Bioreactor Design and Analysis
Dr. Smita Srivastava
Department of Biotechnology
Indian Institute of Technology – Madras

Lecture - 38
Non-Ideal Reactors: Design and Analysis – Part 1

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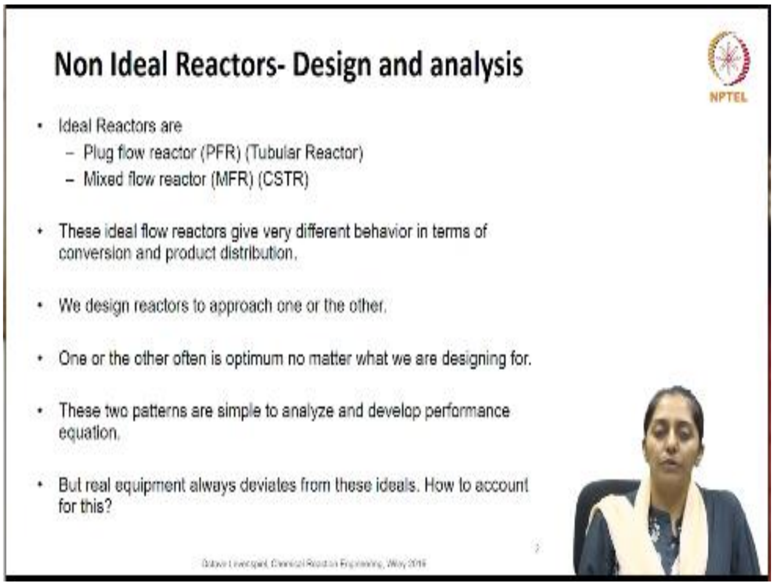

Welcome back students. Now, we are going to talk about non-ideality in reactors. To understand first, what are non-ideal reactors, their design and then analysis? So, ideal reactors, we know now, we have come across plug flow reactors, where kinetics is like a batch reactor and mix flow reactors, where we have come across continuous stirred tank reactors in as one of them mix flow reactors.

And plug flow reactors was nothing but a tubular reactor with batch kinetics. These ideal flow reactors, they give very different behaviour in terms of conversion or the product distribution. So, generally when we are designing reactors, we are trying to approach to any one of such kinetics, either of the mix flow type or the plug flow type. One or the other is always found to be often found to be optimum, no matter what we are designing for.

So, these 2 patterns, they are pretty simple to analyse and develop the performance equation. This is what we have done in the past. But practically speaking, there is always deviation from ideality. So, how to account for this deviation?

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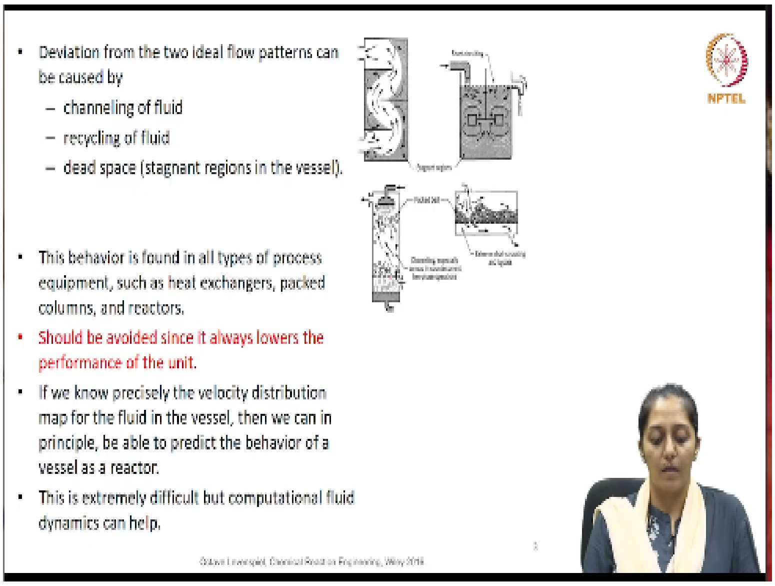

First, we need to understand, what are the source of deviations? So, deviation from the 2 ideal flow patterns, it can be caused by channelling of the fluid, recycling of the fluid or presence of dead space, which is the stagnant regions in the vessel. So, if you see on the slide, various kind of flow patterns have been shown here including the stagnant regions shown above in the 2 figures, where there is effectively no mixing happening, no fluid currents are there.

And then the bottom to show the channelling and the short circuiting, not going through the entire path, but taking the shortest route or the least resistive route. Now, this behaviour is found in all types of process equipment like for example, heat exchangers, packed columns or your bioreactors. It should be avoided, since this will lower the performance of the unit.

So, if we know the velocity distribution map for a fluid in the vessel, then in principle, we should be able to predict the behaviour of the vessel as a reactor whether it will behave as a ideal reactor or there can be non-idealities. So, you see in case of non-ideal behaviour, the flow patterns or the fluid movement changes inside the reactor in terms of its velocity distribution pattern. So, this is extremely difficult, however, your computational fluid dynamics here can help.

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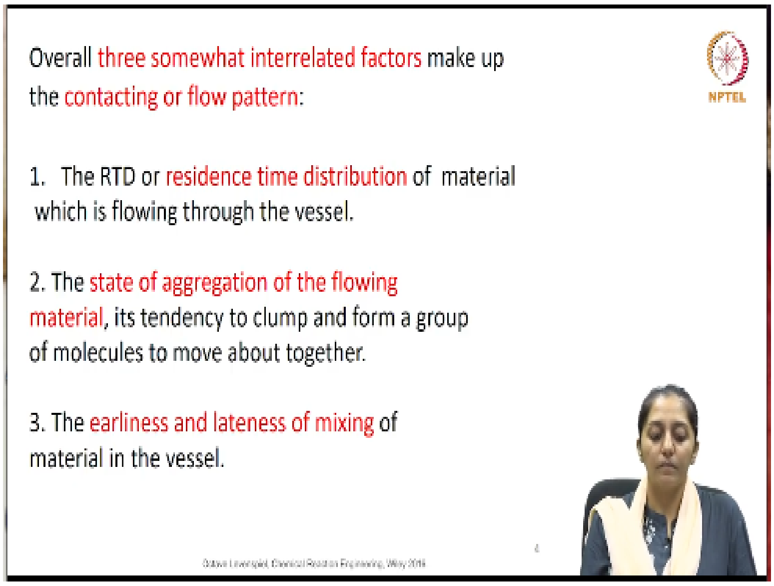

So, 3 somewhat interrelated factors, they make up the contacting of flow patterns. One is the residence time distribution, this is of the material which is flowing through the vessel. Then the state of aggregation of the flowing material which means, it is tendency to clump or form a group of molecules which move together. The third aspect is earliness and lateness of mixing of the material in the vessel.

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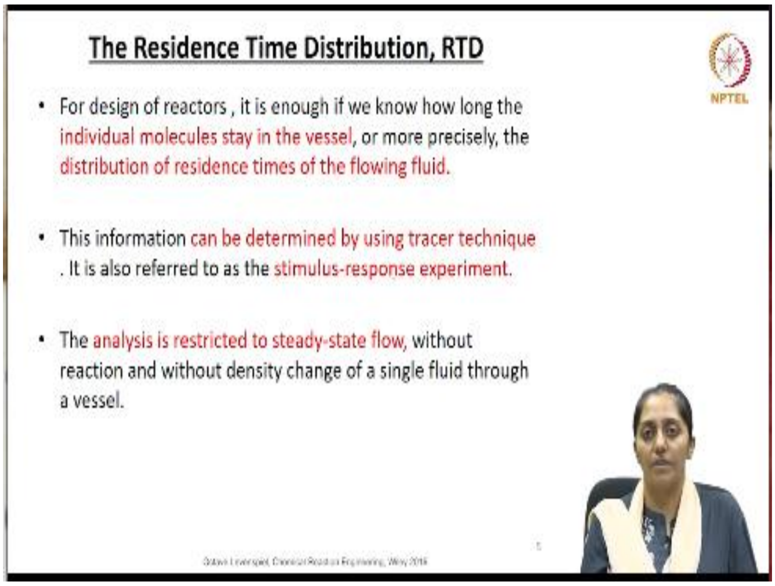

So, let us talk more about residence time distribution. Now, for designing the reactors, it is enough if we know how long the individual molecules are staying in the vessel or know precisely the distribution of the residence times of the flowing fluid elements. Now, this information can be determined by using tracer techniques. It is also referred to as stimulus response experiments.

The analysis is restricted to steady flow patterns without reactions and without any density change of the fluid through the vessel.

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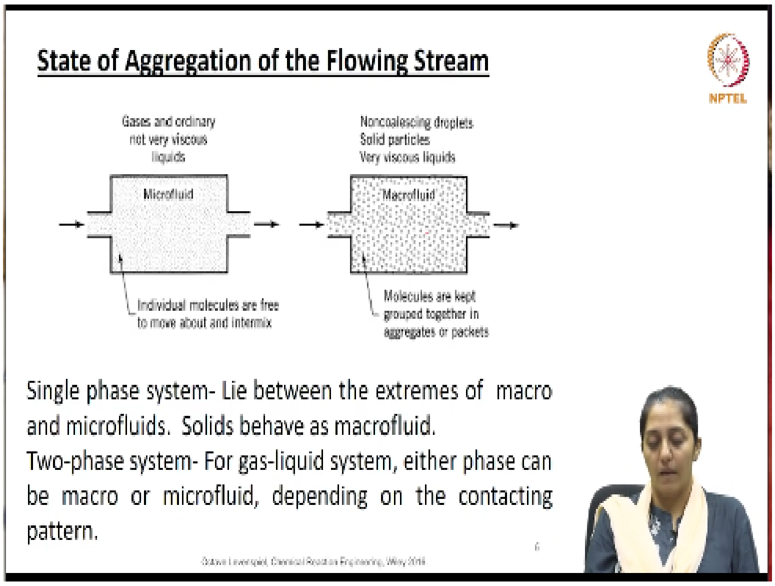

So, state of aggregation of the flowing stream. If you see the picture on the slide, this is a mixing where they have shown gas, mixing with not very viscous liquid. So, individual molecules, they are free to move about and intermix in case of micro fluids. Non coalescing droplets or solid particles are very, very viscous liquids. These are some examples of macro fluids.

So, you can see here in the picture, the molecules, they are grouped together as aggregates or as packets. So, this is the way the 2 fluids can behave differently. One is the micro fluid and the other is macro fluid. So, single phase system, it will lie between the extremes of the 2 macro and micro fluids. The solids, they behave as a macro fluid, while the gases will come under micro fluids.

Now, for a 2 phase system like for example, gas liquid system, either phase can be a macro or micro fluid depending on the contacting pattern, which means that either gas can be dispersed in the liquid phase or the liquid can be the dispersed phase in the gas.

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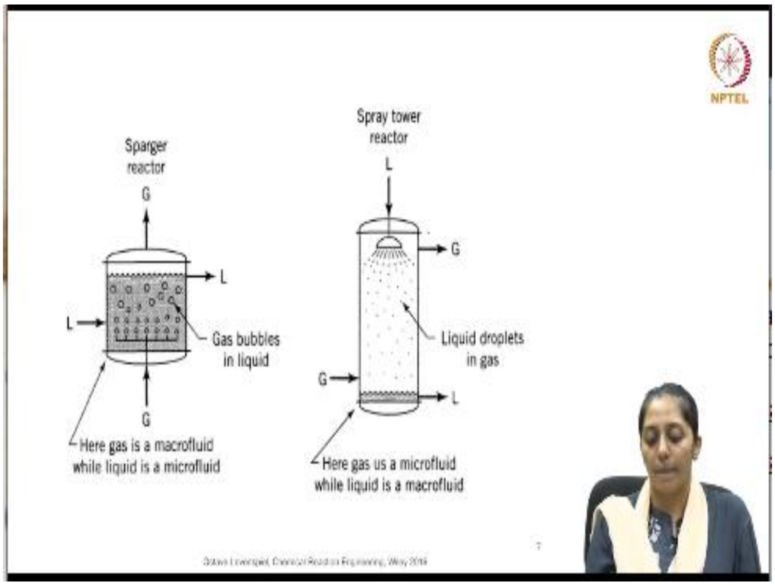

So, like the picture shown here, this is a sparged reactor. So, here the gas is the macro fluid while the liquid is the micro fluid. So, the gas bubbles are moving up. Now, if you see triple bed reactor or a spray reactor, tower reactor, then the liquid becomes the macro fluid and the gas is the micro fluid. The liquid is being dispersed in the gas phase.

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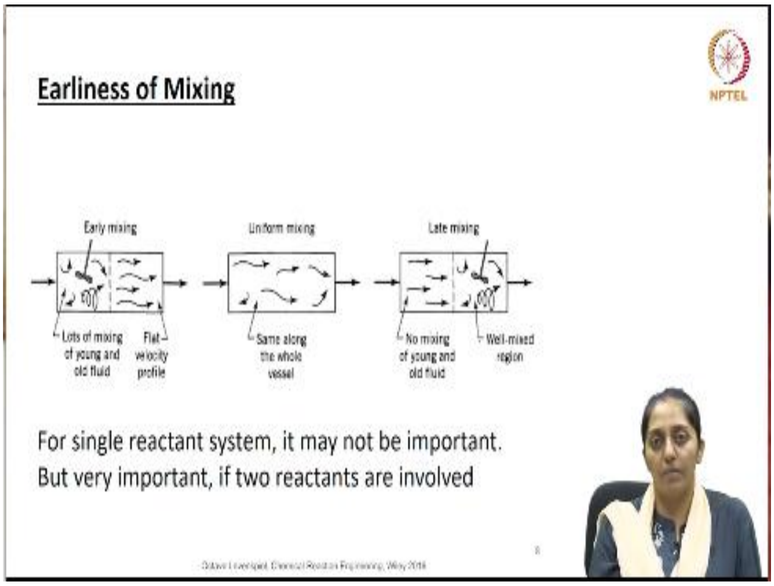

Talking about the earliness of mixing, if you see the picture on the slide, where the incoming stream, it is mixed early on. So, there is a lot of mixing of the old and the young fluid elements and then in the later half, it is almost flat velocity profile. In a uniform mixing through the entire vessel, the fluid patterns will be similar. Now, in the late mixing in the early phase, there is no mixing of the young and the old fluid while in the later half, this becomes a well mixed region where the mixing is happening.

Now, for a single reactant system, this may not be of that importance, but it becomes very important when there are 2 separate reactant streams and they are supposed to react to give the product.

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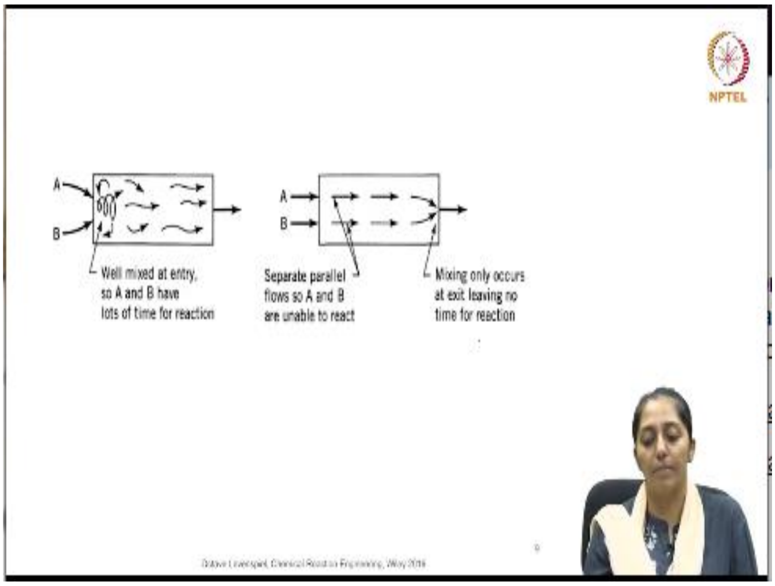

Like, as shown in the picture on the slide. So, A and B, they have to be well mixed at the entry. So, that they have enough time for reaction. If A and B have late mixing, then there are separate parallel flows of A and B, they are unable to react and only at the end, the mixing is happening. So, giving no time for reaction.

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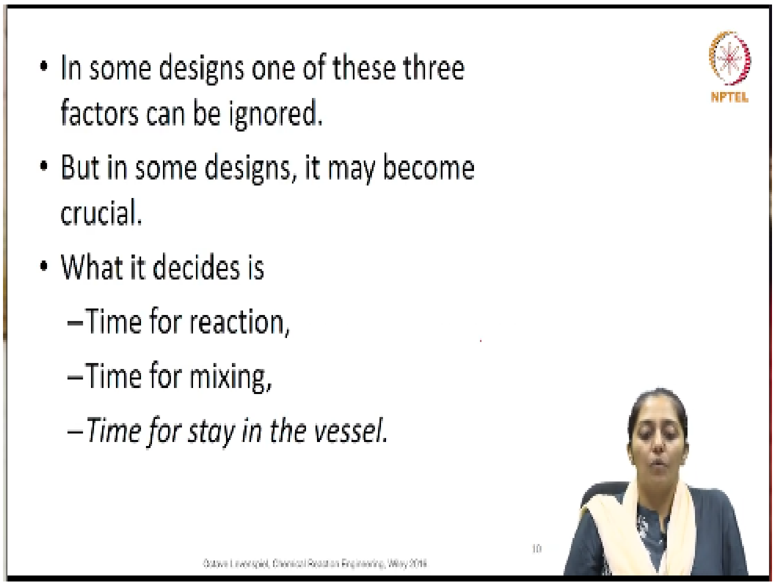

So, in most designs, one of these 3 factors, they can be ignored. But in few designs, it may become crucial. Why? Because it decides the time for the reaction, the time for the mixing and the time for stay in the vessel. So, all these 3 things are governed.

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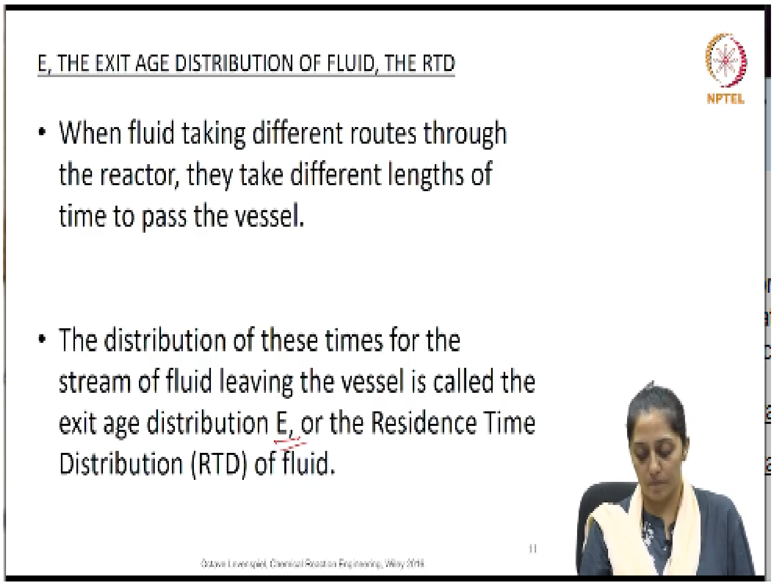

So, in order to find the residence time distribution, which is also called as the exit age distribution of the fluid, we use make use of the tracer experiments. Now, when the fluid is taking different routes through the reactor, they can take different lengths of time to pass the vessel. Is not it? Now, if we consider all these different fluid elements entering the reactor going through different time spans inside the reactor before they pass the vessel.

This distribution of times for which the stream of fluid leaving the vessel is called the exit age distribution, denoted as capital E or the residence time distribution of the fluid. So, I will repeat. The distribution of these times for the stream of the fluid is called a exit age distribution, denoted as capital E which is same as the residence time distribution, we generally call it as RTD of the fluid.

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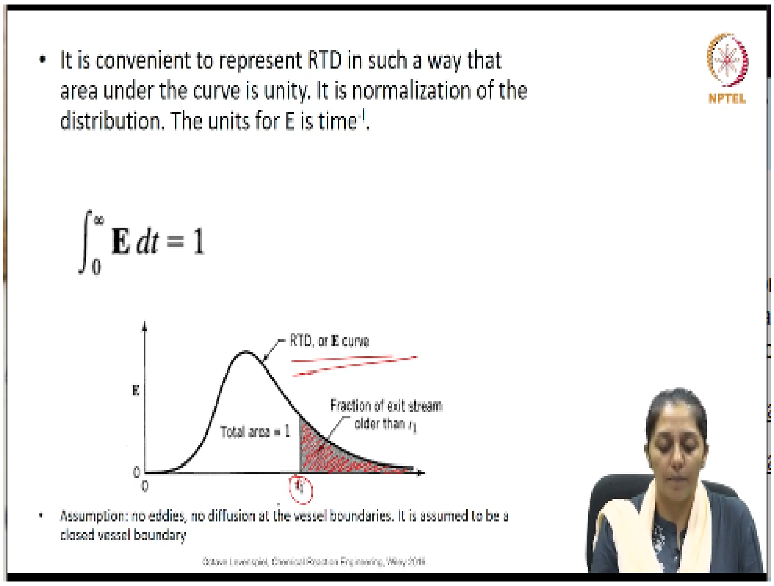

Now, it is convenient to represent the RTD in such a way that the area under the curve of E versus time which is nearly unity. So, is unity or in a sense, we are trying to normalise the distribution. So, if you make a plot of exit age versus time, then the area under the curve is unity, where E versus t plot is what is called as residence time distribution and this is also called as E curve.

So, if in this picture which is shown on the slide at time t 1, if you see the fraction of the exit stream which is older than time t 1 is what is represented in that dark grey colour. Here, we are assuming that there are no Eddies, no diffusion at the vessel boundaries and it is assumed to be a closed vessel boundary. So, using the E curve, one can determine the fraction of the exit stream older than a particular time or age.

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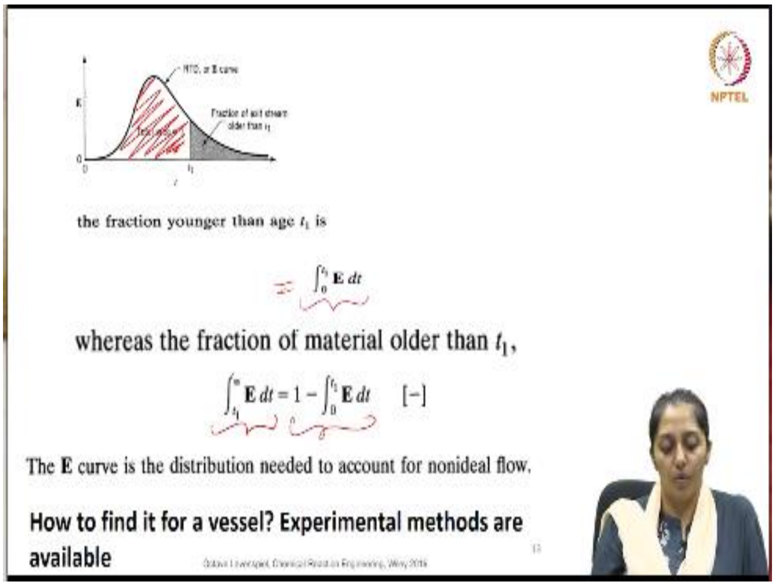

So, the fraction younger than age t 1 can be given in terms of integral 0 to t 1 E dt, the portion shown in white colour here. So, the older than t 1 would be 1 – 0 to t E dt which is same as integral of E dt with the time limits of t 1 to infinity. So, E curve is the distribution needed to account for the non-ideal flow. Now, how to find it for a vessel?

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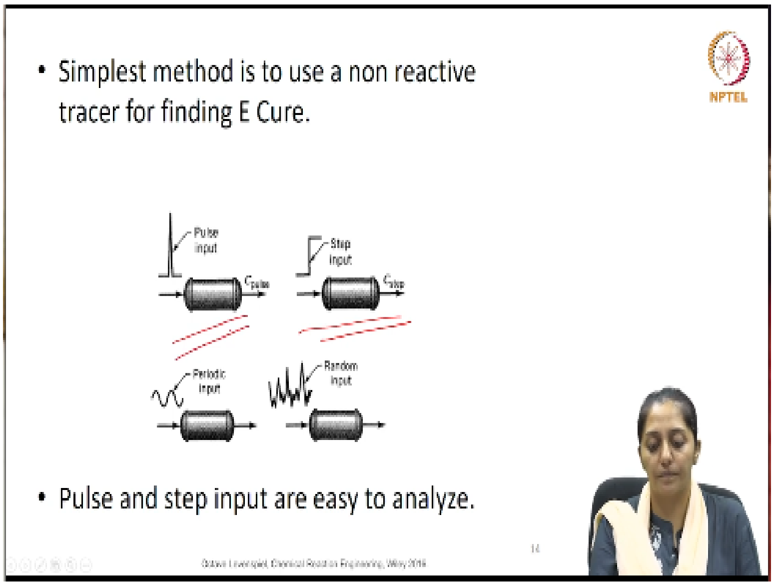

The simplest method is use, is to use a non reactive tracer for finding the E curve. So, where you can make use of a pulse input or a step input or a random input or periodic inputs, mostly pulse and step inputs are used because they are easy to analyse as shown on the picture here.

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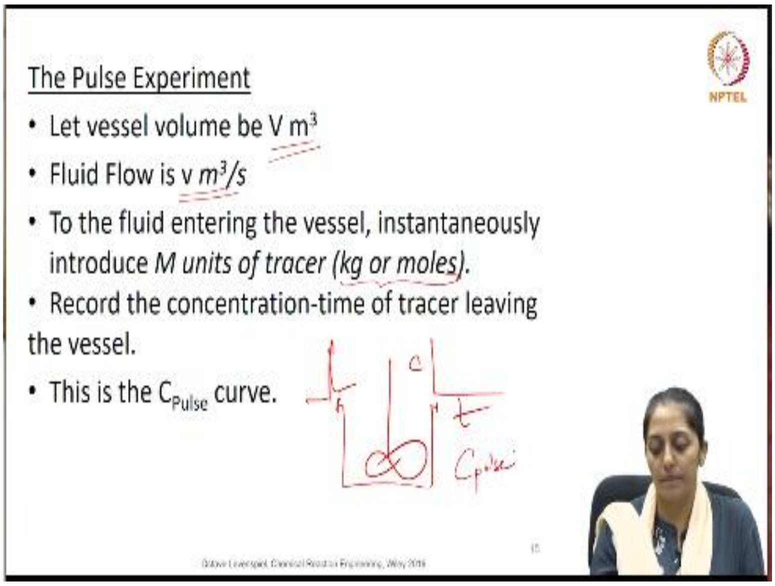

Let us take first, the pulse input. So, in the pulse tracer experiment, please make note of the notations to be used here. Let the vessel volume V metre cube, the fluid flow is being represented by small v and the vessel volume was capital V. So, the fluid entering the vessel instantaneously they introduce M units of tracers, which is in kgs or moles. So, this is a pulse experiment.

So, suddenly, we introduced M units to the entering fluid. And then at the same time, we begin recording the concentration versus time profile of the tracer leaving the vessel.. on the other end. Here, we are giving the pulse input and here, we begin recording concentration versus time of the element. Now, this concentration versus time profile of the tracer in the vessel will be called as C pulse curve.

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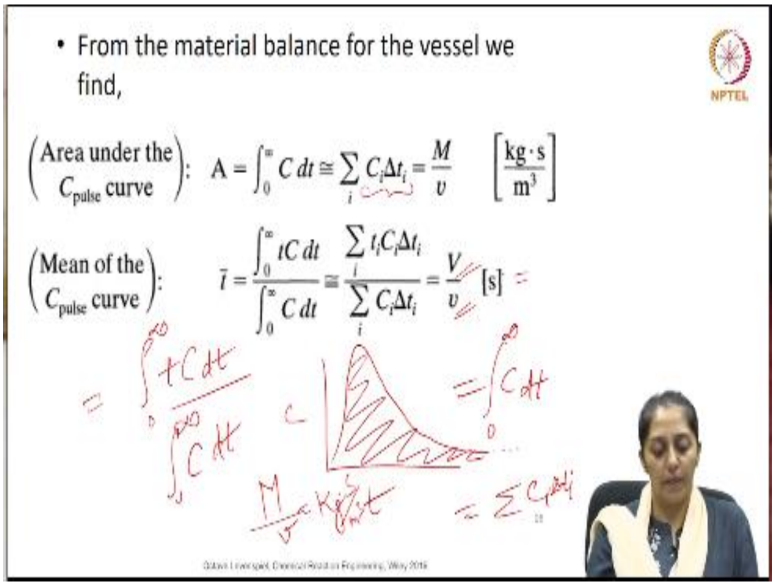

So, if we do the material balance for the vessel, we find that area under the C pulse curve can be called as 0 to infinity C dt. So, this will be the entire area under the curve which is 0 to infinity C dt. Now, in terms of small time distributions delta t equally distributed, we can further reduce it in the form of summation C i delta t i, which is nothing but total amount of tracer which was added divided by the volumetric flow rate which is metre cube per second.

So, this is the area under the curve. Now, mean of this curve can be determined by using statistics as shown here. So, your mean residence time or mean time can be obtained, we now know, it is F by V inverse, so, which is V by F. So, volume and small v, volumetric flow rate.

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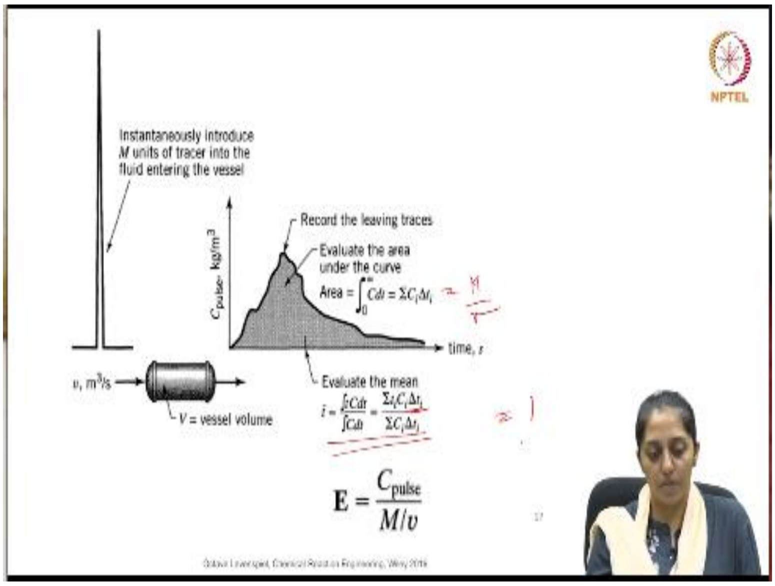

Now, as the M amount of tracer is instantaneously introduced into the fluid entering the vessel as shown here. When we start noting down the concentration, it will rise to a value and then it starts decreasing because of the subsequent dilution of the incoming stream. So, this area under the curve is nothing but your M by small v and your residence time or mean residence time can be given as delta t i C i dt by C i delta t.

So, your E curve can be obtained from C pulse curve. Now, the area under the curve is equal to 1 for an E curve. So, if we divide the C pulse values by M by V, then we should be able to get E values.

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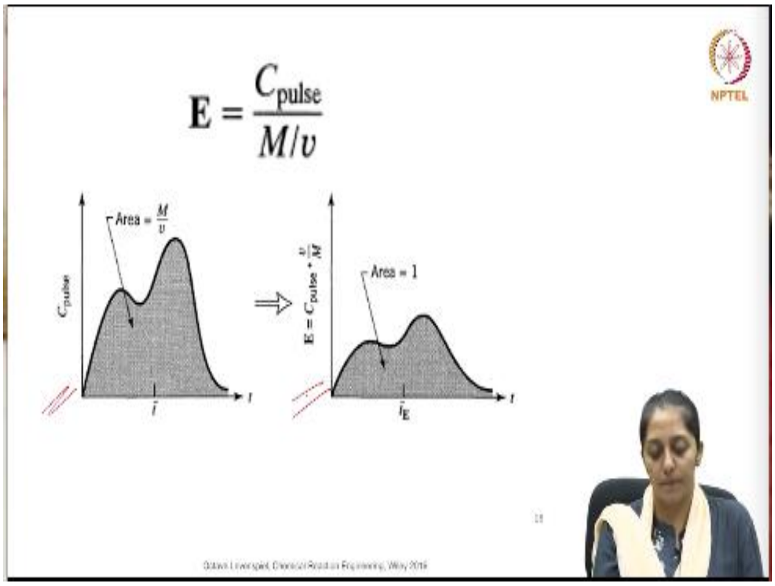

So, this is what is done to converter C pulse curve to an E curve.

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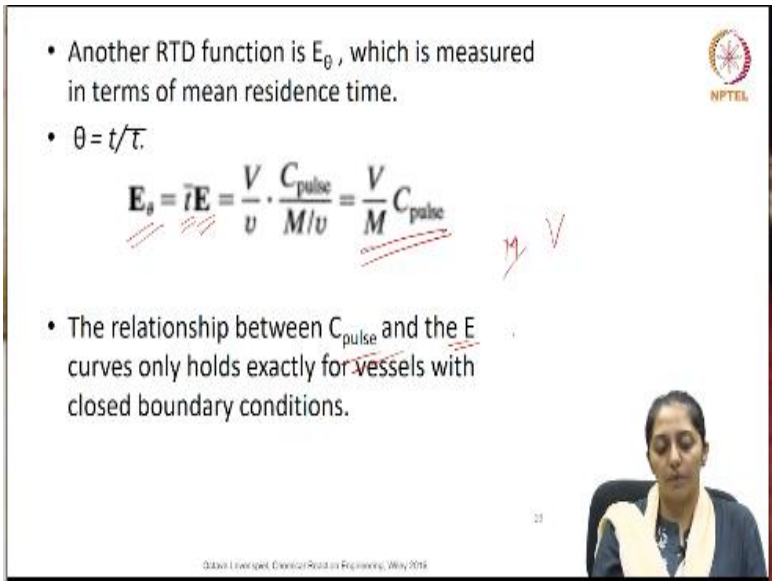

Now, another RTD function is called E theta which is measured in terms of the mean residence time. So, here, E theta is mean residence time multiplied by the E values. So, residence time is nothing but V by F, so, which is capital D by small v and E was given as C pulse by capital M by small v. So, effectively E theta can be obtained, values can be obtained from the C pulse curve, if we divide the corresponding C values by M and multiply by the volume.

So, now, we have correlation between the C pulse and the E curves and E theta which is true for the vessels with closed boundary conditions.

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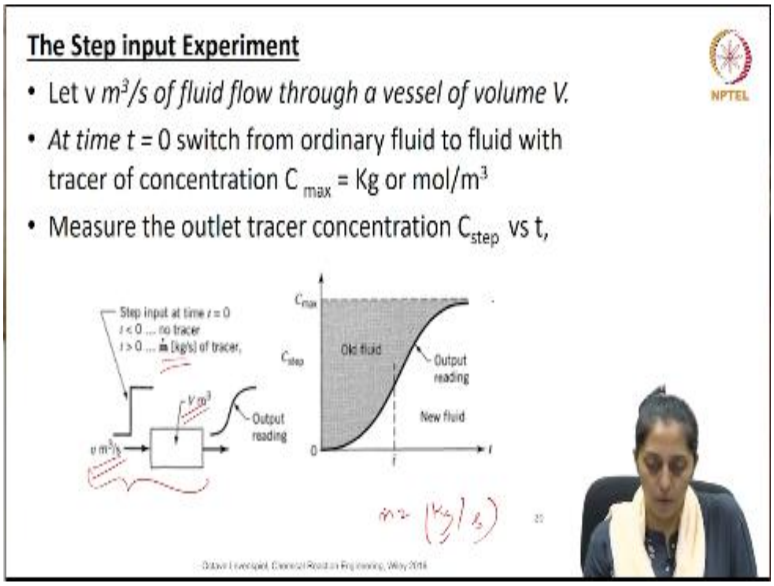

Now, if we use a step input rather than using a pulse input, then how does it change? How to determine the E curve? Now, when we use a step input, this is how it can be demonstrated. At time t is equals to 0, there is no tracer or less than 0, no tracer and at time t greater than 0, let us assume this the amount of tracer being dropped in is m dot which is nothing but in terms of kg per second.

Small v again is your volumetric flow rate; capital V is the volume of the reactor. So, once we start sending in the step input, we start determining the concentration of the exit of the tracer. Being a step input, the profile would look like as shown here. We will call now the concentration profile as C step versus time profile and it will take a form as shown here. So, gradually the new fluid is going to take over the old fluid.

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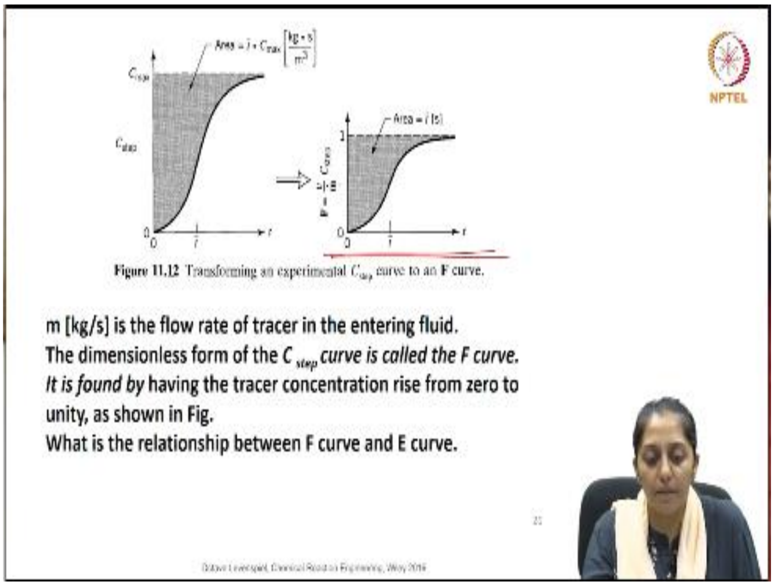

So, for your C step, it is converted in order to normalise into the area one, it is converted into an F value such that its value is ranging from 0 to 1. Now, m dot is the flow rate of the tracer in the entering fluid. So, the dimensionless form of C step curve is called the F curve as shown here. So, it is found by having the tracer concentration rise from 0 to unity as shown here in the figure.

So, now, let us see, how we can relate F and E values? So, your F value in order to change it to C max, it will become C step divided by m dot by v.

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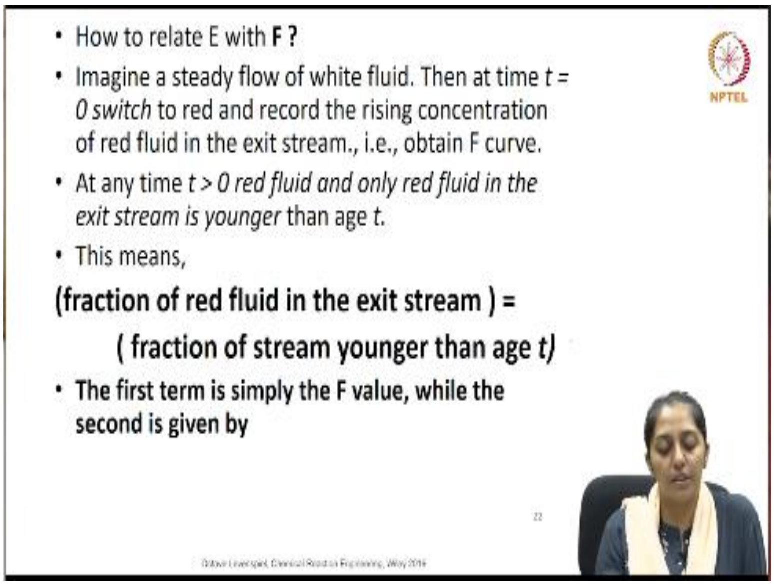

So, how do we relate E with the F values? Imagine a steady flow of the white fluid, then at time t which is equal to 0, we switch to a red and record the rising concentration of the red fluid in the exit stream and then we obtain the F curve. At any time t greater than 0, the red fluid and only the red fluid in the exit stream would then be younger than the age t. This means what? This means that if you see on the screen, the fraction of the red fluid in the exit stream is equal to the fraction of the stream younger than age t.

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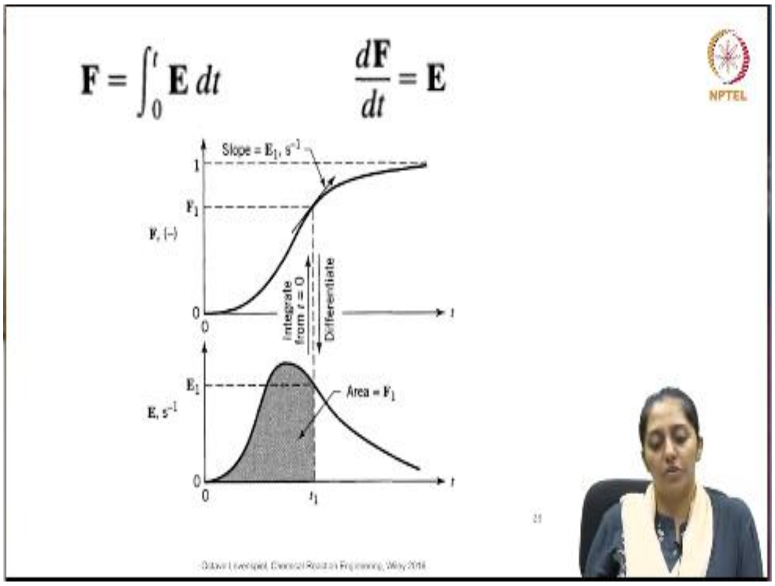

The first term simply means the F value can be given as 0 to t E dt is what is F which is the fraction younger than time t. So, if 0 to 2 E dt is F, then dF by dt is E, if you have the F curve at every time point, if you find the slope at that point in the F curve, you can determine the value of E. And this is how F can be changed to the E curve as shown in the picture here.

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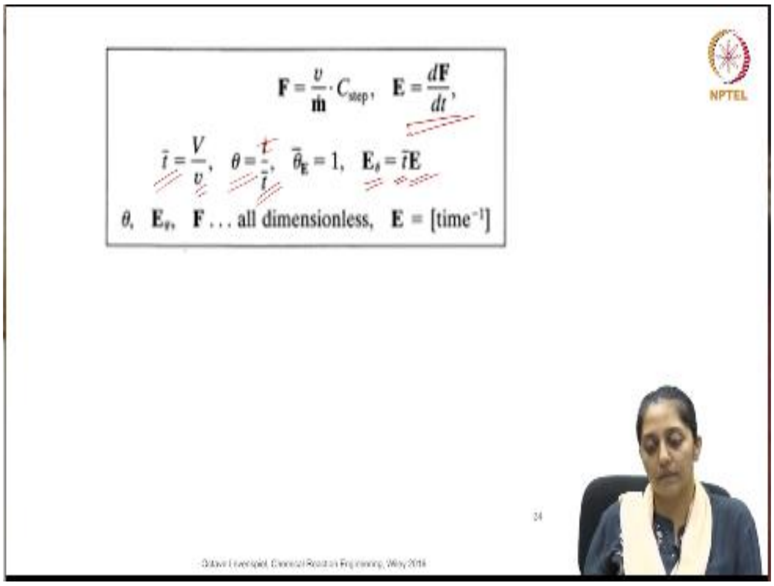

So, now, just to consolidate, F is related to C step where E and F are related as shown here, E equals to dF by dt. And your mean residence time is V by F, F is small v, theta is the dimensionless time factor, where the time is getting divided by the mean residence time. So, E theta is related to E by the mean residence time. So, your theta, E theta, F, they are all dimensionless entities and E is time inverse.

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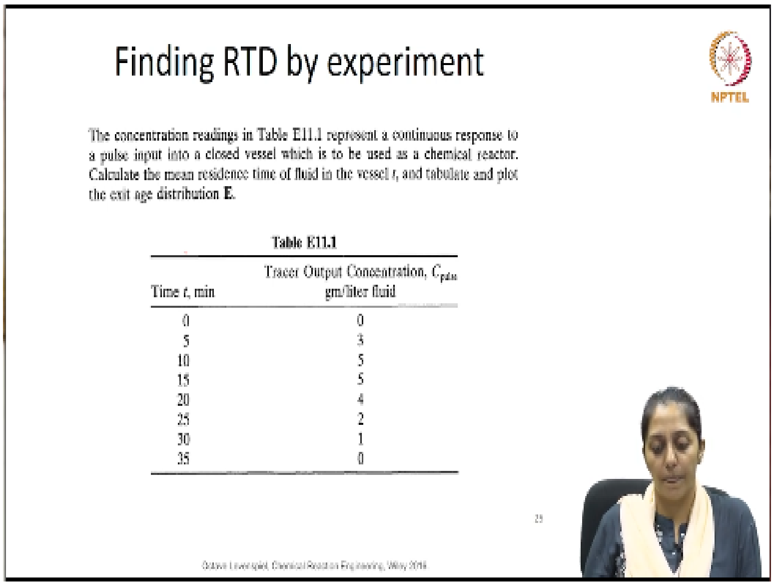

So, let us try to find the RTD where an experiment done using C pulse or using a pulse tracer, the data which is collected of the concentration of the tracer at the exit with respect to time is shown here in the table. Now, it is asked to determine the mean residence time of the fluid and to plot the exit age distribution, which means E versus t curve. What we have in hand is the C pulse and the unit given here is grams per litre.

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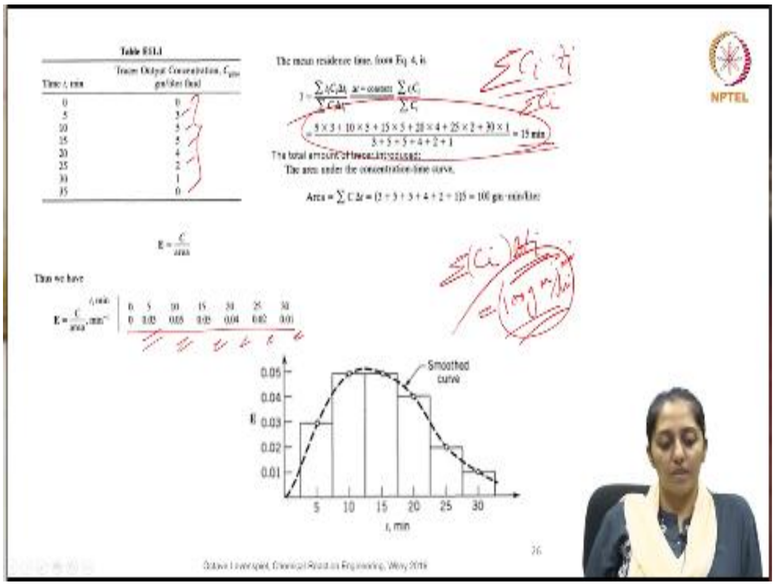

So, effectively, we can find first the C pulse by t and then the area under the curve can be divided to get the E curve E values. So, how to find the area under the curve? First, we calculate the mean residence time. So, mean residence time, you see the time intervals are equally distributed. So, we can have it as delta t i is 5 minutes here. So, we will have C i D i by summation C i.

So, if we do that as shown here on the right hand side by calculating summation C i t i by summation C i. So, here if we do this using the table data, we find that the mean residence time is 15 minutes. If the main residence time is 15 minutes, the area under the concentration time curve can be given as addition of all concentrations multiplied by del t i which is 5 minutes. So, then we calculate the area as 100 grams per litre in 2 minutes.

Now, we divide all these C pulse values by this area and we get the corresponding E values which was 100. So, if you are dividing all these C values by 100, you will get your E values. So, this is your E curve, E versus t curve.