Chemical Reaction Engineering II
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Lecture - 33
Reactor diagnostics and troubleshooting

Friends, in the last lecture we initiated discussion on the estimation of the residence time distribution for a laminar flow reactor; let us continue with that.

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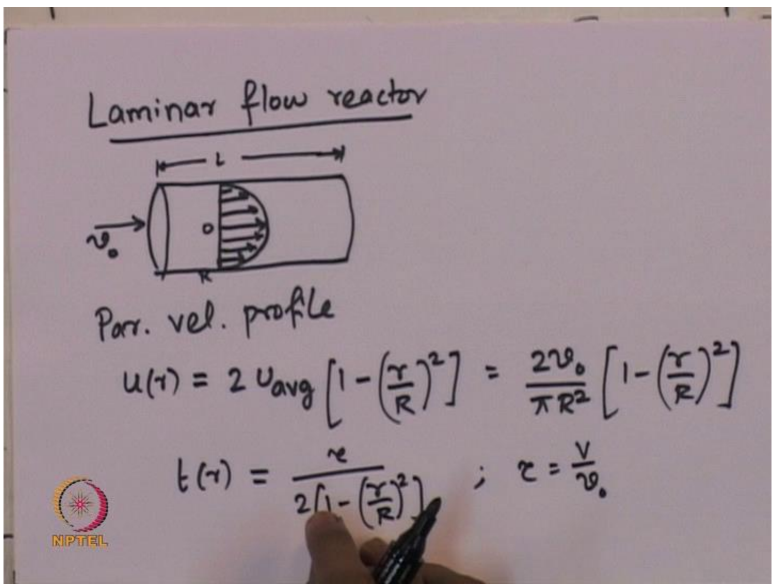

So, laminar flow reactor is essentially at a tube through which a fluid is flowing and let say that the volumetric flow rate with which the fluid is actually flowing through the reactor is v naught, and if the length of the reactor is l, then the velocity profile of the fluid in the radial direction will be parabolic with maximum velocity at the center and all the other fluid streams which is flowing at any other r location will be smaller than the maximum. So, this is r equal to zero and this r equal to capital R which is the radius of the cylindrical tube. So, the maximum of velocity will be at the center. So, the parabolic velocity profile as we saw in the last lecture is actually given by u at any r location is two times the average velocity in a cross section or the cutting velocity in a cross section multiplied by 1 minus r by r the whole square.

And that is equal to 2 into v naught which is the volumetric flow rate with which the fluid is actually flowing through the reactor divided by the cross sectional area pi r square into 1 minus r by capital R the whole square. So, that is the dependence of the velocity in any radial position with respect to the position. Now we said that the time that is actually taken by different fluid in different r location is going to be different, because the velocity with which they are moving through the reactor is different. So, therefore, the time that they would different fluid elements at different r location would take in order to traverse from the entry to the exit of the reactors will be tau divided 2 into 1 minus r by capital R the whole square where tau is actually given by v volume of the reactor divided by the volumetric flow rate which is essentially the space time of the reactor.

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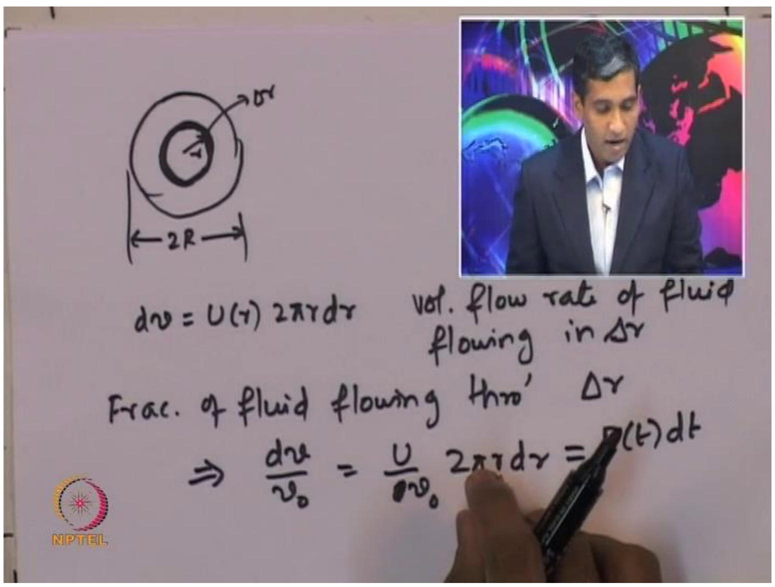

So, now let us look at a particular cross section. So, if at any radial location if we identify a small thickness of delta r; so suppose if thickness is delta r and this thickness is located at some r location. So, the inner radius will be r of this element and the outer radius will actually be r plus delta r, and the diameter is given by 2r, where r is the radius of the tube. So, now the volumetric flow rate of the fluid that actually flows through that small element delta r is essentially given by d v; if u is the velocity with which the fluid is actually flowing in that r location multiplied by 2 pi r d r. So, that is the volumetric flow rate of fluid flowing in delta r; so that is the volumetric flow rate.

Now what is the fraction of the total fluid that actually flows through that small element delta r? So, that fraction of fluid flowing through delta r; so that is actually given by d v by v naught, where v naught is the flow rate with which the fluid actually is entering the reactor, but that is equal to u by r u by v naught into 2 pi r t r. And that is nothing but the e of t d t which is the fraction of the fluid that is actually going through the small element whose volumetric flow rate is actually between v and delta v. And also the time that is actually spending inside the reactor is given by the time that is between t and t plus delta t. So, therefore, the fraction of the fluid that is flowing through should be equal to the corresponding residence time of that particular fluid element.

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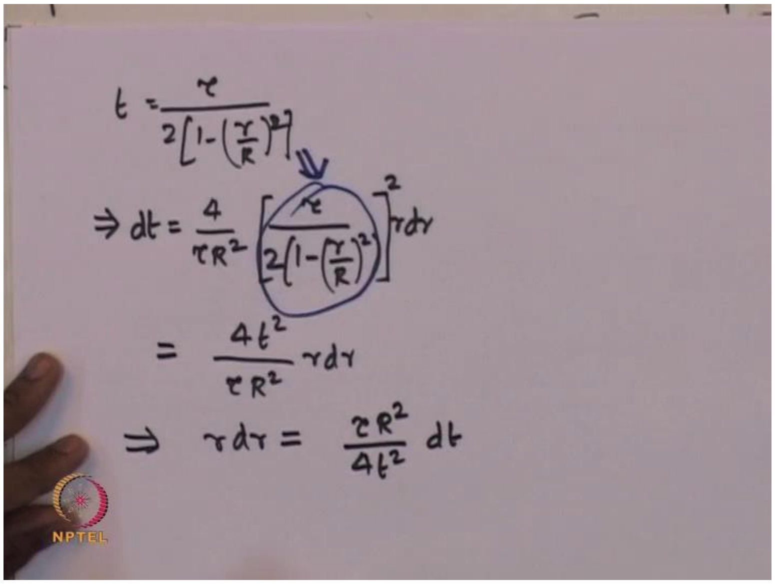

So, now we know that the time that the fluid element takes to actually traverse from 0 to l; that is along the length of the reactor is actually given by t equal to tau divided by 2 into 1 minus r by capital R the whole square, where capital R is the diameter of the tube. Now from here by differentiating this expression, we can find out that d t equal to 4 by tau r square multiplied by tau divided by 2 into 1 minus r by r square. So, one needs to perform a little bit of algebra to get this expression so into r d r. So, that is the expression for d t as a function of. So, when we take the first differential of this expression, this is the expression that one would get as a function of d t equal to r and d r, okay. So, we can further simplify this by substituting the expression for the time that the fluid which is present in a particular r location takes to travel from the inlet to the exit stream of the rector.

So, that is given by 4 t square divided by tau r square into r d r. So, this is obtained simply by substituting this expression which is present inside these brackets with the corresponding time. So, that is nothing but the time taken by the fluid at our location to travel from the inlet to the exit of the reactor. So, from here, we can find out that r d r is actually given by tau r square by 4 t square into d t. So, now we can plug this in to the expression for the fraction of the fluid whose volumetric flow rate is between v and v plus v naught v and v plus d v and the fraction that spends the residence time of that fraction is between t and t plus d t.

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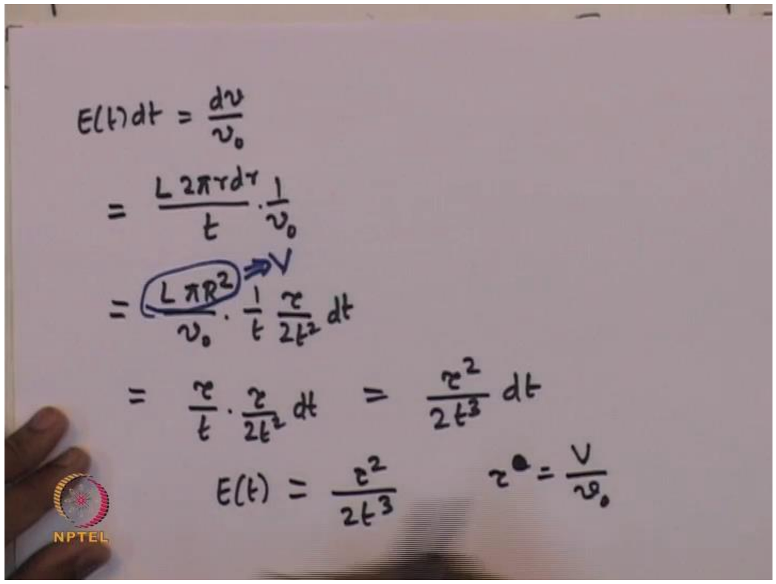

So, that is given by e of td t and that is equal to d v by v naught. And that is given by l d v is nothing but length of the reactor into the area of that small element that is 2 pi r d r divided by the time that is actually taken by the fluid in that particular element to travel from the inlet to the outlet of that particular reactor of that particular shell. And that ratio will give what is this differential volumetric flow rate multiplied by 1 by v naught. So, that is the expression for d v by v naught. So, now from here we can substitute r d r using the time that it actually differential time that the fluid actually takes to travel from one end to the other end of the reactor.

So, that can actually be related, and so one would get that l into pi r square divided by v naught into 1 by t into tau by 2 t square into d t. So, all that has been done is we have substituted r d r with the corresponding expression we just derived a short while ago. Now l into pi r square is nothing but the volume of the reactor itself. So, l into pi r square is the volume of the reactor. And so therefore, v by v naught is nothing but the space time of the reactor. So, that is given by that is equal to tau by t into tau by 2 t square into d t. So, that is nothing but tau square by 2 t cube into d t.

So, e t d t which is the residence time of the fluid fractional time that is actually spent fraction of the fluid that spends that time t whose residence time is between t and t plus d t is actually given by e t d t and for laminar flow reactor that is equal to tau square which is the square of the space time divided by the 2 into t cube, where t is the time that is spent by a particular fluid element at a particular location from the entry to the exits of the reactor. So, therefore, by simply comparing simply by observation we can deduce that e of t should be equal to tau square by 2 t cube, where tau is given by volume of the reactor divided by the volumetric flow rate if we assume that the flow rate is actually constant.

So, now the question is when is this particular expression valid? What is the validity of this expression or the question is when will the fluid start living? Suppose I put a tracer at the entry of the reactor, how much time will it take for this tracer to first appear at the exit stream of the reactor; that is if I put tracer let us say pulse tracer at the entry of the reactor, how much time will that pulse take to travel through the reactor and what will be the first time at which the fluid will actually leave the reactor at l. And this is important because e of t is essentially the age distribution of the effluent stream. So, therefore, the e of t d t is actually valid only from the time at which the fluid is actually at which the tracer is actually seen at the exit stream or the effluent stream of the reactor. So, how do we find this? So, we can find this by observing that for a laminar flow parabolic profile, the fluid elements which is actually present at r equal to 0, it travelers at a maximum speed.

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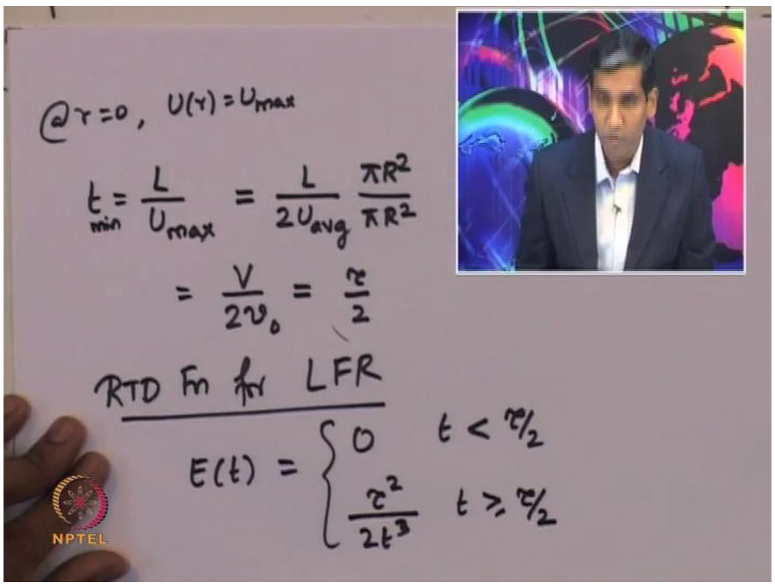

So, at r equal to 0, the fluid travelers the u of r equal to u max; so that is the maximum velocity. So, now, therefore, the residence time of the fluid element which is actually sitting at r equal to 0 or entering the reactor at the center of the reactor would actually spend the least time to travel from the inlet to the exit of the reactor. So, therefore, the minimum residence time should actually be equal to the residence time of the fluid stream which is actually entering at this location r equal to 0. So, how do we find this? So, we know that the time that is actually taken for the fluid elements to travels from one end of the reactor to the other end of the reactor is simply given by l by u.

And the minimum time is actually given by l by u max; that is the maximum velocity and that is at the center of the reactor. So, from here by simply plugging in the corresponding expression, we can find that minimum time that is actually taken for the tracer to be seen at the exit of the reactor is given by l by 2 u average; that is the cup mixing average into pi r square divided by pi r square. And that is nothing but v by 2v naught and that is equal to half of this space phi. So, the fluid element that is actually entering the reactor at the center of the tube would actually take half the space time before it actually reaches the other end of the reactor.

And in fact the residence time distribution actually starts from that particular time tau by 2 the minimum time. So, therefore, the r t d function for the laminar flow reactor is actually given by e of t that is equal to 0 if time is less than tau by 2 which means that there is no fluid stream which is actually leaving the reactor if the time at which it is monitored is less than tau by 2, whereas at for any time greater by tau by 2, the residence time distribution is actually given by tau square by 2 t cube for t greater than or equal to tau by 2. So, this is a nice example of how to find the residence time distribution function for a real reactor. So, such kind of a method can actually be employed to find the residence time distribution of any reactor where the dispersion is not present.

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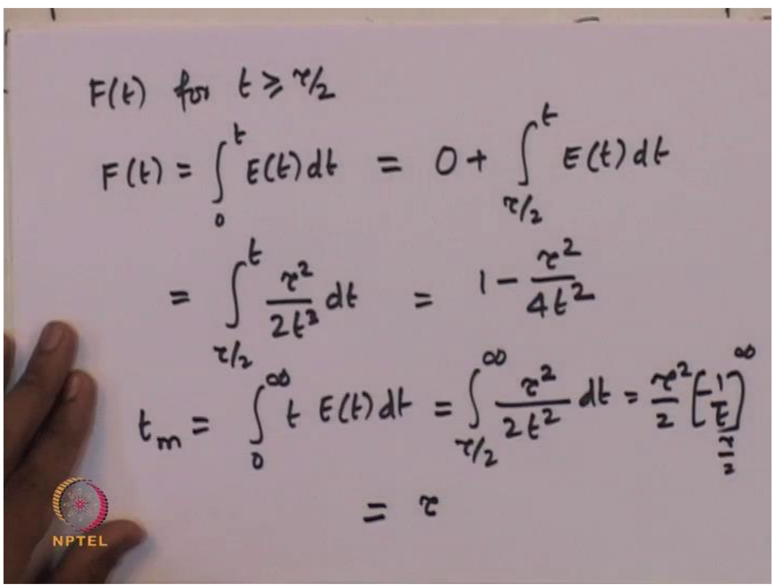

So, now what about f of t the f curve for the lamina flow reactor? So, for t greater than or equal to tau by 2 that is the time for which e of t is actually valid and f of t is given by integral 0 to t e of t d t and that is equal to 0 plus integral tau by 2 to t e of t d t. And now plugging in the expression for e of t, we can find that this is equal to integral tau by 2 to t tau square by 2 t cube d t, and on integration, one would find that will be equal to 1 minus tau square by 4 t square. So, therefore, the mean residence time which is the one of the property's of the residence time function is actually given by 0 to infinity t of e t d t.

So, this is the f curve; this is the relationship between f curve f and the time and the mean residence time is actually given by a integral 0 to infinity t e t d t and that is because it is between 0 and tau by 2 e t is 0. So, this integral simply becomes tau by 2 to infinity the limits will change and the integral will be tau square by 2 t square into d t which is equal to tau square by 2 into minus 1 by t. And the limits are tau by 2 and infinity. So, that is the limits, and substituting the limits, we will find that that will be exactly equal to tau which is what we instituted before that if there is no dispersion, then the mean residence time would be equal to the space time itself irrespective of the r t d function. And, in fact, we have shown this for three different types of reactors, the plug flow reactors, CSTR and that of the laminar flow reactor. Now let us look at the normalized residence time distribution function.

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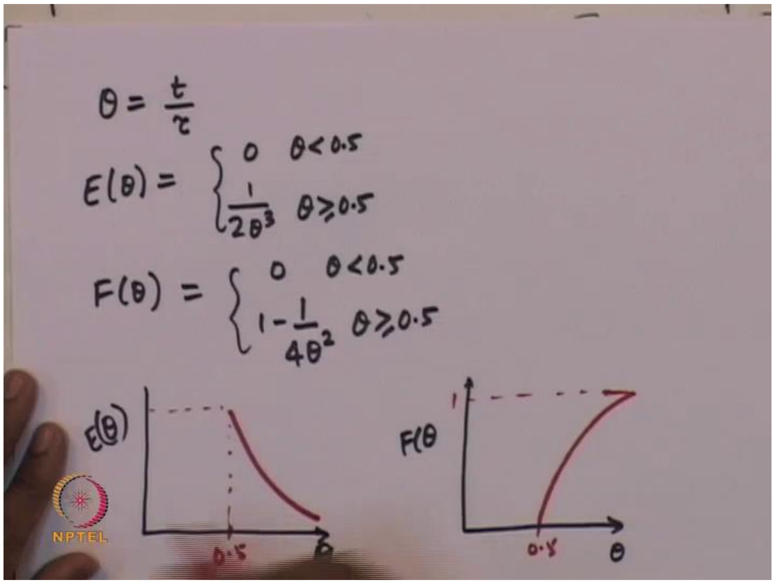

So, suppose if he define theta as t by tau, tau is the space time or the mean residence time for this particular case. And so e of theta would be 0 for theta less than 0.5, and it will be 1 by 2 theta cube for theta greater than or equal to 0.5. And similarly, f theta will be 0 for theta less than 0.5, and it will be 1 minus 1 by 4 theta square for theta greater than or equal to 0.5. So, now if we look at the e curve and the f curve, suppose if I sketch the e curve of the normalized residence time distribution function, then we can observe that the e curve is going to start at 0.5 because before 0.5 it is not valued. So, at 0.5 it will start and so it will start it will look something like this.

And the f curve can actually be again f curve will also start at 0.5. This is the f curve and it will start at 0.5 and then it will actually it will slowly increase and go to 1. So, that is the f curve. So, now we have looked at the residence time distribution functions of three different reactors. So, let us now attempt to put them all together and compare how the residence time distribution functions are actually different for these three reactors.

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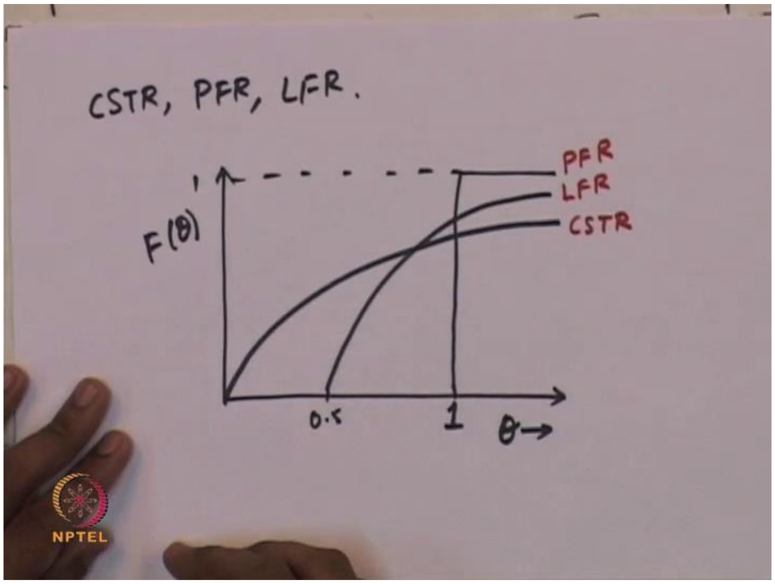

So, now let us compare the residence time distribution function the f curve for CSTR plug flow reactor and the laminar flow reactor. So, if we plot the normalized f curve, then for a plug flow reactor the f curve would start exactly at the space time of the reactor. So, therefore, it is exactly at 1, because it is a delta function, and so the f curve will actually be. So, that will be 1, then for a CSTR that is the f curve that one would get for a CSTR. Now if we plot for laminar flow reactor, so it starts at 0.5 and it appears somewhere in between the CSTR and the plug flow reactor. So, this is CSTR the f curve for CSTR, and this the f curve for plug flow reactor, and this is the f curve for laminar flow reactor.

So, one can actually experimentally if one performs the one estimates the f curve and the e curve experimentally from the methods that we described earlier that is if we use a pulse or a step input and one finds out what is the f curve for the reactor, then by simply making a comparison of this chart, one can actually estimate whether the real reactor is closed to what type of these three reactor that we have actually looked at so for; that is the CSTR, the laminar flow reactor and the plug flow reactor. So, such kind of a comparison provides a method for actually diagnoses of the nature of the RTD function for a given real world reactor.

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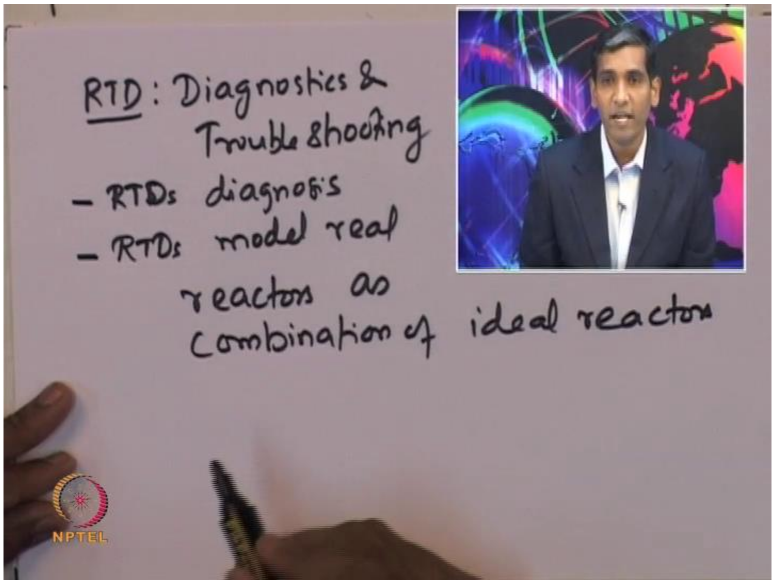

So, that brings us to the next topic where we want to see how to use RTD function for diagnoses diagnostics and troubleshooting. So, RTD functions can actually be used for diagnoses of certain properties of the reactor or certain aspects of the reactor and also to troubleshoot if something undesirable is actually happening inside the reactor. So, how do we do this? So, the RTDs are actually used for diagnoses. So, by comparing the RTDs is that are actually theoretically estimated for certain type of reactors and comparing that with the RTD of the real world reactor which may be estimated using experimental methods. By comparing that, one can actually find out what is the class of the real world reactor based on the RTD function.

So, RTD function can actually be used for diagnoses and not just that it can also be used RTD functions can also be used in order to model the real reactor as a combination of ideal reactors. So RTDs play a huge role in actually modeling real reactors as combination of ideal reactors. So, the RTDs the residence time distribution function, they play a crucial role in this process as well in order to model the real reactors as a combination of ideal reactors. So, before we get into how to do the diagnostics, let us look at what are all the common residence time distribution functions.

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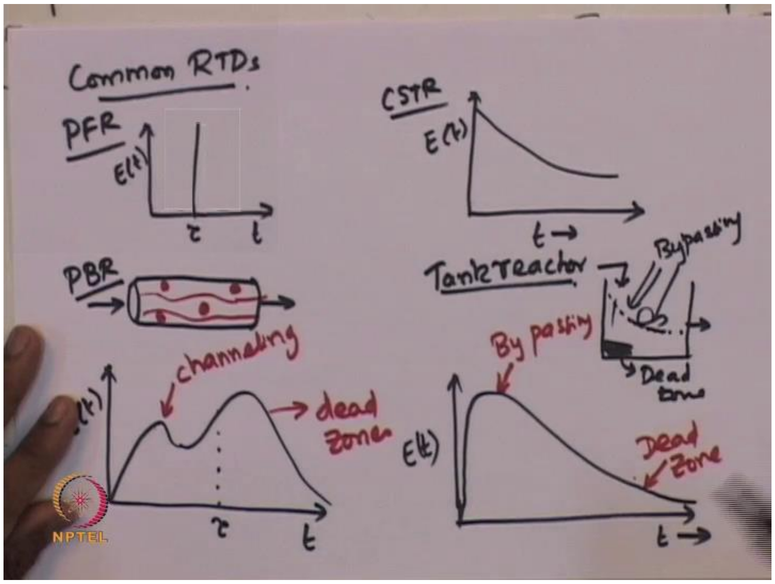

So, he common RTDs, so for a plug flow reactor the residence time distribution is essentially a dell function. So, that is the residential time distribution and it is entered at the space time of the reactor and that is the e curve e of t. And if I look at CSTR, so the residence time distribution is actually exponential that is e of t and that is the e curve for CSTR. Now if I take a packed bed reactor, now what has been observed; so suppose if there is a reactor and there is a fluid which is actually flowing through this reactor. One of the commonly observed RTD curve for such kind of a real world packed bed reactor, that is actually it look as below. So, two peaks have been observed; this is one of the commonly observed type of RTD function, where two peaks are observed, and typically, the first peak if there are two peaks and the first peak which actually appears before the space time of the reactor indicates that there may be channeling in the reactor, channeling or the bypassing inside the reactor.

So, that is the first peak which appears before the space time of the reactor and the second one the second peak which actually appears after the space time of the reactor; that indicates that there may be dead zones which may be present inside the reactor which does not serve any useful purpose inside the reactor. So, now if we attempt to depict this in the packed bed reactor, so there may be channels which may be present inside the reactor through which the fluid which is actually going through the packed bed reactor will easily escape and leave the reactor. And because there is a channel with which the fluid easily escapes, the time that they spend inside the reactor should actually be is actually smaller than the space time of the reactor.

And that is the reason why the first peak corresponds to the channeling of the fluid steam inside the reactor. On the other hand, if there are dead zones which are actually present inside where the reactor is virtually inaccessible, then there will be some of these fluids which are actual present; they will spend too long time inside these dead zones before they leave the reactor. And that is why it appears as a second peak particularly the tail part of the distribution curve. So, another commonly observed RTD function is that of a tank reactor a stir tank rector.

So, suppose if we have a tank and its well stirred and let say this is the inlet to the tank and this is the outlet to the tank and ma be there is bypassing through this particular tank and maybe there are some dead zone which are present here. So, this is the dead zone, and this is the bypassing. So, if such kind of a situation is there in a tank reactor that can actually be observed in the RTD curve in the RTD distribution function. So, the typical so the first peak which appears very close to time t equal to 0 is because of this channeling or because of this bypassing. And this bypassing can occur because of the placement of the entry and the exit fluids stream of the tank reactor; that these fluids streams simply quickly escapes and leaves the reactor, and that can actually be captured by this sharp peak which is actually present at time close to 0.

That is at the initial stages and then the long tails which is actually, so this is corresponds to the channel bypassing, and then the long tail which is actually present here is because of the dead zone. So, the launch tail indicates the presence of a dead zone inside the tank reactor, and this long tail is because this dead zone is actually not available for the fluids to actually go and they are not exchanging material with the location inside the tank which is well mixed. And, therefore, whatever residual fluid which is present here, they will take a very long time before they actually appear at the effluent stream of the reactor. Therefore, this dead long tail virtually corresponds to the dead zones that may be present inside the reactor. So, this kind of an approach the detection of the residence time distribution curve can actually provide a lot of information about what is actually happening inside the reactor, and this common RTD that has been explained just now is a good example of that.

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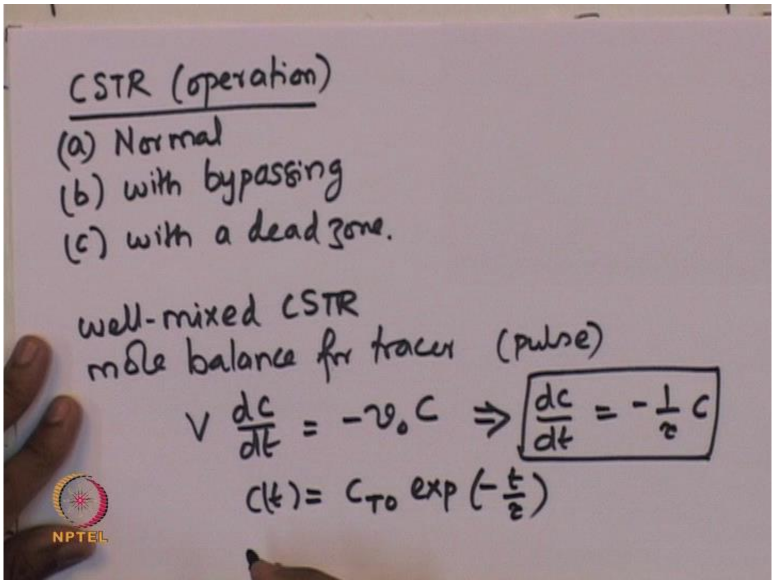

So, let us now look at the operation of CSTR. So, let us consider a CSTR, and let us look at what are all the various types of operations of CSTR, how it can be operated, and what are the distribution curves for each of these situations? Now this is very important to understand because if there is a problem with the CSTR and if it falls in one of these operational modes, it helps in diagnosing what is the problem with the actual reactor what is the problem with the functioning of the actual reactor, and then the methods to correct it can actually be implemented or actually can be deciphered later or can actually be thought of and strategies can actually be improvised later.

So, there are three modes of operation. Suppose, if there is real reactor whose volume is known and let us say a volumetric flow rate with which the fluid is flowing through the reactor is known, then one could actually look at what is called the normal operation where it behaves like an ideal CSTR, where all locations in the reactor is actually available for the reaction which means there are no dead zones where the reaction does not happen. And also it is assumed that there is perfect mixing in the reactor, and there is no bypass of fluid which means that all fluid that comes in actually undergoes reactions, spends the sufficient amount to time inside the reactor and then they leave the reactor.

So, as a second mode of operation is CSTR with bypassing. So, if we understand how the residence time curve of a CSTR with bypassing is going to appear, the shape of the curve can actually provide a clue as to if we understand what it is, then that actually be used as a diagnostic tool to find out if there is bypassing in the reactor. And then the third operation is with dead zone. So, now for a well mixed CSTR, suppose if I put a tracer suppose if I actually insert a tracer into the CSTR, then one can write a mole balance for the tracer and the mole balance will be. Suppose there is a tracer and the mole for the tracer will be v into d c by d t; that is equal to minus v naught into c suppose if it is a pulse tracer minus v naught into c and that should be equal to d c by d t minus 1 by tau into c. So, that is the mole balance for the tracer, and by integrating this expression, one would find that c of t is equal to the initial total concentration of the traces c t naught into exponential of minas t by tau

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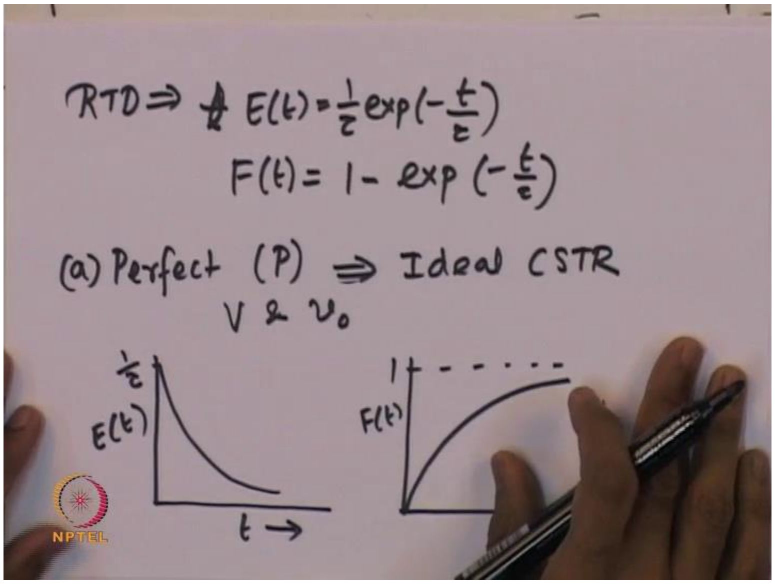

And we know that the RTD function for this reactor is actually given by the RTD function is given by 1 by tau that is the RTD function and then the FT curve which is the f curve is actually given by 1 minus exponential of minas t by tau. So, this we have already seen. Now suppose if you want to compare these three cases that is the three modes of operation, then we can now slowly try we can now attempt to find the RTD curve for these three operations. So, suppose let us start with the perfect so let start with the first case of perfect CSTR, so we tagged we used the symbol p for the perfect CSTR or operation of the CSTR in a perfect mode that is there is no bypass and there is no dead zone which means that this CSTR is actually an ideal CSTR.

And the volume and the volumetric flow rate are basically the measurable quantities of a real reactor; let us say we know of the volume and the volumetric flow rate with which the fluid is actually flowing inside the CSTR. So, we know of the residence time distribution curve and e of t versus t and so this starts at 1 by tau and then it actually decreases with time. And then we know the corresponding f curve that is an exponential increasing function and then it goes all the way up to 1. So, this is the f curve and the e curve for a CSTR. So, now if the space time of the reactor tau is that is very large, then the decay of this exponential curve and the corresponding concentration curve is actually going to be extremely slow which means that is the space time is large, then the tracer actually spends a lot more time inside the reactor.

And, therefore, the decay of this e curve as a function of time is going to be very slow. On the other hand, if the space time is very small then the amount of time that the tracer spends inside the reactor is going to be very small. And, therefore, the e of t and the time curve is going to have a sharp slope at small times which means that it is going to decay faster. So, now let us look at the second case of bypassing CSTR operation under bypassing conditions.

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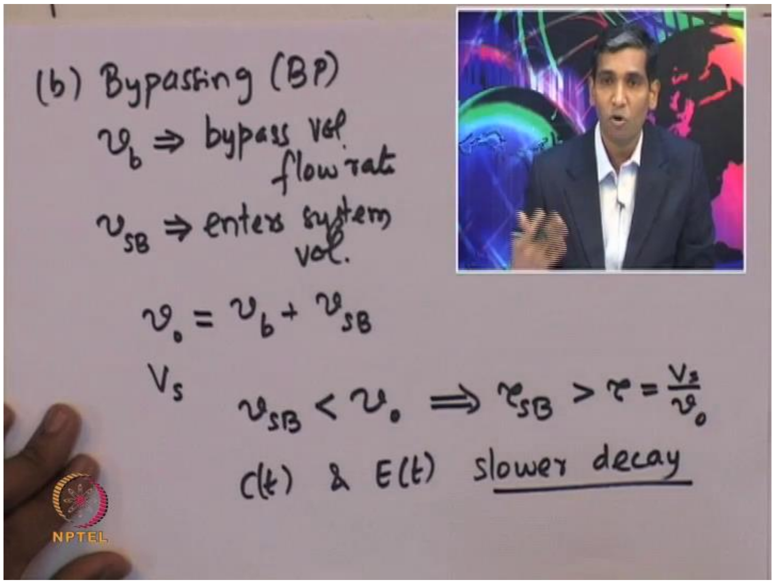

So, suppose we look at suppose we consider a CSTR where bypassing is known that bypassing is present. So, we refer to that as BP. If v b is the volumetric flow rate of the fluid which is actually bypassing the reactor; so that is the bypass volumetric flow rate. So, v b is the bypass volumetric flow rate and let us assume that v s b is the volumetric flow rate which is the actually going through the system volume. So that is that enters the system volume. So, therefore, v naught which is the volumetric flow rate with which the fluid is actually entering the reactor should be equal to v b plus v s b.

Now if we assume that v s is the volume of the tank, then we know that v s b is actually less than v naught because it is only a fraction of the total volumetric flow rate with which the fluid is actually being pumped that goes into the reactor. So, therefore, clearly tau s b should actually be greater than the space time of the reactor which means that the amount of time that this fraction of the fluid which is are not being bypassed the amount of time that it spend inside the reactor is actually larger than the actual space time of the reactor itself based on the overall volumetric flow rate.

So, remember that tau is actually defined as v by v naught where v and v s is the volume of the reactor and v naught is the volumetric flow rate with which the fluid is actually flowing through the reactor. So, therefore, because this tau s b is greater than tau, the CT the concentration curve and the e curve, they are going to decay very slowly. So, as we observed a few minutes ago as we actually discussed a few minutes ago because the resident time of the fluid stream which is actually going through the system volume is actually larger than the space time. The decay of the concentration and the e curve is going to be slower when compared with the case of a perfect operation that is there it is no bypassing, okay. So, in a similar fashion, now we can actually look at what is the possible residence time distribution under this condition. So what is possible?

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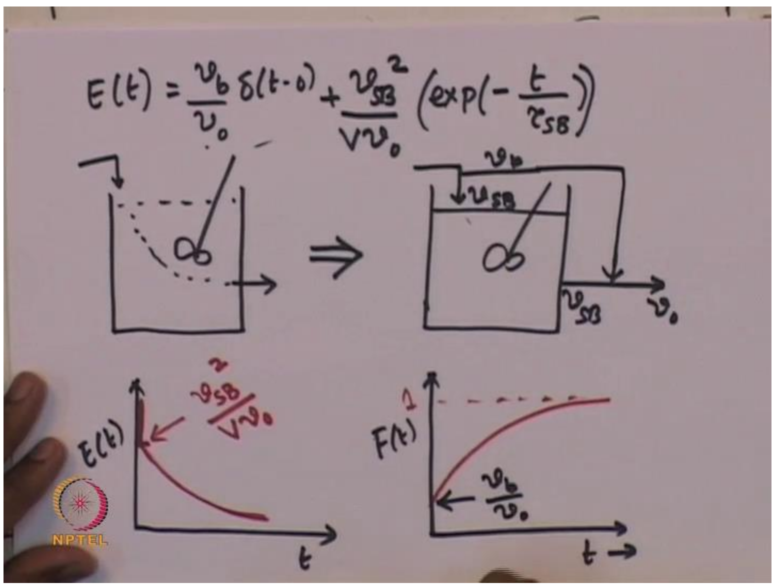

So, various possible residence time distributions have been considered and one of the possible distribution is that it will be v b divided by v naught into delta t minus 0; that means this is the component or fraction which is actually bypassing the reactor and leaving the fluid stream very soon after it actually enters the reactor that plus v s b square dived by v into v naught that multiplied by exponential of minus t by tau s b. So, that is a possible residence time distribution function that actually describes the residence time distribution of a CSTR which is actually operated along with a bypassing of same part of the fluid stream that enters the reactor.

So, now the system can actually be depicted in the following way. So, suppose if this is the CSTR and this is the inlet stream and if there is a bypassing of the fluid stream in the CSTR, then this can actually be depicted in the flowing cartoon. So, suppose if here is a tank and if let us say that the inlet fluid stream is actually split into two parts where there is a bypass component v b which actually goes and directly joins the exit stream and only fraction of the inlet fluid stream actually which is v s b the volumetric flow rate v s b actually enters the CSTR and participates in the same volume which is available, otherwise, and leaves the reactors.

So, this is the s p and it leaves the reactor, otherwise, same volume; the amount of the volumetric flow rate of the tracer that actually enters the reactor is v s b and then v s b is what this it actually leaves if we assume that bypass is essentially taking some of the volumetric flow rate and directly joining it with the effluent stream. So, this kind of a distribution curve essentially captures this representation. So, now If I attempt to sketch the e curve; so right at t is equal to 0, there is going to be a fall in the e curve. And this is because some fraction actually gets bypassed and directly goes and joints the effluent stream, and therefore, there is going to be a sharp fall in the e curve that is the fraction that is actually leaving.

And then after which there is going to be a exponential fall in the e curve. So, this first part corresponds to the bypass and the second part corresponds to this exponential term, and this location here is essentially given by v s p square divided by v into v naught. So, that is this location from where the exponential fall in the e curve actually starts. Now the corresponding f curve will be, so if this is the corresponding f curve, then we will see that the f curve actually has a jump right at t equal to zero. So, this is one; this is the f curve. So, there is a jump right at t equal to zero and the jump actually occurs up to v b divided by v naught which corresponds to the bypass the fraction of the inlet volumetric flow rates the fraction of the inlet stream which actually gets bypassed and leaves the effluent stream immediately.

And that is reflected in the f curve and also in the e curve. So, the important message from here is that an e curve and f curve if actually measured experimentally can indicate whether there is a bypass in such kind of a system. So, the third mode of operation is what happens if there is dead volume which is present inside the tank reactor inside the CSTR.

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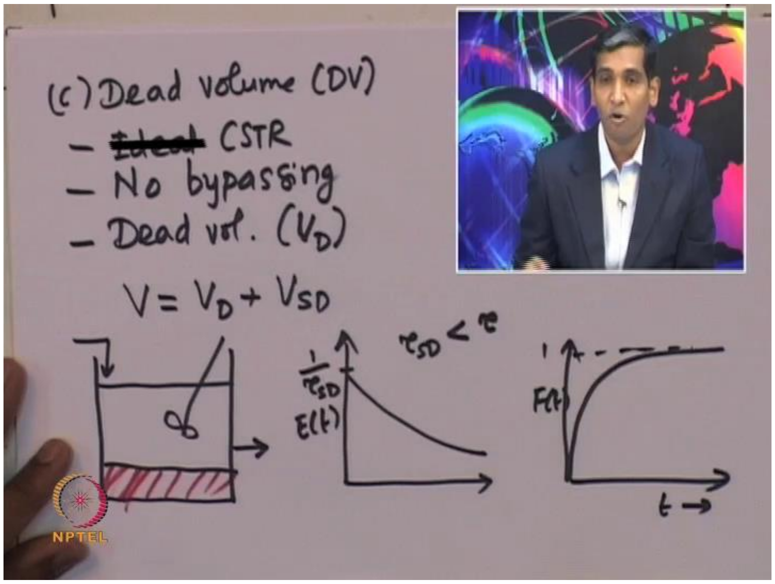

So, if there is a dead volume inside, so let as assume that it is a CSTR; there is no bypassing. It is assumed that there is a no bypassing inside the reactor and then there is some dead volume. Let us say that the volume of this dead zone is essentially v d, and this is dead volume essentially is one is the volume where the fluid stream does not reach that location and so it is the presence of this location is of no use for the performance of the reactor. So, the overall volume is actually equal to v d plus v s d where s d is the available volume which is actually accessible by the fluid stream which is flowing into the reactor.

So, now this can actually be depicted as so there may be some zone below which is actually a dead zone where the fluid stream actually does not access this location and then there may be an exit stream effluent stream through which the fluid that enters actually leaves the reactor. So, the e curve for this particular situation would actually look like it starts at 1 by tau s d. So, remember that the accessible volume is v s d which is smaller than the actual volume of the reactor, and for the same flow rate if it was conducted under perfect conditions that there no dead volume, then the tau s d which is the space time of the reactor for the fluid stream which is actually accessing the non dead volume space in the reactor.

So, that will actually be smaller than that of the actual space time of the reactor v by v naught. And as a result, the exponential curve the c curve and the e curve is going to decay faster than if it were to be conducted under normal perfect operation and the corresponding f curve would be. So, the f curve will also will be correspondingly steeper and it will actually slowly increase and go to 1. So, now if we put all these three together, let us make a comparison of the RTD functions for these three modes of operations.

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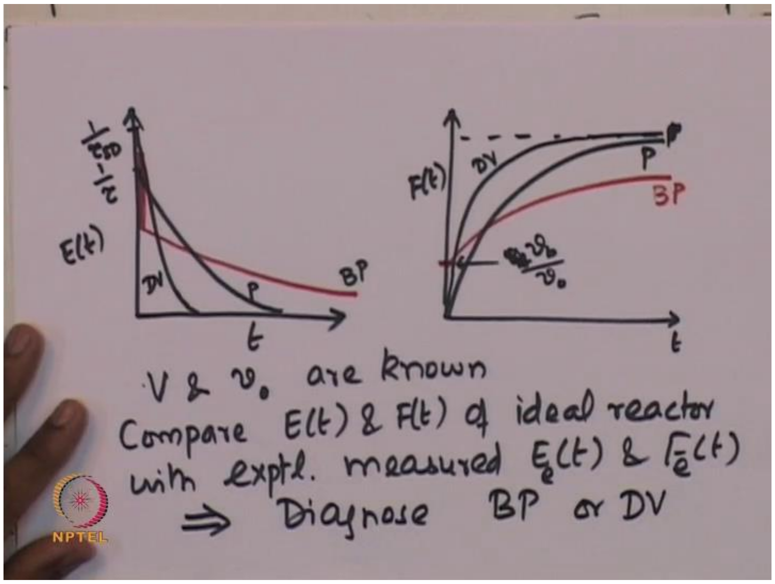

So, suppose let us draw the e curve. Now for a perfect operation, the e curve starts at 1 by tau which is the tau is the space time of the reactor and then it is exponential decay as a function of time; this is the e curve. Now is there was bypassing in the reactor, then right at t is equal to zero, there will be a sharp fall in the e curve and then followed by an exponential decay with respect to time. Now supposing if there was dead volume inside the reactor supposing if this corresponds to the perfect operation, this corresponds to bypassing; now if there were to be decay if there were to be dead volume inside the reactor, we just observed we just noted a few moments ago that the decay of the e curve is going to be significantly faster.

And, therefore, the curve starts above 1 by tau because tau s d so this starts at 1 by tau s d. And we said that tau s d is actually smaller that of tau, and, therefore, 1 by tau s d is going to be larger than 1 by tau and then it start's from here and the decay is actually faster than that of the perfect operation, because tau s d is actually smaller than the space time of the reactor. So, now if there is a real data for a tank reactor, then one can actually look at one can compare the actual RTD function measured experimentally with the RTD functions present in this graph, and that can actually provide a clue as to compare that with the perfect operation that can provide a clue whether there is a bypass or if there is a dead volume present inside the reactor.

Now similarly we can actually plot the f curve. So, for a perfect operation that is the kind of behavior that is the perfect operation and then for bypassing there is a jump right at t equal to 0; that is the kind of behavior for bypassing and the bypassing the curve starts exactly at v b by v naught and then for dead volume case, the curve actually increases rapidly and then it reaches 1. And so this is for the dead volume case, and this is for the perfect operation case. So, either e curve or the f curve can actually be used to detect what is the diagnosis if there is any problem in the operation of that particular CSTR.

So, therefore, the recipe is that if the volume of the reactor and the volumetric flow rates are known. So, volumetric flow rare can actually be measured and v is the volume of the tank. So, one can actually compare e t and f t f curve of ideal reactor. So, ideal CSTR and that is the perfect operation, and you can compare that with experimentally measured e and f curve. So, I put a subscript e for experimentally measured. So, one can actually compare the experimentally measured RTD functions with the RTD functions of the ideal reactor, and that can be used to diagnose the presence of the bypassing or the presence of dead volume inside the CSTR. So, next let us look at these three operations for a tubular reactor.

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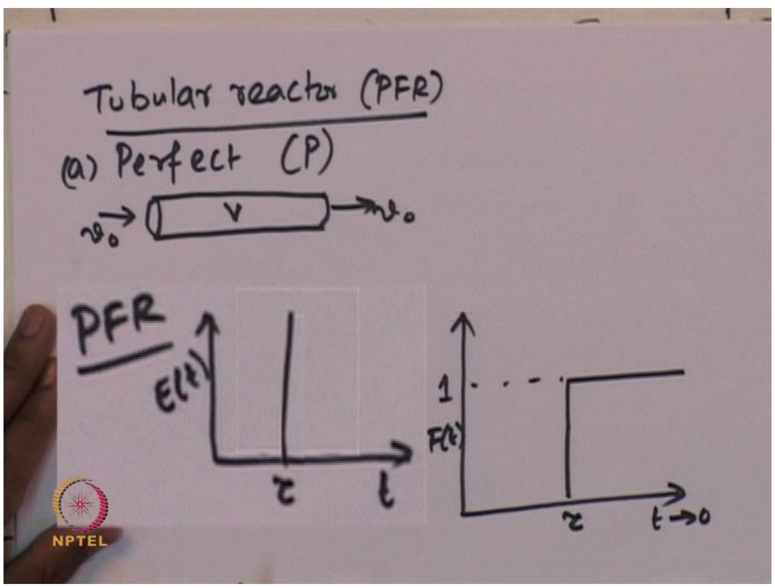

So, let us assume that it is a plug flow reactor. So, the first case is perfect operation. So, let us tag that with a p. So, here is the tube, and there is a fluid which is actually flowing at a volumetric flow rate of v naught and the volume of the plug flow reactor is v. So, now the RTD curve we know that it is a delta function centered at the space time of the reactor. So, that is e of t, and then the f curve is essentially given by it starts at tau and reaches 1. It is a step function in the f versus t plane. So, that we already know. Now what happens in the bypassing case?

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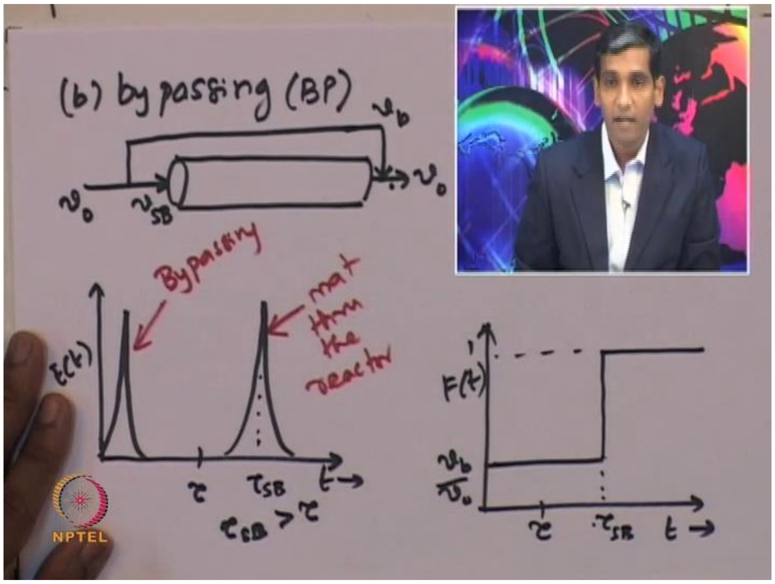

So, suppose if there is a bypass in the reactor suppose if there is bypassing in the reactor, so if I tag that with b p, then that can actually be depicted as suppose if v naught is the volumetric flow rate with which the fluid is supposes to enter the reactor and if this is the reactor and that is the final effluent stream volumetric flow rate, then a fraction of the fluid is actually bypassed and so we can represent that using by actually taking some part of the feed and the directly connecting it to the effluent stream. So, that is the depiction of the bypassing in the reactor and v s b is the volumetric flow rate with which the fluid it is actually flowing through the reactor.

Now the residence time distribution for this kind of a system can actually be written as will actually have two peaks. So, the first peak will actually appear very close to time t equal to zero, and this is because of the bypassing of the fluid and then there will be another peak which will appear much later and that is because of the fluid that is actually flowing through the plug flow reactor. And the residence time the space time of the reactor will actually appear somewhere in between. So, this is the e curve, and so the first peak is due to bypassing. The first curve is actually due to bypassing, and the second curve is actually due to the material through the reactor. That is because of the material that is actually flowing through the reactor.

Now why is there a delay in these two peaks or why is there a delay in the residence time for the material that is flowing through the reactor. The delay is because the tau s b which is the space time based on the fluid that is actually flowing through the reactor is actually larger than the space time of the reactor based on the overall volumetric flow rate that is actually expected that is the actually flowing through the reactor. Now, one can actually sketch an f curve for the same f of t. So, that starts at v b by v naught that goes to one and this is tau and this is tau s b. So, remember that this second peak is actually centered at the space time based on the volumetric flow rate of the fluid that is actually flowing through that is the actual volumetric flow rate which is accessible to all parts of the reactor.

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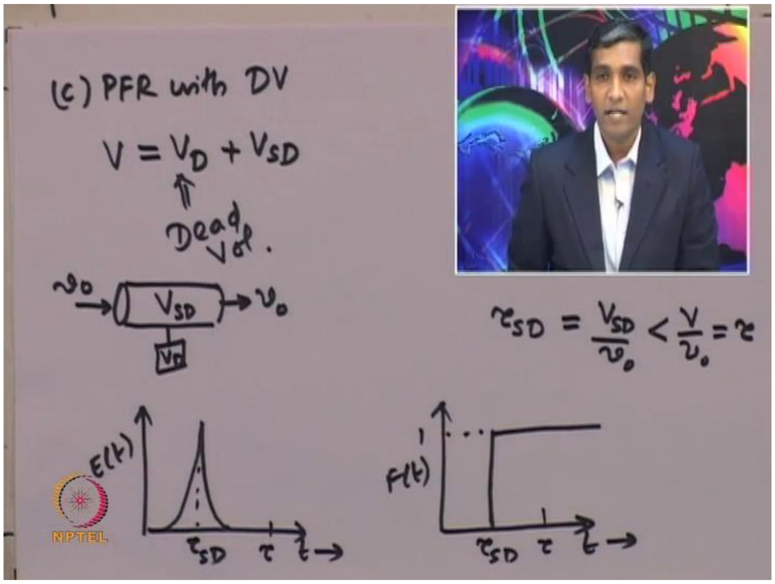

So, now let us look at the third case of plug flow reactor with dead volume; we tag it with d v. And suppose if the volume of the fluid volume of the reactor which is actually not accessible to the fluid is given by v d, then the total volume is v d plus s d. So, this is the dead volume. So, that is the dead volume and typically this happens because there will be recirculation of the fluid at the entry locations in the reactor and that causes the inaccessibility of those regions for the fluid stream and that can virtually be called as the dead volume inside the reactor. So, that can actually be depicted as. So, this is the volume of the reactor v naught v s t that is the dead volume which is removed from the reactor and that is the volumetric flow rate with which the fluid is actually entering and leaving the stream.

So, now in this case the tau s d which is the space time based on the volume of the reactor which is actually accessible for the fluid stream that is given by v s t by v naught and that will be less than v by v naught because v s t is smaller than the volume smaller than the total volume of the reactor which is and v by v naught is nothing but the space time. So, in this case, the tracer will actually leave the reactor early because some part of the reactor is actually inaccessible and so the space time is actually the actual space time the space time based on the volume which is available in the reactor is actually smaller than the actual space time of the reactor.

And so the e curve would actually look like there will be one delta function and that will actually be centered at tau s d and the space time will be much later that will be the e curve. And similarly, the f curve will be, so that is the e curve and the f curve for a plug flow reactor with a dead volume. So, what we have seen in the this lecture is looking at the different RTD functions for different operation of a CSTR and different operations of a plug flow reactor, and we will continue from here in the next lecture.

Thank you.