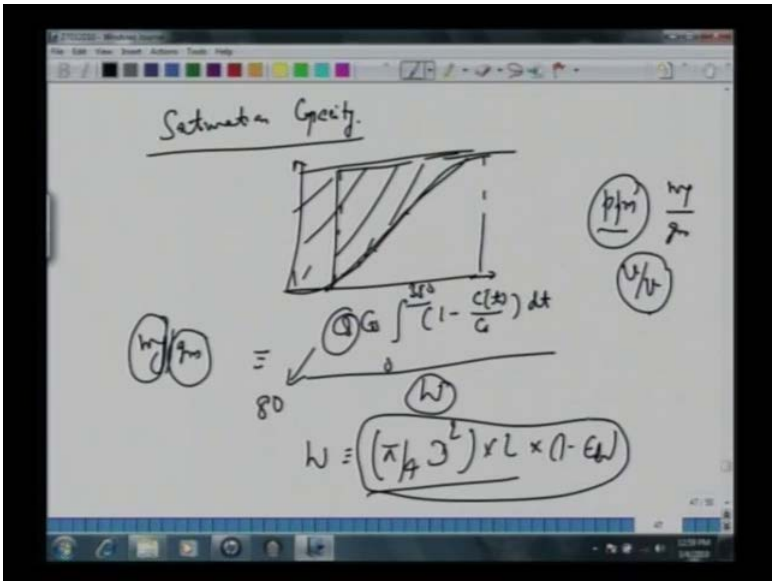

So, what is this saturation capacity it is very easy to find out just find out the area above this curve. So, one has to integrate or one can make some approximations finding out how much is this area and how much is this area. So, saturation capacity is nothing, but milligram per gram how much milligram of absorbent? You see has been absorbed per amount of this absorbent. So, how much it has been absorb you have to one has to integrate (( )) C 0, 350 minutes that is your saturation time 1 minus C t over C 0 into t t

since this area under curve, either you solve numerically. You know of this data points make use of this certain numerical methods calculate this area or even approximately. One can measure assuming this rectangular may be this is a very close to the triangle. So, half length into ideal divide by the total amount of absorbent.

So, all this quantity we know this Q is a t C per second; this C 0 we know how much p p m. We have you can convert this p p m in the gas volume to some milligram per gram mind you for the gas this volume by volume. One can make some stoichiometric here to convert this to this milligram per gram as well; C we know is a response C 0 is again known to us we can integrate from 0 to 350 minutes what is the total amount of absorbent we have used. So, we have the total volume pi by 4 D square that is the diameter of the column into the length so, this total volume of the column into 1 minus epsilon b. So, bed positive as given 0.36. So, this is the total volume of your particles adsorbents multiplied by the particle density will give you this W. So, this milligram per gram would be your saturation capacity corresponding to this 190 p p m.

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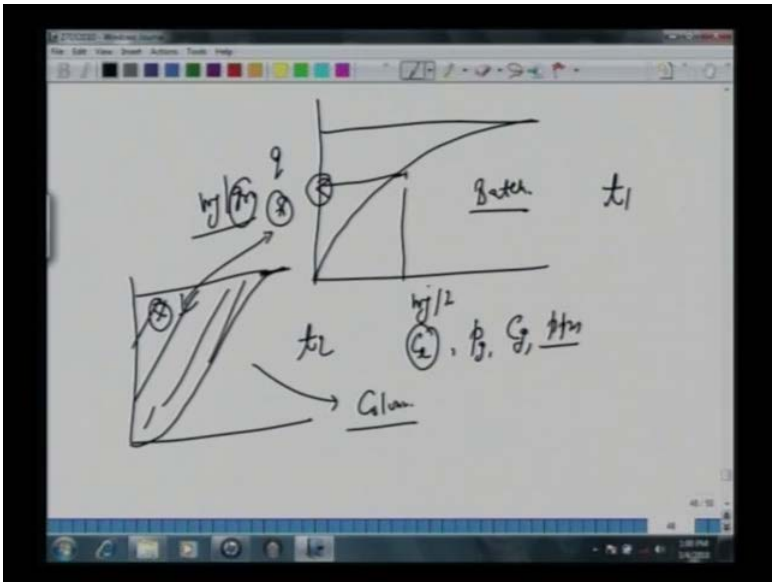

What is that physically means this also very important that we understand that we have done this jobs, and experiment or isotherm experiment, where we have this isotherm like this. So, where we plotted milligram per grams the say (( )) isotherms or b e t isotherms or temkin q versus this concentration milligram per liter c l aqueous phase concentrations are partial pressure of the gas or concentration in the gas phase or p p m mole fraction etcetera.

If you take this 190 p p m have read this number; this milligram per gram must be the same as, what you have calculated just now from this break through analysis area under the area above the curve divide by the total amount of this absorbent two number must be the same. Here, this is exercise you must check yourself for the system whatever you do address the absorption, which we done in the batch conditions. This has to be same as what we have done in this column experiment. Because it is just a question of time here may be the time is different here the time is different, but at the end of with the equilibrium when the bed is saturated. The entire adsorbent column is saturated with this 190 p p m. If you do the batch experiment no flow experiment even there this 190 p p m of vapor will give you the same loading here. So, this is the example we have taken for this adsorption for this column experiment as we said again you know we repeat that column experiments may be simpler to do, but we need want to do this mathematically very regress analysis to find out the response how to predict the response of the break through curves or how much is the saturation capacity. It is a very - very extensive competition mathematically, very extensive one has to get into the higher level or graduate level of courses on adsorptions, and see what type of calculation one can do solving this partial differential equations for this course, whatever we have done a stage wise at a third year level. That is one thing for the column experiment our maximum our maximum computation will be limited to the calculation of MTZ, and LUB length of unutilized bed.

What is the physical significance of MTZ, and LUB, you must have appreciated you may not have appreciated what is the utility how to be a scale to a large practical columns that again when you get expose it to the graduate levels, you will see that difference. More important here is that, whether it is a column experiment or the batch experiment when the bed gets saturated in the column or when the bed gets saturated in the batch experiment the loading must be the same corresponding to the same inlet concentrations, and the final concentrations. So, that is the more fundamental of these absorptions. So, this is the end of our discussion on absorptions, we have taken several examples - couple of examples, the rest of the examples, are given in the text book by Treybal by Dutta solve examples or the problems you are, it is a strongly recommended that you try to solve those problems on your own. Next time, when we meet take up a new topic, new unit operations that is a drying. So far, we have done adsorption, then distillation,

extractions, absorptions, and the last unit operation we will be take that is on drying of a solids.