Chemical Reaction Engineering - II
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Module - 11
Lecture - 51
Measurement of RTD I

Friends, in the last lecture we looked at the, what is residence time distribution and what is non-ideal reactors. And we initiated discussion on what are the experimental methods to measure the non-ideal situation inside a reactor. So, let us look at little bit more into it.

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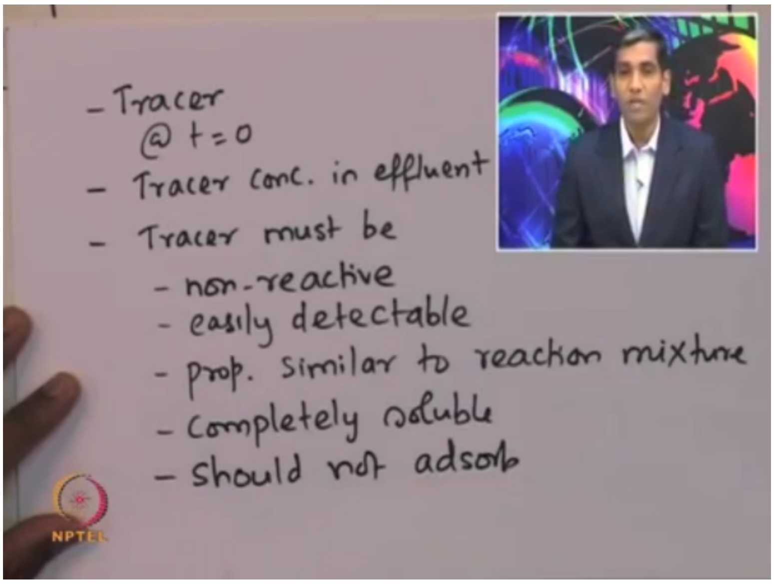

So, the method to do that is basically to inject a tracer. We need to inject a tracer into the reactor. And let us say, at time t = 0, a certain concentration of tracer is actually inserted, injected into the reactor. And then, the effluent concentration the tracer concentration in the effluent is measured. So now, if we measure the tracer concentration in the effluent, then this gives an idea about the non-ideal behaviour of the reactor.

Now, in order for this to conduct the such an experiment and to measure the tracer concentration, the tracer has to possess a certain properties. And the tracer must be non-reactive. Otherwise, the tracer is not going to reflect the true non-ideal behaviour because, in some amount of tracer which is actually injected into the reactor is now going to be consumed in some reaction. And it should be easily detectable.

The experimental methods that are available, the measurement techniques that are available should be sensitive enough to detect the tracer concentration, even small amounts of tracer concentration in the effluent stream. And then, the properties of the effluent must be similar to that of the reaction mixture. So, the properties must be similar to that of the reaction mixture. Otherwise, it reflect a different behaviour.

So, in order to capture the non-ideal behaviour of the, a reactor, the properties must be similar. For example, viscosity, etcetera. And then, it has to be completely soluble in the reaction mixture and it should not adsorb onto the reactor walls. Otherwise, some of the tracer is actually consumed. And so, it does not reflect the non-ideal behaviour completely. So, now the question is, how do we measure the residence time distribution.

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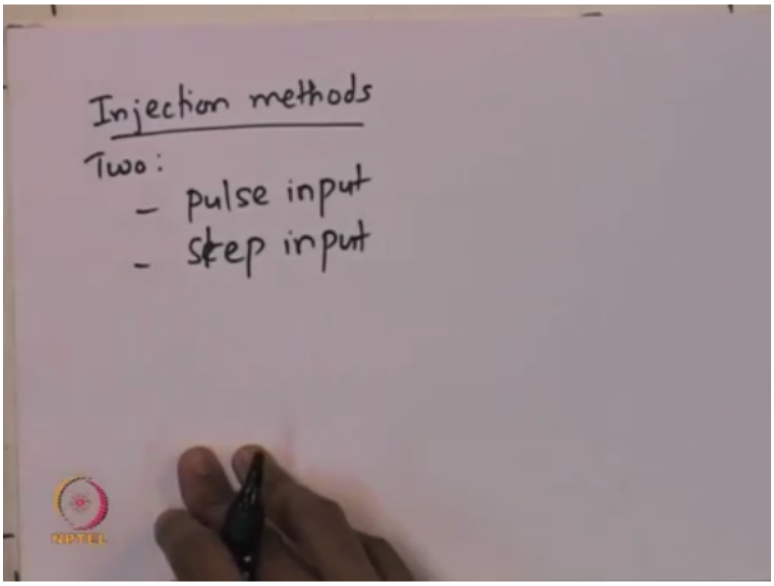

So, there are 2 injection methods. There are 2 methods which are commonly used. Which is, in order to detect the residence time distribution which is a reflection of the non-ideal behaviour of the reactor. And the 2 methods are the pulse input method and the step input method. These are the 2 methods that are used experimentally to measure the residence time distribution. So, let us look at a little bit more deeply into the pulse input method. And later we will look into the step input method, as to what these 2 different methods are and what are the purpose of these 2 methods.

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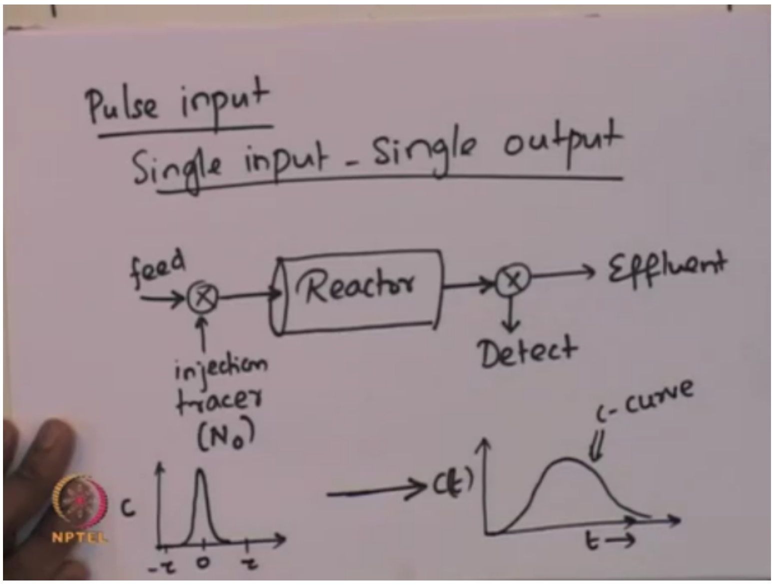

So, let us look at the pulse input method. So now, suppose we consider a single input-single output system. That is, suppose if there is a reactor. And then, there is a single input stream to the reactor and single output stream to the, from the reactor. And suppose if there is a feed stream which is present here. And let us say that we put a an inject, we inject the tracer along with the feed which actually goes into the reactor.

And may be the total amount or total concentration of the tracer is N nought. And it has to be a pulse tracer. And we will describe is a short while what is meant by a pulse tracer injection. And then, suppose there is an effluent stream. And then, we can actually detect the concentration of the tracer in the effluent. So, this is a reactor. And it has a single input and a single output system. So now, the tracer that is injected has to be a pulse at a certain time.

So, let us say at time t = 0, we inject a pulse of tracer. That is, a certain concentration of the tracer in as short time as possible, it is actually injected into the reactor. So, that is what is called as a pulse input. So, suppose if this is the concentration of the tracer. And this is – tau, sometime before and sometime later. So, there is some time before the injection point is no tracer in the reactor and sometime later also there is no tracer in the feed.

So, just give a short pulse and then leave it. Now, once we do this, if we monitor the concentration of the tracer in the effluent stream of the reactor, then the kind of concentration profile that one would expect is basically, it looks like this. So, this is time and this is the concentration of the tracer as a function of time. So, this kind of a curve is what is called as a c-curve in residence time literature.

So, the concentration of the tracer as a function of time is what is called as the c-curve. So now, suppose if we know, suppose if such is a system, question is, how do we find this concentration curve. So, how do we find this?

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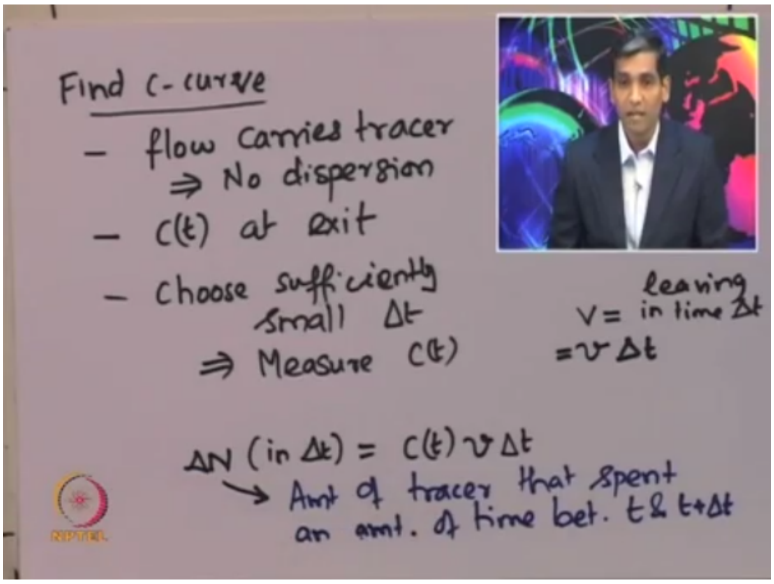

We need to find the c-curve. And how do we find the c-curve? So, we have to make some assumptions. So, if we assume that only flow, fluid flow through the reactor is the only one which is actually carrying the tracer. And if we assume, which means that there is no dispersion between the point of injection and the entrance of the reactor. And later, in one of the lectures, we will actually account for the presence of dispersion in the reactor.

Suppose, if we assume that there is no dispersion. And then we measure the concentration of this tracer at the exit. That is the effluent stream. Now, the trick to measure the concentration, or to construct a c-curve, is basically to choose a very small time step delta t, and the delta t should be chosen such that the concentration of the tracer in the effluent stream within this delta t does not change significantly.

And then, measure the concentration of the tracer at every delta t which is very very small. So, measure the concentration. So, choose sufficiently small delta t. And then, measure the concentration C of t. Now, once we measure this concentration and suppose if v is the volumetric flow rate of the effluent stream. And the volume of fluid that actually is leaving the reactor in the time delta t, volume in time delta t, so leaving in time delta t.

The volume of the fluid leaving in time delta t should be = the volumetric flow rate at the effluent stream multiplied by the corresponding delta t. So therefore, the amount of tracer that is actually leaving the effluent stream in time delta t, that is given by the concentration of the tracer in the effluent stream at that time multiplied by the volumetric flow rate v multiplied by delta t. So, that gives the total amount of tracer that actually leaves in this time delta t.

Now what does this mean? So, this is the amount of material, this is basically the amount of material, amount of tracer that spent an amount of time between t and t + delta t. So, what this means is that, this is the amount of tracer which is actually reside, spent the amount of time between t and t + delta t. So, that is the total amount of tracer in that times that has actually spent that much time inside the reactor. So now, if N nought which is the total injected as we observed in the schematic before.

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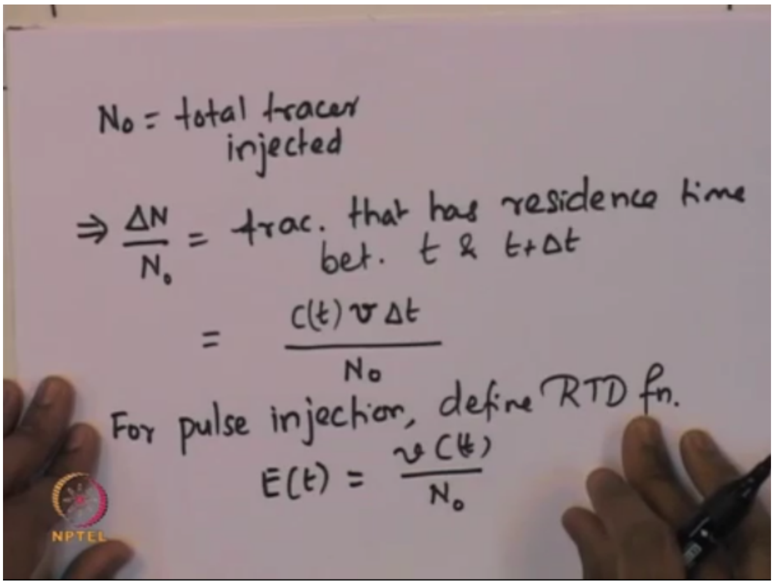

If N nought is the total injected, total tracer. So, that is the total amount of tracer which is actually injected into the vessel. Then, delta N by N nought is nothing but the fraction that has residence time. So remember, residence time is the time spent by the material inside the reactor whose residence time is somewhere between t and t + delta t. So, the time that certain amount of material has spent inside the reactor, if that is between t and t + delta t.

And that will be the fraction of, that will be the material which is going to come out of the vessel in that time delta t. And therefore, the fraction that has residence time between t and t + delta t is simply given by delta N divided by N nought. And that is = C which is the concentration of the tracer in the effluent multiplied by the volumetric flow rate of the effluent stream into delta t which is, this whole numerator is nothing but delta N divided by N nought.

Now, suppose for pulse injection, if we define a RTD function E of t which is basically given by v into C of t divided by N nought. So, that is the definition. So, that is the concentration of the tracer in the effluent stream multiplied by the corresponding volumetric flow rate divided by N nought. So, that is the amount of, that is the, if we define that as the RTD function, then we can write the fraction that has the residence time between t and delta t as delta N by N nought.

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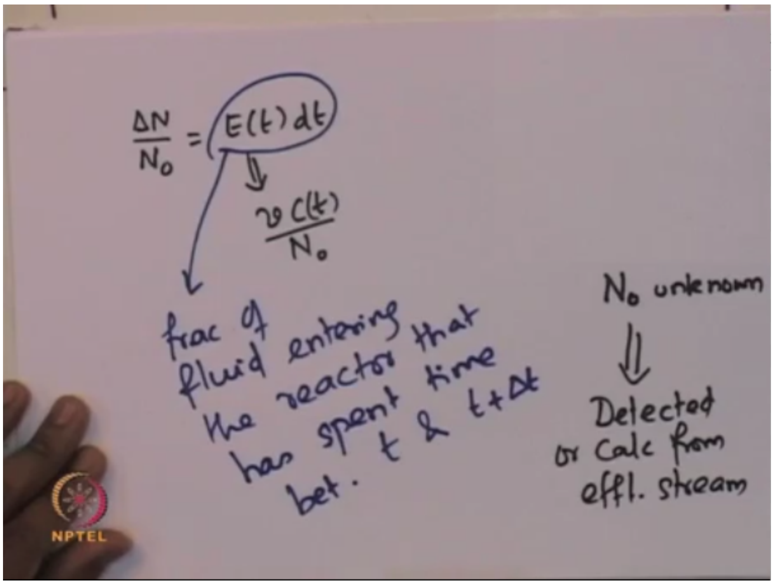

That is = E of t into d t. So, what is this E of t represent? E of t is the RTD function which is v into C t divided by N nought. What it represents is, it basically describes how much time different fluids elements are actually spent in the reactor. So, this quantity E of t which is the residence time distribution function, it quantifies or describes how much time different fluid elements have actually spent or have resided inside the reactor before they leave the reactor.

So, that is an important property of the reactor which is actually captured in this residence time distribution function. So, what can we do with this? So, if E of t is basically, describes the amount of material that is actually residing in the reactor. Then E of t d t is basically, so this quantity, it represents the fraction of fluid entering the reactor that has spent time between t and t + delta t. So, it is very important to understand this function E of t times d t.

That is the fraction of the fluid. That is basically delta N by N nought which is basically the fraction of fluid, total fluid that enters the reactor and has spent time between t and t + delta t. So, suppose if the total amount of tracer that is actually fed into the vessel N nought, if that is not known. Suppose if it is unknown, which may be the case in many situations. If that is unknown, then, the amount of N nought can actually detected from the effluent stream. It can be detected or calculated from the effluent stream concentration, from the concentration in the, concentration of the tracer in the effluent stream. So, how do we do this?

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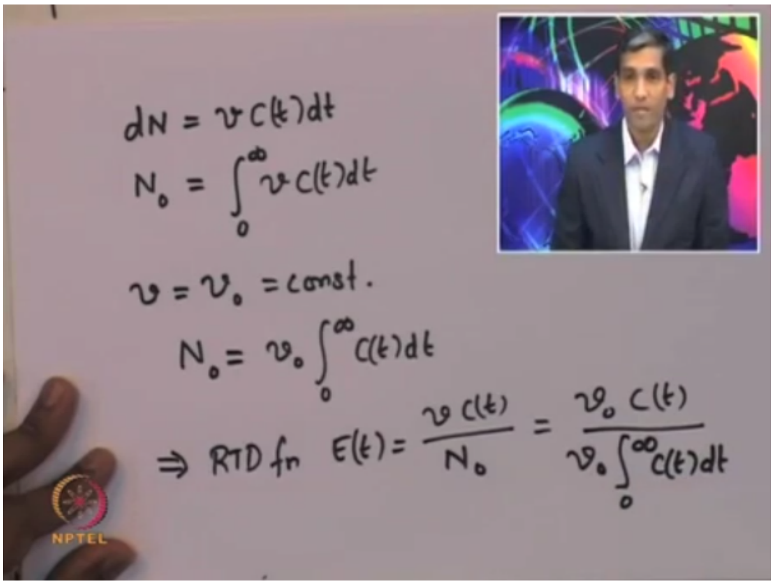

So, d N is essentially given by the volumetric flow rate v multiplied by C of t into d t. So, therefore N nought which is the total amount of tracer that is actually fed into the reactor. Remember it is a pulse tracer. That means, there is a sudden injection of the tracer at a certain time and very very short time. And therefore, the total amount of tracer that actually leaves the reactor from 0 time to infinite time should be = the total amount of tracer that has actually been fed into the reactor as a pulse.

So therefore, the N nought will be 0 to infinity multiplied by v into C of t into d t. So, that is the total amount of tracer that has actually been fed into the reactor. Suppose, if we assume that the effluent stream volumetric flow rate is constant, then N nought which is the total amount of tracer that has been fed inside is given by v nought into integral 0 to infinity C of t into d t. So therefore, the residence time distribution function E of t, that is given by v into C t divided by N nought. And that is given by v nought, because the effluent stream volumetric flow rate is maintained constant. We assume that is constant, divided by v nought into integral 0 to infinity C of t d t.

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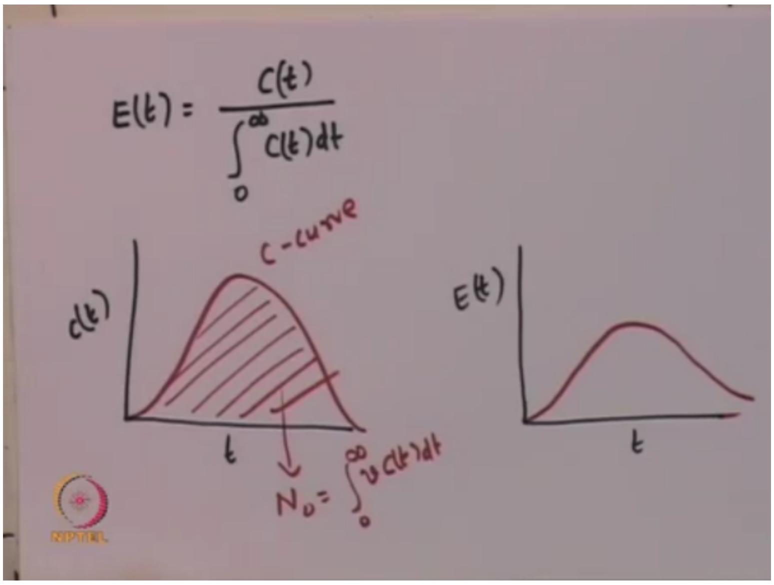

So, from here, we can easily see that the residence time distribution function E t is essentially given by the concentration of the tracer at any time divided by the total amount of tracer that is actually leaving the reactor. Or the total amount of tracer that is actually entering the reactor. So, if I plot this function. So, suppose the concentration versus time graph. So, the effluent concentration as a function of time, if it looks like, suppose if it is a bell-shaped curve.

So, that is the concentration of the tracer in the effluent stream as a function of time. Then, the area under this curve; so, this area under this curve is essentially N nought which is the integral 0 to infinity, v into C of t d t. So, a waited area under this curve essentially gives the total amount of tracer that is actually been fed into the reactor. So now, if I plot the corresponding residence time distribution function. So, E of t, then the curve essentially looks like this.

And this is, so if we know the, if we know what is the C t versus, or the c-curve. So, this is the c-curve. So, if the c-curve is known, then we can actually find out the e-curve. But, in order to find out the e-curve from c-curve, we need to be able to integrate the expression or find the area under the c-curve. Only if you are able to find the area under the c-curve, you will be able to construct the residence time distribution function. So now, from this we can actually find out what is the fraction of material which is with, that is leaving the reactor with a specified residence, specified range of residence time.

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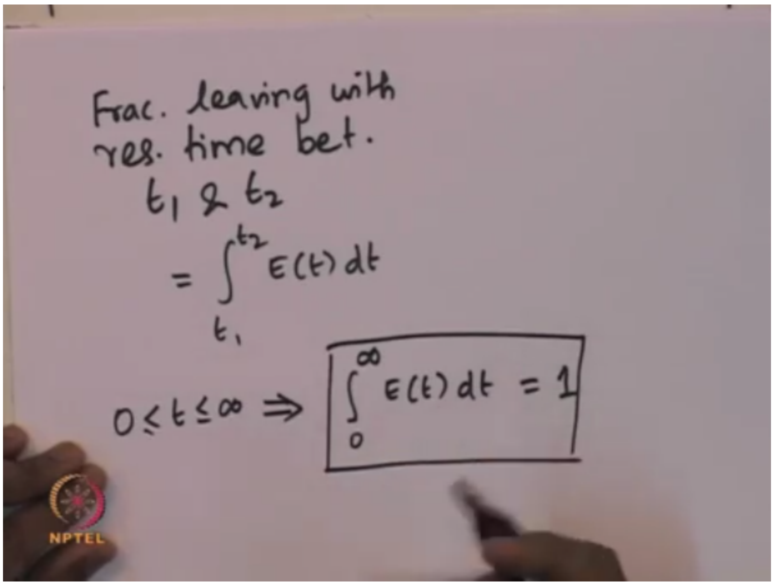

So, suppose if I want to know what is the fraction of material leaving with residence time between t 1 and t 2. So, I want to know what is the fraction of the material which is being fed into the reactor and that has spent, the residence that has spent sufficient time, but the time that is spent is between t 1 and t 2, certain time between t 1 and t 2. So, that can, that fraction is essentially given by integral t 1 to t 2 E of t d t.

So, if we know the residence time distribution, then there are lot of properties or lot of information about the reactor, can actually be extracted from the RTD function. Now, suppose if I want to know what is the fraction that leaves a reactor with residence time from time t = 0 all the way to infinity. Which means, what is the amount of material which leaves the reactor with residence time in the whole spectrum of time.

So, that will simply be given by for 0 less than t less than = infinity. That fraction will simply be 0 to infinity E of t d t. And that is = 1. Which means the area under the RTD function curve is 1. Which is true because it is a fraction and so the area under the curve should be = 1. Now, the question is, how good is this pulse input method? Can it be used in all situations in order to find out the residence time distribution function? And that is not, and that is really not the case. There are certain limitations.

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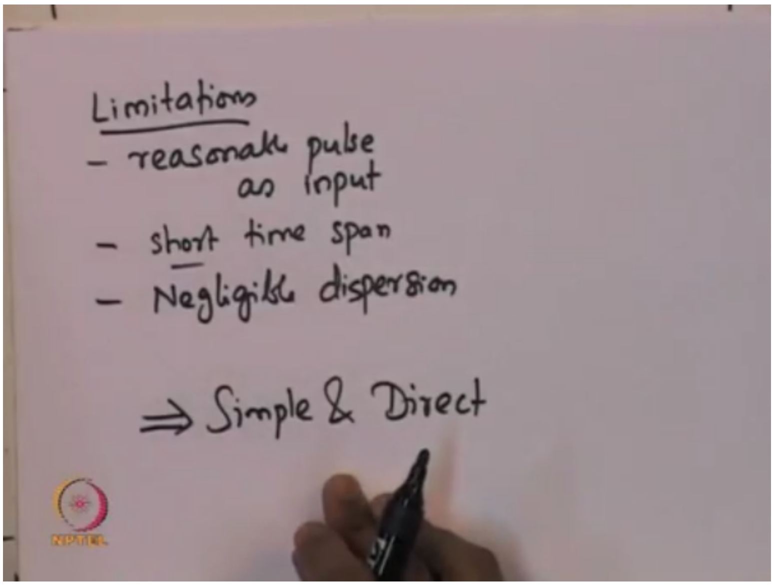

So, the limitations are, there are certain limitations. So, it is important to obtain a reasonable pulse as the input. So, that is so often not very easy to do. So, it is very difficult to get reasonable pulse as input. Why is that? Because the injection has to be done at a very short period and a sufficient quantity of the tracer has to be injected in this very short period. So, that is not a very easy task and it is not very easy to perform certain experiment where the tracer is actually injected into the stream in a very short time and sufficient quantity.

So, injection has to be in a very short time. It has to be in a very short time span. And more importantly the reactor must have negligible amount of dispersion between the point of injection and the entrance of the reactor, over which very limited control can actually be established on the reactor. One cannot control the extent of dispersion. So, if the reaction has reasonable dispersion then this pulse input method simply does not provide a clean way to find the residence time distribution.

However, pulse input method is basically, it is a very very simple, it is a simple and direct method provided these 3 conditions are actually satisfied. Now, another important caveat associated with the pulse input method is that;

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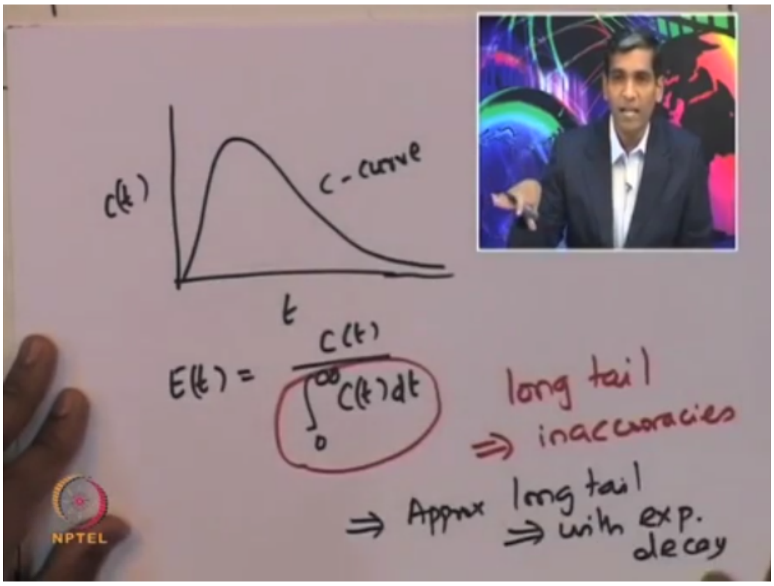

If I look at the concentration curve, in certain situations there can be a very long tail which is present in the c-curve. So, this is the c-curve. So now, the concentration curve has to be integrated. Remember that E of t is basically given by c t divided by integral 0 to infinity C t d t provided that the effluent volumetric flow rate is constant, there is no dispersion, etcetera. So, in order to perform such an integration, one needs to do a numerical integration of this curve, this c-curve.

And if the tail is very long, then it is not easy to integrate this expression numerically and it can actually cause inaccuracies in the integral. So, therefore the long tails can actually lead to inaccuracies in estimating this. Long tail causes inaccuracies in estimating this integral. And therefore, 1 specific reconciliation is, 1 specific method in order to get over, circumvent this problem is basically to use approximate long tails if long tail is observed, approximate long tail with exponential decay.

So, assume that the long tail is exponentially decaying. And so now, there is, it is an analytical function. It can be used to find out the integral C of t d t to a reasonable accuracy. So therefore, if there is long tail, then it can lead to all kinds of numerical issues in order to estimate the RTD.