ENZYME SCIENCE AND ENGINEERING

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LECTURE-20

IDEALIZED ENZYME REACTOR PERFORMANCE

So today we shall discuss the performance of enzyme catalyzed reactors, the reactors in which enzyme catalyzed reactions are supposed to take place.

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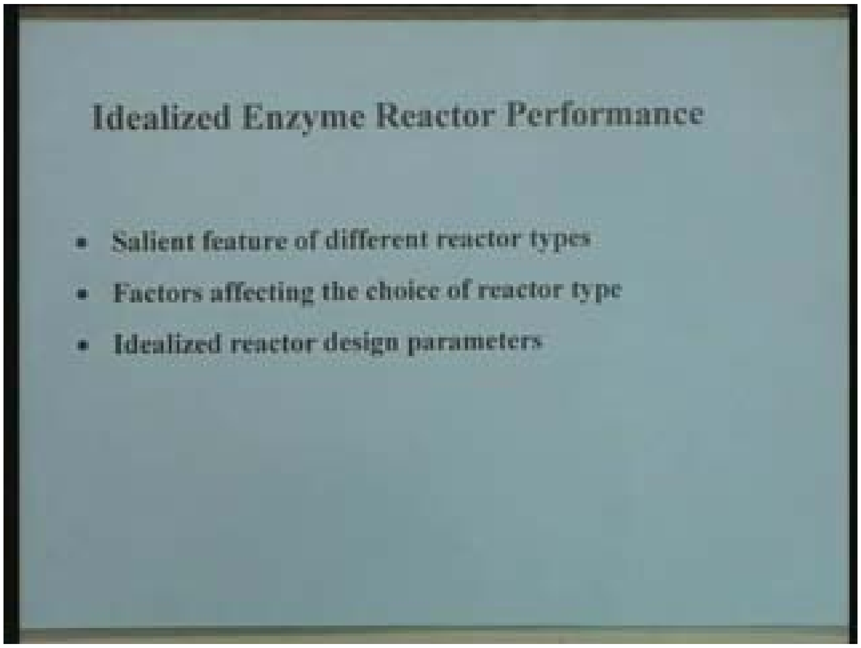

Idealized Enzyme Reactor Performance

- Salient feature of different reactor types
- Factors affecting the choice of reactor type
- Idealized reactor design parameters

You will recall earlier we had discussed some of the salient features of different reactor types ranging from batch reactors, batch stirred tank reactors to continuous stirred tank reactor or plug flow reactors and fluidized bed reactors. In fact some of the unusual reactor configurations which have been proposed to catalyze to be used for carrying out enzyme catalyzed reaction like hollow fiber reactors also arbitrarily fall into one of those categories of plug flow or CSTR which were discussed. We had also seen earlier the factors that affect the choice of different reactor types and to recall some of the factors that we had talked about the most important ones are listed here like form of the enzyme.

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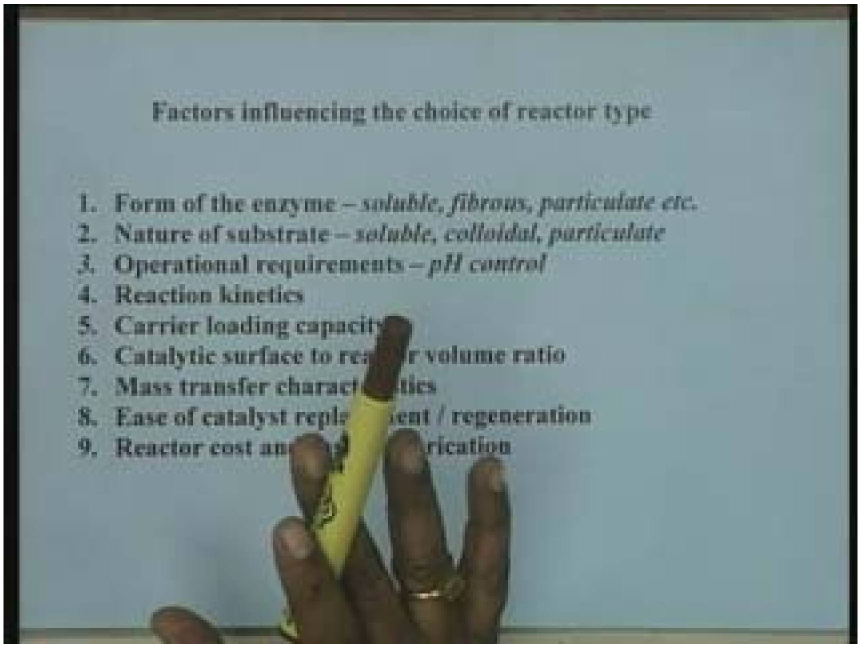

Factors influencing the choice of reactor type

1. Form of the enzyme – *soluble, fibrous, particulate etc.*
2. Nature of substrate – *soluble, colloidal, particulate*
3. Operational requirements – *pH control*
4. Reaction kinetics
5. Carrier loading capacit
6. Catalytic surface to rea r volume ratio
7. Mass transfer charact tics
8. Ease of catalyst repl ent / regeneration
9. Reactor cost an rication

That is soluble, fibrous or particulate. The nature of the substrate whether it is soluble, particulate or colloidal, operational requirements; the control of pH in case an acid is produced or consumed in the reaction, reaction kinetics, carrier loading capacity, catalytic surface to reactor volume ratio, mass transfer characteristics, ease of catalyst replacement and regeneration, reactor cost and ease of fabrication. All these factors that I have listed here can be considered mainly under two categories. One category contains the factor which becomes fixed once an immobilized enzyme is prepared. That means the factors that are dictated by the immobilization enzyme preparation itself. For example form of the enzyme; the nature of the substrate is also fixed. Once the enzymatic reaction is defined the nature of substrate is fixed. The operational requirement is also fixed depending upon the nature of the enzyme catalyzed reaction whether an acid is produced or consumed and pH control is a requirement. Similarly the catalytic surface to volume ratio is also fixed once an immobilized enzyme preparation is available. The carrier loading capacity also depends on the bulk density of the immobilized enzyme preparation and things like that. Ease of catalyst replacement and reactor cost and ease of fabrication are the factors which are dependent on the type of enzyme reactor. But the two important class of factors which I wanted to point out here is one is reaction kinetics and mass transfer characteristics. They are the ones which very heavily dictate the choice of the reactor; whether to go for a plug flow reactor or to go for a batch reactor or to go for a continuous stirred tank reactor are very heavily dictated by mass transfer requirements and reaction kinetics. I would once again point out that we have knowingly ignored heat transfer requirements assuming that for most of the enzyme catalyzed reaction the rate of reaction is very, very small and so heat transfer during the reaction is not a major critical factor. In certain cases if it is so, the heat transfer characteristics also must be taken into account. Last time I was taking we had also considered certain idealized reactor design parameter. That means for design of a particular type of reactor what kind of design parameters are important and you will recall that we had also hypothesized certain conditions or assumptions which define an idealized enzyme reactor system and the assumptions were that isothermal operation, ΔH is very small, uniform enzyme distribution, plug flow behavior or completely back mix behavior, that means you have one of the extreme fluid dynamics in the reactor system. Either it is a plug flow motion or it is a completely back mix and nothing in between. That is what we have assumed and there are no mass transfer limitations and no significant partitioning of substrate between bulk and the carrier phase.

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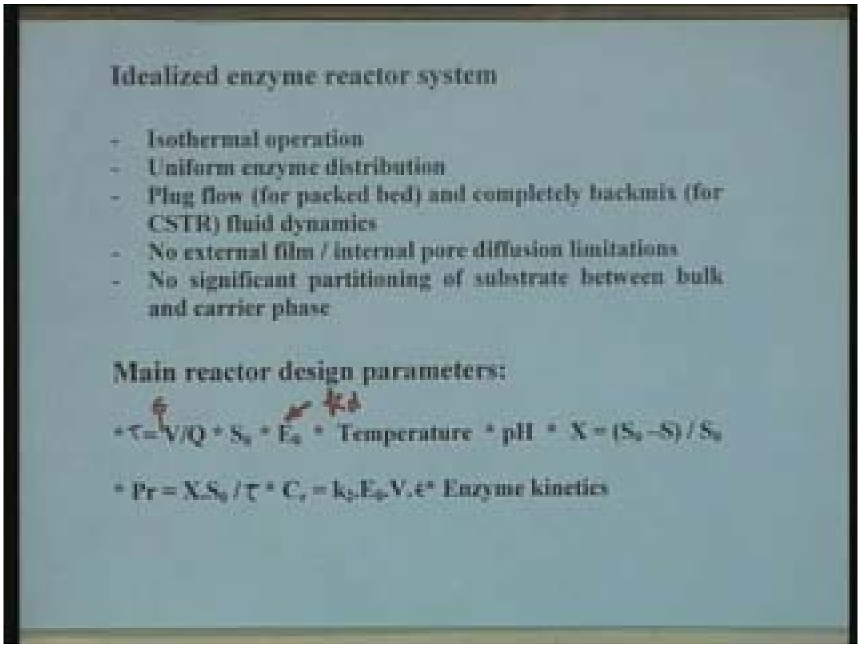

Idealized enzyme reactor system

- Isothermal operation
- Uniform enzyme distribution
- Plug flow (for packed bed) and completely backmix (for CSTR) fluid dynamics
- No external film / internal pore diffusion limitations
- No significant partitioning of substrate between bulk and carrier phase

Main reactor design parameters:

* $\tau = V/Q$ * S_0 * $\overset{k_d}{E_0}$ * Temperature * pH * $X = (S_0 - S)/S_0$

* $Pr = X.S_0/\tau$ * $C_r = k_2.E_0.V.\epsilon$ * Enzyme kinetics

These are the basic assumptions which define our ideal enzyme reactor and the reactor design parameters. That means the parameter which we should define initially before we go on to design any particular reactor was “tau”, the space time in the reactor; initial substrate concentration, enzyme loading, E_0. In the case of continuous operation, the information about the deactivation rate constant is also required, k_d. Then the temperature of operation, pH control and these are the reaction conditions. Other design parameters are fractional conversion and productivity and reactor capacity.

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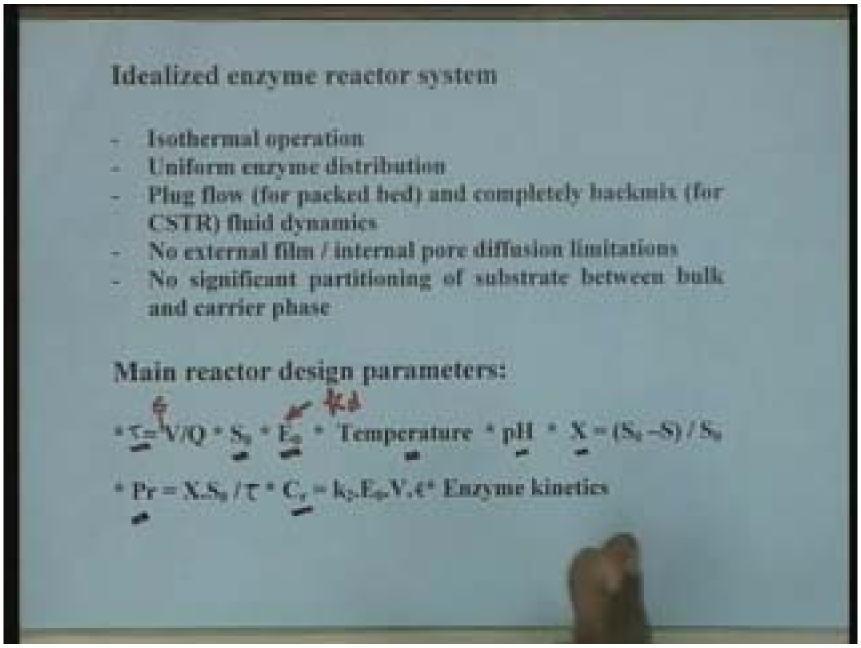

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That is the maximum reaction capacity assuming that the enzyme reaction follows a maximum reaction velocity, that is zero order profile and the productivity of that kind of the reactor will be your reaction capacity. Ultimately the performance will be dictated very heavily by enzyme kinetics. If we consider ….. (7:35) enzyme reactor we can safely say that Michaelis Menten kinetics provides us a basis for carrying out a universally accepted kinetics for enzyme catalyzed reactions and so therefore we will assume in most cases v is equal to

$$v = k_2E_0S/K_m+S$$

Wherever we are talking of immobilized enzyme we must also clearly understand that these two terms k_2 and K_m are denoted by prime indicating only that they are immobilized enzyme parameters and not the soluble parameters.

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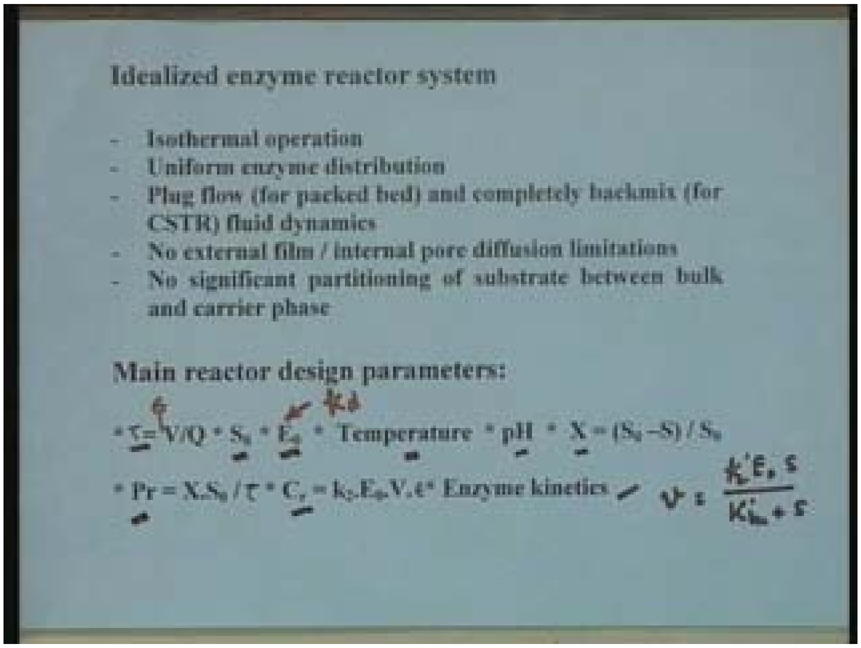

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Main reactor design parameters:

* $\overset{t}{\tau} = V/Q$ * S_0 * $\overset{k_d}{E_0}$ * Temperature * pH * $X = (S_0 - S)/S_0$

* $Pr = X.S_0/\tau$ * $C_r = k_2.E_0.V.t$* Enzyme kinetics $v = \frac{k_2' E_0 S}{K_m' + S}$

The first and probably the most simplest reactors is the batch reactors. The batch reactor can be used both for soluble enzyme as well as for immobilized enzyme.

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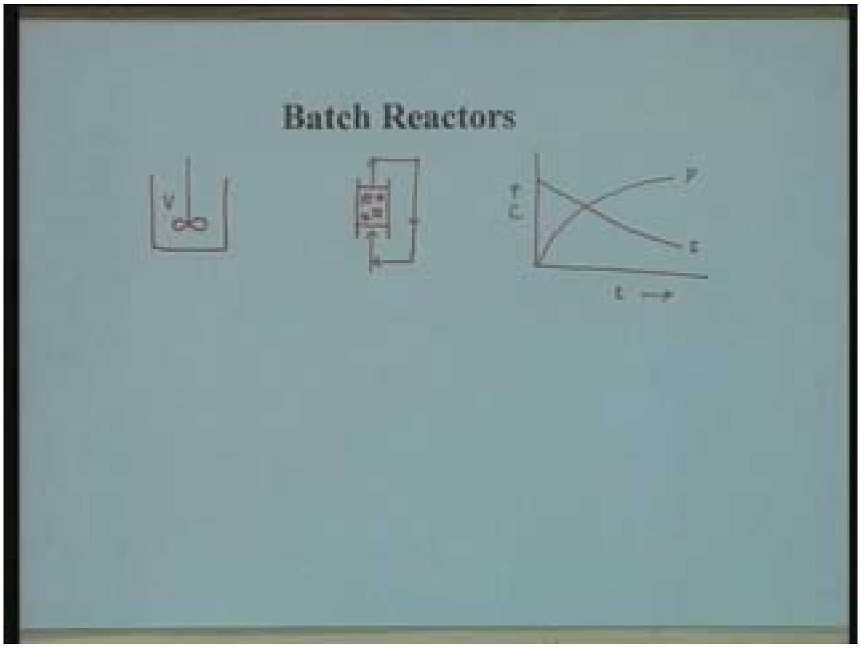

Batch Reactors

You can carry out a batch reactor in a stirred mode or in a packed bed mode with using total recycle and on the right hand side is the characteristic profile of the reaction species that is the substrate and product with reference to time. The substrate concentration drops and ultimately depending upon the extent of conversion which we require, the product concentration increases. A typical profile; it can change from reaction to reaction. If the reaction is very strongly inhibited by products or strongly inhibited by substrates the profile might undergo a change. One of the probably very general features of analyzing the reactor performance as you may be aware is material balance across the reactor. You take material balance for one of the reaction species say substrate and make a material balance; simplify it. Do mathematical steps and you will arrive at the reactor performance equations which will give you the performance of reactor. When I say performance of reactor I mean the extent of conversion as a function of space time or in a batch reactor with the reaction time. In the case of a batch reactor the reactor performance can be just simplified integrated form of the reaction equation and that is

$$-ds/dt = \frac{k_2.E_0}{K_m/S + 1}$$

Typical Michaelis Menten equation. Even when we write integrated form of equation we can assume that this is also valid if you make a material balance across the batch reactor because the classical material balance equation requires that input minus output minus conversion should be equal to accumulation. Here in the case of a batch reactor the accumulation is volume multiplied by rate of change of substrate concentration that is –v.ds/dt. Input and output here are taken as zero because there is no continuous input and output. Only initially we feed the reactor and at the end of the reaction time the output is taken out. There is no continuous output or input in the system and the conversion is given by the rate of reaction. So v into rate of reaction is the total accumulation and the conversion factor and by canceling the volume term from both the sides you can arrive at the integrated form of the equation and this equation if you integrate, it will lead to the reactor performance equation.

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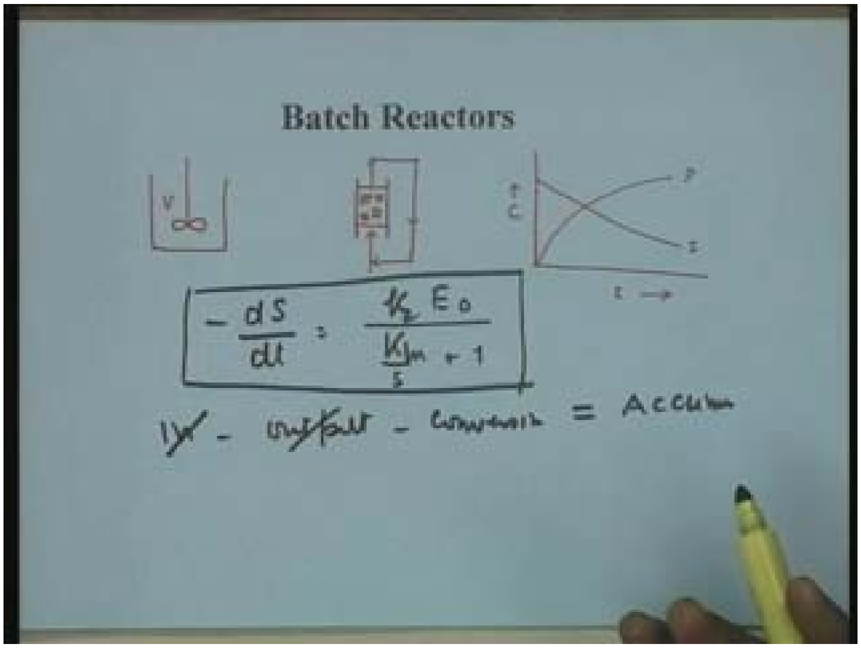

Batch Reactors

$$\boxed{-\frac{dS}{dt} = \frac{k_2 E_0}{\frac{K_m}{S} + 1}}$$

~~In~~ - ~~output~~ - conversion = Accum

If you just simplify it, you will get

$$K_m \ln S_0/S + S_0 - S = k_2.E_0.t$$

Again I like to repeat that in case if we are using a batch reactor for immobilized enzymes we should replace K_m and k_2 by prime terms. This is equation 1 and this is equation 2.

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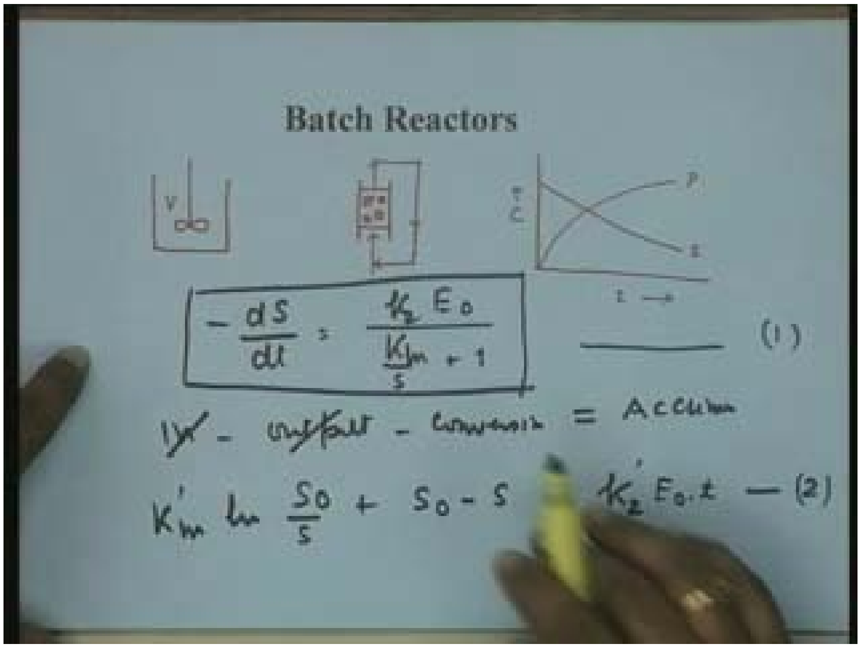

Batch Reactors

$$\boxed{-\frac{dS}{dt} = \frac{k_2 E_0}{\frac{K_m}{S} + 1}} \quad \text{———} \quad (1)$$

I/P - output - conversion = Accum

$$K'_m \ln \frac{S_0}{S} + S_0 - S = k'_2 E_0.t \quad — (2)$$

If you want to describe the equations in terms of reactor performance then X is equal to

$$X = \frac{S_0 - S}{S_0} = 1 - S/S_0;\ S/S_0 = 1 - X$$

So if you substitute all these parameters you get in terms of reactor performance equation for a batch reactor in the form of fractional conversion that is

$$XS_0 + K'_m \ln 1/1-X = k'_2 E_0 t$$

The reaction performance equation for a batch reactor if we want in the terms of product concentration, product concentration is nothing else but

$$P = S_0 - S$$

assuming that its a unimolecular reaction. If in case you are handling with a different kind of a reaction scheme let us say one mole of substrates goes into two moles of products then accordingly one has to make a change in the definition of X as well as P. This will be equal to

$$P = S_0 - S = XS_0$$

Therefore you can also write in terms of product concentration

$$K_m \ln S_0/S_0 + P = k^{'}_2 E_0 t$$

If you look at these equations you can use the reactor performance data of a batch reactor. That means you take a single batch performance data; take the maximum conversion at different times of reaction. You can write down the expression

$$\frac{\ln S0/S}{S_0 - S} + \frac{1}{K_m} = \frac{k^{'}_2 E_0 t}{K^{'}_m (S_0 - S)}$$

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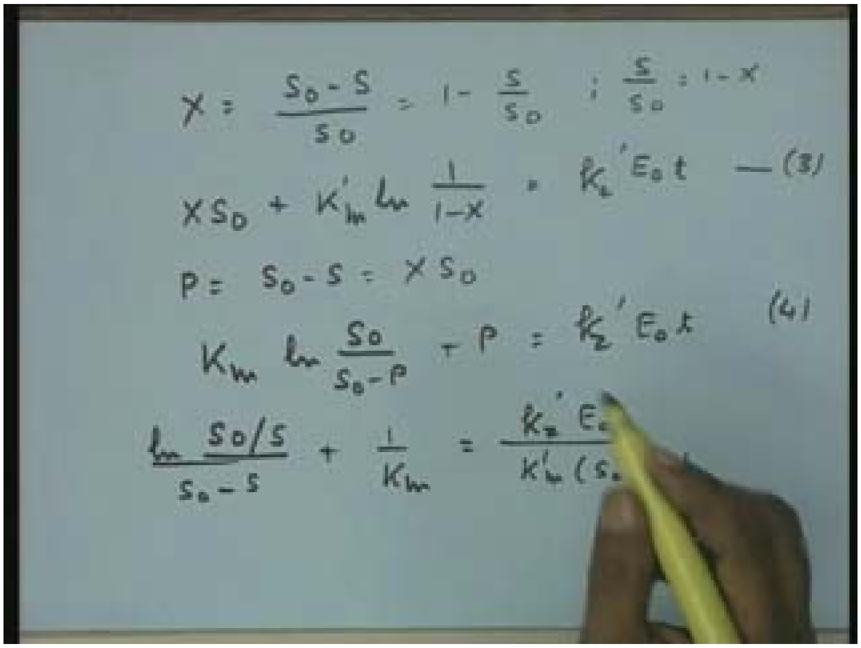

$$X = \frac{S_0 - S}{S_0} = 1 - \frac{S}{S_0} \; ; \; \frac{S}{S_0} = 1 - X$$

$$X S_0 + K'_m \ln \frac{1}{1-X} = k_2' E_0 t \quad \text{— (3)}$$

$$P = S_0 - S = X S_0$$

$$K_m \ln \frac{S_0}{S_0 - P} + P = k_2' E_0 t \quad (4)$$

$$\frac{\ln S_0/S}{S_0 - S} + \frac{1}{K_m} = \frac{k_2' E_0}{K'_m (S_0}$$

From the equation two if you just simplify you get a straight line equation which can give the values of K_m and v_m. If you plot let us say $\ln(S_0-S)/S_0-S$ and t/ S_0-S, you get the slope of k'2E0/ $K^{'}_m$ and with the intercept as $-1/ K^{'}_m$

Sorry. X-axis is $\ln S_0/S$.

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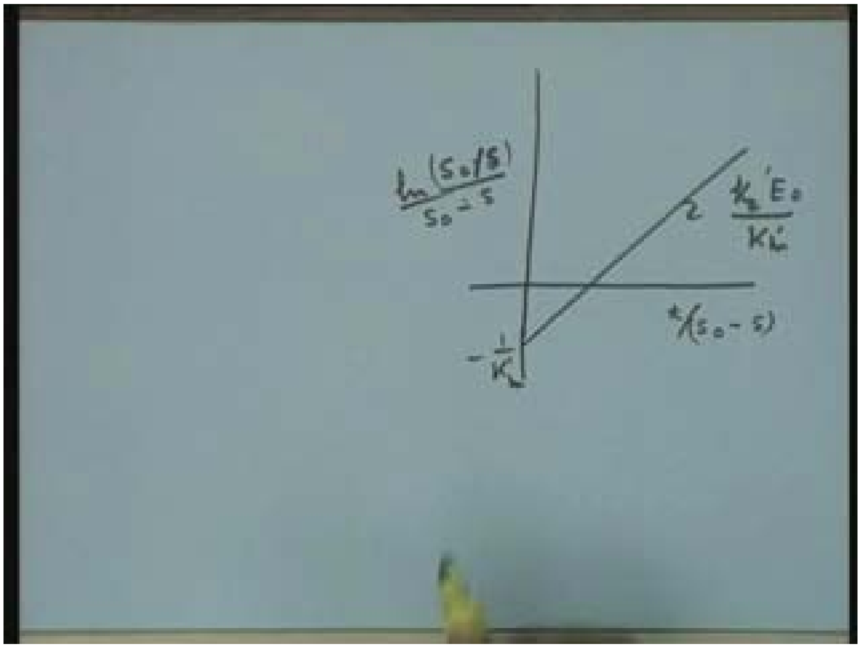

This provides you one of the simple methods. When we immobilize enzymes if we monitor the kinetics parameters K_m and v_m, the simple way to measure the kinetic constants for an immobilized enzyme reaction will be to carry out the reaction in a batch stirred reactor. Monitor the substrate concentration or fraction of conversion with reference to time and determine the parameters by a single reactor performance data. That provides us a simple tool, batch reactor for small scale laboratory experiments to determine the kinetic parameters both for soluble enzyme as well as for immobilized enzyme.

Here I must again put a caution. When we used the Michaelis Menten equation you will recall that we had made certain assumptions and the assumptions were that we are talking of the initial reaction rate. That means at a time equal to zero. Whereas when we integrate the equation from zero to time t let us say to a conversion factor of 90% or 95% or 99%, the reaction rate is not likely to remain the same as that of the initial time. So here we are violating some of the basic assumptions of the Michaelis Menten equation. But still it gives you a very approximate situation for designing a reactor or making some design calculations to work out reactor size or the capacity of the reactor, accepting that and even compare between soluble enzyme and immobilized enzyme but otherwise under idealistic conditions, the assumptions in the Michaelis Menten equation that of the initial reaction rate, absence of product division is not met here. So when we apply the integrated Michaelis Menten equation for looking at the performance of an immobilized enzyme reactor in the batch mode we must keep in mind that it only gives you an approximate situation just to tell the sizing of the vessels required for a particular enzyme catalyzed reaction and to compare the soluble enzyme with that of immobilized enzyme performance. Even while looking at the kinetics of the soluble enzyme we always look at the situations when it comes to extreme substrate conditions. That means either when the substrate concentration is much, much smaller than K_m or when it is much higher than K_m. That means it ranges from first order to zero order regime (18:30). How the reactor performance will change? For example when substrate concentration is much, much smaller than K'_m, reactor performance becomes

$$-K'_m \ln(1-X) = k'_2E_0t$$

When S_0 is much, much greater than K'_m that is zero order regime.

$$XS_0 = k'_2E_0t$$

If suppose you approximate an enzyme reactor to follow either a zero order or a first order regime, knowing the values of K_m and k_2 the error involved in that will be determined by the ratio of K_m/S_0. If the ratio of K_m/S_0 is very, very small you will hardly incur any error if you assume it to be a first order.

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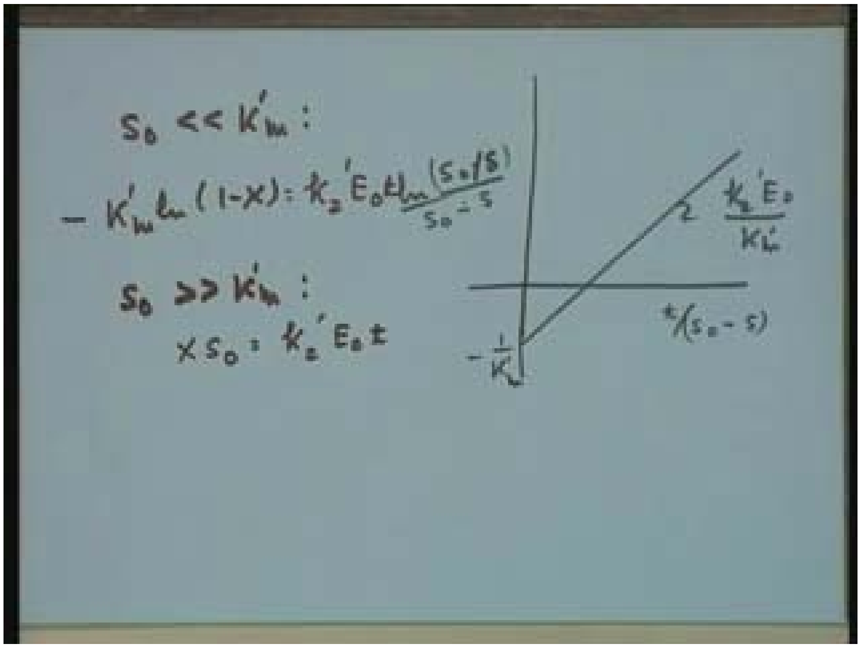

$S_0 << K'_m$:

$$-K'_m \ln(1-X) = k'_2 E_0 t$$

$S_0 >> K'_m$:

$$X S_0 = k'_2 E_0 t$$

When we go on to consider along with the reaction kinetics we consider mass transfer and all more complications we will tend to approximate our reactor performance in either zero order or first order regime rather than making it a Michaelis Menten equation which might make the solution of the expressions more difficult or it can be done by any numerical methods. But analytical solutions may be difficult. We make an assumption depending upon the range in which our substrate concentration exists in relation to K_m value. The error involved will increase if you increase the ratio of K_m to S_0 and you assume a first order because then both will go towards the zero order kinetics.

If the K_m to S_0 ratio increases and you assume a first order kinetics error will keep on increasing. K_m is much, much larger than the S_0 in the first order. So the value of K_m/S_0 will be larger. K_m/S_0 will be large and under that condition you must assume a first order kinetics and if the value of K_m/S_0 decreases the error will continue to increase. In fact one can make a hypothetical computation and then we take up an assignment to design an enzyme reactor or for that matter any process equipment. A 10% error in calculation is usually taken for granted. If you are going to measure let us say the value of K_m or v_m, you need an accurate value. But when you want to go for design, let us say a reaction capacity; what is the volume of the reactor required to carry out this conversion? You are not going to be very specific that this is the volume required. You will add on to that about 10% open added space or for various purposes. So if let us say the error involved is less than 10%, I think there is no harm in making an assumption of zero order or first order. If the error involved is much larger then our assumptions will be slightly hazardous.

The next simple form of reactor system which is commonly employed is a continuous stirred tank reactor. In the continuous stirred tank reactor one is a continuous flow reactor. That means the feed rate of the substrate is same as the output rate of the product stream. So if the feed is added at the flow rate of “F” let us say litres or moles per unit time, what ever unit you follow, the volume remains the constant. Substrate concentration S_0, changes at the exit. But one of the characteristic features is that all the parameters at the exit stream are same as in the reactor itself. That means the reaction will take place under conditions of S, P or X which exist at the exit stream. Therefore if you just write a material balance for such a reactor system you can write accumulation as

$$V.ds/dt = FS_0 - FS - v.V$$

FS_0 is the input; S is the substrate concentration in the outlet and v is the reaction velocity that is the conversion due to the reaction and V is the reactor volume.

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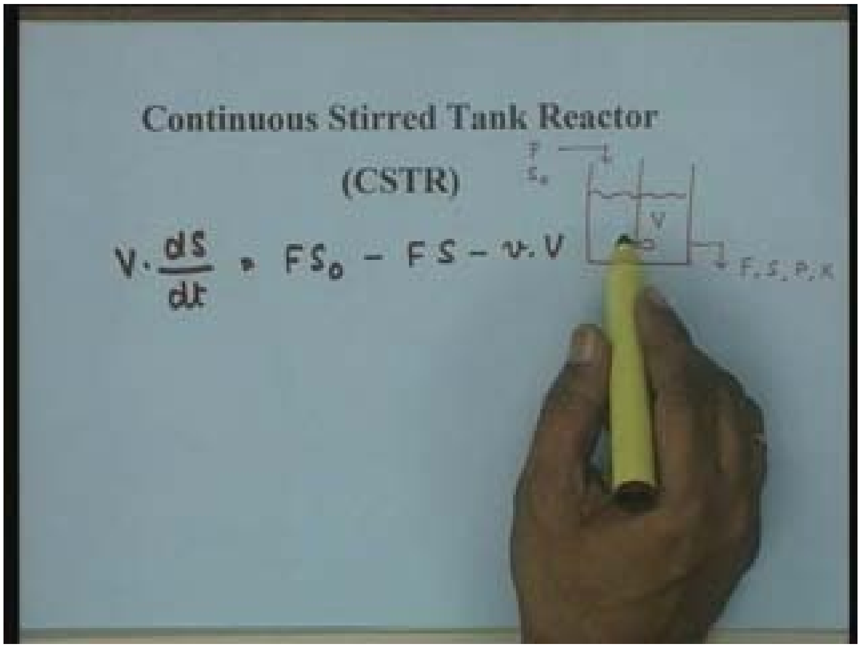

Continuous Stirred Tank Reactor

(CSTR)

$$V.\frac{ds}{dt} = FS_0 - FS - v.V$$

Consider that after a certain period of time the reactor comes under steady state situation. When we say steady state situation it means that the concentration of any species does not change with time in the outlet stream. Under that condition the accumulation term will tend to be zero because whatever material is coming in, either it is getting converted to do reaction or it is going out of the reactor. There is no accumulation of any species in the system and therefore one can write

$$v = D(S_0 - S) = \frac{k'_2E_0S}{K'_m + S}$$

D is the term here what we understand as dilution rate or F/V or in other words V/F is the resistance time, inverse of space time. So this D is the term and you can also write

$$\frac{k'_2E_0S}{K'_m + S} = \frac{S_0 - S}{\tau}$$

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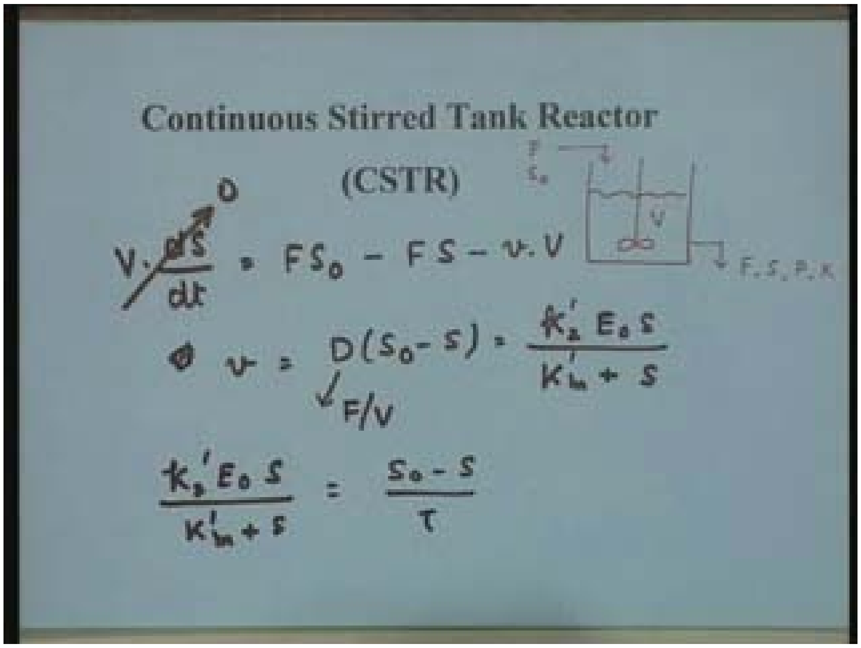

Continuous Stirred Tank Reactor

(CSTR)

$$V.\overset{0}{\cancel{\frac{dS}{dt}}} = FS_0 - FS - v.V$$

$$v = \underset{\downarrow F/V}{D}(S_0 - S) = \frac{k'_2E_0S}{K'_m + S}$$

$$\frac{k'_2E_0S}{K'_m + S} = \frac{S_0 - S}{\tau}$$

That is your space time that was defined in the earlier expressions. Solving these equations you can also get

$$k'_2E_0\,\tau = S_0X + K'_m\,(X/1-X)$$

That gives you a reactor performance for a CSTR and from the substrate concentration if you make a substitution for X, you arrive at detector performance for CSTR. Similarly here also if you make assumptions of zero order or first order situation when K'_m is much, much smaller than S_0, that is a zero order system

$$\tau = XS_0/k'_2S_0$$

For first order system where K'_m is much, much greater than S_0, you have

$$K'_m(X/1-X) = k'_2E_0\tau.$$

Second expression is $\tau = XS_0/k'_2E_0$. So you get the two expressions for CSTR the general reactor performance expression and also under conditions of zero order and first order scenario.

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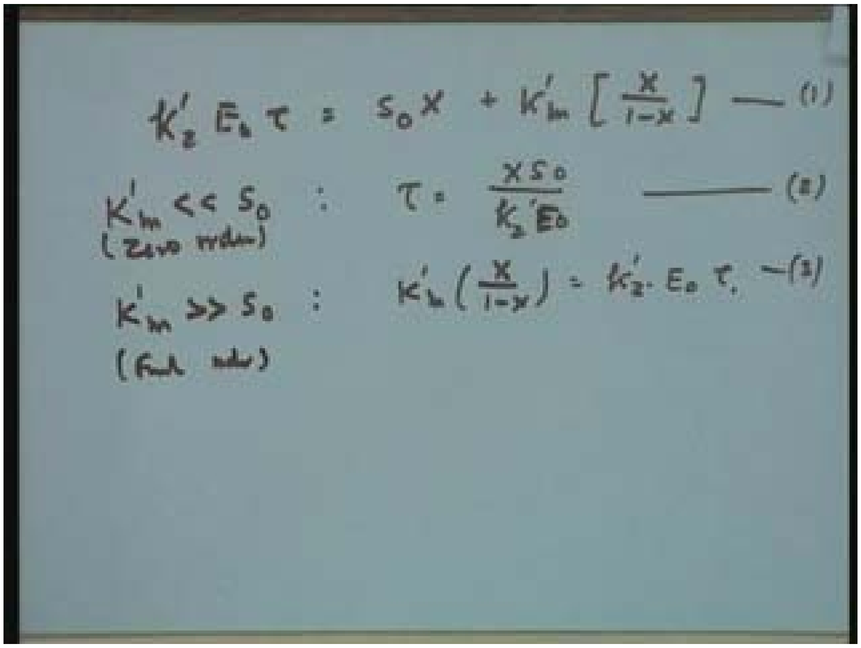

$$K'_2 E_0 \tau = S_0 X + K'_m \left[\frac{X}{1-X}\right] \text{ — (1)}$$

$K'_m << S_0$ (zero order) : $\tau = \frac{XS_0}{K'_2 E_0}$ ——— (2)

$K'_m >> S_0$ (first order) : $K'_m \left(\frac{X}{1-X}\right) = K'_2 \cdot E_0 \tau.$ —(3)

The expressions are very simple and if you have the data available for any reactor performance for S_0, fraction of conversion required, you can determine the volume of the reactor required or the feed rate required depending on the tau and one can make computation to define the reactor performance under given conditions.

The other idealized reactor or which is what we understand as the plug flow is slightly typical in the sense that unlike in the case of a CSTR, the concentration of the substrate or the product vary along the length of the reactor. So making a material balance across the reactor you cannot choose any concentration term because the concentration term for substrate changes with the length of the reactor and the concentration of the substrate or product is not constant throughout the reactor. It varies; that means if you consider along the length of the reactor, kind of a batch reactor with different reaction times but to arrive at the reactor performance what we can do is we can make a material balance across a differential element of the plug flow reactor and if we consider differential element of volume d v you can make your material balance say under same conditions like the feed flow rate as “F”, the conversion changes from X to X +ΔX at the inlet X is equal to zero at the outlet X has some value.

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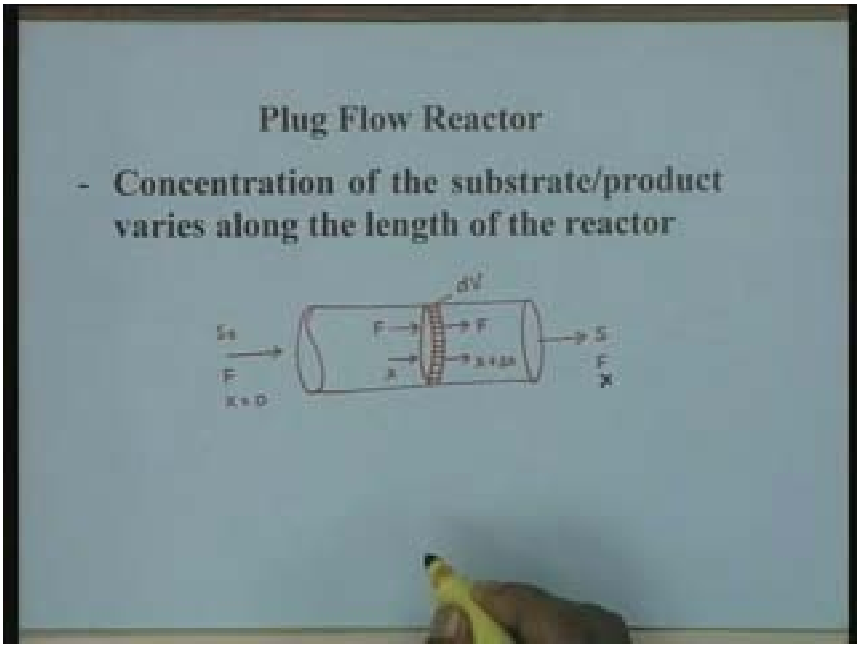

Plug Flow Reactor

- **Concentration of the substrate/product varies along the length of the reactor**

If you consider here input to the system is F.S and this input I am writing at the entry of the differential element and output, not at the entry of the reactor, is equal to F(S+dS) and the disappearance of the substrate by the reaction will be the continuation of the reaction to the disappearance of the substrate is –v.(dV)

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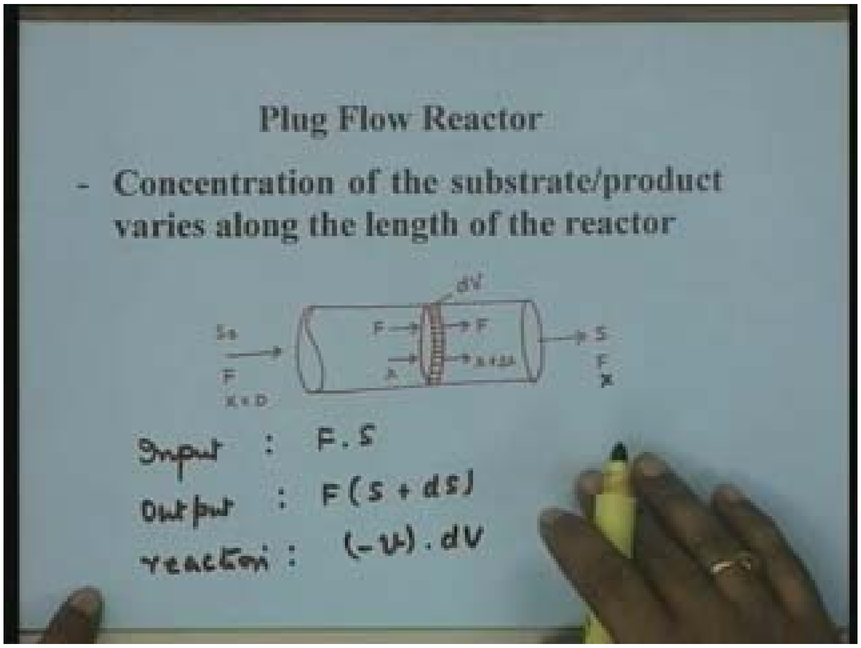

Plug Flow Reactor

- **Concentration of the substrate/product varies along the length of the reactor**

Input : F . S

Output : F (S + dS)

reaction : (-v) . dV

Under these conditions one can write the material balance under steady state assuming that the accumulation is zero.

$$F.S = F(S+dS) + (-v).dV$$

One can simplify it to get

$$F.dS = v.dV$$

Here for the fraction of conversion

$$X = S_0-S/S_0;\ dS = -S_0dX$$

$$F.S_0.dX = -v.dV$$

You can integrate this and the integrated form will give you the zero to v dv /FS_0 which will be equal to zero to X dX/-v or V/FS_0 because feed rate is constant, substrate concentration is constant and so the definite integral will come to V/FS_0 and that is τ/S_0 which is equal to zero to X dX/-v. If you look at the performance of a plug flow reactor you ultimately arrive at or transfer the S_0 to here so tau is equal to S_0.dX/-v. That is the reaction rate.

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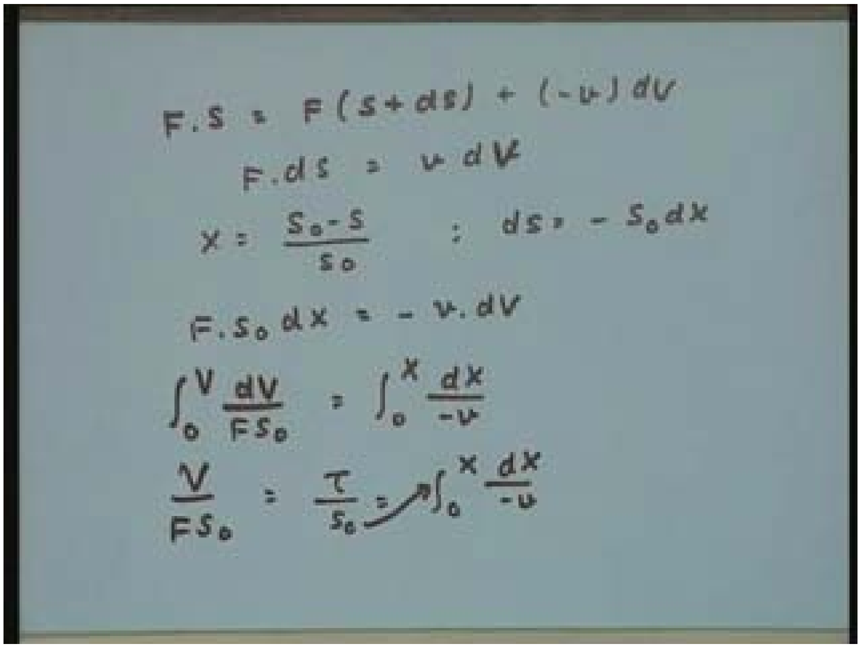

$$F.S = F(S+dS) + (-v)\,dV$$

$$F.dS = v\,dV$$

$$X = \frac{S_0 - S}{S_0} \quad ; \quad dS = -S_0\,dX$$

$$F.S_0\,dX = -v.dV$$

$$\int_0^V \frac{dV}{FS_0} = \int_0^X \frac{dX}{-v}$$

$$\frac{V}{FS_0} = \frac{\tau}{S_0} = \int_0^X \frac{dX}{-v}$$

So the performance will be almost identical to that of a batch reactor excepting with the difference that the reaction time here is replaced by the space time and the reactor performance therefore on the same lines you can write as

$$S_0X - K'_m \ln(1-X) = k'_2E_0\,\varepsilon\,\tau$$

Epsilon, while in the case of a stirred bed reactor, is taken to be one. That means the volume of the reactor occupied by the enzyme preparation is negligible compared to the total reactor volume whereas in the case of a packed bed a significant proportion of the reactor is occupied by the enzyme preparation.

I was just trying to define the term what I introduced here as epsilon. In the case of a batch stirred reactor we have not considered epsilon because the quantity of enzyme or the volume of enzyme in the reactor is negligible compared to the total volume of the reactor. A very small fraction of the total volume is occupied by the enzyme preparation. On the other hand in the case of a packed bed reactor a significant fraction of the volume of the reactor is occupied by the packed bed and the volume occupied by the fluid or the feed substrate is only the wide volume of the reactor and therefore the volume occupied by the feed in the reactor is considered as the actual reactor volume. This tau term has been defined earlier as V/F; in the case of a packed bed reactor we define tau as $\varepsilon V/F$. That is for CSTR or for a stirred batch reactor the magnitude of epsilon is one. So this gives you the reactor performance for a plug flow reactor following Michaelis Menten kinetics. The same analysis as we did earlier if you consider for zero order kinetics the tau is equal to

$$\tau = XS_0/k'_2E_0\varepsilon$$

For first order, tau is equal to

$$\cdot\tau = -K^{'}_{m} \ln (1-X) / k^{'}_{2}E_0\varepsilon$$

A very important feature which I like to recall is the relative performance equations for zero order regime for both CSTR as well as for PFR, which are identical. If you look at the equation number two here for the CSTR and the equation for the zero order regime here in the case of the PFR, they are identical.

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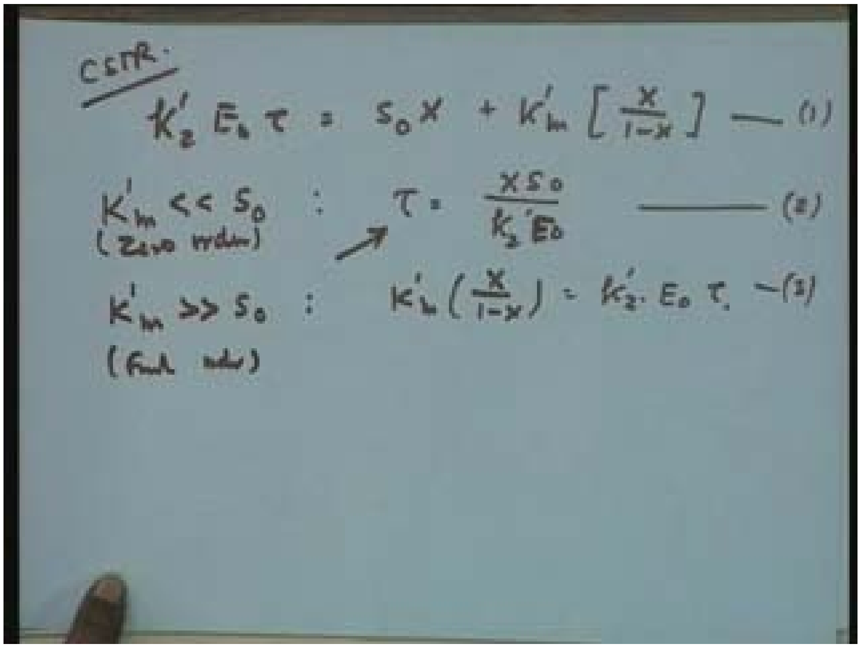

CSTR:

$K_2' E_0 \tau = S_0 X + K_m' \left[\frac{X}{1-X}\right]$ — (1)

$K_m' << S_0$ (zero order) : $\nearrow$ $\tau = \frac{X S_0}{k_2' E_0}$ ——— (2)

$K_m' >> S_0$ (First order) : $K_m' \left(\frac{X}{1-X}\right) = k_2' E_0 \tau$ — (3)

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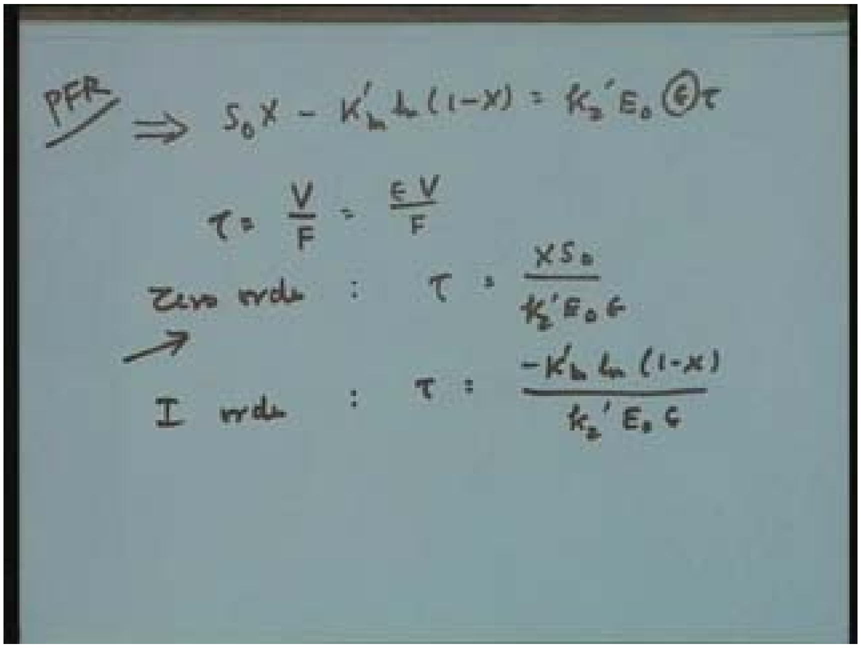

PFR $\Rightarrow S_0 X - K_m' \ln(1-X) = k_2' E_0 \boxed{\epsilon} \tau$

$\tau = \frac{V}{F} = \frac{\epsilon V}{F}$

Zero order : $\tau = \frac{X S_0}{k_2' E_0 \epsilon}$

$\nearrow$

I order : $\tau = \frac{-K_m' \ln(1-X)}{k_2' E_0 \epsilon}$

That means the fluid dynamics in the reactor whether it is a back mix system or its a plug flow system does not influence the reactor performance as long as the reaction is in the zero order regime or the concentration of the substrate is much, much higher than the K_m value and you must appreciate that if it is in our limits we will always like to use a very high substrate concentration. If the system doesn't undergo substrate inhibition that is if it undergoes inhibition, we have no choice other than to using a lower substrate concentration. There are two things one will always like to have a high substrate concentration for a reaction; for commercial purposes also we like to have a very high fraction of conversion and one would like to carry out the reaction almost to conversion levels of ninety five percent plus so as to achieve a complete conversion of substrate as much as possible so that the recovery and the purification stages are simplified or the product stream can be used as it is for end applications. So the only difference lies in the case of reactor performance of plug flow reactor.

Consider a first order regime where K'_m is much, much greater than S_0. In the case of CSTR, you have the reactor performance as

$$K'_m(X/1-X) = k'_2E_0\tau$$

In the case of PFR, the expression changes to

$$K'_m \ln(1-X) = k'_2E_0\,\varepsilon\cdot\tau$$

Our interest will always be to have a high fractional conversion. That means most of the substrates which is being fed gets converted into product. If we want to compare the performance of both CSTR and PFR as I mentioned in the case of zero order regime there is no change and the performance remains identical. That means the quantity of the enzyme required will be identical in both cases for carrying out the same conversion and at the same enzyme loading. But if you consider the first order regime the performance are quite different and if you compare the relative performance, relative quantity of the enzyme required that is E_{CSTR}, the quantity of enzyme required in CSTR and PFR relative quantities or we can define this term as E_{rel} will be equal to

$$E_{CSTR}/E_{PFR} = E_{rel} = -X\,\varepsilon/(1-X)\ln(1-X)$$

The relative quantity of enzyme required in the case of CSTR and PFR under first order regime can be given by this expression.

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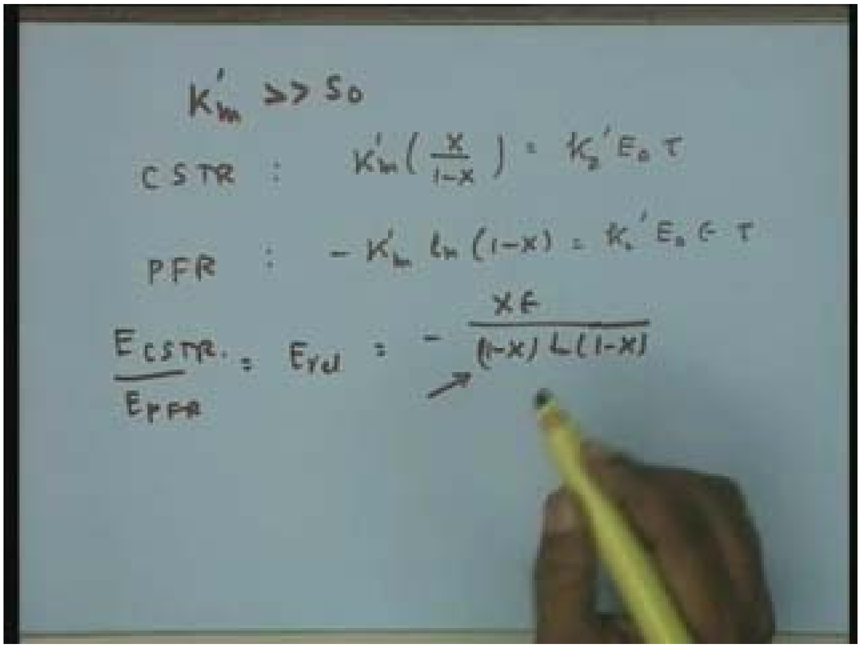

$K'_m >> S_0$

CSTR : $K'_m \left(\frac{x}{1-x} \right) = k_2' E_0 \tau$

PFR : $- K'_m \ln (1-x) = k_2' E_0 \epsilon \tau$

$\frac{E_{CSTR}}{E_{PFR}} = E_{rel} = - \frac{x\epsilon}{(1-x) \ln(1-x)}$

You notice in this expression that higher the required conversion level, higher the relative amount of the enzyme required in the CSTR. You can just hypothetically put some values of let us say a safe value for epsilon for a typical packed bed reactor varies from between 0.4 to0.5. You take a simple value of 0.5 and if you make calculation for X=0.90, the E_{rel} required will be equal to 4.5. That means the enzyme required for the same fractional conversion that is 90% in the case of a CSTR will be 4.5 times more than that required in the PFR for the same conversion. The same enzyme, the same reaction, the same conversion factor but the quantity of enzyme required in CSTR will be much, much higher compared to PFR. If you change the fractional conversion to, let us say, 0.99, the E_{rel} value shoots up to 25.

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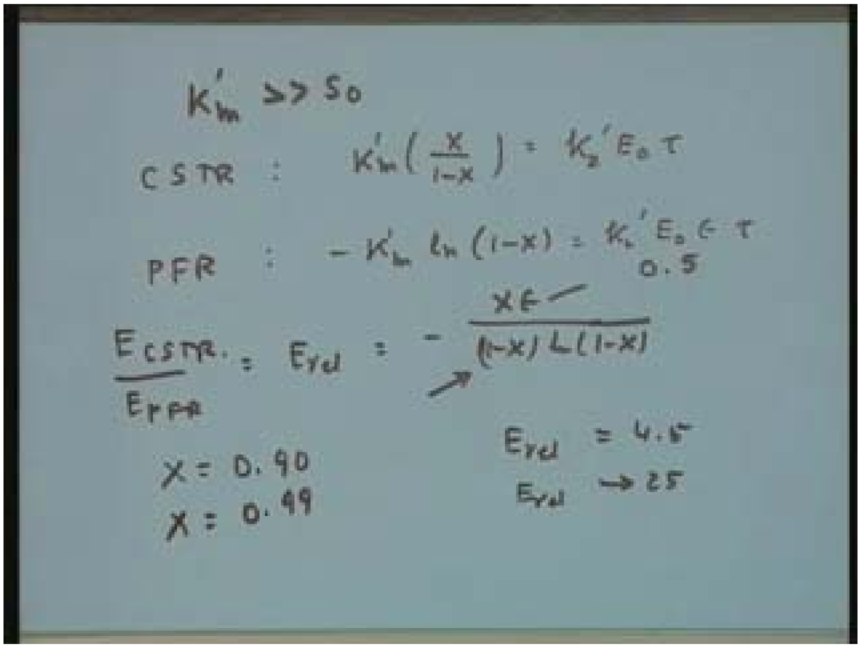

$K'_m >> S_0$

CSTR : $K'_m \left(\frac{x}{1-x} \right) = k_2' E_0 \tau$

PFR : $-K'_m \ln(1-x) = k_2' E_0 \varepsilon \tau$

0.5

$\frac{E_{CSTR.}}{E_{PFR}} = E_{rel} = -\frac{x\varepsilon}{(1-x)\ln(1-x)}$

$x = 0.90$ $\quad E_{rel} = 4.5$

$x = 0.99$ $\quad E_{rel} \rightarrow 25$

The inference I want to arrive at is that higher the fractional conversion required for a particular reaction under first order regime, the relative quantity of the enzyme required in the CSTR will drastically increase. That means even for certain reasons if you want to use CSTR pH control is a requirement and we are obliged to use CSTR, then it is always advisable only to use if the fraction of conversion required is not very high. In case if the fraction of conversion required is very high if you are looking for a 99% conversion, it will be desirable to use a plug flow reactor with a partial recycle. You can have facility for pH control with some inconvenience; may be some more additional equipments has to be added but still that will be better because the quantity of the enzyme required will be much less and that gives us a significant advantage for using immobilized enzyme in PFR and that is one of the reasons why you will notice in the literature that almost about 70-80% of the total reports which appear on the use of the immobilized enzymes are in a plug flow reactors and the advantage lies in the quantity of the enzyme required and this advantage will keep on reducing. That is the relative quantity will keep on reducing if the shift is from first order to zero order ultimately it will reach to same quantity. If we take the value of K_m/S_0 from a very high value to a very low value, the relative quantity of the enzyme will also keep on reducing and it will become equal to the relative enzyme value, E_{rel} and will become one. Then the value of S_0 is much, much higher than K_m.

A typical profile for relative quantity required is shown here. As you notice here what ever I mentioned, it signifies the same thing. There are two things to be looked at. One is the relative quantity of substrate to K_m. Here instead of K_m/S_0 I plotted S_0/K_m. The top profile, the first profile indicates a very low value of S_0/K_m which means a first order regime. That means as the fractional conversion increases, the relative quantity required also increases and towards the final stages of the fractional conversion, the quantity very significantly goes up. The increase in the quantity of the enzyme required is not very large in the low fractional conversion levels whereas as soon as you cross 0.90% conversion, the quantity required becomes significantly high.

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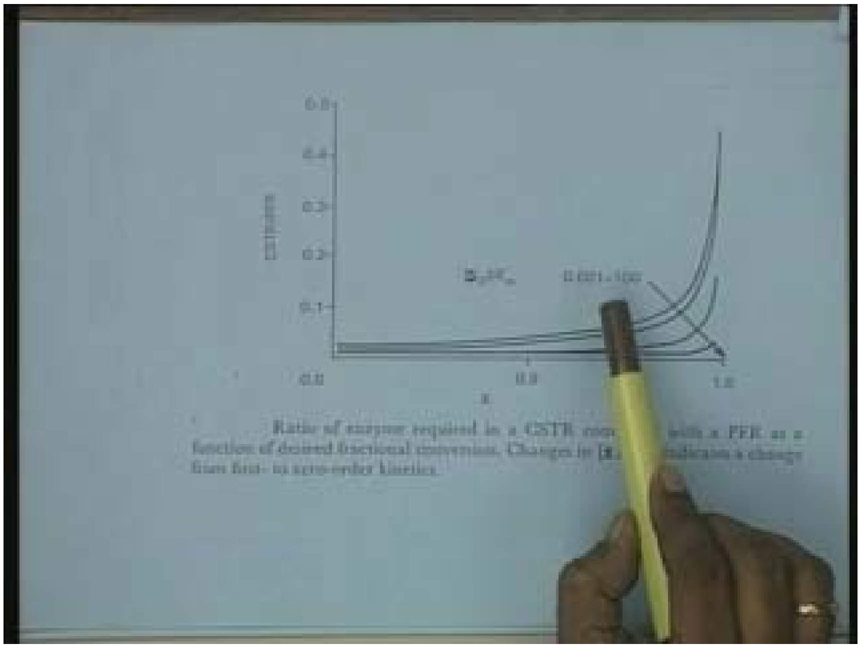

On the other hand you also see when you come to S_0/K_m as hundred approaching towards zero order regime the quantities remain almost equal all through, till you arrive at 90 plus or more than 95% fractional conversion.

One can have such a profile and when one wants to analyze the reactor performance for any given immobilized enzyme system, one must really characterize a system with reference to such kind of profiles so that one can get a feel of the substrate concentration required and the fractional conversion required, one can choose where to bank upon. For example in the earlier phases let us say up to 90%, there is no major gain in using PFR. But if you want to use a fraction of conversion much higher than 90% then the PFR becomes more and more matter of choice. Then the immobilization will be identical. Your choice should depend upon the operational convenience. For example if the pH control is required CSTR is preferable and then the nature of the substrate, the nature of the enzyme and the form of the enzyme. If suppose your substrate is colloidal, we will prefer to use CSTR rather than the PFR; it will choke. The pressure drop will continuously keep on increasing. If suppose the enzyme particles are in the form of fibers or spherical beads, it is easier to pack them rather than putting in the CSTR where there might be abrasion. So the form of substrate and form of enzyme will dictate the choice. The kinetics will not be dictating. So far we have not considered the inhibition patterns. We have not considered the behaviour of the reactor performance if the enzyme undergoes inhibition kinetics. That means either a substrate inhibition or a product inhibition or a third inhibitor an external inhibitor available in that. We have also not considered the deactivation of the enzyme on the reactor performance. All these parameters particularly the inhibitors, rather their inhibition pattern, their deactivation pattern, the mass transfer requirements, the mass transfer limitations and the non-ideal flow behavior; these are the four things. So far we have been talking assuming that the enzyme reactors are ideal in performance and they are following Michaelis Menten type of kinetics. At best the extremes of those cases under zero and first order but we have not considered the inhibition pattern, we have not considered the deactivation kinetics, mass transfer limitations and non-ideal flow behavior. That is we are considering only either a PFR or CSTR which is an ideal flow dynamics in the reactor.

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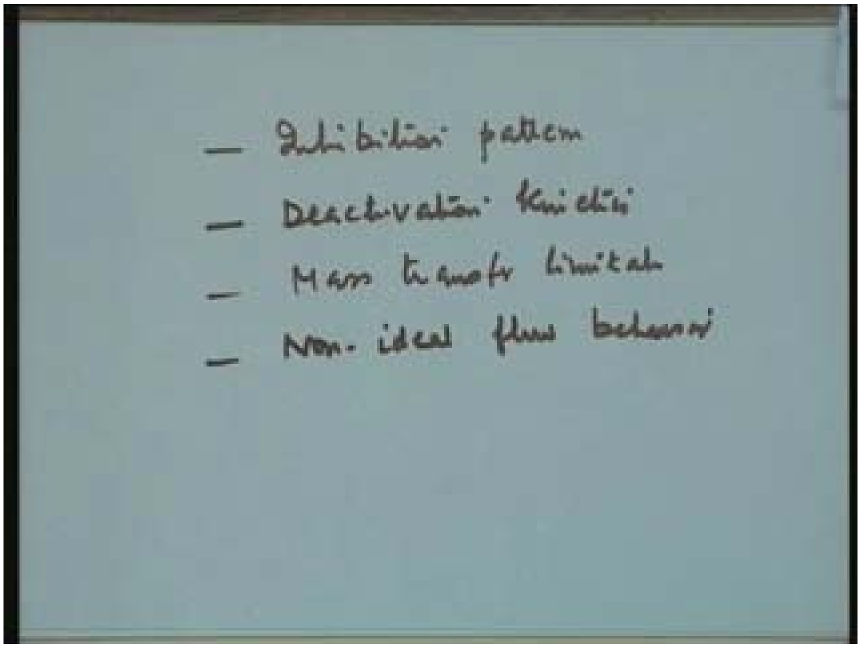

- Inhibition pattern
- Deactivation kinetics
- Mass transfer limitation
- Non-ideal flow behavior

In many cases practical reactors may not be an ideal CSTR or ideal PFR. They might be some kind of deviation from the ideality because of the packing characteristics or some channeling taking place or in laboratory you can very easily maintain a good plug flow reactor. But in a large system it is always difficult to maintain and it is always desirable to identify or characterize your reactor with reference to flow behavior and then make a correction factor when the design part comes into. So all these issues we will take individually rather than compounding all of them because not that all the issues will be applied in a particular reactor system we will have to identify the issues which are important. For example we identify let us say the mass transfer limitations are the most acute. The system is mass transfer limited. There is point to consider reaction kinetics; you design your reactor system based on mass transfer diffusional requirements. Similarly if you consider that the flow behavior is drastically non-ideal there is a full channeling; then corrections are to be applied to the design expression to get the reactor performance. So I think we will stop here and continue to discuss the behavior of enzyme reactors.