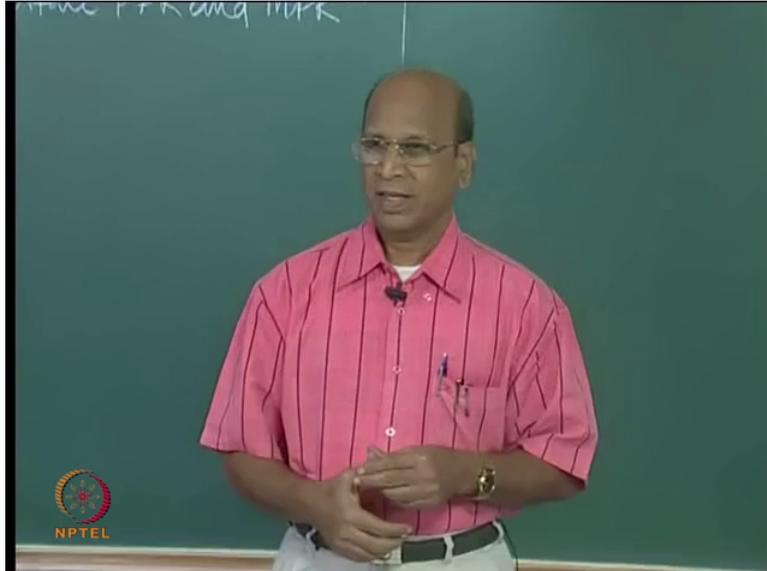


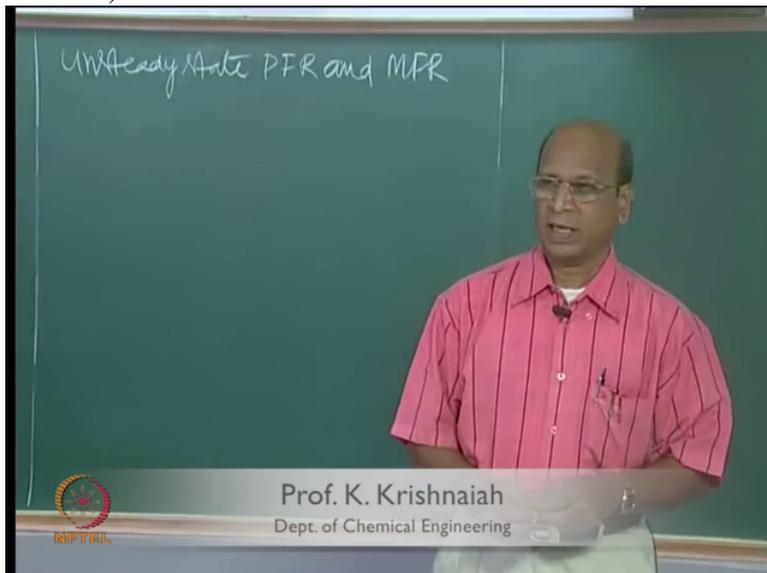
Chemical Reaction Engineering 1 (Homogeneous Reactors)
Professor R. Krishnaiah
Department of Chemical Engineering
Indian Institute of Technology Madras
Lecture No 28
Unsteady state MFR and PFR

(Refer Slide Time: 00:11)



This one P F R and M F R. Yeah, our idea is to find out, under unsteady state conditions if I start P F R under unsteady state conditions or M F R under

(Refer Slide Time: 00:19)



unsteady state conditions, when do I get steady state? Because we should know, no, approximately we should have that idea. Ok let us take first P F R. Easiest one. When do I get a steady state if I take a P F R? Unsteady state, yeah

(Professor – student conversation starts)

Student: When

Student: Residence time

Student: Tau

Professor: Residence time, yeah

Student: At the time input...

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Professor: Why?

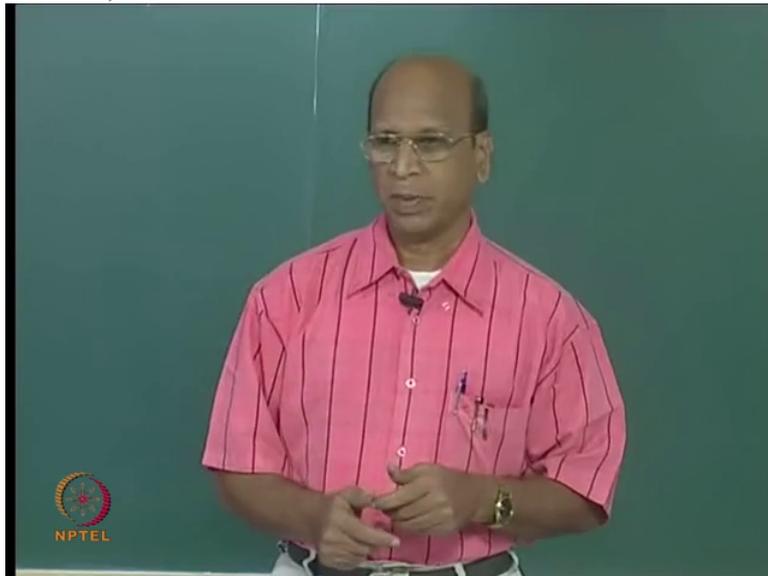
Student: 0:00:46.1

Professor: Yeah

Student: Then there will be equal input and output.

Professor: Very good. Yeah if you go to C S T R,

(Refer Slide Time: 00:50)



mixed flow reactor? M F R, C S T R?

Student: Space velocity, because one 0:00:58.7 reactor, time required.

Professor: That also no problem, that is also 1 only. One mean residence time

Student: In the P F R I think steady state is reached after twice

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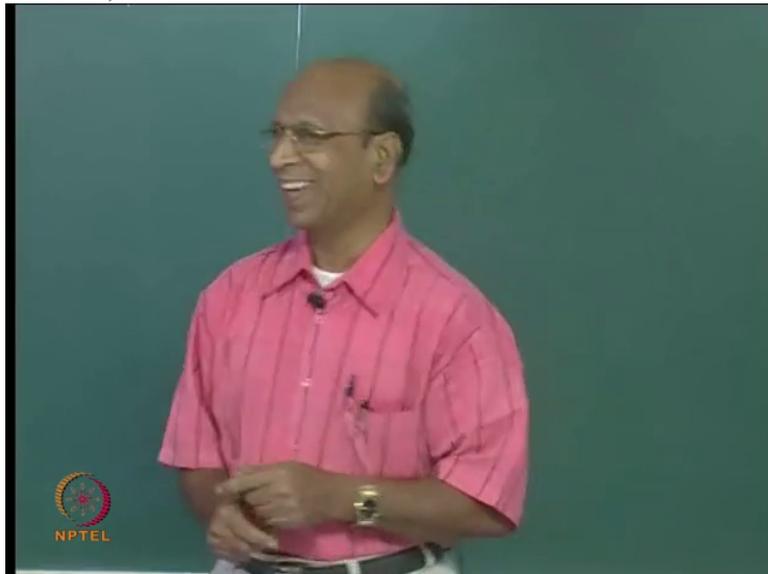
of the space time, in two tau

Professor: Why?

Student: I do not know.

Professor: That you do not know means (laugh),

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you have to tell.

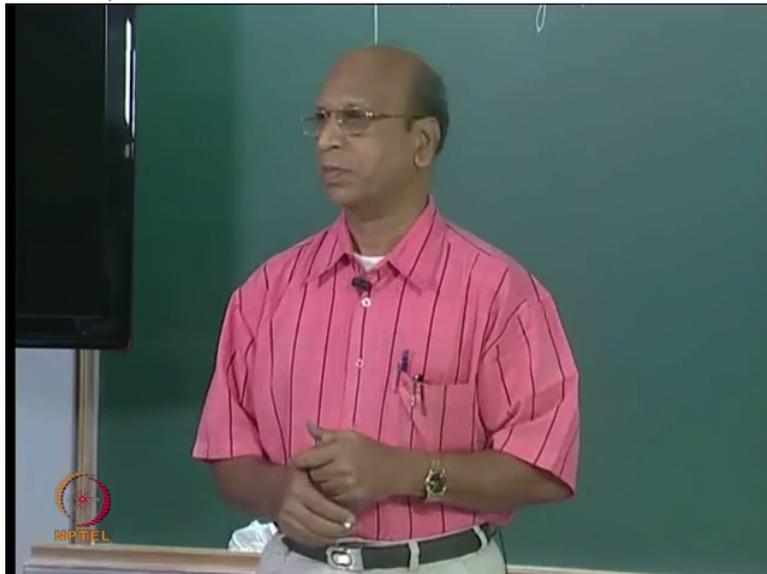
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Student: All are particles pass in the same time.

Professor: Yeah, in a plug flow reactor when do they pass and in a mixed flow reactor, when do they pass?

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Student: In P F R it should be zero, Sir

Professor: Zero that means even before starting you will get steady state?

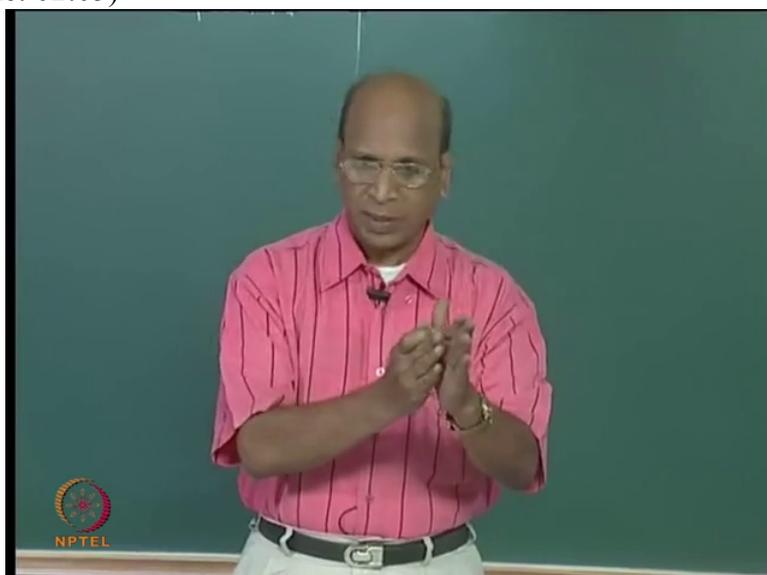
Student: (laugh)

Professor: What do you mean by zero? Zero time? Zero time means you have not started. Ok, what is the time required for, you know P F R, all the particles to come out one batch, Ok. One batch is one volume it has to come out. So that means one t bar, or tau, right? Ok.

(Professor – student conversation ends)

So that is why as far as P F R is concerned, steady state is no problem. If it is really ideal steady state, you are starting, Ok. So then the material will start coming,

(Refer Slide Time: 02:05)



entered and then slowly coming out, right? So once it fills up and it comes out, then we know it is equivalent to one, one mean residence time.

Ok, so then afterwards, next batch will enter and then exactly it also comes out in next t bar. So that is why, once first t bar comes out, Ok, so then onwards you have always the steady state. That means just one mean residence time is enough for unsteady state PFR to become steady state. From then onwards it should not change. Ok, and mixed flow reactor?

(Professor – student conversation starts)

Student: 1 tau

Professor: That is also 1 tau then what is the difference between this and this? All the particles will come out in a mixed flow reactor in 1 tau? What has happened to your R T D funda?

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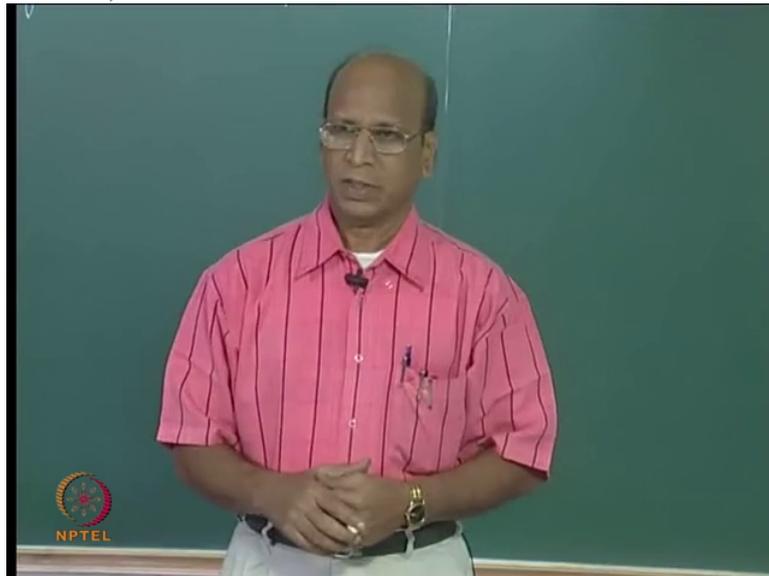
Student: 0:02:55.6

Professor: Theoretically it is infinite. Theoretically it is infinite.

(Professor – student conversation ends)

Because

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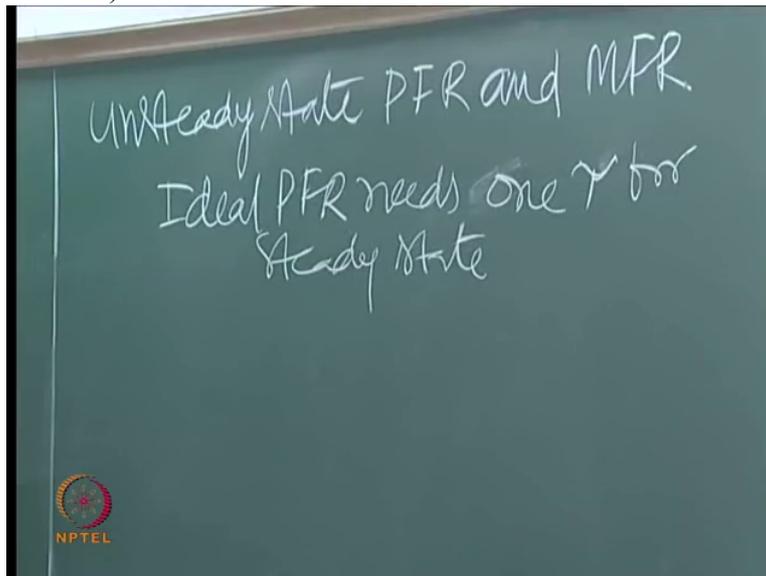


theoretically it is infinite and you cannot wait for infinite time, because you never get the product. Correct no, theoretically if you want to infinite, till you know infinite time, so that is why we have to now find out that what is the practical time?

So the practical time even for mixed flow, sorry plug flow, the theoretical time is 1, mean residence time. Practically you know you have the slight disturbances near the walls, and also you have that small fluctuations, Ok. If we give that allowance, normally 1 point 2, 1 point 5 times you should be able to get steady state in a plug flow reactor. So plug flow is no problem.

Ok, so ideal plug flow, P F R needs, needs 1 tau; Ok 1 tau for steady state. You know we are talking about ideal. Practically it may be

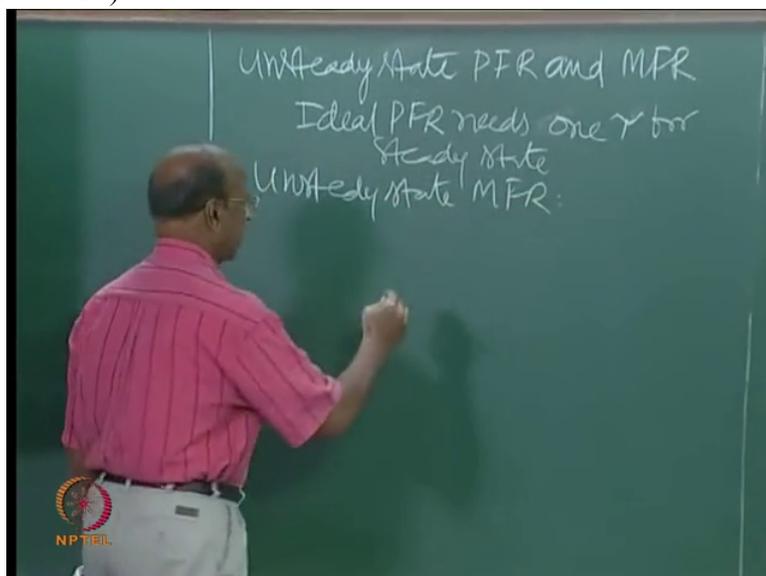
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you know 1 point 5 or sometimes you know if you have slightly more disturbance, then you will have twice, Ok, so like that I think one can wait that much time and we have that much time to wait and we can get it, no problem.

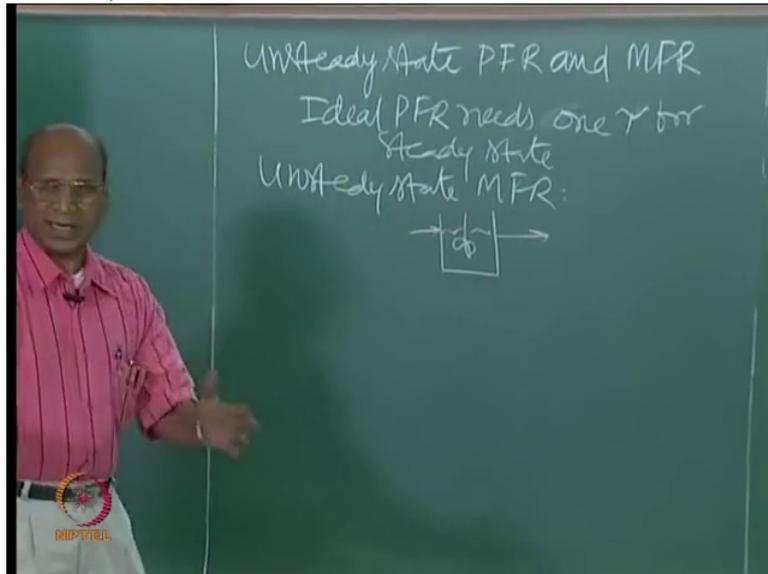
But for M F R, unsteady state M F R, we cannot say so easily,

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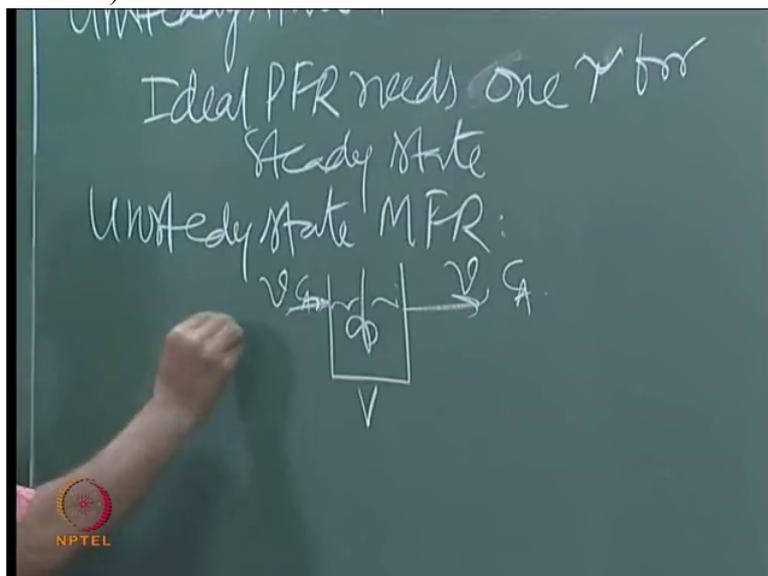
so that is why now let us

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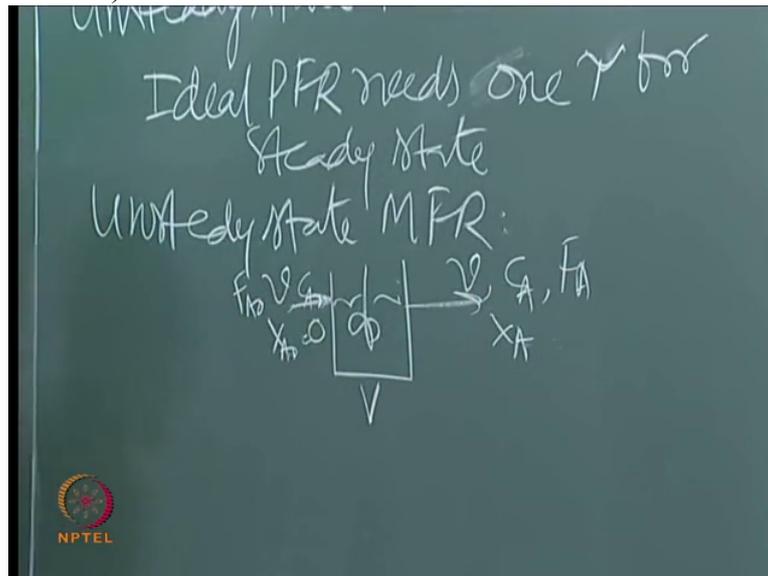
write the equation. So here I have $v C A$ naught, this is $v C A$, I have volumetric flow rate V and of course

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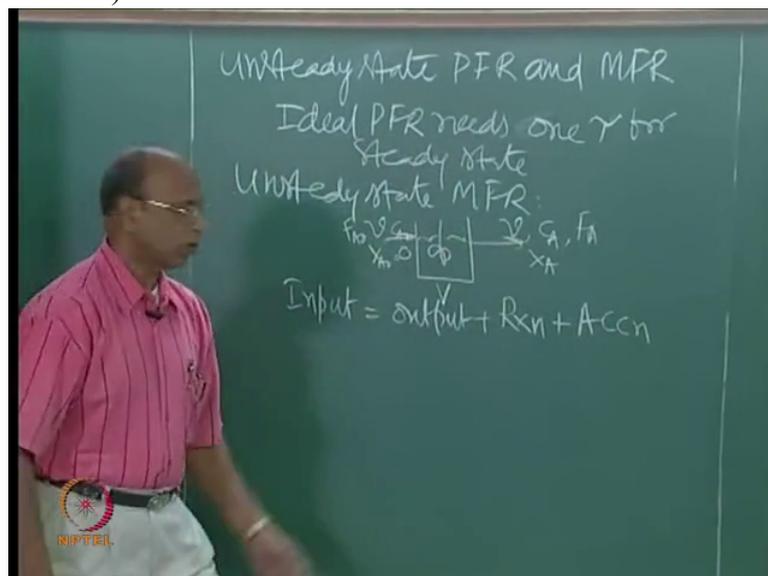
I may also have $F A$ and all that, $F A$ naught, $F A$, $X A$ here $X A$ naught equal to zero, all that we have.

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So now we have to write the balance for unsteady state. Ok, so unsteady state here we have input equal to output plus reaction plus accumulation.

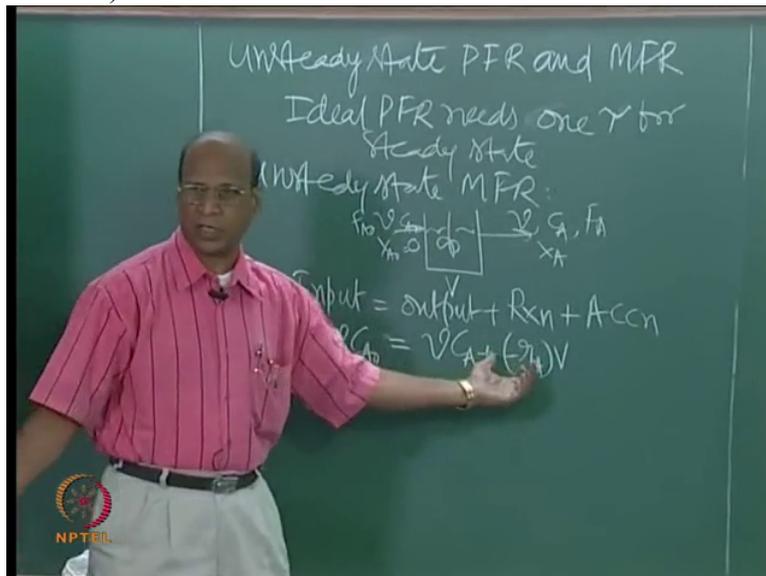
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Now this we cannot ignore. So that is why we write you know, easily in terms of concentration, that is easy. So $V C_A$ is input, what are the inputs of these? Moles per time, Ok good.

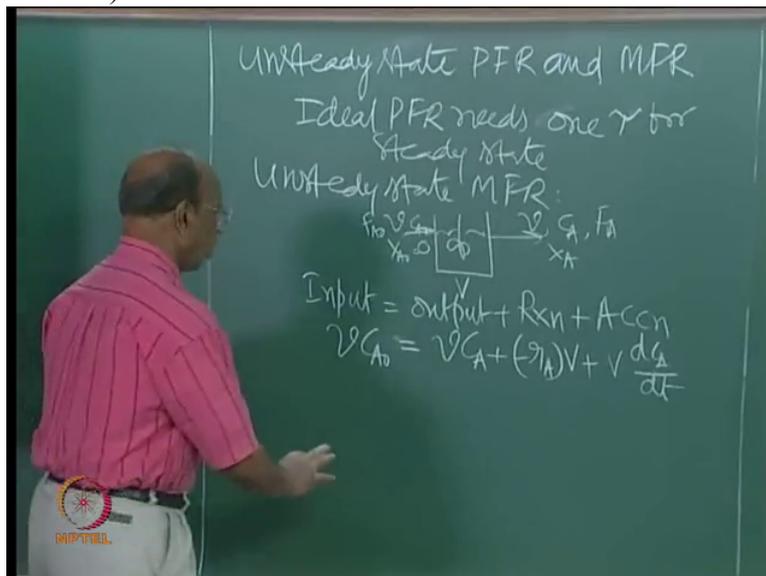
So this is $V C_A$, outlet. This one is minus r_A into V , so I can write

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if it is first order, Ok I will take if it is first order plus accumulation is, yeah $V \frac{dC_A}{dt}$.

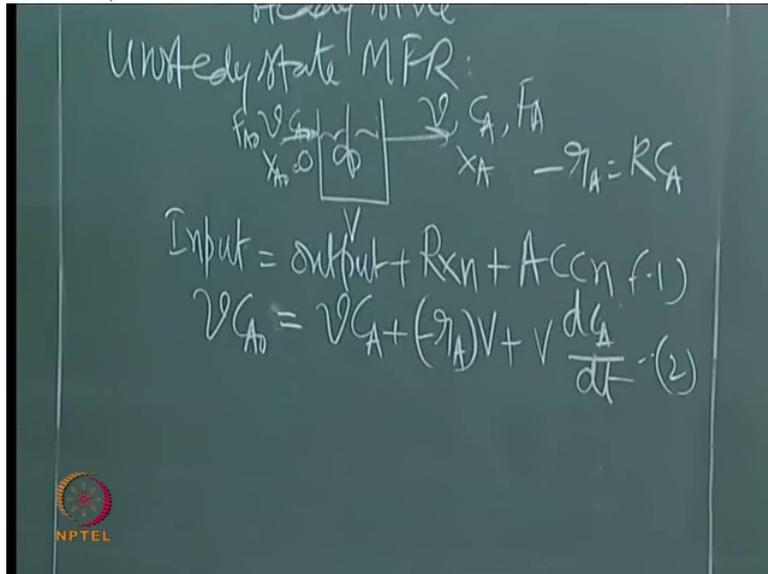
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So now this, now let me say that I have first order reaction. So if I have minus r_A , somewhere here I will write, minus r_A equal to $k C_A$, liquid phase reaction, so now we will substitute that and then we will arrange this equation.

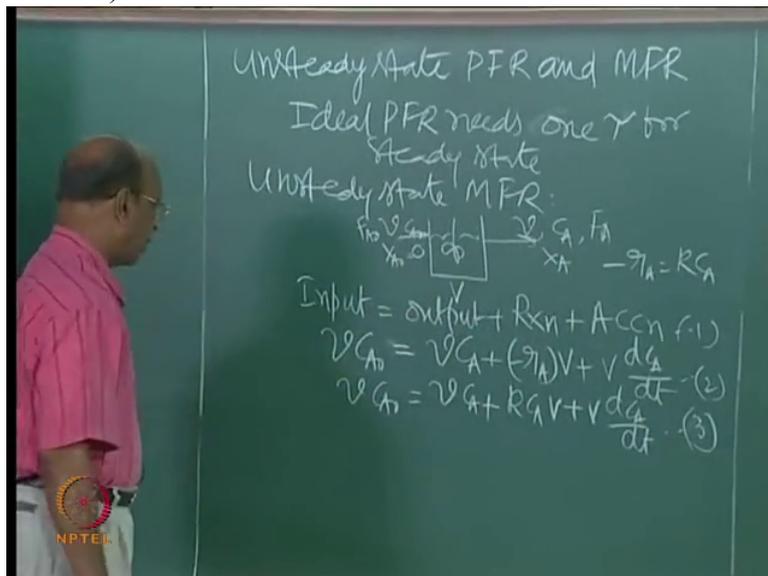
I will give the final

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expression, $V C_A$ naught $V C_A$ plus $k C_A$ into $V \tau$ plus $V \frac{d C_A}{dt}$, that is equation number 3, so divide the whole thing by volumetric flow rate,

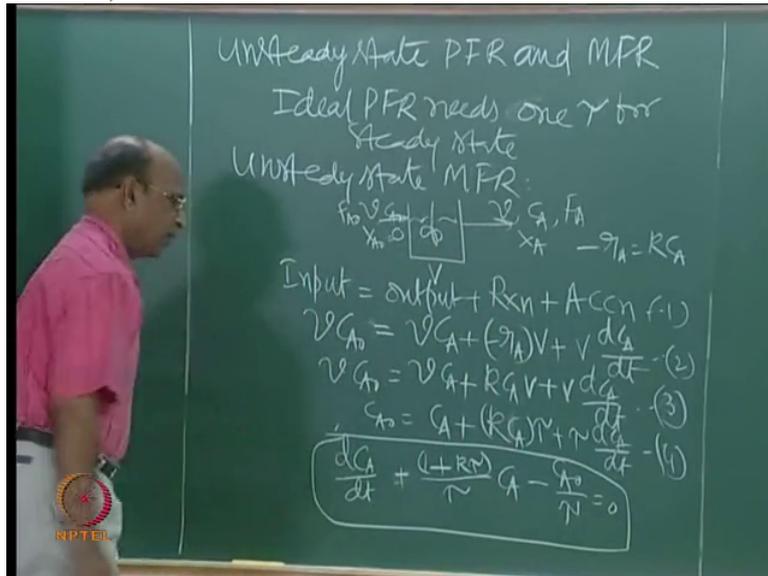
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then you will get in terms of τ , C_A naught. So that is C_A naught equal to C_A plus $k C_A$ into τ plus τ into $\frac{d C_A}{dt}$. So this is equation 4.

So now I will also write this one in terms of differential equation. This is, $\tau \frac{d C_A}{dt} + C_A$ I can take this is minus C_A naught by τ equal to zero. So this is the differential equation.

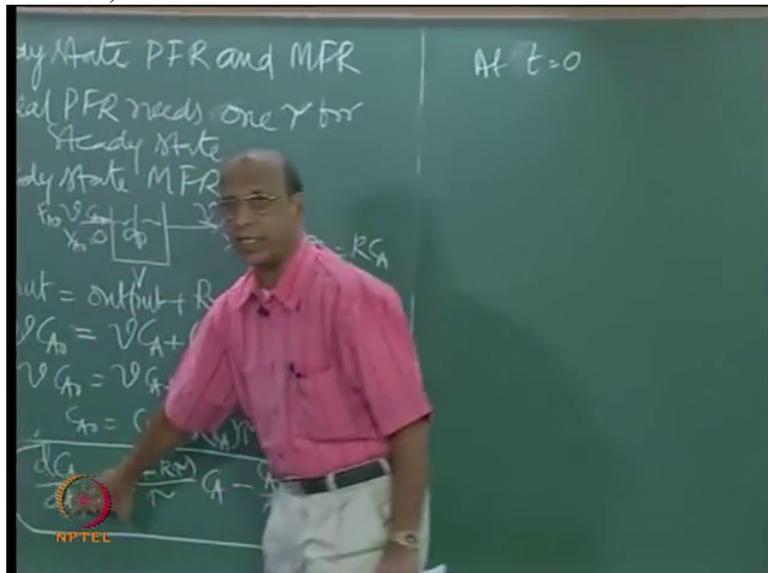
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Ok.

So this needs the boundary conditions, Ok, good so now the boundary condition is that, at time t equal to zero, one boundary condition, this is first order differential equation, we need one boundary condition. So at τ , t equal to zero, because this is unsteady state, you know, this is t ,

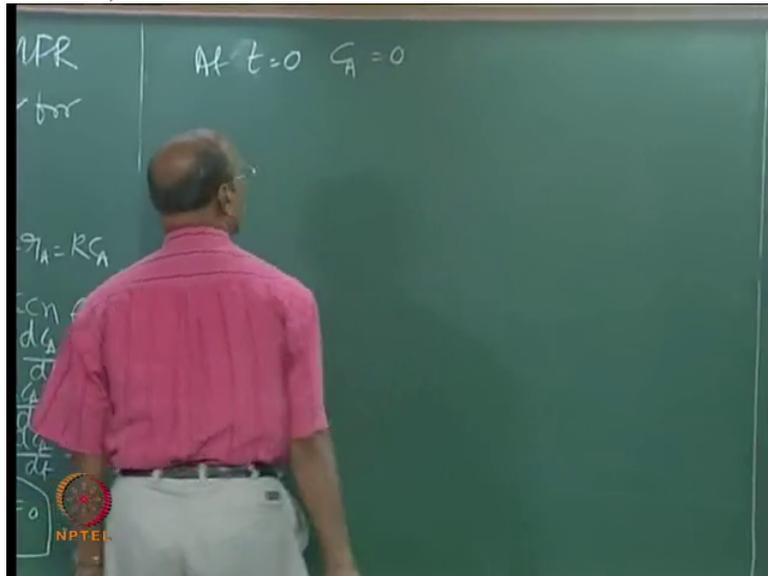
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Ok.

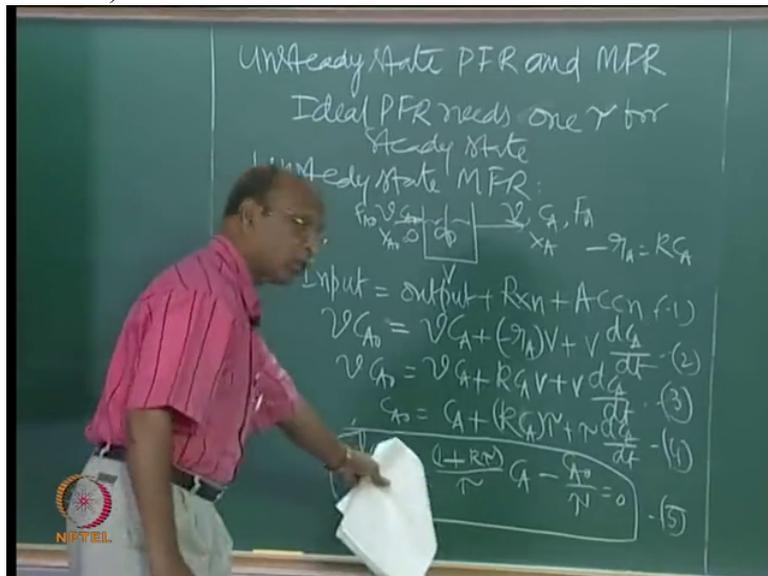
Yeah, at time t equal to zero, we have C_A equal to zero,

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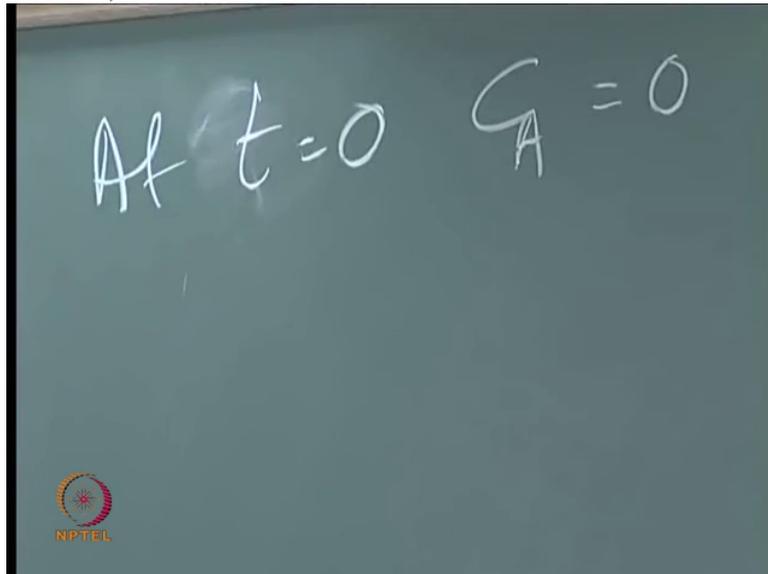
that means in the outlet, at that instance of time, the moment you put t naught is zero, I mean that is one logical explanation, Ok, good. So that is the one. And substituting this, boundary conditions and if you solve this equation,

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Ok what do you get? I am not

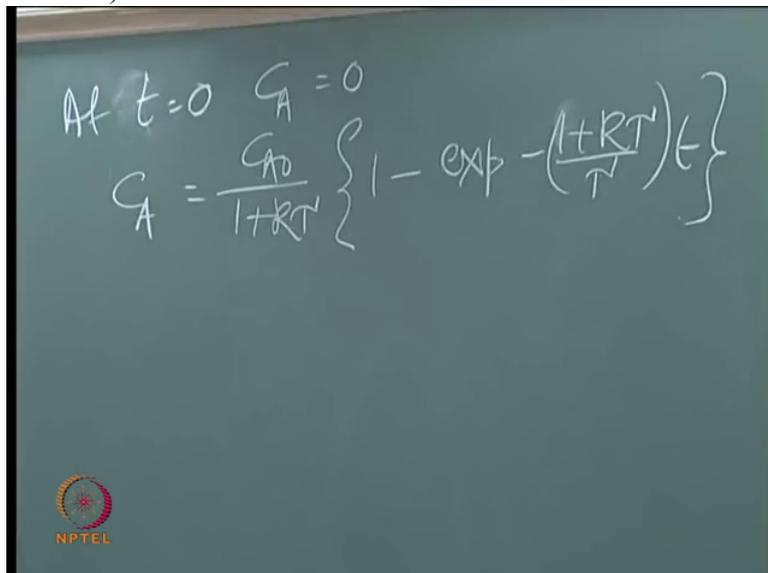
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giving the solution, you have to do it, right.

What you get is C_A equal to $C_{A0} / (1 + k\tau)$, $1 - \exp(-\frac{1 + k\tau}{\tau}t)$

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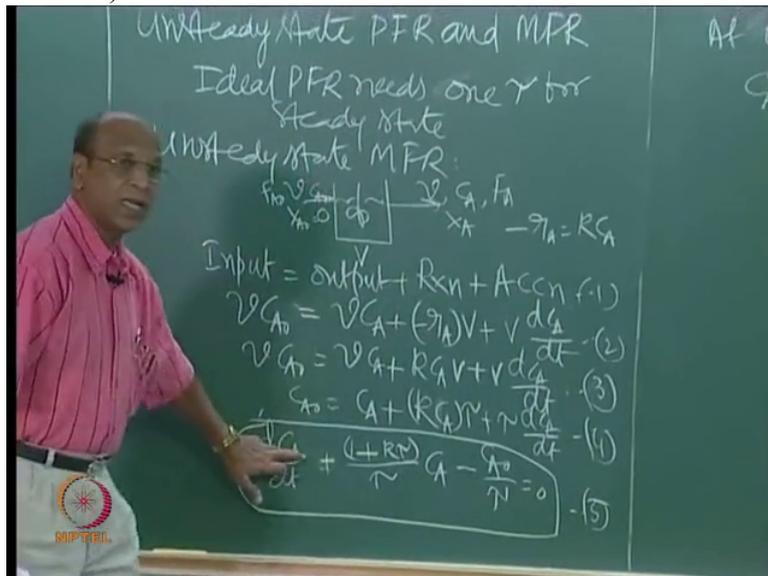


(Professor – student conversation starts)

Student: A C zero

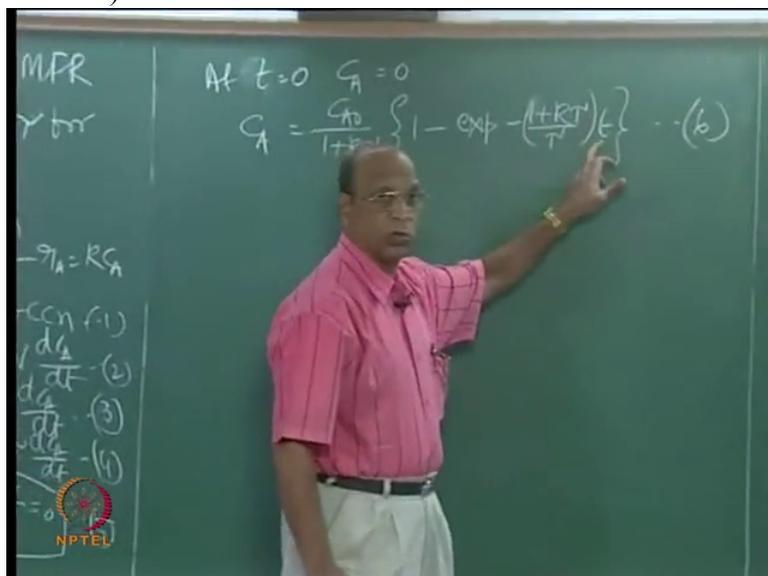
Professor: Outlet concentration. Because this equation is C A,

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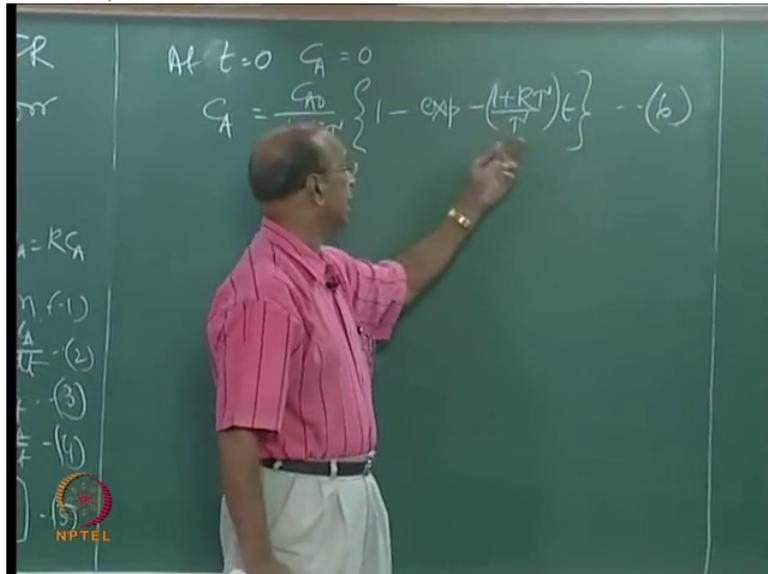
C A outlet, Ok. So that is why, good? Yeah boundary conditions, mathematical boundary conditions sometimes confusing with physics. So that is why we have to be careful. So this is the equation number 6. Ok. Yeah, So theoretically speaking, that is what Ramakrishna was telling, you know if I take t equal

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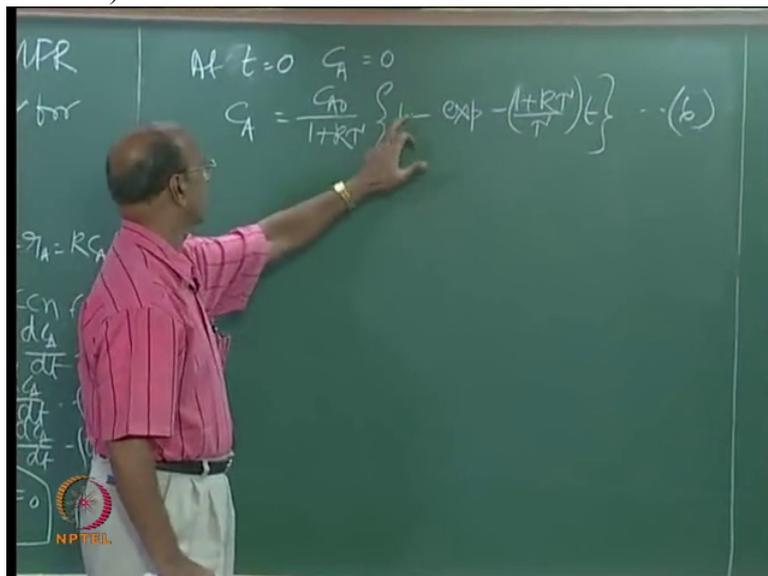
to infinity only then this becomes

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zero then this becomes

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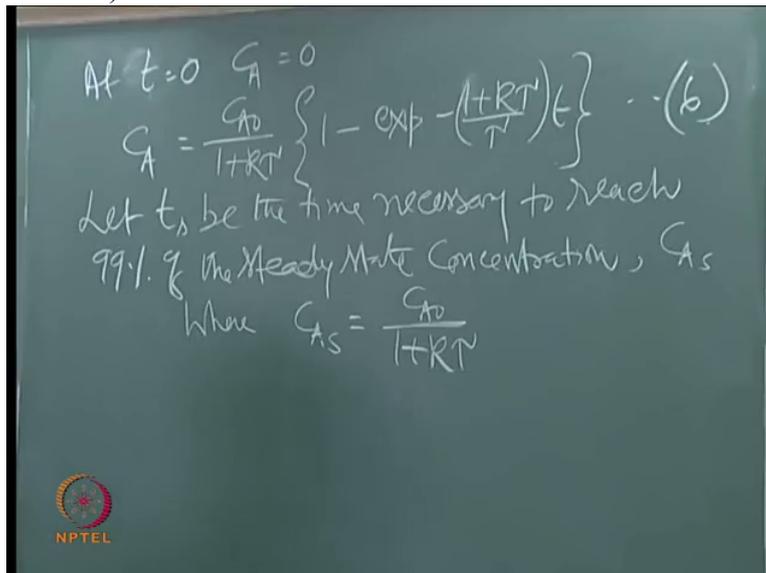
Student: C_A naught by $1 + k\tau$

Professor: Yeah, C_A naught by $1 + k\tau$ which is nothing but steady state concentration.

(Professor – student conversation ends)

But you do not have to wait till, you know infinity. Practically we have to also think, Ok. So that is why what we do is, let, let t_s , t_{small} be the time, be the time necessary to reach, to reach 99 percent of the steady state concentration that is C_{As} , steady state concentration C_{As} where C_{As} equal to C_A naught by $1 + k\tau$,

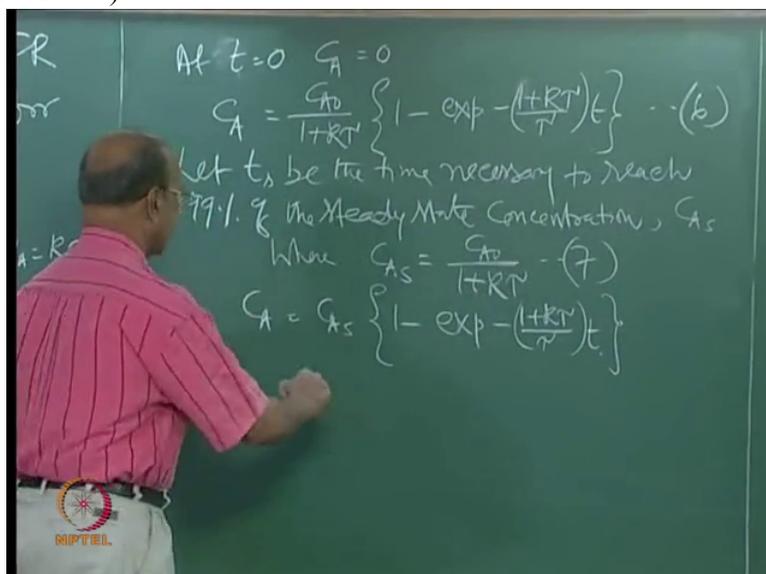
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I am assuming, not infinity, but I am assuming that I have 99 percent. Ok, good.

So now if I substitute equation 6 you know because I want to write this one as steady state. So I have, this is equation 7, equation 7 I will substitute here. So that will be C_A equal to C_{As} $1 - \exp\left(-\frac{1+K_T\tau}{\tau}t\right)$, Ok, yeah so this is the equation

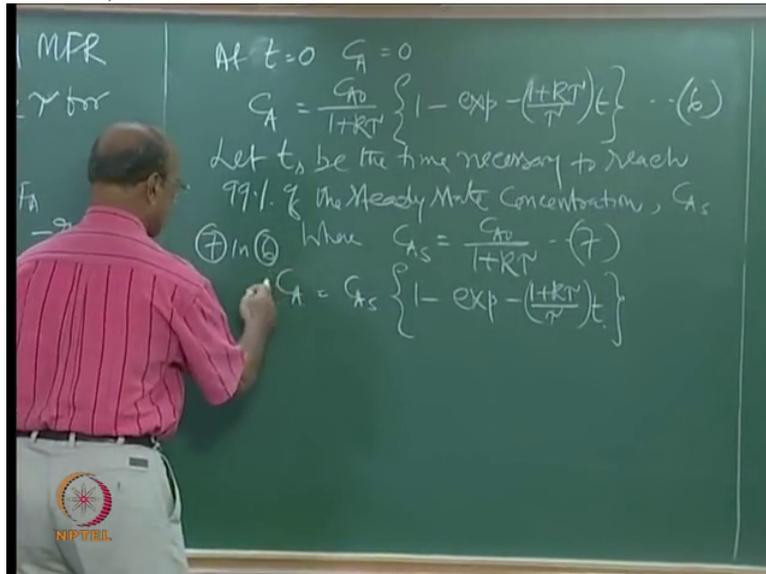
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after substituting 7 in 6, Ok, 7 in 6, Ok, good.

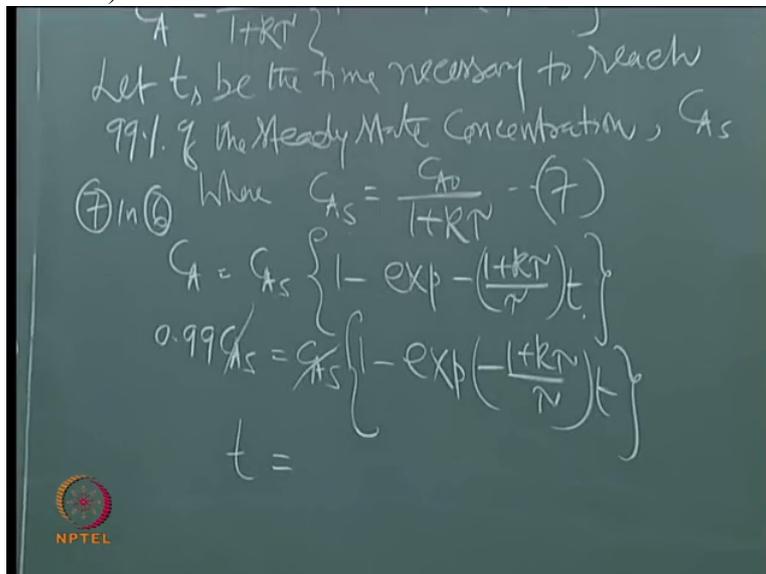
Yeah so here, my definition is that you know, this C_A I will get the steady state when

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this is equal to point 9 9 C A s, point 9 9 C A s. Please remember, point 9 9 C A s. That is what is given here, Ok, point 9 9 C A s, so then I have here C A s, Ok into 1 minus exponential minus 1 plus k tau all this stuff. Here t, Ok, good. So now this, this I can cancel out. Now can you find out the t equal to how much, from that equation. Exponential

(Refer Slide Time: 11:52)



you separate, 4 point

(Professor – student conversation starts)

Student: 4 point 5 2 tau by C A s.

Professor: How fast you have done. So yeah, what he said is right. I think you have to do that.

(Professor – student conversation ends)

So that is t_s is, t_s , 4.6τ by $1 + k \tau$, this is the time.

So that means this steady state time for 99 percent you know reaching steady state value, depends on the kinetics

(Refer Slide Time: 12:23)

$$t_s = \frac{4.6 \tau}{1 + k \tau}$$

as well as residence time, Ok kinetics as well as the space time. Ok.

We will now assume that we have $k \tau$ very small, that means k may be very, very small. And $k \tau$ is also very, very small. So then we can neglect

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At $t=0$, $C_A = 0$

$$C_A = \frac{C_{A0}}{1 + k \tau} \left\{ 1 - \exp\left(-\frac{(1 + k \tau)t}{\tau}\right) \right\} \quad (6)$$

let t_s be the time necessary to reach 99% of the steady state concentration, C_{As}

$$C_{As} = \frac{C_{A0}}{1 + k \tau} \quad (7)$$

$$C_A = C_{As} \left\{ 1 - \exp\left(-\frac{(1 + k \tau)t}{\tau}\right) \right\}$$

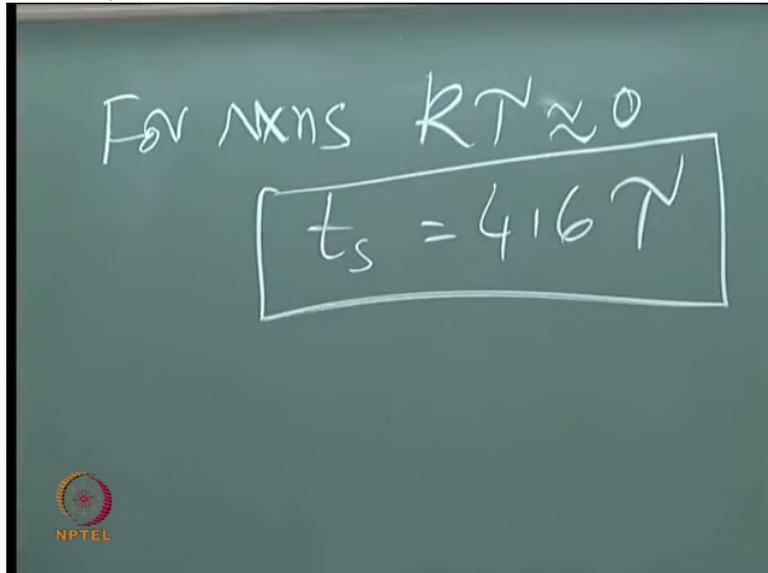
$$99 C_{As} = C_{As} \left\{ 1 - \exp\left(-\frac{(1 + k \tau)t}{\tau}\right) \right\}$$

$$t_s = \frac{4.6 \tau}{1 + k \tau}$$

k tau. Ok, so you can neglect k tau. So that means when I say that I have, for reactions where k tau is approximately zero then what do you have here?

So t_s is 4 point 6 tau, excellent. That is the equation. So this will tell you,

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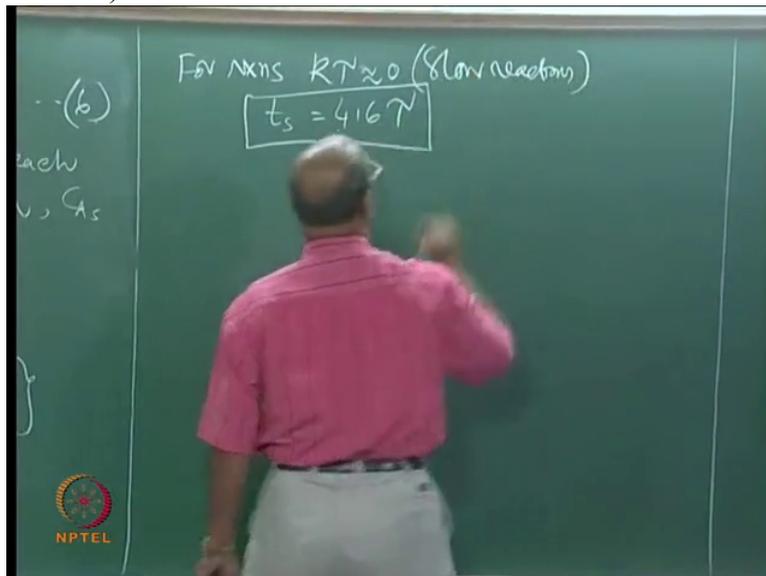
Ok volume by volumetric flow rate, now you see. It is not 1, minimum 4 point 6. Ok. So if I have 1 minute for example, 1 minute is the tau, then I have to wait minimum 4 point 6 to reach 99 percent, yeah that steady state conversion. Ok, if it is 10 minutes?

(Professor – student conversation starts)

Student: 46

Professor: 46, Ok, so this is the practical time. Generally we say 5 to 6 mean residence times, that is the thumb rule in the laboratory. 5 to 6 mean residence times. That has come only from this. But that too, strictly valid for slow reactions. Ok, I think I have to also write. For reactions, this is slow reactions. Otherwise you do not know what is that, after some time.

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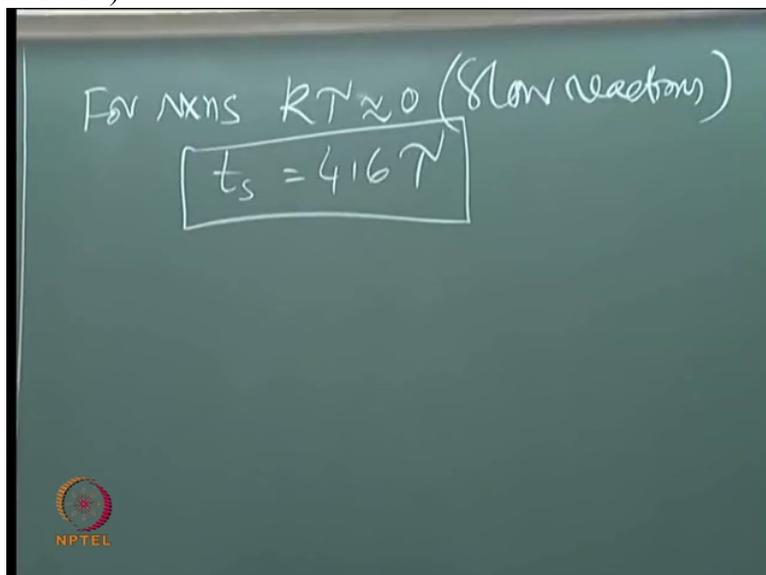


Minimum 4 point 6.

(Professor – student conversation ends)

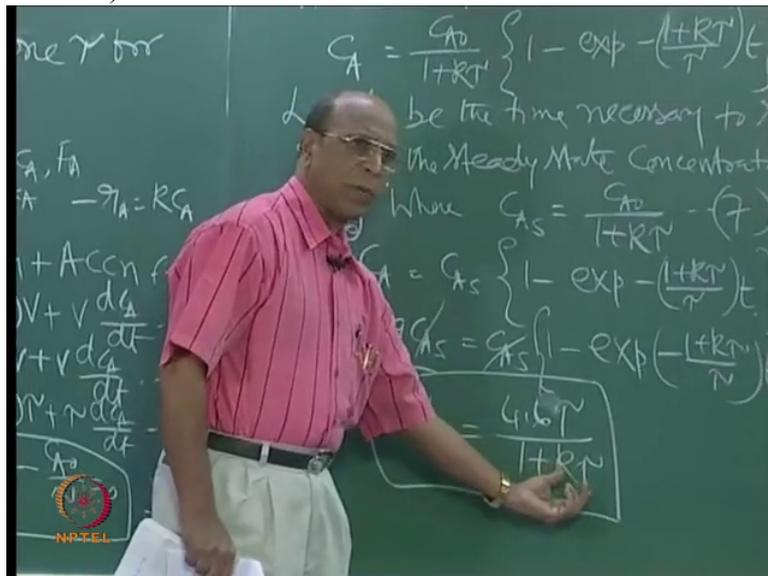
Maximum, minimum is same here. Because to get point 9 9 C A s, Ok, steady state value, I have to wait this much time. There is no

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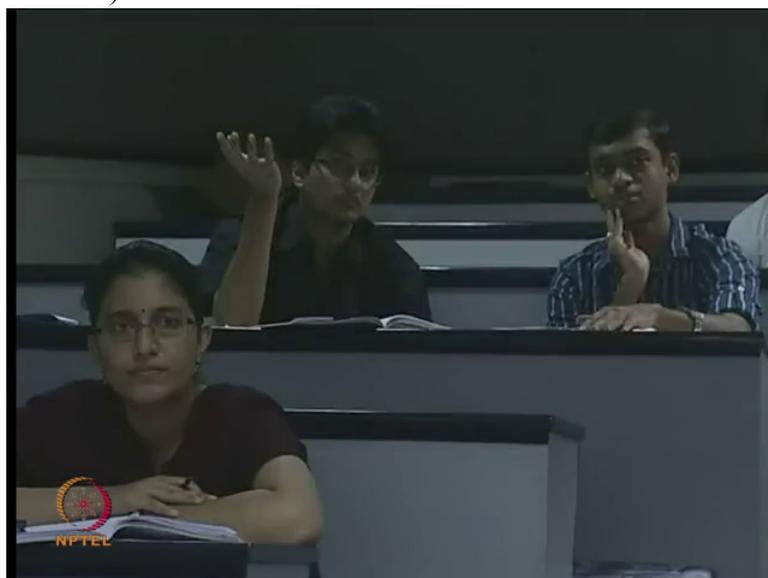
question of maximum, minimum there. So k tau

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is approximately zero for very, very, slow reactions because k value is very, very small. Ok, so then this is zero, this is 1, I have 4 point 6 tau.

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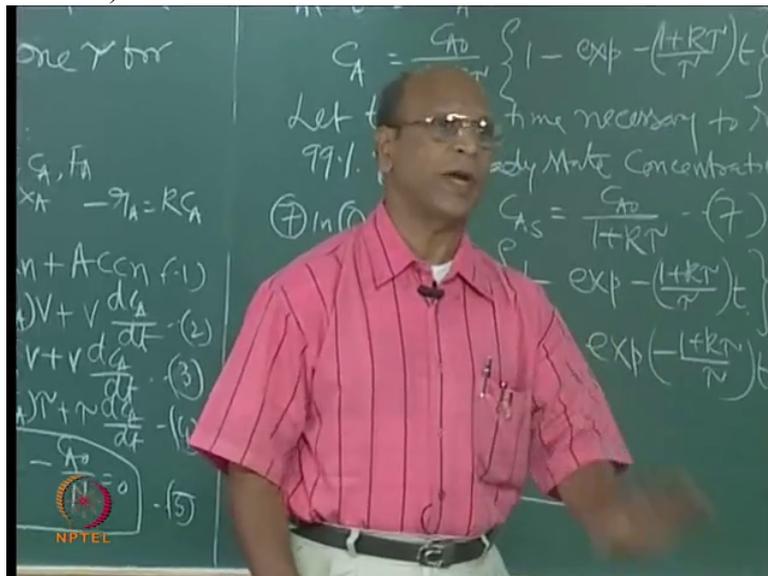


(Professor – student conversation starts)

Student: 0:14:32.8

Professor: You do not know. I think I do not want to call that as maxima or minima. That is the time I want to wait

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to get point 9 9 C A S

Student: Reaction is

Student: Fast reaction

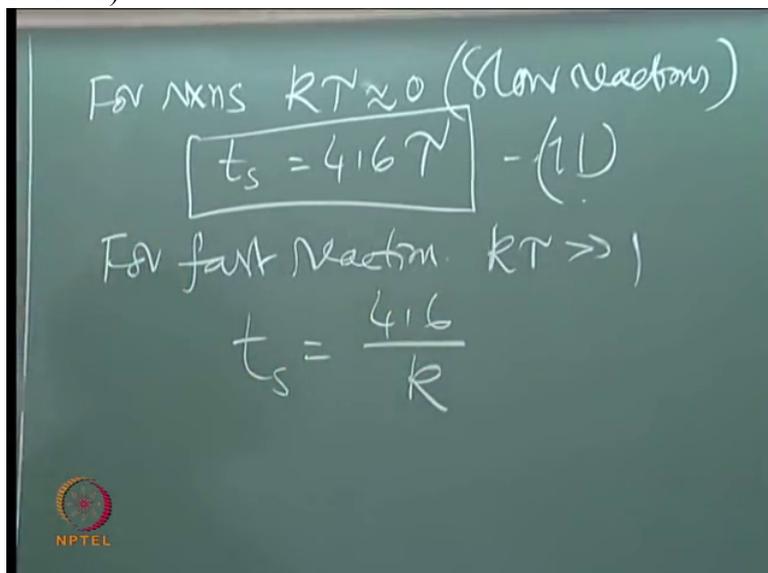
Professor: If the fast reaction is there, that means the $k\tau$ is very large, for fast reactions, $k\tau$ is far greater than 1, Ok. So now what you have there from this equation?

(Professor – student conversation ends)

Ah, numbers, this is 8, 9, 10, 11,

Ok so then of course 1 is neglected, then you will have t_s is 4 point 6 by k .

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See now kinetics also come there. And life is not that easy. Why? Because I have done only for first order reaction. In the examination I can ask you second order reaction, second order reaction.

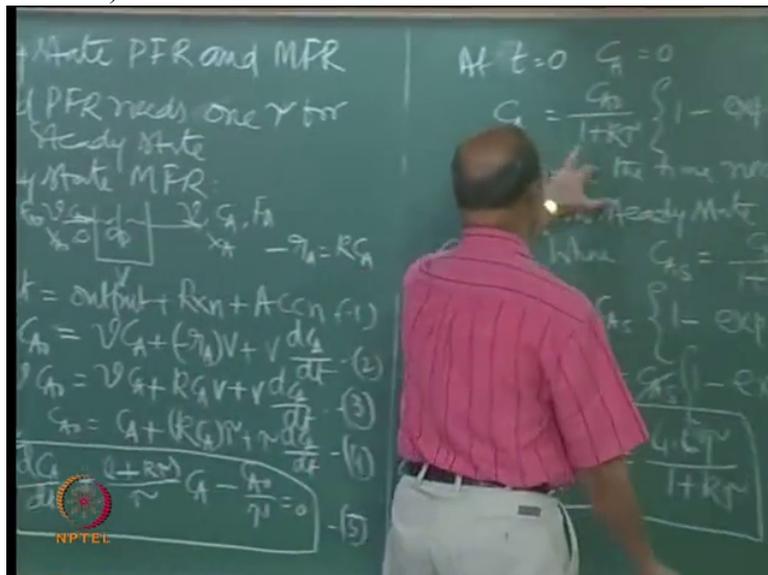
So that is why the steady state value for a C S T R is not that kind of a simple thing, Ok, but in industry they wait for, you know 10 times, Ok, 7 times, 8 times, 10 times, 12 times like that. And then finally measure the concentration for may be 1 hour, 2 hour, 3 hour, 4 hours and if almost all that is same, then we will say that we have steady state.

You see, very innocent looking C S T R, where happily we ignored that we do not have steady state, we have only, sorry we do not have unsteady state, we have only steady state how much thing is involved there. Ok. So this is the information.

But I think you know plug flow is a nice guy. Because ideal plug flow, it will simply, sweeps the entire volume out once and then onwards you will have steady state. Ok, good. So now. I think the story is not yet over here.

If I plot this concentration

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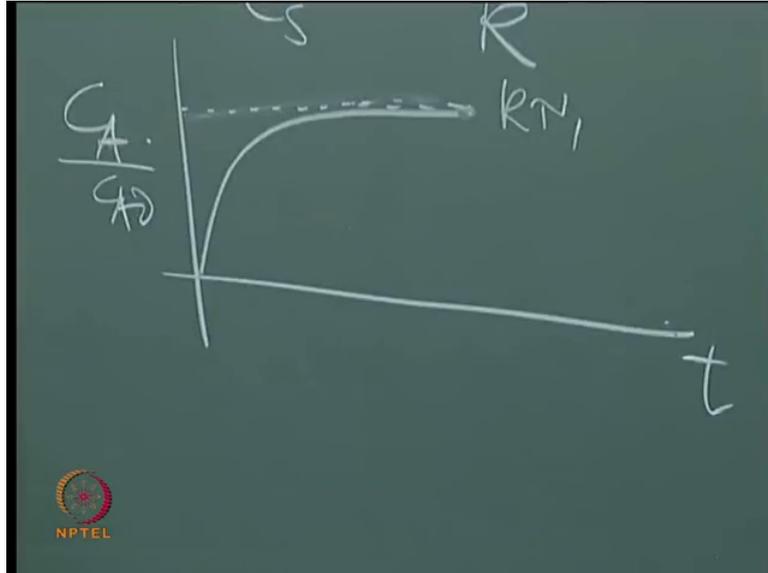


C A versus time, Ok, that means this equation, which equation, 6, yeah, when I plot that, what do you get is, for of course you have to plot that for a given tau, the k tau I have taken as 1,

right so what do you get here is C_A by C_{A0} . Because this C_{A0} I can take here, so then it is only in terms of $k\tau$, right.

So when $k\tau$ equal to 1, you will get like this. Ok, there will be slight

(Refer Slide Time: 17:26)



increase. Yeah. There will be slight increase. That depends on the conversion and, conversion depends on $k\tau$. Now I have not told you the real story behind this. And now we have, we may operate this in various ways, right?

There are 3 ways of operating C S T R for getting steady state, Ok. So this one is, somehow that we filled up and then the outlet concentration at time t equal to zero, Ok. So how can I do that? I can do that by filling up the entire reactor with inert and then fill up.

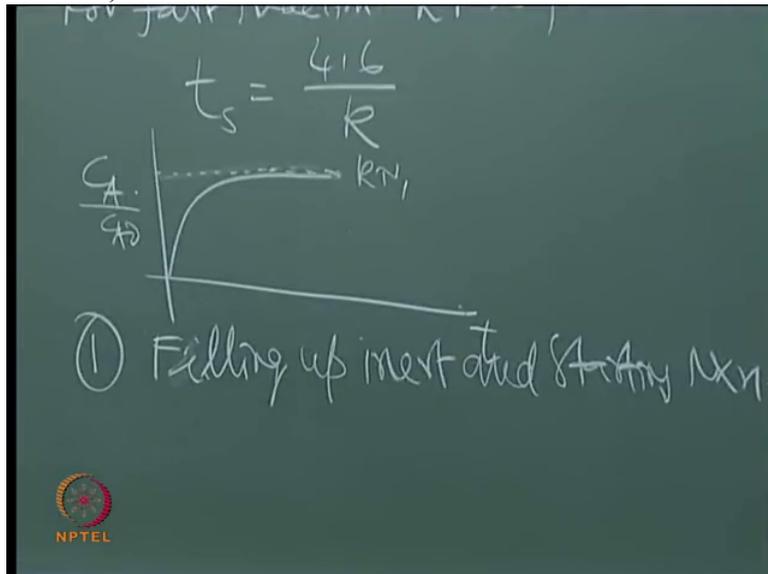
The entire volume is occupying by some inert liquid. So then when I start the actual reaction, my reaction, then at that time only t equal to zero, C_{A0} equal to, C_A equal to zero, because only first inert comes out. Inert means fraction of second, zero plus we are saying instantaneous mixing, so zero plus if I take, you know these are all mathematical boundary conditions, no.

Zero plus if I take I may get some concentration. Exactly at zero, I may...I do not see that concentration that means not even 1 molecule coming out. But zero plus means because of mixing some molecules may come out. Ok. So that is one thinking, right? That means

mathematics and physics you have to really try to match in your mind and then only write the boundary conditions. At that, at that time this is fantastic. This is fine. I will now, inert we have now filled up.

The second option is, Ok first option is inert. Filling up with inert and starting reaction. That is one. Here only you will get C_A equal to C_{A0} at time t equal to

(Refer Slide Time: 19:31)



zero, because inert you have. I take water and then I actually put my reactants later so that is inert because water is not reacting with that at all, so that is some inert, so at time t equal to zero, exactly at that time when I start outlet concentration of this reactant will be zero, this is one condition.

There is another way of operating. You tell me what is the other way of operating?

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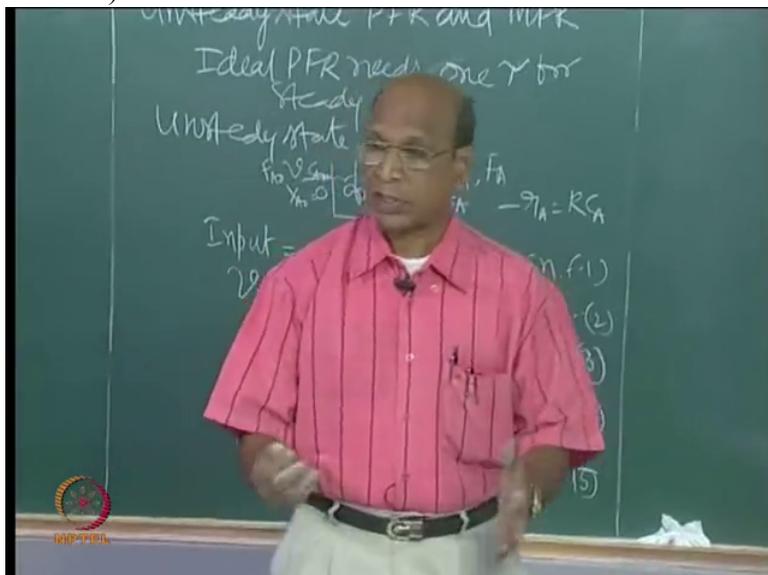


(Professor – student conversation starts)

Student: Slowly we have to take the 0:19:56.5

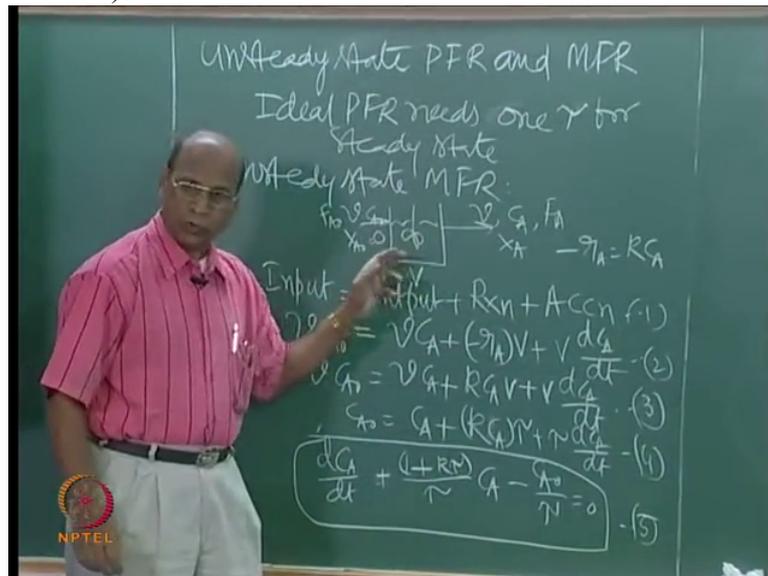
Professor: Yeah that is one, Ok, that means

(Refer Slide Time: 20:00)



I have C S T R, I have C S T R. Nothing is there inside. And then slowly you fill up.

(Refer Slide Time: 20:06)



What is the method of filling up you call, I mean, in our continuous system, batch system?

Student: Semi-continuous

Professor: Semi-continuous.

Student: Semi, yes.

Student: Semi-continuous

Professor: You are only feeding, nothing is

Student: Only input

Professor: Only input. It is semi-continuous. That is much more difficult. That we will give you in the examination, Ok. You think about it. But Ok, that is one. Other one? What is the other operation? This is one.

Student: Semi-batch

Professor: Semi-batch only he told. Semi-batch only no, you start putting both the reactants. Slowly it builds up. During the time, reaction also will happen. Correct no? Like batch, exactly. But batch with variable volume

Student: That is variable volume

Professor: Variable volume, you have to think all this, I say. Think, think, think, think, think. Right, yeah variable volume and then when it comes to overflow from then onwards, it comes out, from then onwards how much time it takes for steady state. This time to find out is very easy. Can you tell me how? Rashmi?

Student: Sir we can just put it in batch reactor with...

Professor: Till it comes

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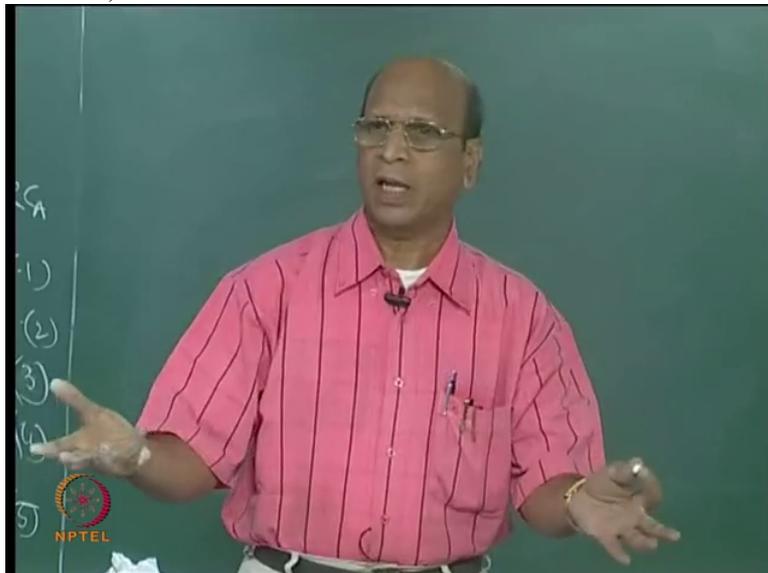


to overflow

Student: Volume by volumetric flow rate

Professor: That is all, very simple. Ok, volumetric flow rate. That will give you, that is straightforward

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calculation. If I have 10 liters and I am sending 1 liter per minute, so 10 minutes it takes for

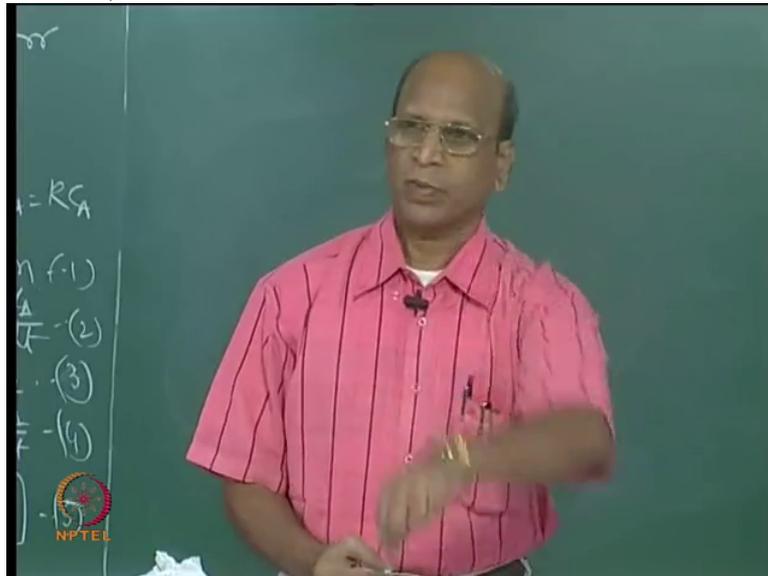
Student: Filling up

Professor: To filling up. That is what every day we can also see when you are pouring water in the glass or in the bottle all that you know.

(Professor – student conversation ends)

How much time it takes is depending on how much time you know, rate of flow

(Refer Slide Time: 21:45)



into the bottle. That is what every day you are doing for drinking water and all that. That is very simple. So then once it fills up, reaction also is happening during that. That is complicated. Semi-batch. So from then onwards, it overflows and comes out. Then it reaches steady state.

That is the actual practical way of doing things. Ok, right. That is what. Empty. But need not be. I think if I am an intelligent fellow, I will say that no, no, no why should I put that? Other way is to fill up the entire reactor with C A naught itself. To fill up the entire reactor with C A naught.

And then start reaction conditions. May be temperature suddenly coming to 100 degree Centigrade. There are so many ways of, I mean conducting this steady state operation for C S T R. I do not have I do not have product, no. If I have product, no problem.

(Professor – student conversation starts)

Student: Somehow you prepare product...

Professor: Yeah, somehow you know, in industry you go and tell, Sir somehow we will make the product, Sir, I think that somehow will never work. Ok. So that is not the practical way, no. Because reactants. But C A naught I have, I will fill it up.

(Professor – student conversation ends)

And then I will start the reaction, reaction conditions. That means there is no reaction. That means in the beginning it is almost inert. And then it overflows. And you know at that time I can start the reaction also, reaction temperature.

(Professor – student conversation starts)

Student: 0:23:09.9 affect some time also, 0:23:11.0,

(Refer Slide Time: 23:11)



once it reaches the C A value and then you can make it as a C S T R

Professor: Yeah, that is also, but I think steady state, again I have to wait because I think you know, what he says is, but steady state, all these are the possible things. I mean at least I am happy, you started thinking about this.

(Professor – student conversation ends)

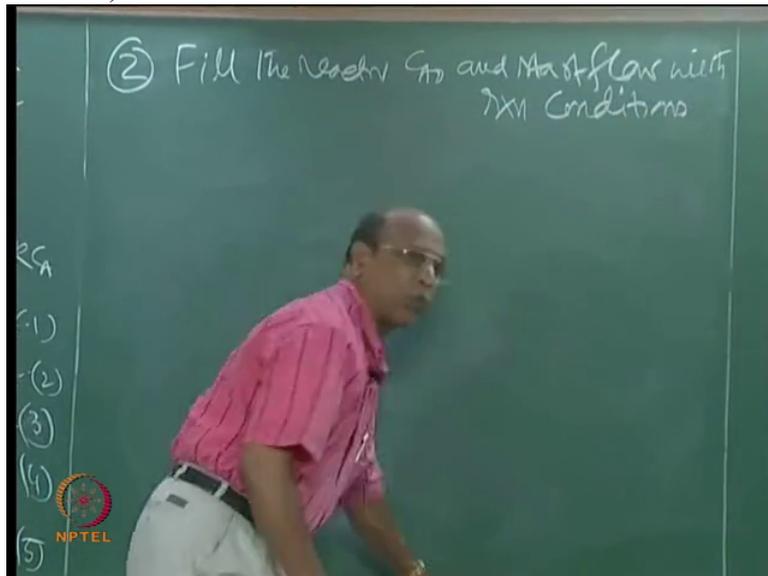
And if I have 2 reactants, A and B? Again you have so many possibilities. Why I have to put only C A naught and then start C A, C B? Ok I can put both and then start. I can put one this way, that way and then start. See how many possibilities are there to start the reaction?

And you will get real award from your boss in the industry, if you go to chemical industry, Ok, if you are able to tell what is the simplest method what you can do? Simplest method means time saving, and also, yeah, I mean that is quick steady state without losing much

reactants. Because unsteady state you lose the reactants, because you are not getting the product what you want actually.

So that is why you have the so many possibilities. I will give you just another possibility that you know that, filling up with C A naught. That is option 1. Option 2, fill the reactor with C A naught and start flow with reaction conditions. This is one of the, this is one of

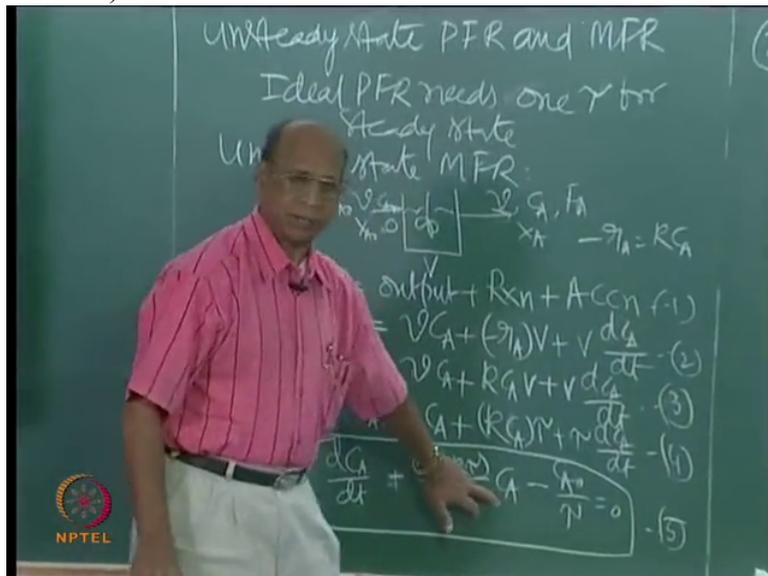
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the ways only, I am not saying that I am right, Ok.

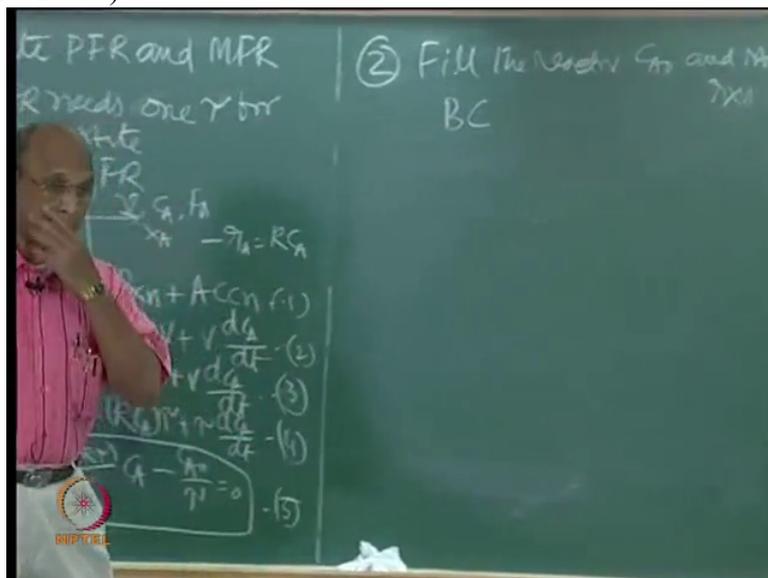
This is one of the methods I have chosen, right, where the differential equation is exactly same,

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equation 5. Only boundary condition is, B C for this is

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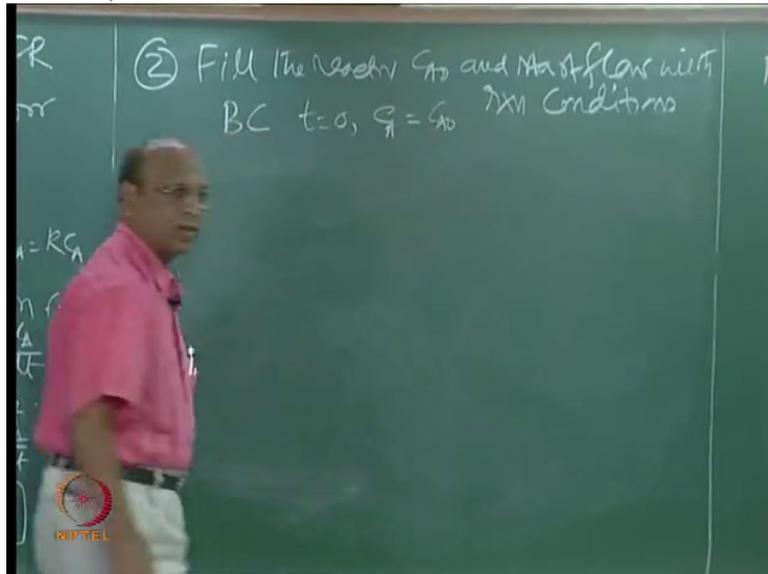


(Professor – student conversation starts)

Student: 0:25:01.3

Professor: Yeah, at t equal to zero, C A equal to

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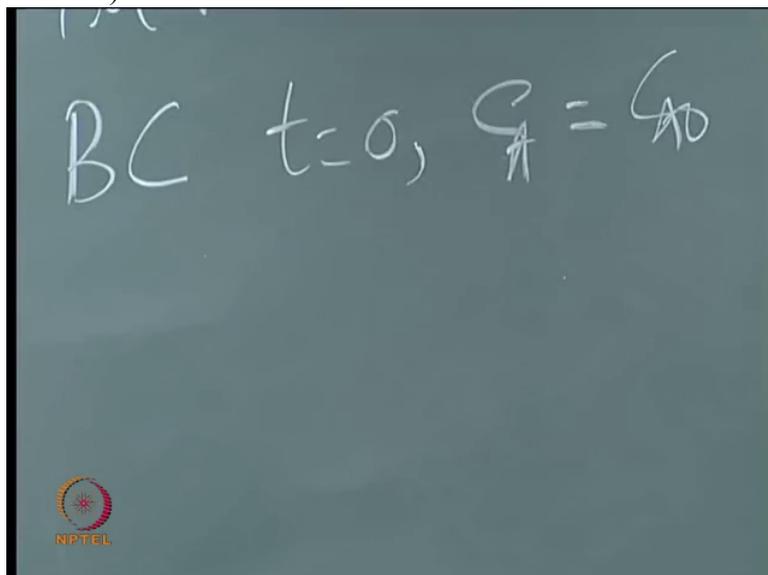
C A naught. Ok. The other things are not that easy.

(Professor – student conversation ends)

You have to solve, you know like for example slowly filling up and then it overflows but the reaction is going on inside that, Ok. So after, by the time it reaches to the top, what is the conversion? From then onwards how much time it takes to reach the steady state? All that one can do it.

And all the time it is only first order differential equation. We do not get more,

(Refer Slide Time: 25:35)



right? So corresponding boundary conditions you have to take and then solve the problem. The solution what you get for this is, the differential equation is same, this only. So then I have $1 - k\tau$ by $1 + k\tau$, $1 - \exp(-k\tau)$ by $1 + k\tau$ into t .

Can you

(Refer Slide Time: 26:09)

BC $t=0, C_A = C_{A0}$ XII Conditions

$$\frac{C_A}{C_{A0}} = 1 - \left(\frac{k\tau}{1+k\tau}\right) \left\{1 - \exp\left(-\frac{1+k\tau}{\tau}t\right)\right\} \quad (13)$$

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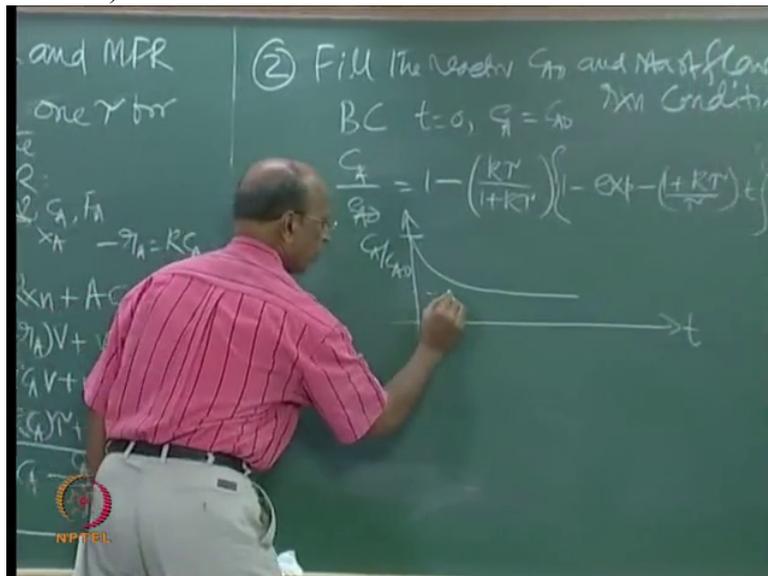
tell me what kind of graph I get when I plot concentration C_A by C_{A0} versus, C_A by C_{A0} versus t ? It starts with 1, no? I mean maximum is 1, I do not say it will start with 1, or end with 1, start with 1, and then?

(Professor – student conversation starts)

Student: Exponentially decrease

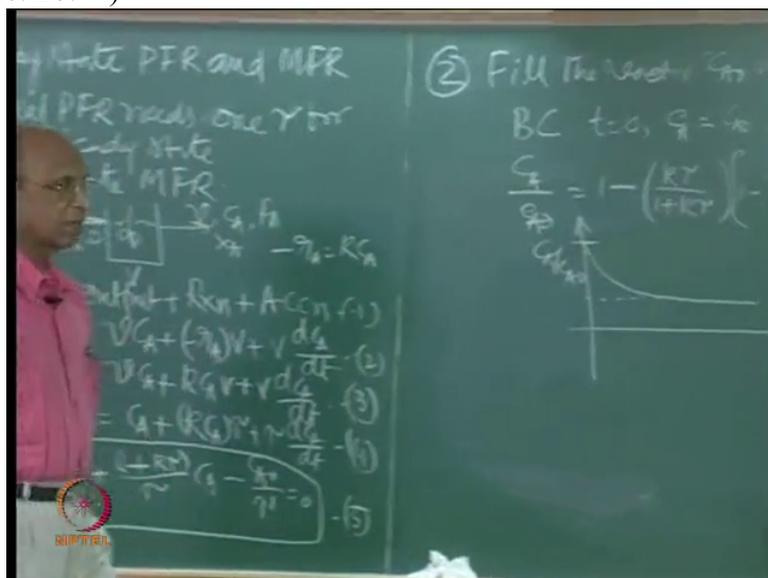
Professor: Very good. I think all of you must be able to imagine this. Yeah. Then it reaches almost steady state so

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this must be the steady state

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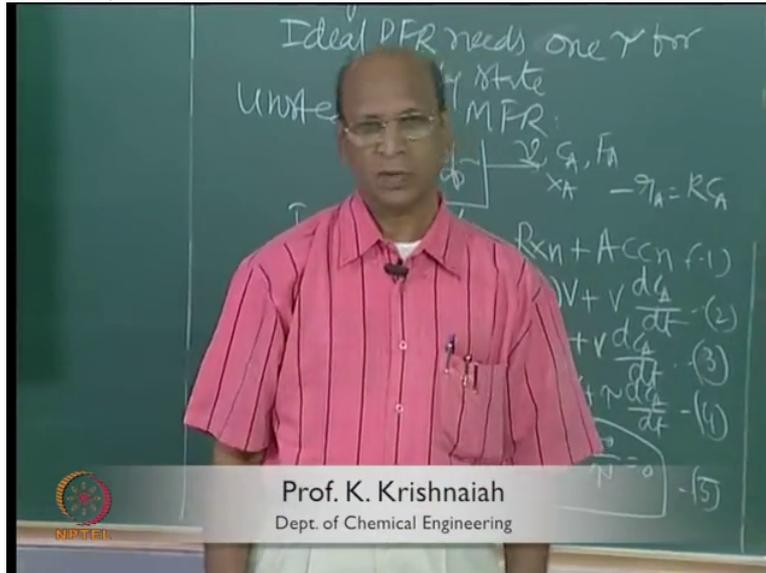
we are getting. Ok, good.

(Professor – student conversation ends)

So there are so many other possibilities which you can do, these are the boundary conditions. I told you know, so when I explained first this one, the first method he was not very happy. Because that was not in his mind. He was thinking something else.

So then I tried to convince him with the first method and then he said finally, yes Sir, and all that but I know that his eyes are not convinced, his head is convinced,

(Refer Slide Time: 27:10)



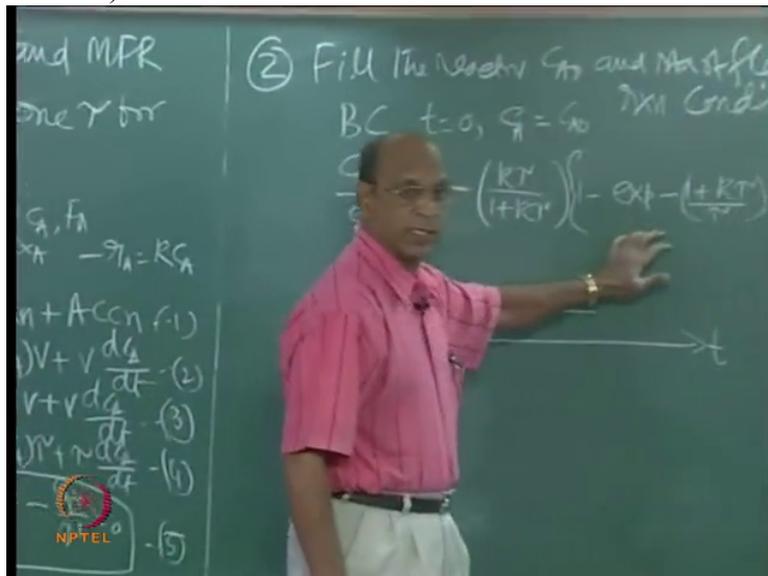
Ok, yes Sir, yes Sir. So then I went home and started seeing this, thinking. That is why, till then I have also not thought.

That is why when you ask questions or when you show unhappy face, I have to think. Then I thought and then I went and again saw, you know transport phenomena book by our grandfather B S L, so grandfathers. Ok then as you know, he has solved it in a different way.

So like that when I thought and then sit down and then think, there are so many of ways of operating this. So many ways of operating this. Ok but P F R is not a big problem because in one residence time everything happens. And normally what is the residence times we use in P F R, very small, gas phase reactions, very small, you know may be seconds so that is why you can wait 10 minutes, you will get beautiful steady state. No problem. Industry has that much time and then you can go, but here you have the problems.

So this is the one and this only to just to give a sample of, you know how you have to operate the C S T R and I have done only for first order. This equation will be very, very

(Refer Slide Time: 28:15)



complicated the moment you go for the second order reaction. That is how I like you to do in the examination. So that is why you have to have all you have to work more and more and more, I tell you.

So now this is the one I think with steady state and you know unsteady state reactors. Yeah, these are the simple things only what we have done. Now let me go to recycle reactor.

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So when you use recycle reactor? To increase the conversion which is wrong answer, Ok any other answer?

(Professor – student conversation starts)

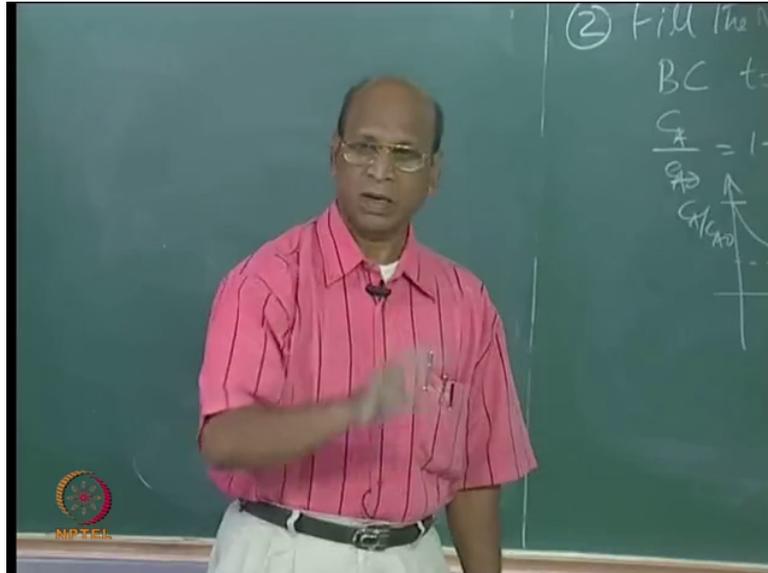
Student: For efficient utilization of reactants

Professor: Yes

Student: For efficient utilization of reactants

Professor: Wrong.

(Refer Slide Time: 28:44)



Student: Autocatalytic reactions

Professor: Autocatalytic, not right.

Student: (laugh)

Professor: Straightaway you cannot say it is autocatalytic. You know why?

Student: When we want...

Professor: No I am asking the reason. You are telling about an example.

Student: 0:28:59.1

Professor: You are giving the example where it is used. But what I asked is when do you use?

Student: For production

Student: Product

Professor: Output is low? For output low, there are thousands of reactors,

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Ok, including us.

Student: Product quality

Professor: (laugh), our output is always less.

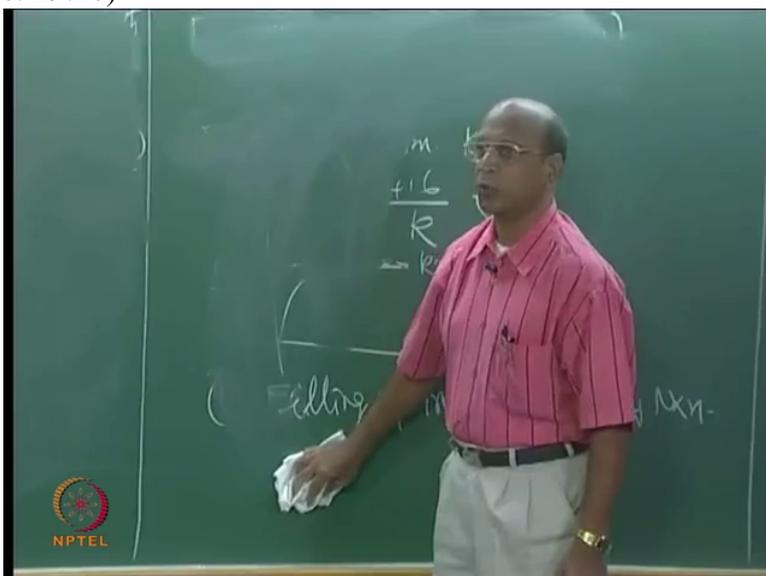
Student: To increase the yield

Professor: To increase the yield

Student: In case of reversible reactions

Professor: In case of reversible reactions,

(Refer Slide Time: 29:26)



who told that?

Student: (laugh)

Professor: 0:29:29.7,

Student: Converting P F R to M F R

Student: Conversion between P F R and M F R

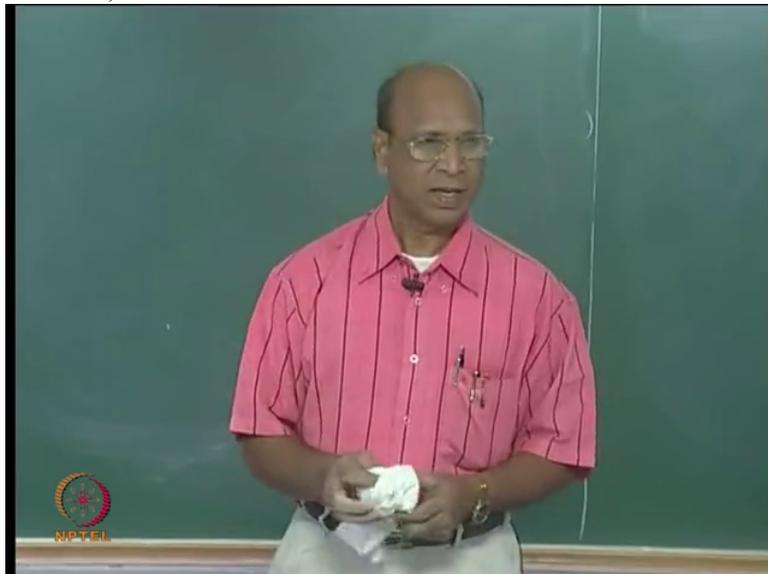
Professor: Who told that?

Student: (laugh)

(Refer Slide Time: 29:38)



(Refer Slide Time: 29:39)



Student: When mixing is required in P F R

Professor: When mixing is required in P F R or when you want to have mixing between P F R and M F R. What is mixing in P F R? Zero. What is mixing in M F R?

Student: Infinity

Professor: Infinity. Somewhere in between when you require, when you require, Ok. So when you require? You told the answer so that is why I am asking.

Student: Increase the conversion

Professor: Not conversion. How can you increase conversion, no by putting mixing? You know that no mixing reactor is the best for normal reactors n greater than zero, right? That is why how can I increase conversion?

(Professor – student conversation ends)

This is a bad thing, to tell you know. At this point of time, recycle reactor is never used for increasing conversion. Because plug flow is the best and now here in mixed flow, in recycle reactor, some mixing is there, some mixing is there where that is bad for the reaction. So that is why maximum mixing in C S T R gives you lowest conversion. Ok. It dilutes the concentrations. So that is the reason.

So intermediate mixing is required sometimes for multiple reactions, multiple reactions A going to R, R going to S. Again this fellow, A going to R, R going to S, that is series. So A go to some other product. B also go to some other product. Under those conditions, sometimes, under some conditions you have to control the mixing, right?

So it is not ideal, plug flow will give you 100 percent, you know yield, Ok yield is the required product, Ok. Yeah, yeah not the conversion, yield. So to improve the yield, in multiple reactions that can be used. Then another example what Rahul told was that autocatalytic reaction. Autocatalytic reaction is beautiful one. Why?

Because I need some mixing...Ok what you mean by mixing? So that means the products as well reactants are mixing. In recycle reactor what I am doing? I am taking out the products and then bringing them and then putting into the

(Professor – student conversation starts)

Student: Inlet

Professor: Inlet, so autocatalytic reactor, for autocatalytic reaction, this is one of the best reactors but there are other arrangements of reactors also for autocatalytic reaction best. Ok it is not the only method.

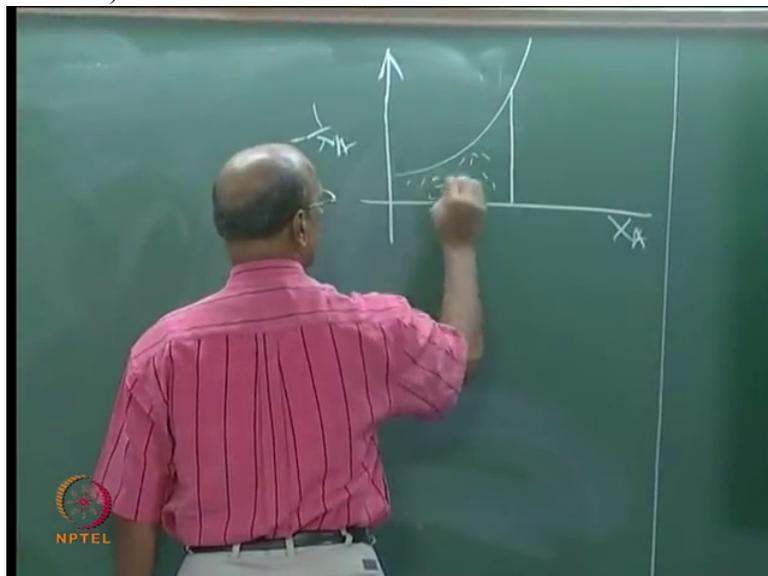
(Professor – student conversation ends)

But if I want to use the single reactor then the best reactor is recycle reactor. But again there are many conditions. That is why autocatalytic happily we cannot accept. If the conversion low is somewhere intermediate, 80 percent conversion, 70 percent conversion. If I have conversions low, around point 5, point 4, C S T R is the best.

How I am able to tell all this is, if you plot $1 - r_A$ versus C_A or X_A for autocatalytic reaction, by looking at that you will know which reactor is the best, Ok. So that is why best way of looking at the, you know which reactor is the best, Ok, the best way is to first plot, I think let me tell this one before going to recycle, so $1 - r_A$ versus X_A plot will give me lot of information, OK

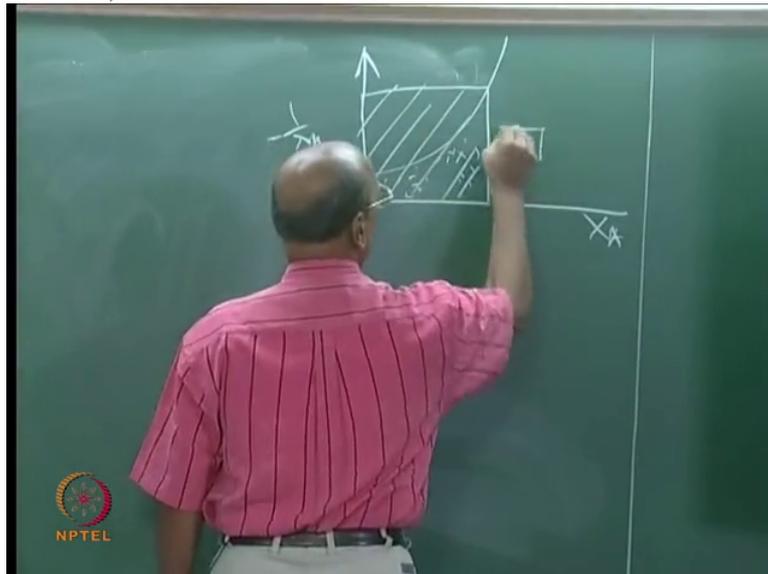
I know that if it is monotonically increasing something like this, which reactor is the best? Because the area is just area under the curve. So here this area only P F R,

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and this area will be

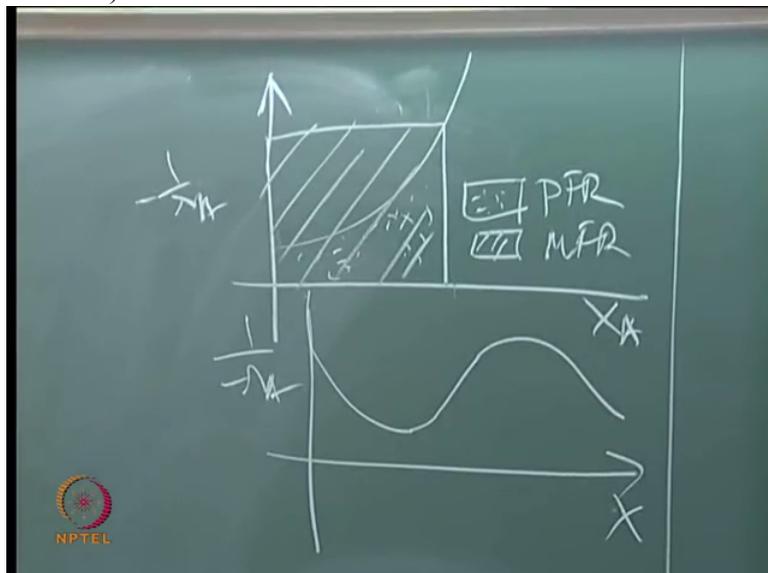
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P F R M F R, that is more area. So if I have a $1 - r_A$ some crazy versus X_A , so I have here like this, goes up like this.

Which reactor

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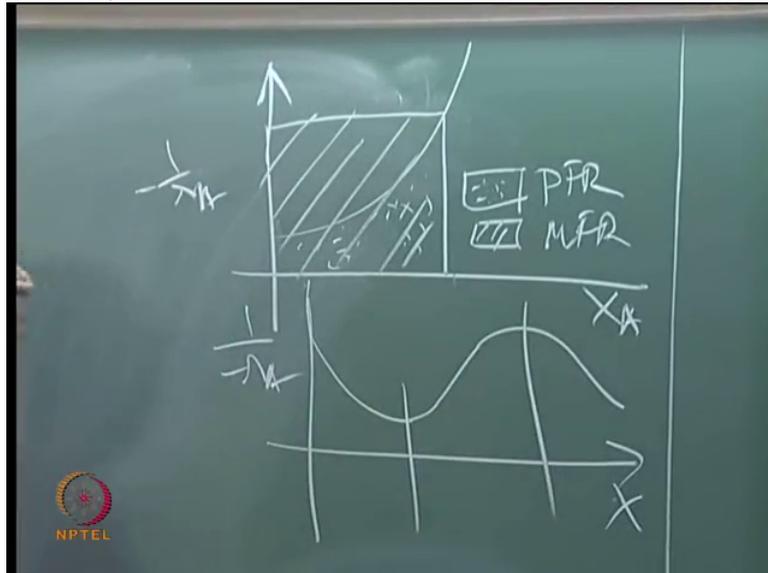
is the best?

(Professor – student conversation starts)

Student: C S T R

Professor: So now we have to divide this as parts.

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Student: P F R

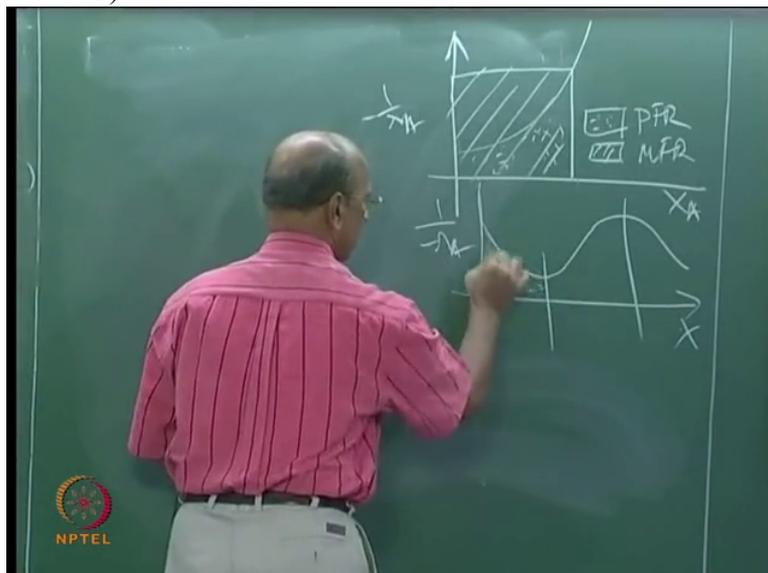
Student: Multiple reactors

Professor: Yeah, one reactor may not give me any idea here.

(Professor – student conversation ends)

So here when it is decreasing, if I use a reactor till here, like plug flow reactor for example. Area under the curve will be this entire thing, same symbols.

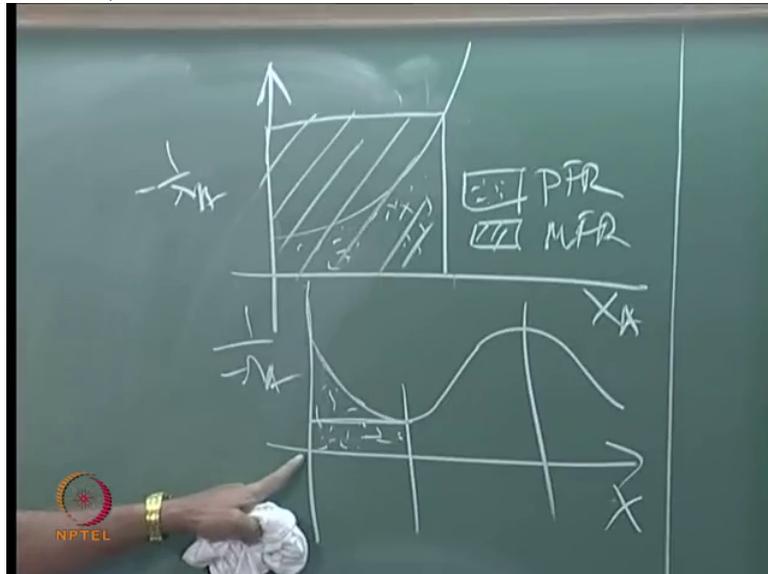
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This is P F R.

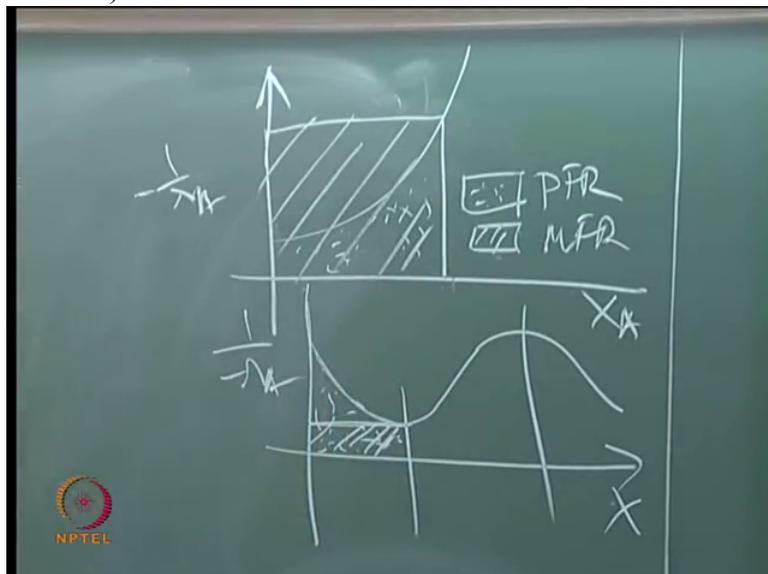
If I use mixed flow there is full region. From here, this is the outlet, this is the outlet, this is x equal to zero,

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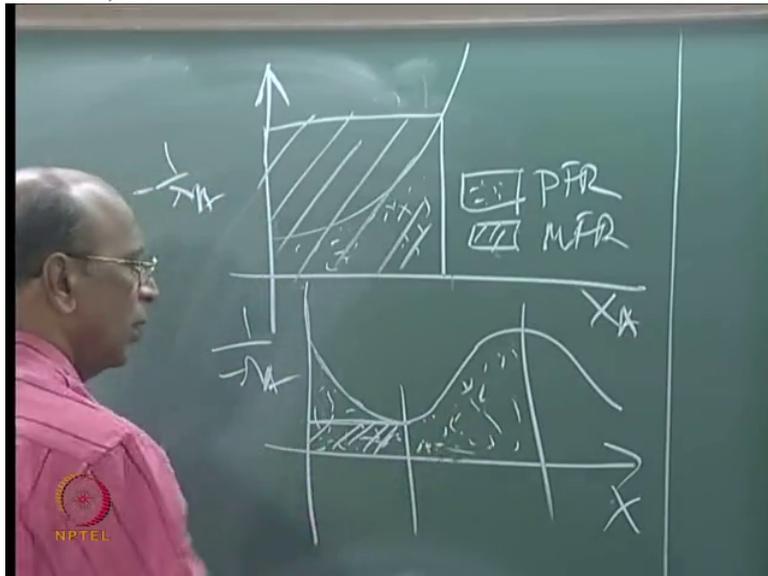
Ok, yeah so this is the one for M F R, same symbols.

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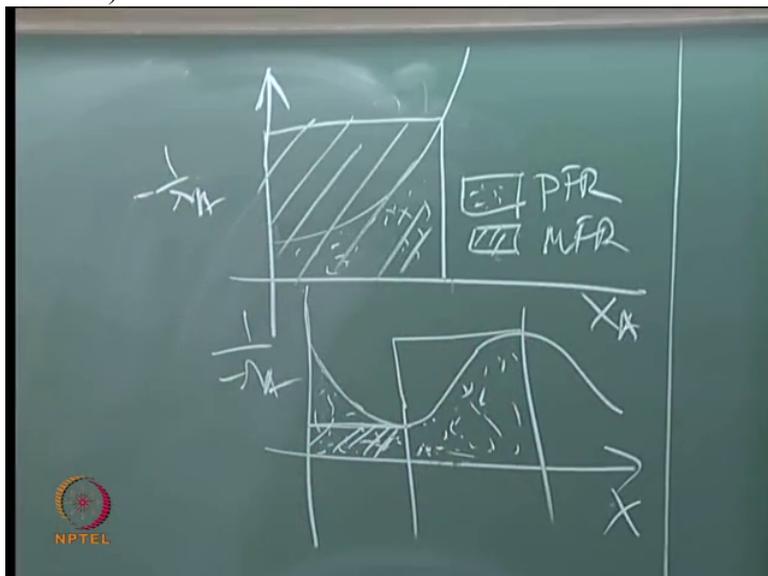
Next one, this is P F R. Ok, if I used here mixed flow? This is

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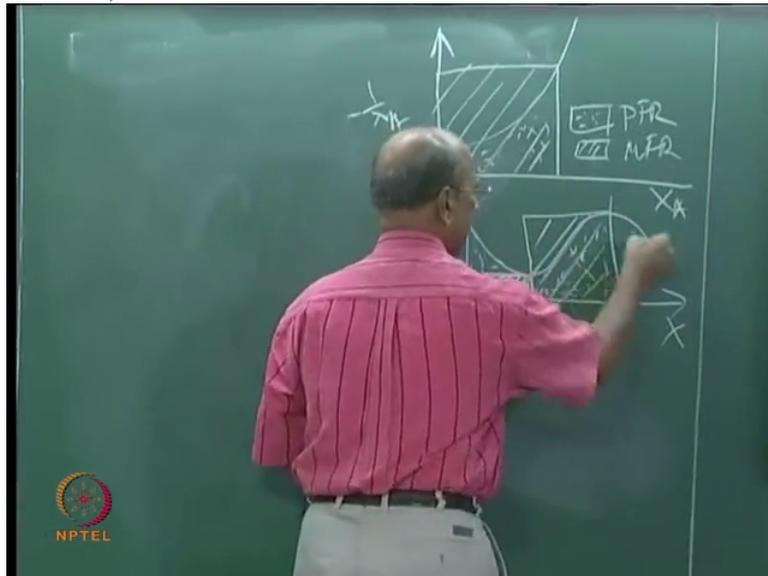
the one,

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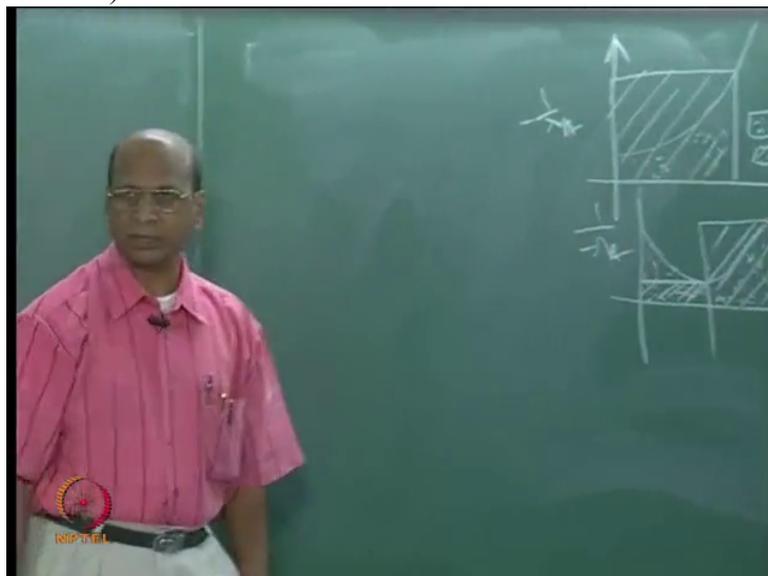
the outlet concentration. So this is the one.

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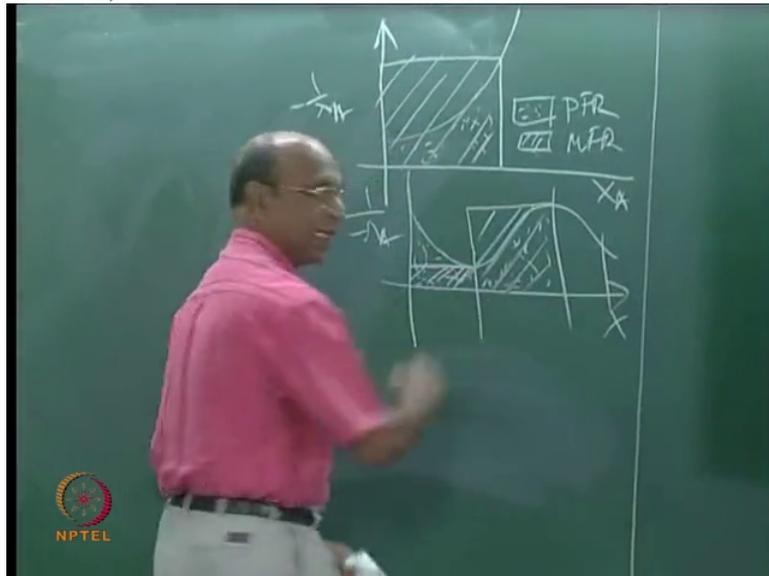
Again next one?

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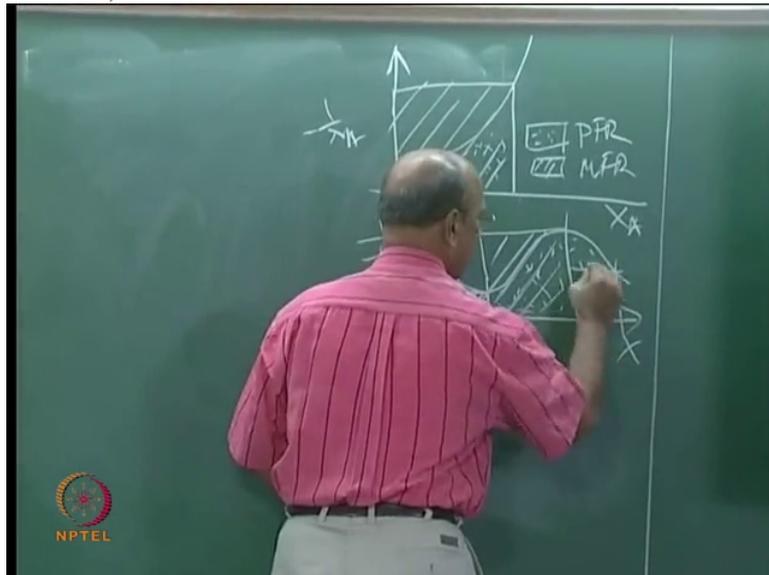
Yeah, that depends on what conversion I need. I need conversion here,

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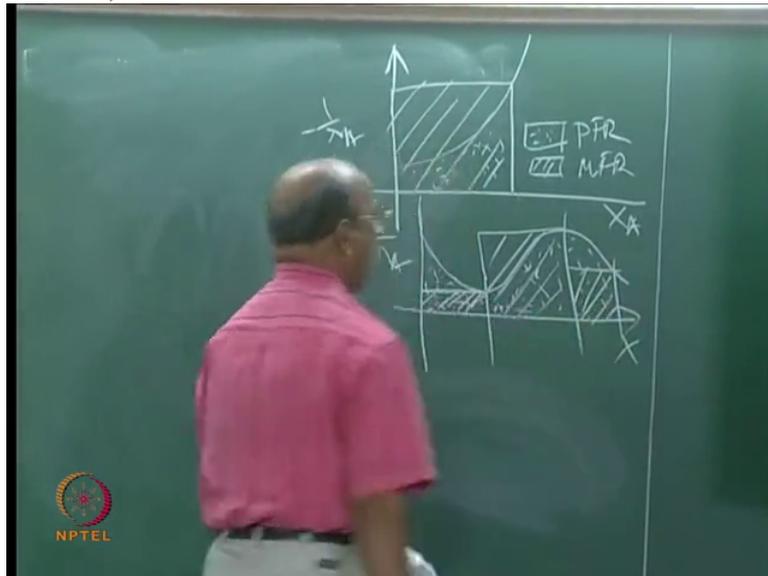
right? So that means this entire thing is P F R and this one is

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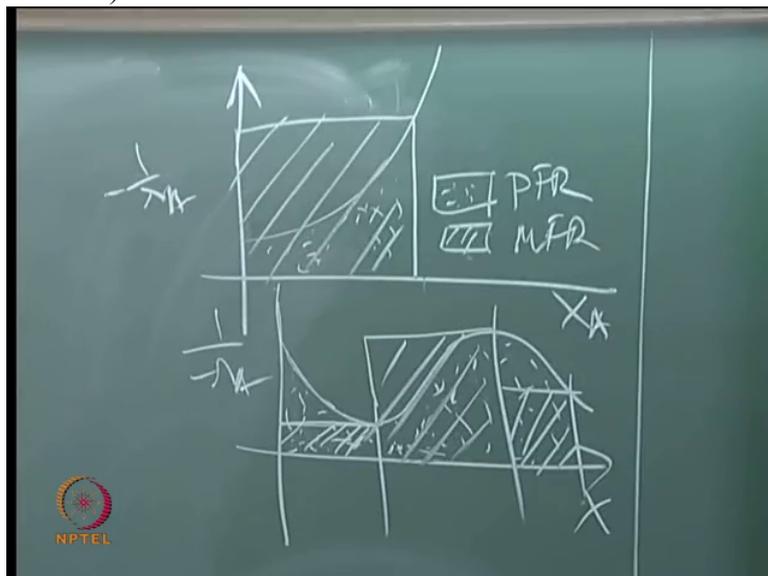
mixed flow.

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Best way is that. That is why you know, our people told that one

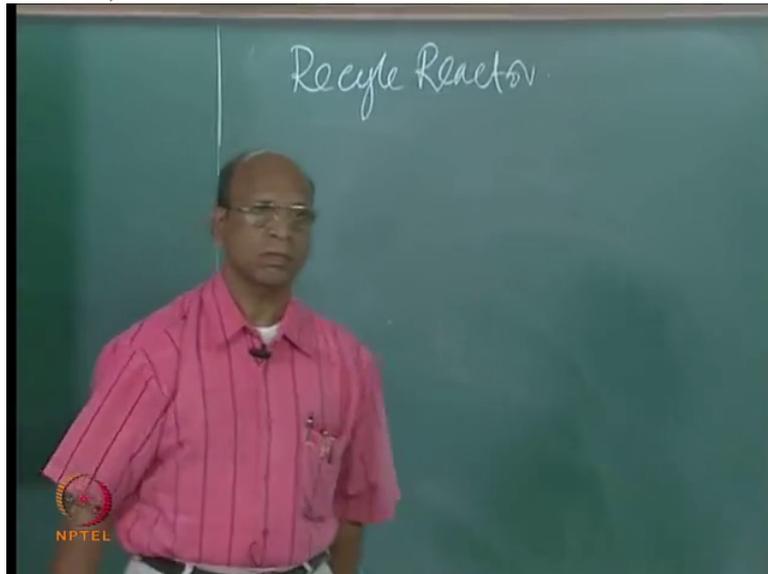
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picture can speak thousand words. Ok, so that is why pictures are best. Good. So that is the one.

Now recycle reactor. First you have to write when the recycle reactor is used.

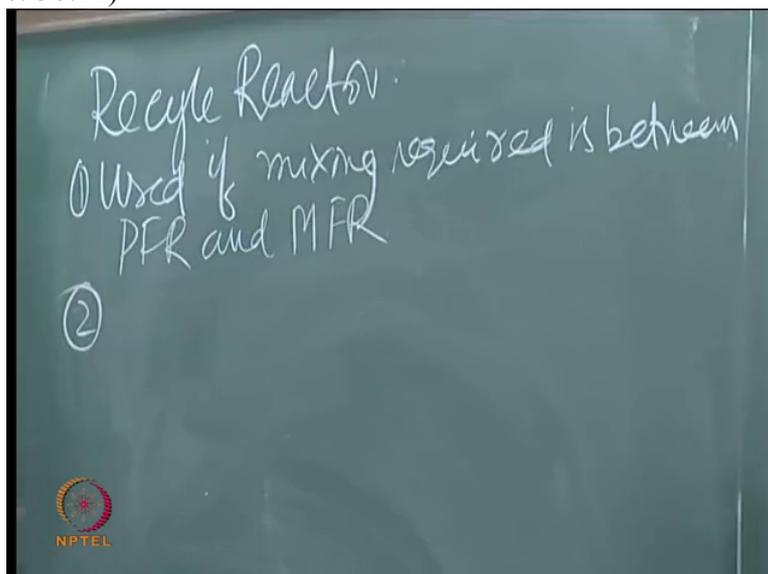
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Whenever we have intermediate mixing between M F R and P F R, Ok, used if mixing required is between P F R and M F R. Ok. Conversion and all that will not come into picture. Ok, that is one.

And another time, one more thing is there. Anyone can say that? Sometimes we do that. Apart from this, of course this automatically tells me that this mixing is required to increase yield and all that. That we are not talking.

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I think everything will come there. Other than that, there is another use.

(Professor – student conversation starts)

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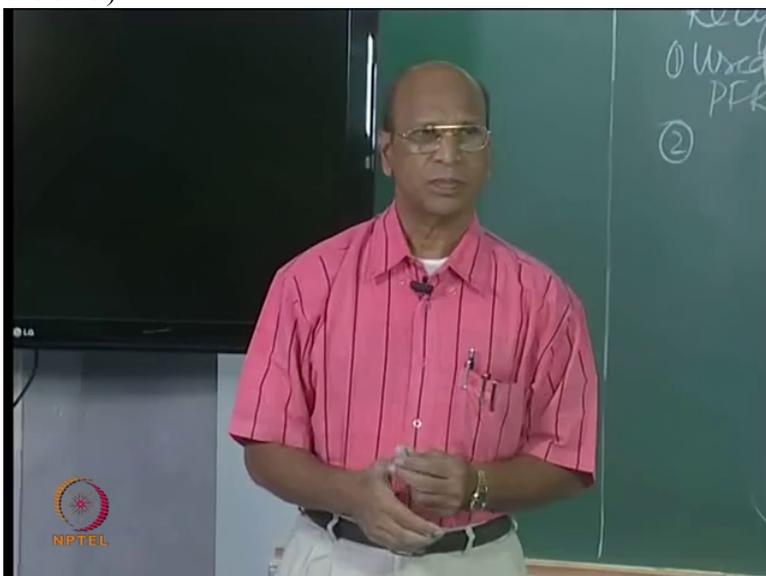


Student: Unreacted material is coming out then it can recycle it back.

Student: When you have...

Professor: That will not help me actually.

(Refer Slide Time: 36:23)



Student: When you have more than 1 reactant, if 1 reactant is like limiting...

Professor: All those things will come under; you know whenever you require different mixing than these ideal mixings. Yeah how do you control the reaction?

Student: Sir by dilution, Sir? Product...

Professor: Yeah, when do you do that? I mean why should I dilute the rate? Correct. Both are telling almost the same. Controlling the reaction, he said, you are saying diluting. By diluting I am controlling the rate only, right? Yeah. Gopi

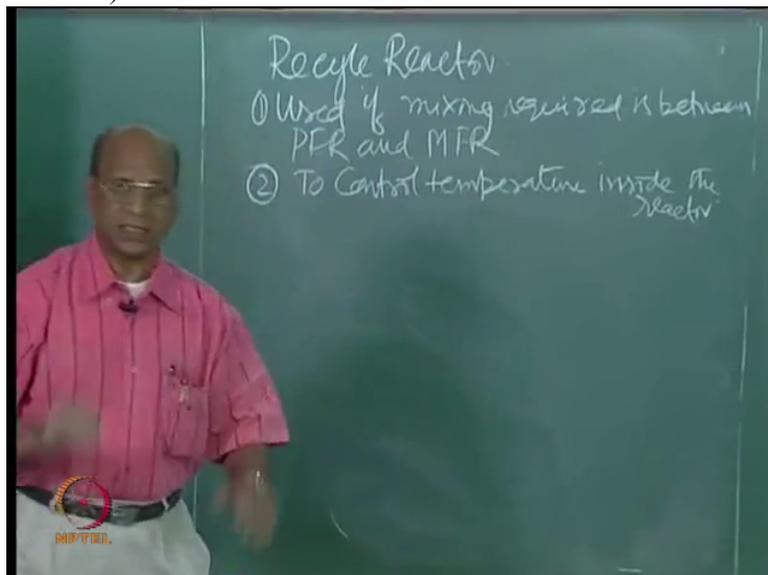
Student: Exothermal

Professor: Yeah if you want to control the temperature, Ok sometimes the products are used and then you can control the temperature inside the reactor. That is the other one. Ok.

(Professor – student conversation ends)

To control temperature inside the reactor. Ok, under these conditions this is done,

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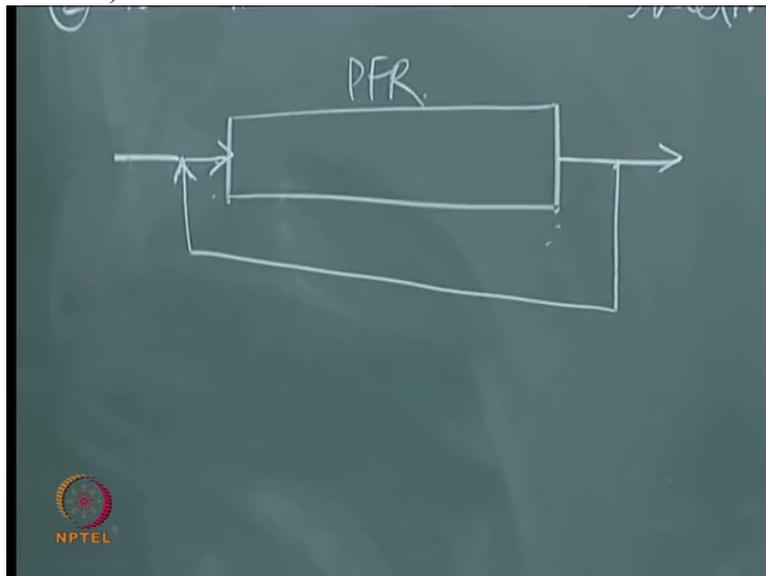


good, very good. So now we will try to, we have to derive an equation for this and the derivation must be somewhere between these two only. Because it is not either mixed flow reactor completely, or it is not completely plug flow reactor. So the derivation also must be in between. The equation must be in between that. Ok.

So now first we, we imagine that we have a plug flow, ideal plug flow element. Ok. Recycle reactor consists of ideal plug flow element and now we will send the reactants, they come out as products and you have to take out some, yeah product and then recycle. This is ideally PFR, good.

So how do you derive an equation? Here there is a slightly confusing

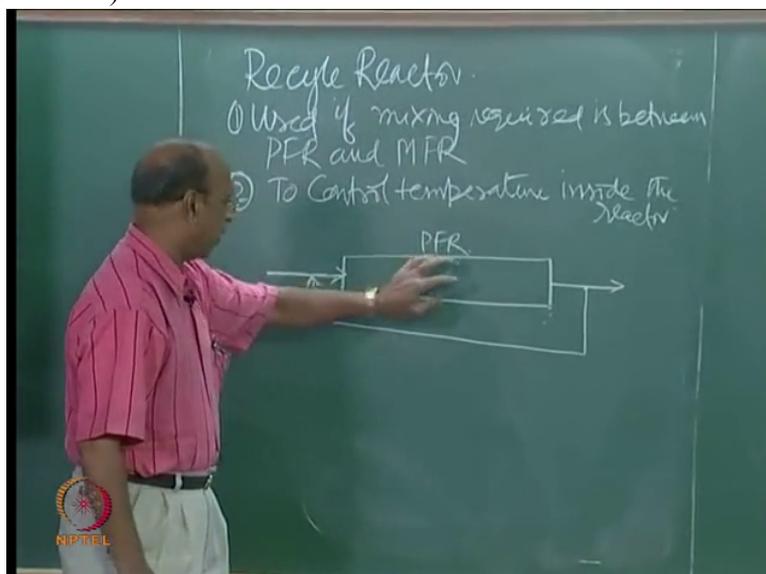
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thing. Levenspiel also, I do not know how many of you, all of you have done it in your B Tech? Do you remember anything? Absolutely no. All files are cleaned, Ok good, right. So that is very good, starting with clean chit. Ok

So I have, we have, yeah this P F R

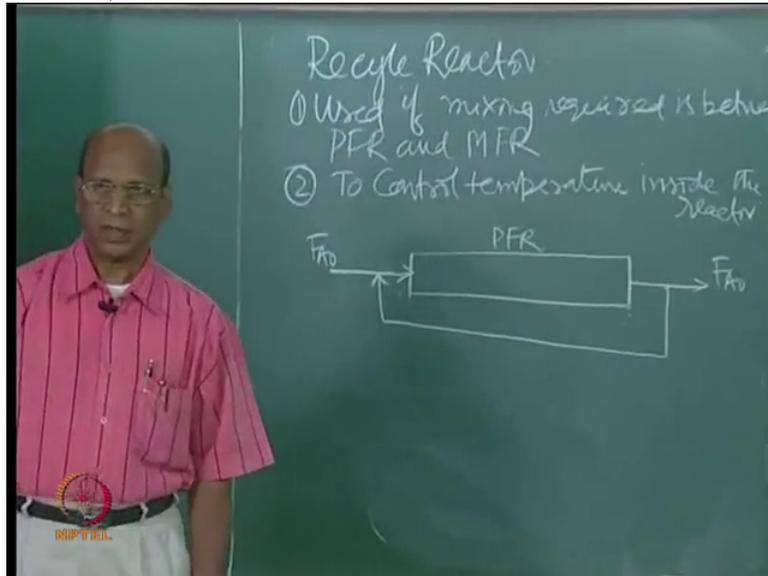
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and the confusion comes there that how do you first of all operate this recycle? My imagination is; I think you know I have not seen, I have drawn my own diagram some time long time back because I also had this confusion, to tell clearly to the student.

But as far as possible I am now trying. Still I do not know how many of you really convinced in what I am telling, trying to tell, all those things, Ok. So what I do is we first introduce $F A$ naught here, no reaction. No reaction. So if there is no reaction, at the outlet also for steady state I should have $F A$ naught,

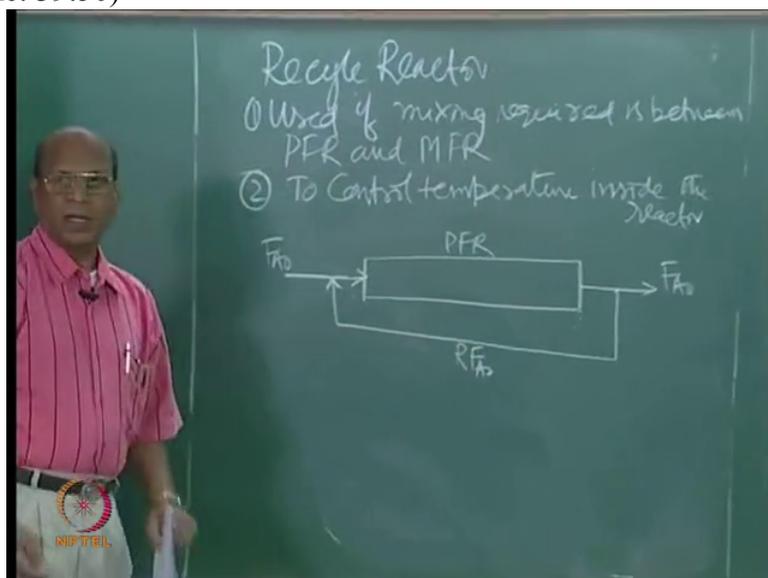
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Yeah.

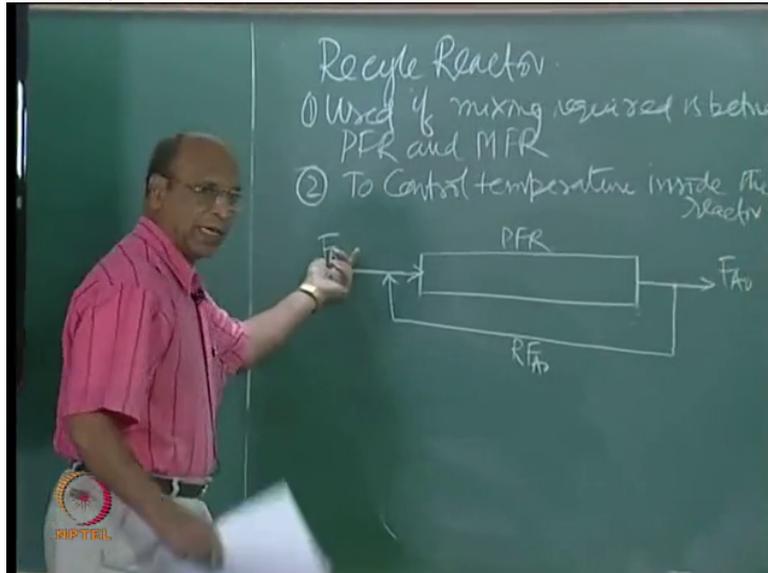
Now but initially this is under steady state, I have to take out something and then recycle, right? Ok. So now that much what I put here is I have R into $F A$ naught will be recycling.

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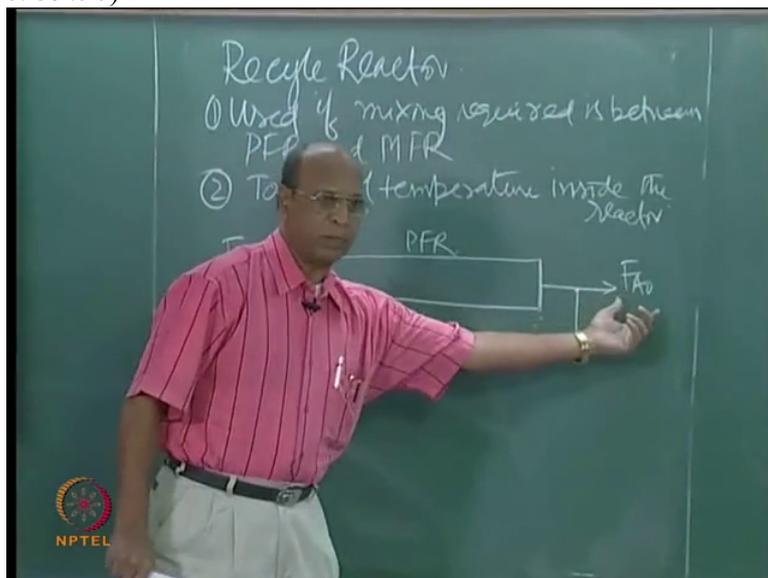
That means if I have $F A$ naught as 1 liter

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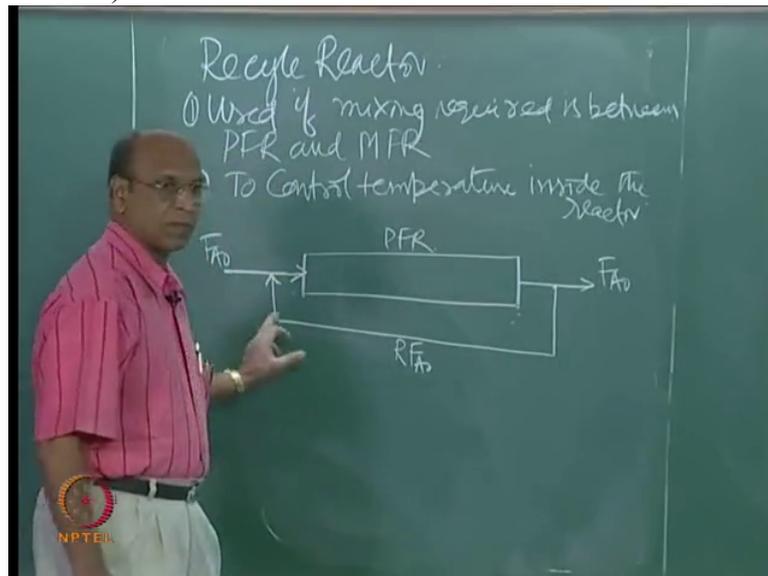
per minute, 1 liter per

(Refer Slide Time: 39:56)



minute will come out, right, then I am now recycling

(Refer Slide Time: 40:02)



depending on recycle ratio, maybe let us say 5, recycle ratio 5 I have taken. So how much I have to recycle now?

(Professor – student conversation starts)

Student: 0:40:10.9

Professor: 1 liter, 1 liter, how much I have to recycle if R is 5?

Student: 0:40:17.5

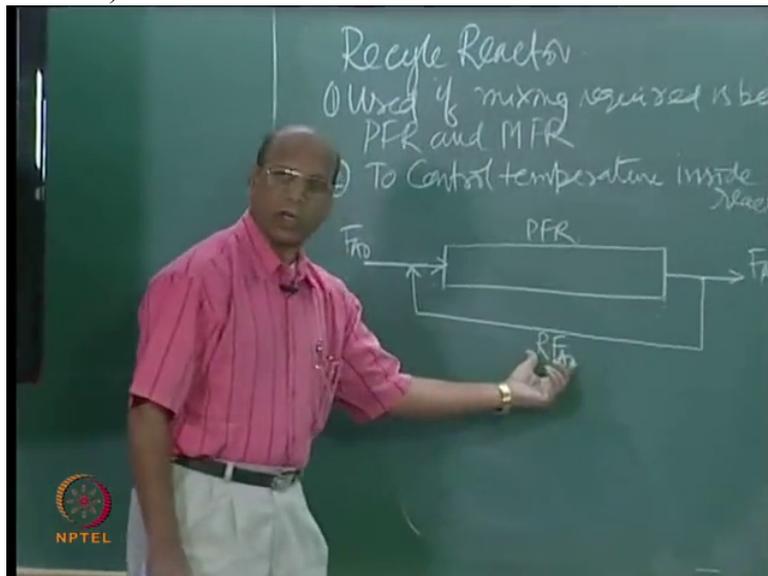
Professor: It is a L K G question, I say.

(Professor – student conversation ends)

Yeah you should scold me, Sir do not ask stupid questions. But I think you are thinking very, very carefully even though it is, you are before Supreme Court where if you tell one word more, I think judge may sue you and all that. Just open your mouth and then say. Ok. So that is what.

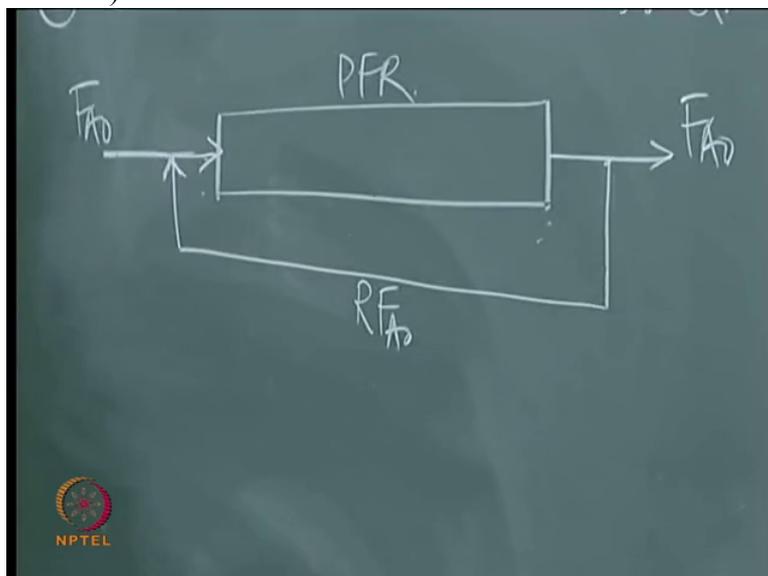
I think in molar flow rates

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also it can be done. That is no problem, right? So that is how only I operate. Otherwise if I send 1 liter and 1 liter and then if I take it back, what will happen here? It is not steady. So that is why initially we fill up. And then we try to recirculate that much all the time. This is before

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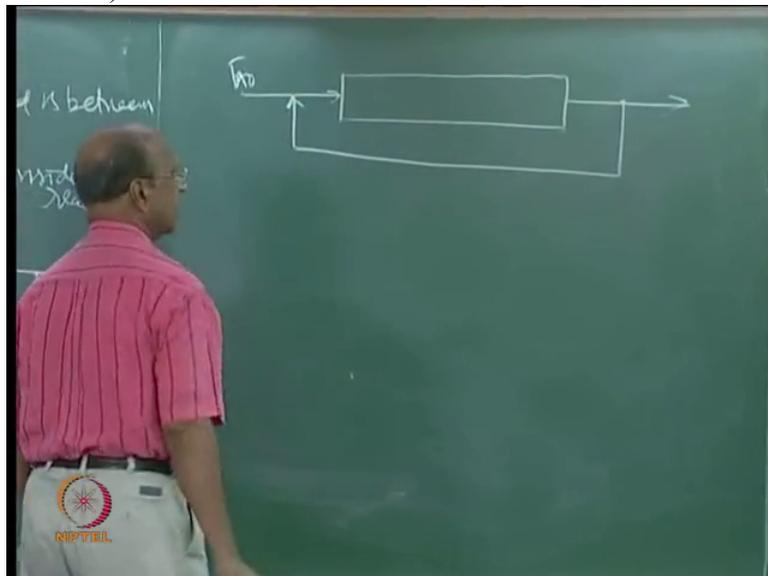
reaction.

There is no reaction. Here there is no reaction, right? And now under steady state, hydrodynamic steady state condition, you know what is hydrodynamic steady state condition? Yeah flow is constant, excellent. Flow is constant. How do you measure that?

Normally we measure in terms of pressure drop for example. If pressure drop is not changing, constant, then we will say flow also is constant. I think pressure drop, we had a sort of discussion earlier, right? So the moment you have the velocity changing, then pressure drop will be different. So that may be unsteady, right?

So that is why you have to wait that time. Hydrodynamic steady state and then suddenly bring this entire thing into a reacting conditions. Then what will happen to this entire diagram? Ok that I will draw now. You have same thing. Ok. Nothing will happen to F_A naught because that is entry, right yeah and now I have, this is the recycle,

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yeah by the by, so how do I define now recycle R?

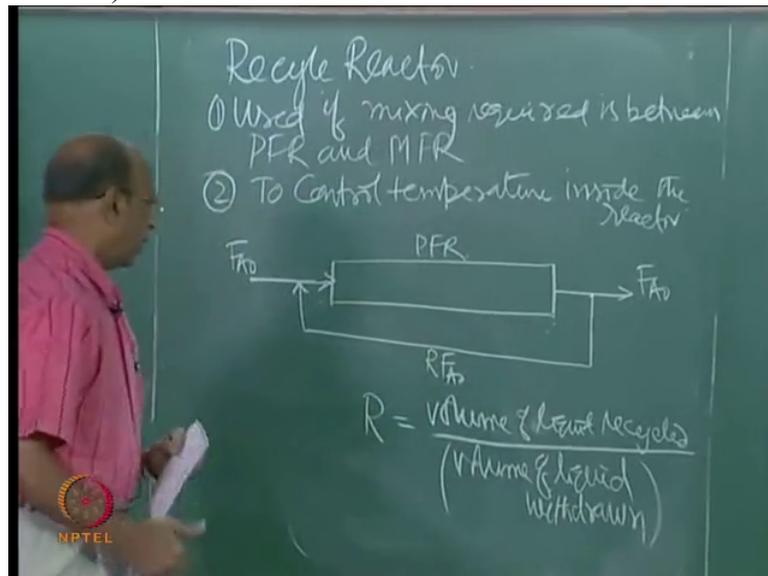
This I have to define before going there.

(Professor – student conversation starts)

Student: R should be defined

Professor: In terms of volumetric flow rate, the amount of liquid recycled back divided by, volume of liquid, not amount, I think volume of liquid coming out, Ok. Volume of liquid, Ok of liquid recycled divided by volume of liquid withdrawn from the reactor. So that is what is

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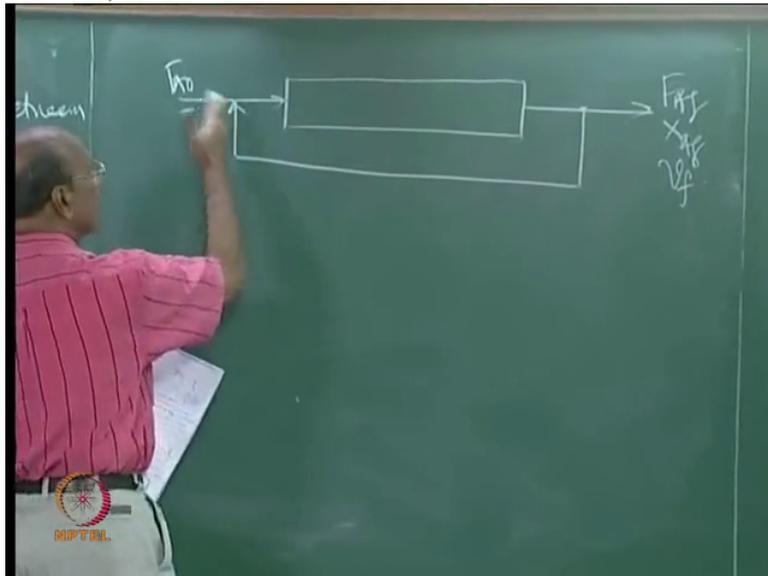
recycle ratio R . Ok, good.

(Professor – student conversation ends)

So then what happens? I have here, reaction condition started. So that means some reaction would have occurred here, good, Ok. So again we are now talking about steady state conditions after the reaction condition started, steady state, this will be $F A f$ and the corresponding conversion will be $X A f$. This is what I wanted earlier. Ok in the beginning before designing. This will be $V f$, good.

So now this point, at this point I have, yeah, so this is already converted one in the reactor, something converted and I am now taking back and then again

(Refer Slide Time: 43:30)



mixing here. Originally I have this R into F A naught also moving, please remember. R into F A naught also moving. Otherwise I cannot operate recycle, recycle 3, 4, 5 whatever.

So now this entire thing, which was inside and then recycling that also will get converted, right Ok and before, Ok, before that reacting conditions what will be the input here? Total input

(Professor – student conversation starts)

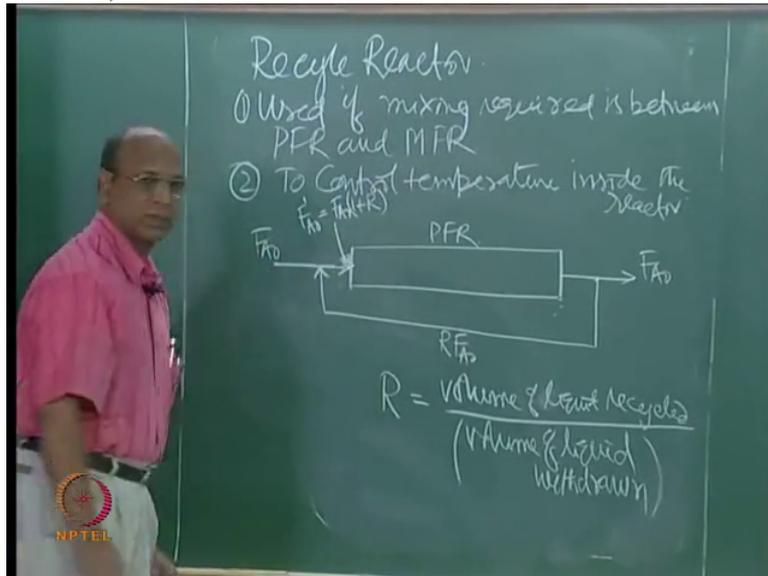
Student: F A naught...

Professor: This is F A naught plus...

Student: 0:44:04.0

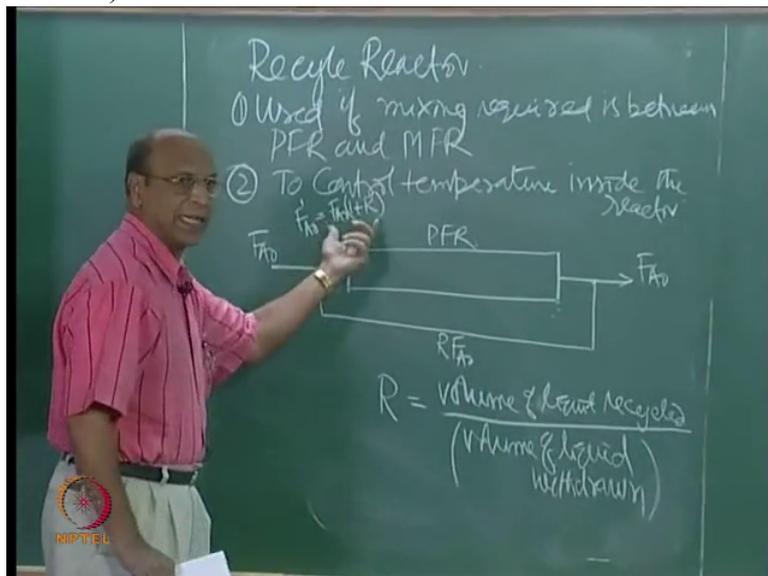
Professor: Yeah so that we call it as F A naught dash as F A naught into 1 plus R,

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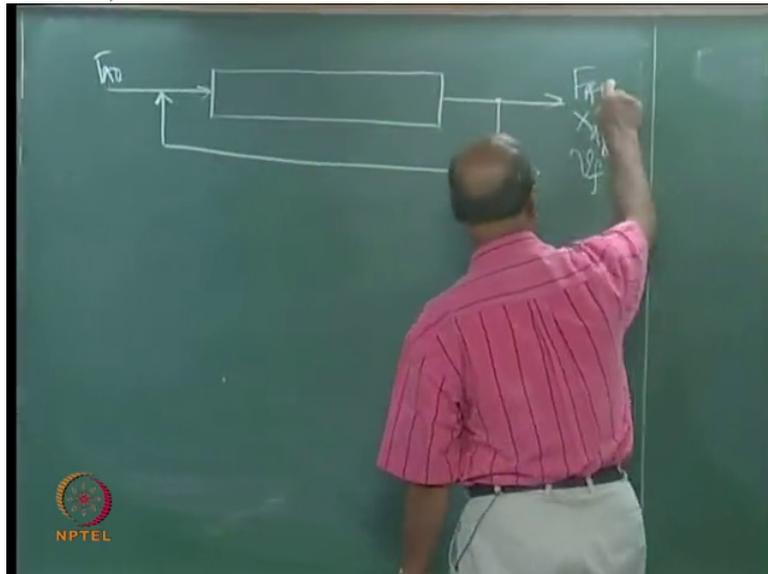
1 plus R or R plus 1, Ok good. So that is the one which is there. That is what is actually entering

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there. That is what is being converted inside and because you are taking out under steady state conditions, it will be $F A f$,

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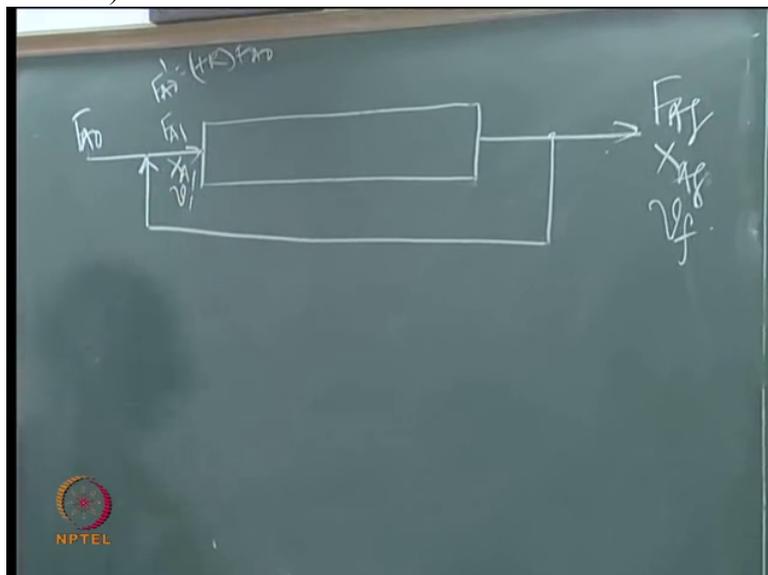


$X A f, V f$ and here now the conditions will change.

(Professor – student conversation ends)

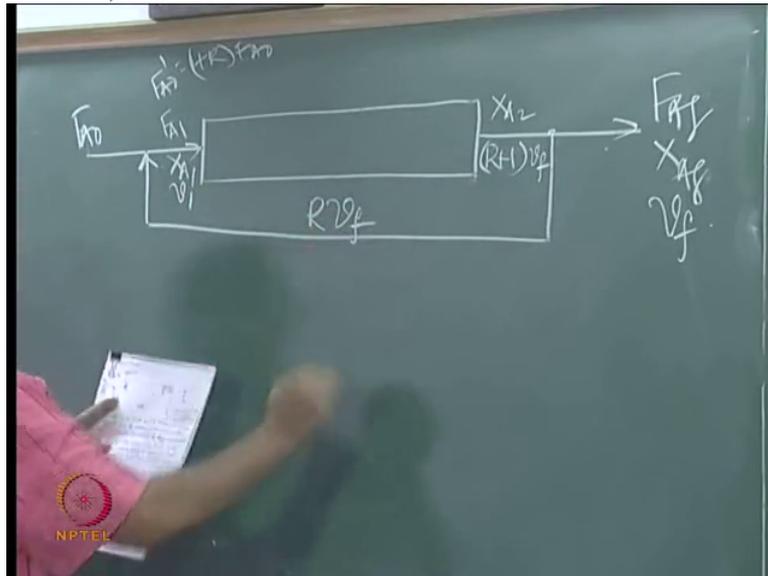
That condition is yeah, $F A$ naught is, originally was there. That I will write, $F A$ naught dashed equal to $1 + R F A$ naught, then I will also have $F A 1$, here. $F A 1$, here also $X A 1$ and also of course

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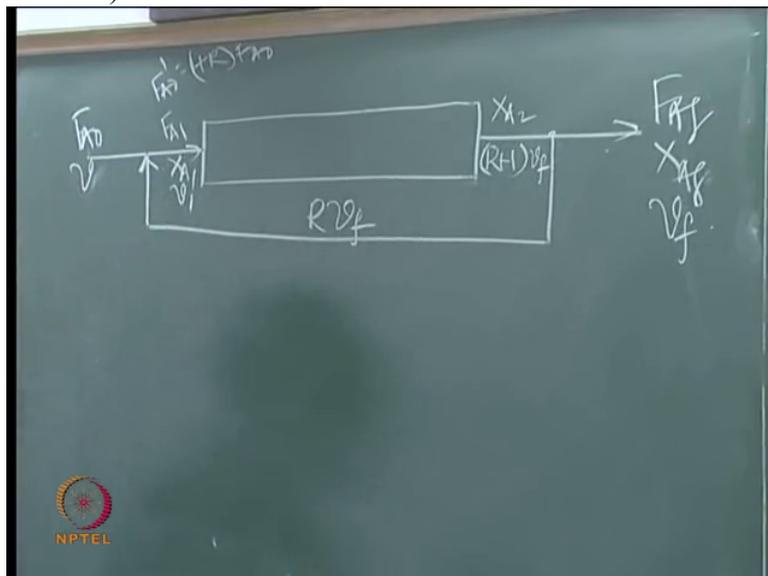
$v 1$ all that, and at this point I call it as $X A 2$ and R plus 1 , $v f$ of I write in terms of f also, this is, now $v 1$ only. This is $v 1$ and at this point I have

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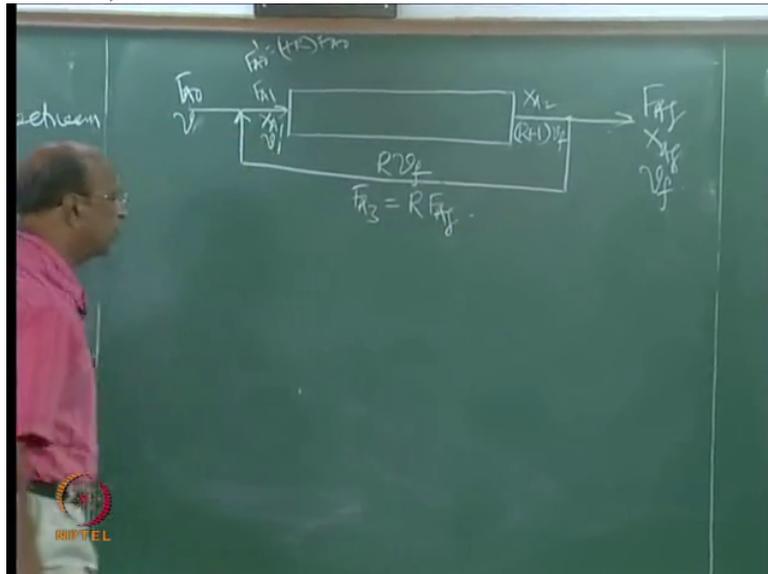
R into v f. v f is coming here, sorry, v is coming here. v also is entering there,

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right. So this is R into v f. And we also call this one as F A 3 which is R into F A f.

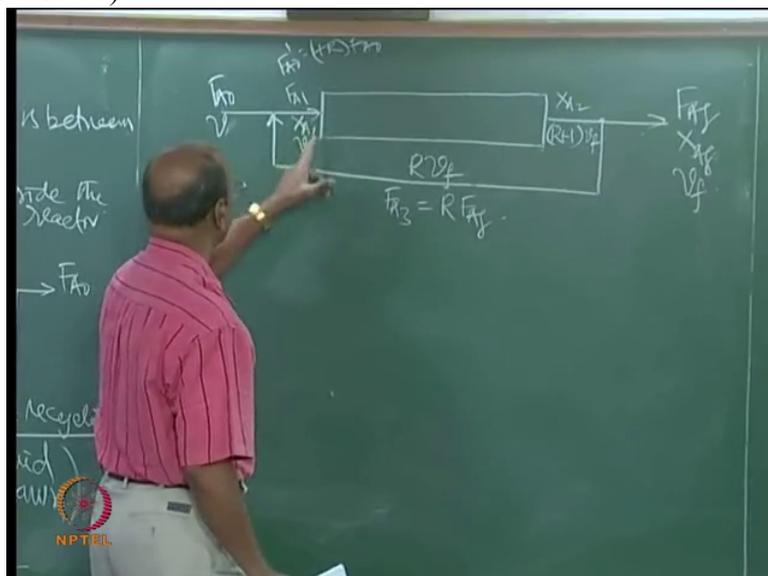
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Either in terms of moles or volumetric flow rate, Ok. I think now, yeah, all these things are Ok.

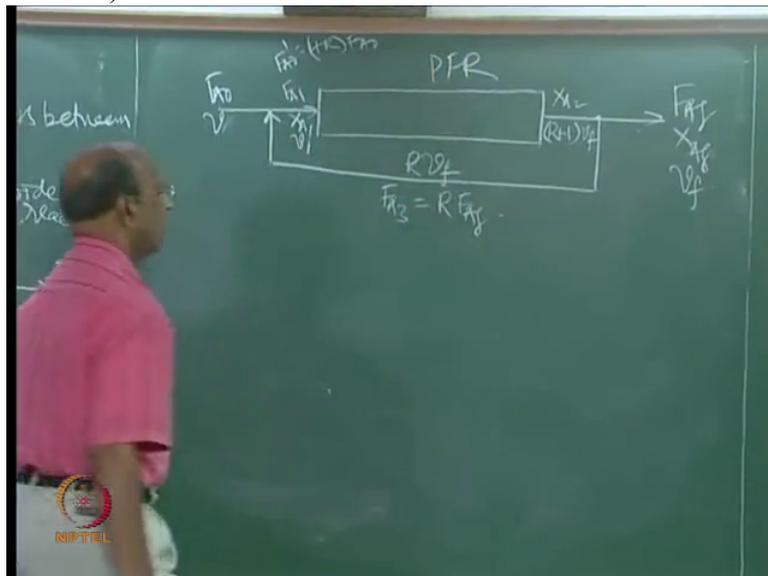
So what we have to do is if you want to develop an equation, I have to develop only in terms of this and then this, because inside I do not know what is happening, right? But that automatically will include this $X A 1$

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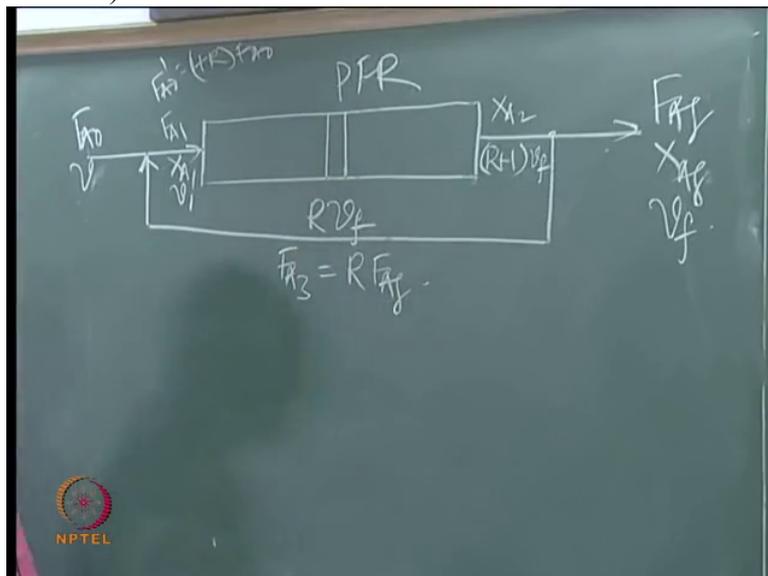
because actual reaction is taking place from here only, right from here only. And this is again P F R, yeah.

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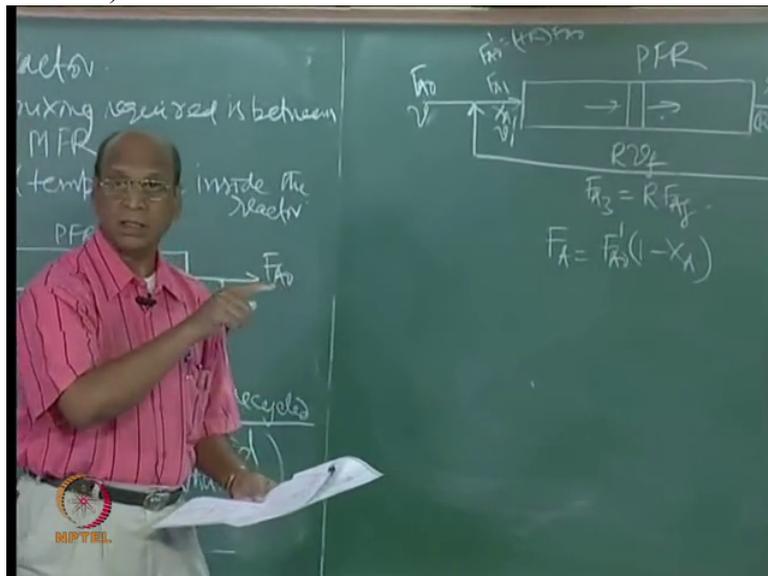
So because it is a P F R, I will take a small volume, and then write the

(Refer Slide Time: 46:16)



material balance entering, leaving all that in that. Ok. Yeah, so now I have to also define my rate, I mean the conversion here, the conversion is defined as $F_{A0} - F_A$ equal $F_{A0} X_A$, please remember, $F_{A0} - F_A$ into $1 - X_A$. $F_{A0} X_A$, what is dash?

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(Professor – student conversation starts)

Student: Original 0:46:46.1

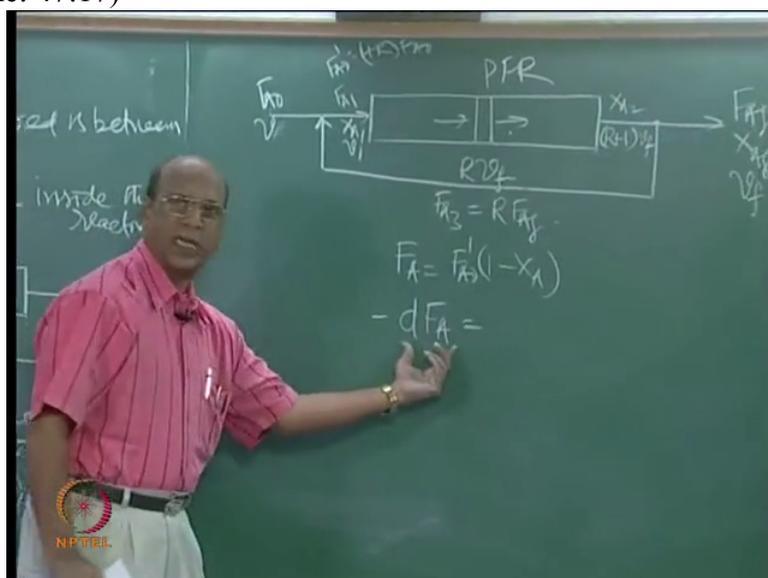
Professor: Originally yeah, it is 1 plus R. So that is what is entering originally all the time, Ok, yeah, because you are recycling that. You are recycling here so this is the one and now this equation, you have this equation as, Ok minus d F A equal to

Student: F A naught dash G X A

Student: Minus d X A

Professor: F A naught dashed will come from this here.

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Other one, minus d F A equal to

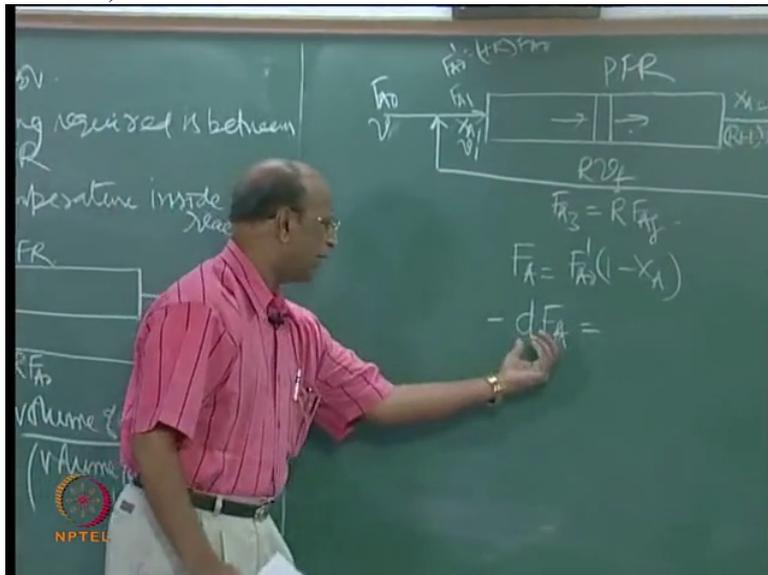
Student: A naught minus d X A.

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Professor: I am talking about balance, material balance here. You are only

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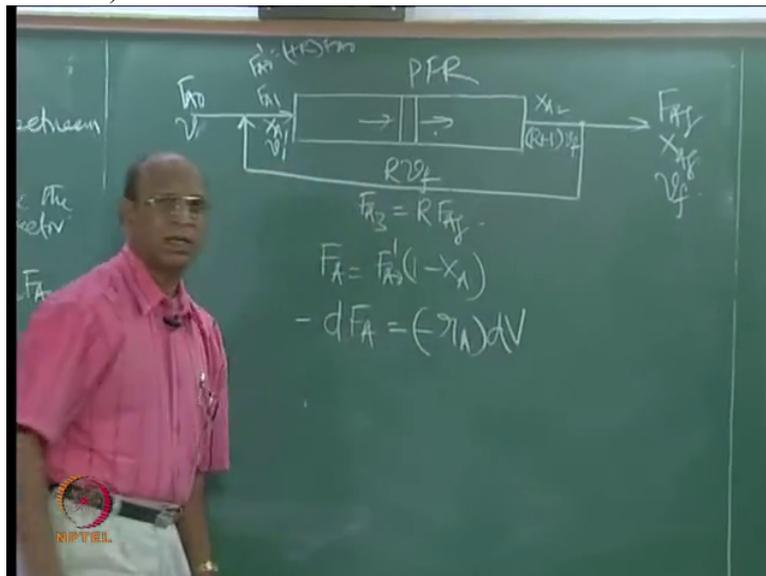


trying to tell what is the meaning of F A. But this is equivalent to what in that volume?
Reaction, Ok, what is that?

Student: Minus r A into d V

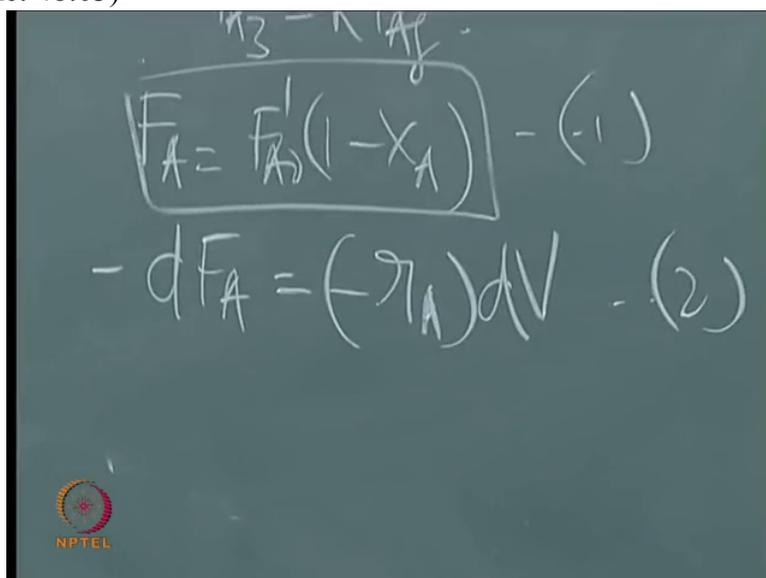
Professor: Exactly. minus r A into d V that you cannot forget, I say,

(Refer Slide Time: 47:49)



should not forget. Ok so now dF_A we can calculate from this. This is equation 1, let me say. This is equation 2. Now substitute that dF_A here and then tell me what is equation?

(Refer Slide Time: 48:03)



Because this I have to simply differentiate, right?

Student: That dX_A equal to minus $r_A dV$

Professor: Yeah, $F_{A0} dX_A$, I will write in a different way, so that means minus r_A into dV equal to F_{A0} into

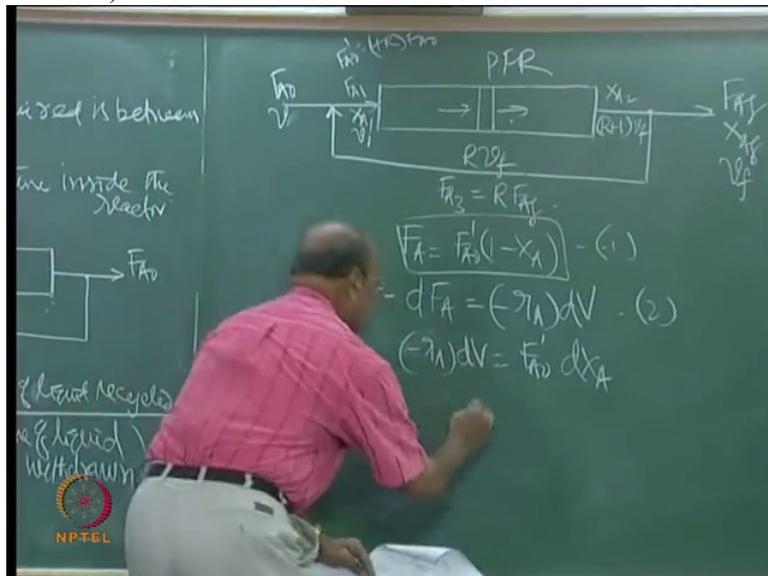
Student: dX_A

Professor: dX_A . So now how do I write this one as an equation in our, because it is a plug flow, V by F_{A0} into.

(Professor – student conversation ends)

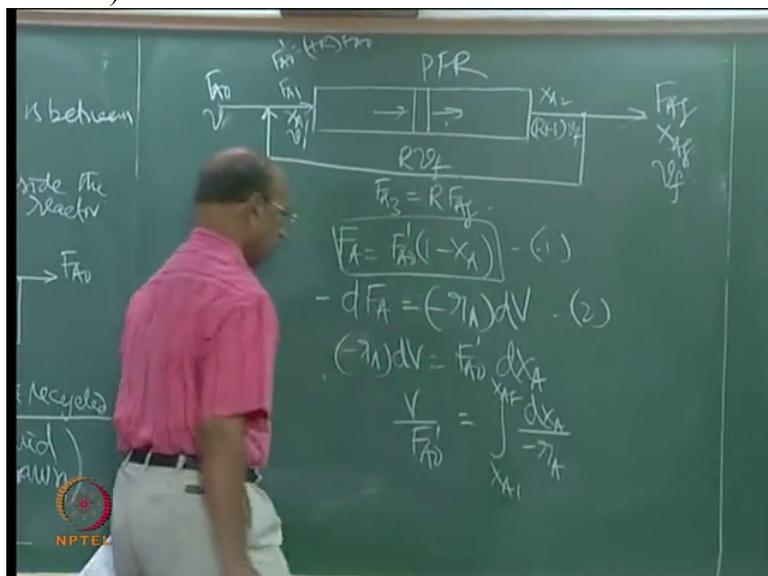
So this is

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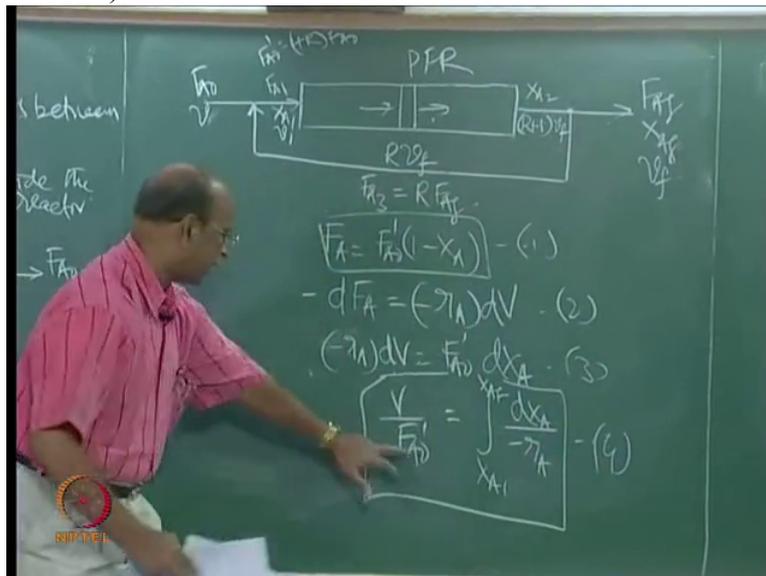
V by F A naught dash equal to integral d X A by minus r A but now what are the boundary conditions, yeah it is X A 1 here to X A f.

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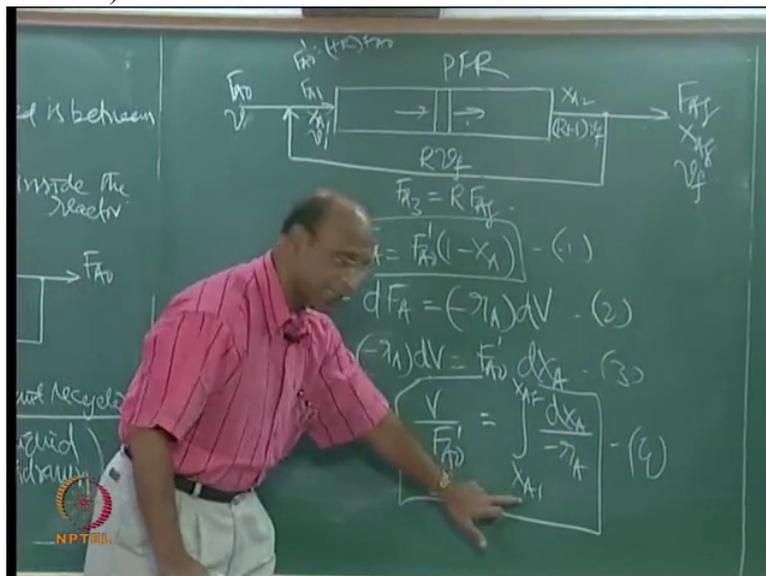
So this is what is the, the design expression for recycle but still it is not completed in the sense that 3, 4 because I do not know what is

(Refer Slide Time: 49:20)



F A naught dash but anyway I know here, F A naught dash and also I do not know what is

(Refer Slide Time: 49:24)



X A 1.

(Refer Slide Time: 49:27)

$$-dF_A = (-r_A)dV \quad (2)$$
$$(-r_A)dV = F_{A0} dx_A \quad (3)$$
$$\frac{V}{F_{A0}} = \int_{x_{A1}}^{x_{A2}} \frac{dx_A}{-r_A} \quad (4)$$

How do you find out X_{A1} ? F_{A0} is easy, that I think you understood. But can I define X_{A1} in terms of, how do I define for continuous systems, you know for flow systems, conversion? I am asking again stupid question. You should quickly react.

(Professor – student conversation starts)

Student: Initial minus final

Professor: What? Initial minuses, donkeys or horses or what?

Student: Molar flow rate

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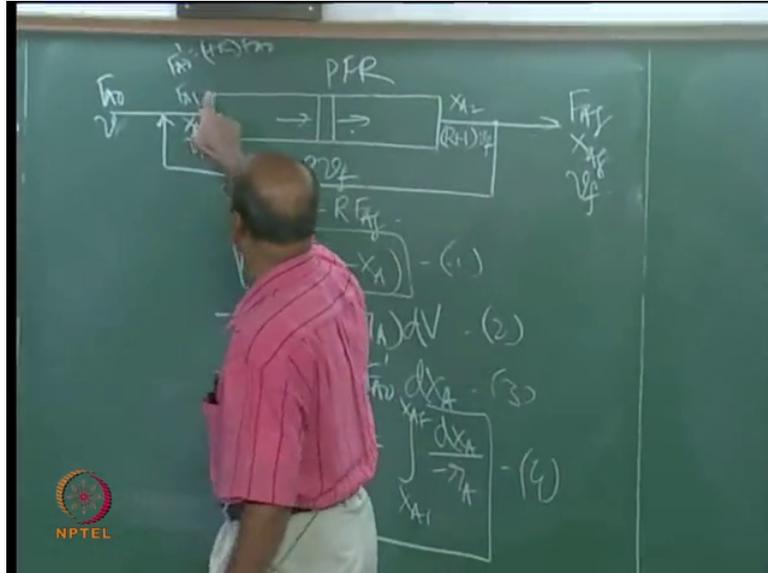
Student: Initial flow rate minus

Professor: Which flow rate?

Student: Molar flow rate

Professor: Yes, that is what. Initial molar flow rate that is F_{A0} , here it is F_{A0} dash, Ok and minus F_{A1} , that is here,

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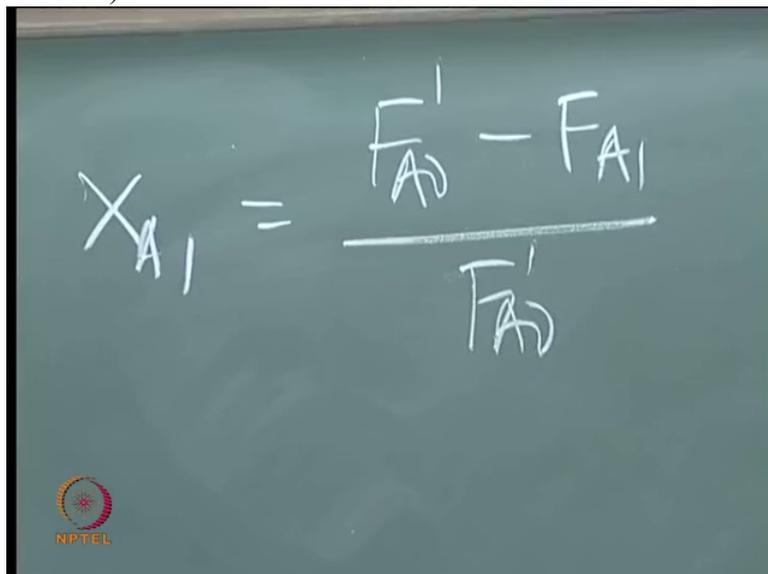


Ok if you are defining X_{A1} , right? So that is what what we do now.

(Professor – student conversation ends)

X_{A1} equal to F_{A0} dashed minus F_{A1} divided by F_{A0} dashed, good? Ok,

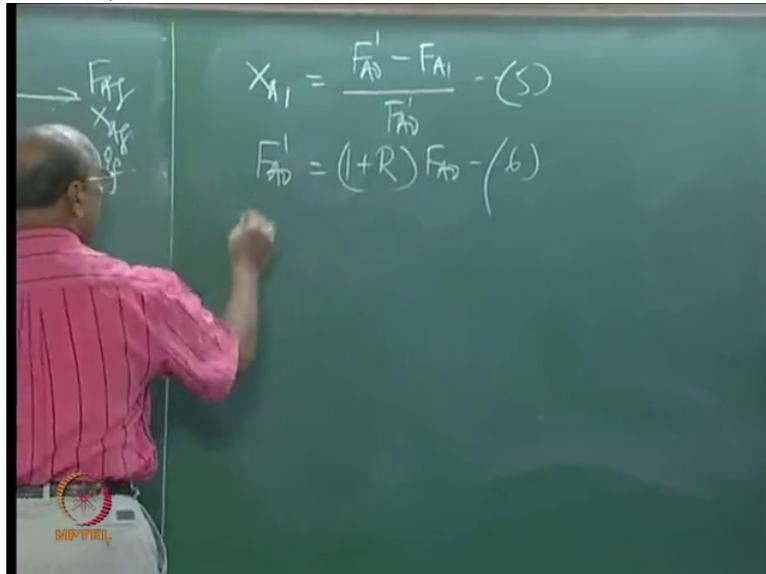
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good. So now we have to find out, to find out X_{A1} , what is F_{A1} and F_{A0} dashed. F_{A0} dashed I know. This is equation number 5.

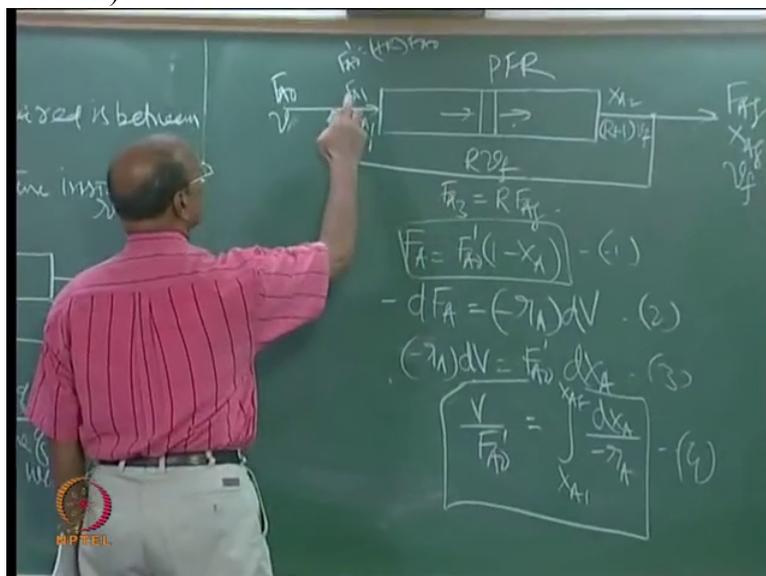
What is F_{A1} dashed? Yeah 1 plus or Ok, 1 plus R into F_{A0} , that is no problem, this is 5 equation given, number? Ok, 6 and we have, yeah so

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F_{A1} I have to calculate now. What is F_{A1} ? F_{A1} is you see the material balance here.

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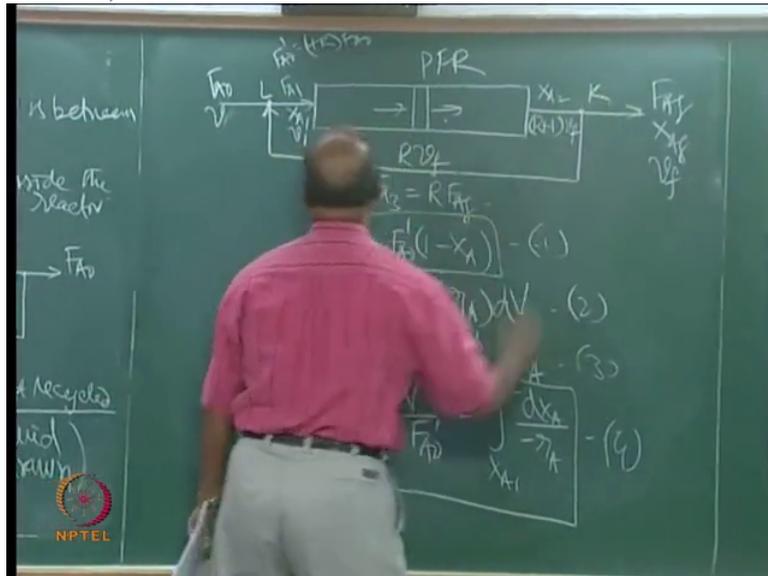
This is F_{A1} .

(Professor – student conversation starts)

Student: F_{A1} is F_{A0} plus...

Professor: Yeah, this is L, this is K. So...

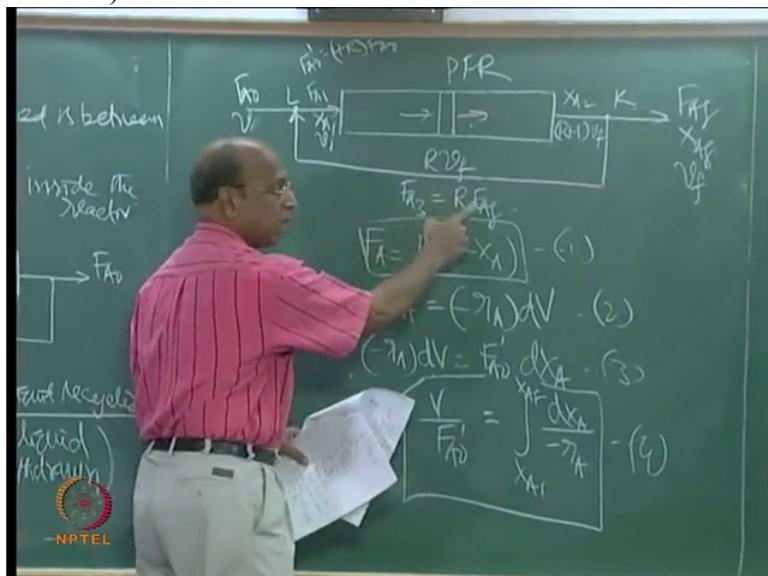
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Student: R F A

Professor: Yeah, I think very good. What you understood, that is fantastic, very good. So this one is, because all of you, I think you know, Gopi, able to follow no? At this junction this is coming and also this is coming. This is coming F A naught, this is coming F A 3.

(Refer Slide Time: 51:29)



F A 3 is nothing but again R into F A 1, so that is why it is F A naught plus F A 3 equal to F A naught plus R into F A f, Ok that is F A 1.

(Refer Slide Time: 51:45)

$$X_{A1} = \frac{F_{A0}' - F_{A1}}{F_{A0}'} \quad \text{--- (5)}$$
$$F_{A0}' = (1+R)F_{A0} \quad \text{--- (6)}$$
$$F_{A1} = F_{A0} + F_{A3} = F_{A0} + R F_{A0}$$


Now substitute this equation 7 and 6 in 5 and tell me what is X_{A1} ?

Student: Sir X_A

Professor: 1 equal to

Student: R_A by

Professor: R_A by

Student: R_A into $X_A f$

Professor: $X_A f$, very good.

Student: $X_A f$ yes, $X_A f$

Professor: Very good, yeah. X_{A1} equal to R by R plus 1, yeah, R by R plus 1 into $X_A f$. That is all, the derivation. So now the equation for you is that V by F_{A0} equal to R plus 1 integral X_{A1} equal to R by R plus 1 $X_A f$ to $X_A f$ d X_A by minus r_A . So this is the design expression for, not dash.

Student: (laugh)

(Refer Slide Time: 52:50)

$$F_{A1} = F_{A0} + F_{A3} = F_{A0} + R F_{A0} \quad (7)$$

$$X_{A1} = \left(\frac{R}{R+1}\right) X_{A2} \quad (8)$$

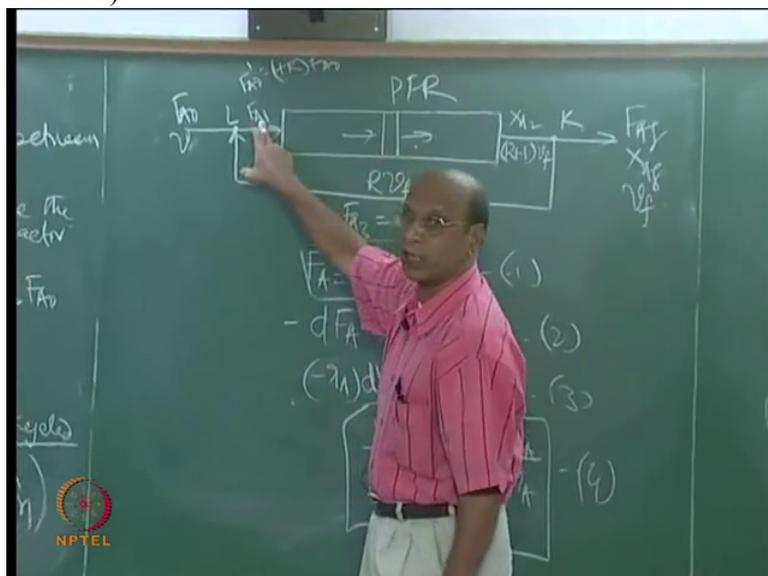
$$\frac{V}{F_{A0}} = (R+1) \int_0^{X_{A1}} \frac{dX_A}{-r_A}$$

Professor: Because dashed is inside. I do not want to go to the dashed. Ok, yeah. So finally I told you no, we have to express only in terms of what is this point and what is this point. So all the things are the things I know. V by F_{A0} which I am continuously putting, and not that F_{A0} comes before starting the reaction, where you have recycle coming and you have so much volume which has to be recycled.

(Professor – student conversation ends)

And that effect of all that is only this, F_{A1} , what is entering, because of some extra F_{A0} was there, that R into F_{A0} , all that together getting reacting and then giving me F_{A0} , F_{A1}

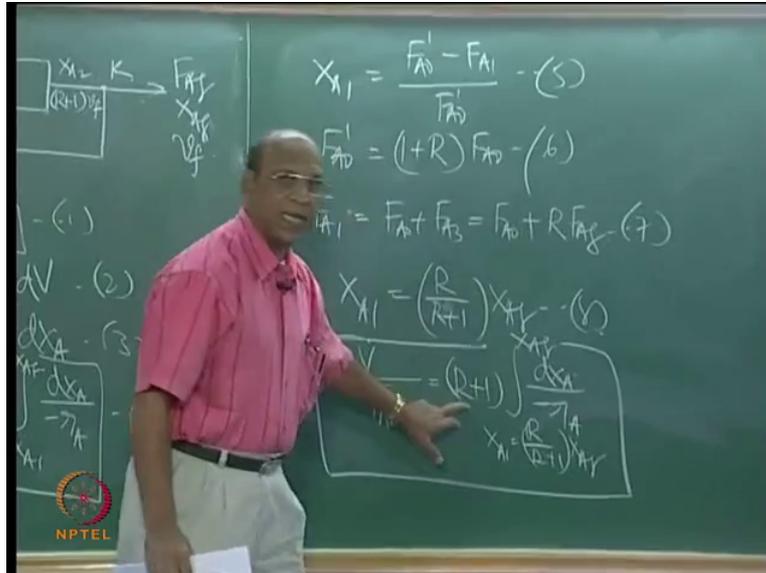
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inside the, at the start of the plug flow element, good? So this is the one.

And yeah, so initially

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most of the time you have to take some recycle ratio. You have to say Ok, my recycle ratio equal to 1. Ok so and conversion is 90 percent. Then you can calculate volume, not volumetric flow rate, volume. Or otherwise if I know volume, you can calculate $X A f$. But again R should be known in the beginning to you. Ok. Yeah, in the beginning you have to choose the R , right? But mathematically, how?

(Professor – student conversation starts)

Student: How do we choose it?

Professor: Ok, how do you choose, Ok, good. How do you choose? So what will happen when R equal to infinity to this equation?

Student: We have mixed flow.

Professor: R equal to zero

Student: Plug flow

Professor: Then why did you say mixed flow?

Student: Sir, R equal to infinity you told.

Professor: I said

(Refer Slide Time: 54:27)

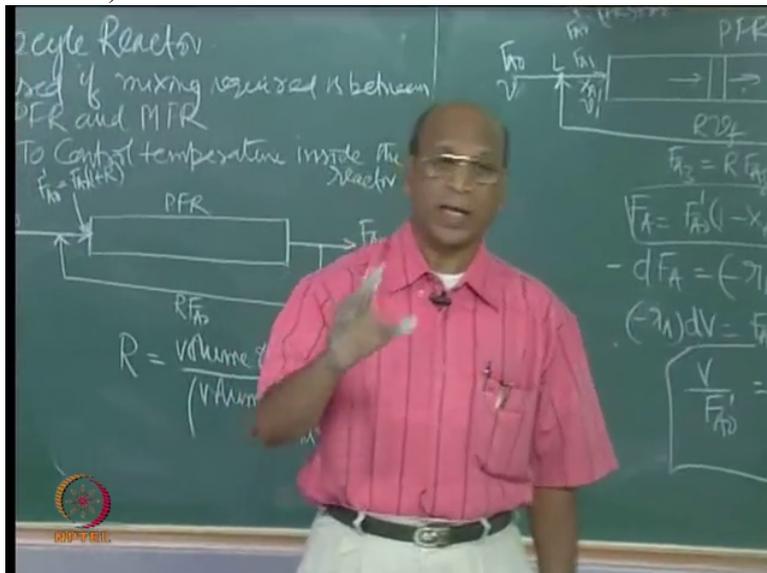


infinity?

Student: Yes Sir

Professor: Oh sorry. Ok, R equal to infinity, mixed flow, right. I am sorry, yeah. So

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R equal to zero is

Student: Plug flow.

Professor: Plug flow now how do I choose?

Student: Between zero and

Professor: Between zero, I think one life; one life is enough to choose, or not enough to choose.

(Professor – student conversation ends)

Because you have to now decide whether you want mixing very close to P F R or mixing close to M F R, right? So when we have close mixing to M F R, then do not go to infinity. Even 500 is too long, too big. 20, 30, 15, 16 is also very high. Ok.

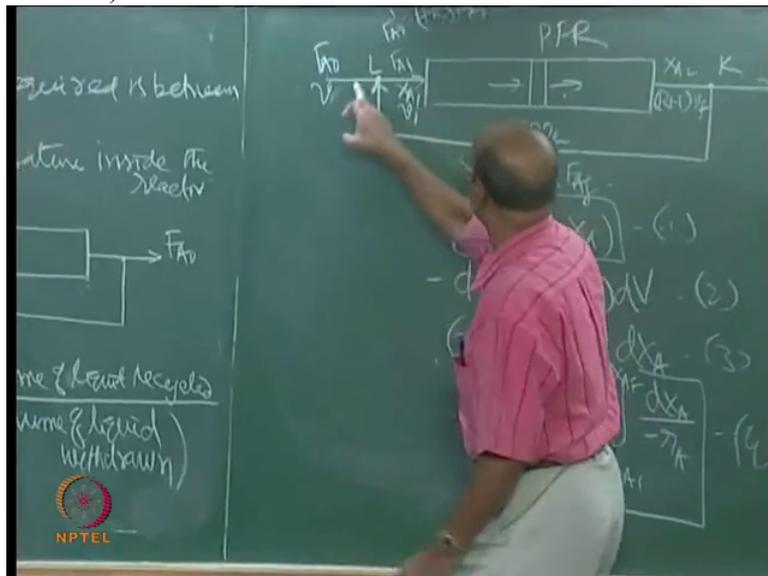
Like exactly, you know you do not have to infinite number of tanks to get plug flow, right? So you have seen no, 6 reactors, after 6 reactors, 6 to infinity number of reactors when you use, then only you will get that small change. I think that is 3 point 3, yeah 3 1 and may be 3 point 5 or something. To compensate only point 5, you will go to 6 to infinity, number of tanks.

So here also, recycle ratio also are same. Ok, beyond 20, 25 you almost reach, 20, 25 also large value I am telling, you can calculate that actually, right? So you will almost get mixed flow. So that is why what you have to choose is Ok, I am very; I want to be very close to plug flow. Then R can be point 1, point 5, 1, 1 also is large when you want to be very close to P F R.

And that comes when you have the sufficient experience, Ok what kind of mixing may be required for me to control my temperature, right and to get some yield? What kind of mixing we need? So that is why we have computers, we have brains. So you have to simulate and then try to find out what is the best recycle ratio.

And there is another way of finding also, optimal recycle ratio and all that, that also I will tell you, Ok. That is all. But only thing is P F R is not receiving

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fresh reactant but it is mixed with product so that means some mixing is happening.

What is happening in mixed flow? You are putting fresh reactant. But it is now perfectly mixed with the products, old ones. Ok. There it is perfect mixing, I think between products and fresh liquid. That is why you have the minimum dilution, not minimum,

(Professor – student conversation starts)

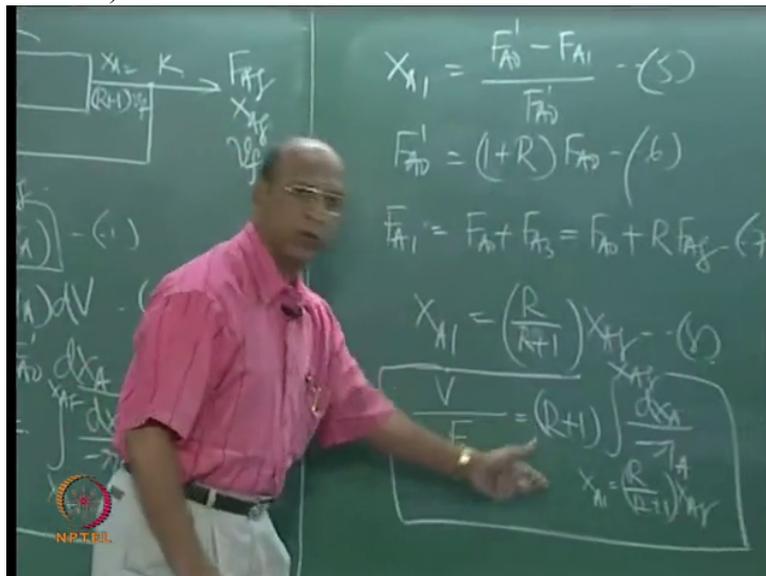
Student: Max

Professor: maximum dilution possible. But here we can control. If I send only very, very small quantity, then I am operating almost P F. If I send very large quantities, this will behave as mixed flow.

(Professor – student conversation ends)

That is I think another my favorite question, this equation can be beautifully

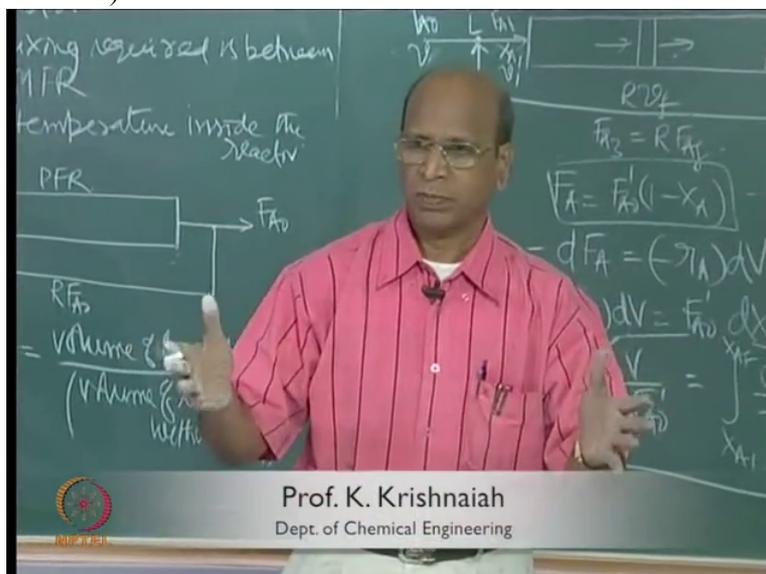
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simplified when R equal to zero, R equal to infinity. Two extremes you can beautifully simplify, that equation, that also please check that. Ok so the next thing will be how do we plot this?

Plotting this is really big headache, because I like graphs.

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Right. So that is why how do I put this information on graphs? That means again I have to plot $1 - X_A$ versus

(Professor – student conversation starts)

Student: X_A

Professor: $X A$, so what is the volume equivalent to area?

(Professor – student conversation ends)

See, like you are, if it is ideal single plug flow you draw like this if it is monotonously increasing, take area under the curve, this area under the curve equivalent to some volume, right? So similarly here also, what areas I have to take and how do you calculate what is the volume from the graph? That we will discuss in the next class.