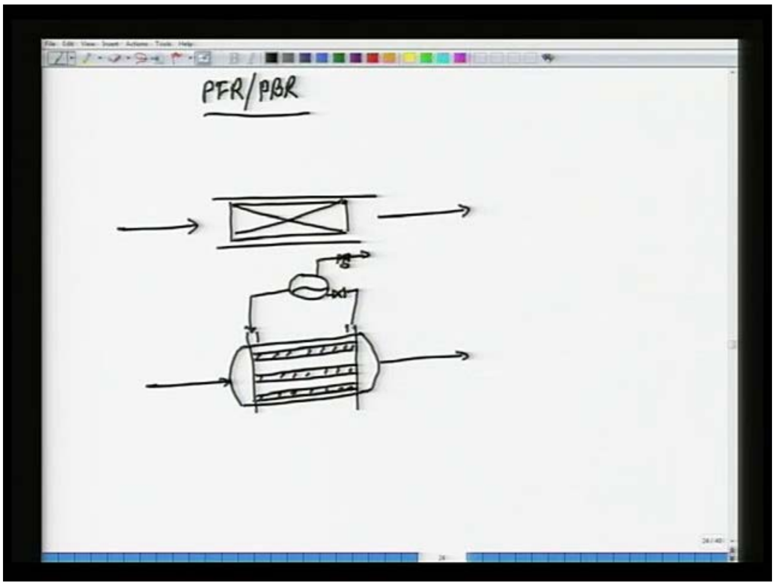
Plantwide Control of Chemical Processes

Prof. Nitin Kaistha
Department of Civil Engineering
Indian Institute of Technology, Kanpur

Lecture - 20
PFR controls (continued) and CSTRs

So, good morning everybody. Welcome once again to this next lecture.

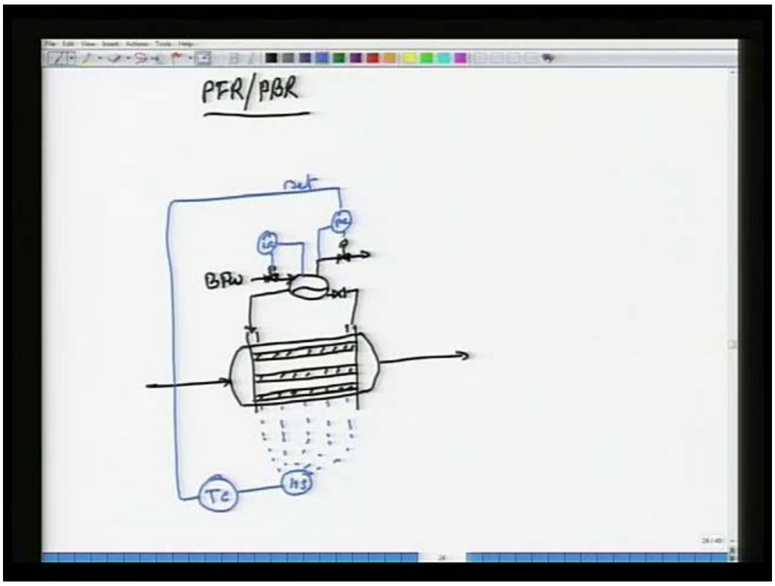
(Refer Slide Time: 00:27)



We have been looking at plug flow reactors or packed bed reactors and what we saw last time was adiabatic operation. So, here is a catalyst loaded tube, heated feed comes in, heated feed goes out, reaction occurs in this bed, then we also saw that adiabatic operation especially for highly exothermic reactions will cause the temperature to rise too much and that would not be good for the health of the catalyst. Therefore, one of the most common configurations is a shell in tube heat exchanger.

So, these are the tubes and let us just say the tubes are loaded with catalyst and what we have is material coming in, reactants coming in and the reaction occurs inside the reactor and what you have on the shell on the shell side is you have pressurized water that is circulating around on the shell side, then you take out the pressure and this hot water goes back into the drum. Because the water has gathered heat from the hot tubes of the reactor, it flashes and as it flashes you get steam out, and what we saw last time was, this is not a control valve it is just a, this is a, this is not a valve that you move. Therefore, I am not showing the the handle on that.

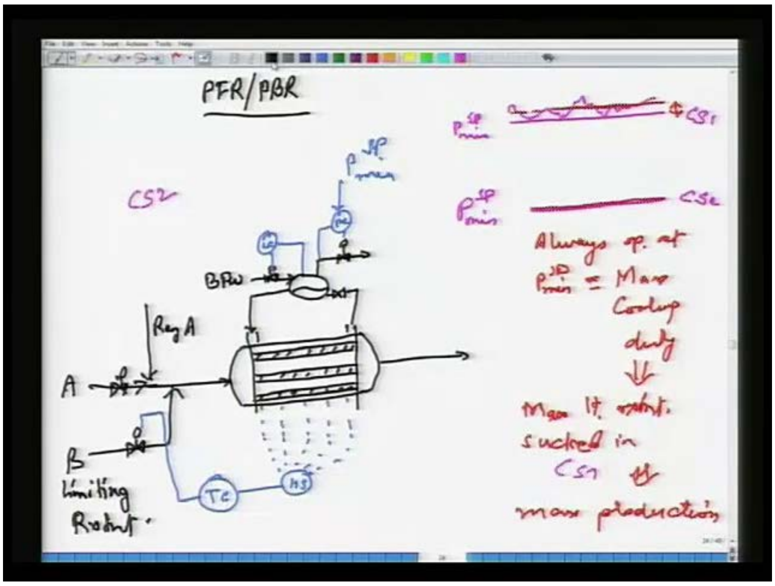
(Refer Slide Time: 02:40)



And what we saw was you have an array of sensors, let us erase this guy, you have an array of sensors, this, these readings are sent to a a high select, the high select selects the highest of all the temperatures, that is the hot hottest spot in the temperature in the reactor is sent to a temperature controller. The temperature controller of course, you have got some boiler feed water coming in, reactor pressure is or the drum pressure in the in the boiler is controlled, the drum pressure in the boiler is controlled using the steam exit rate because water is getting lost as steam, you have make up water coming under level control, temperature controller adjusts this set point and if the pressure set point is reduced the pressure goes down, the temperature of the boiling liquid goes down. Therefore, the water is at a lower pressure. Therefore, it is colder since the water is colder more heat gets transferred across the tubes and therefore, a temperature that is rising will come back to set point and so on so forth.

We also saw some other schemes where that were that were designed to maximize the throughput that means you are trying to maximize maximize the amount of feed that can be put in in light of the fact that heat transfer is your bottle neck constraint is what is what constraints how much you can put in. You are constrained by your ability to remove heat in the reactor that is what constrains how much feed can be pushed through the through the system.

(Refer Slide Time: 04:43)



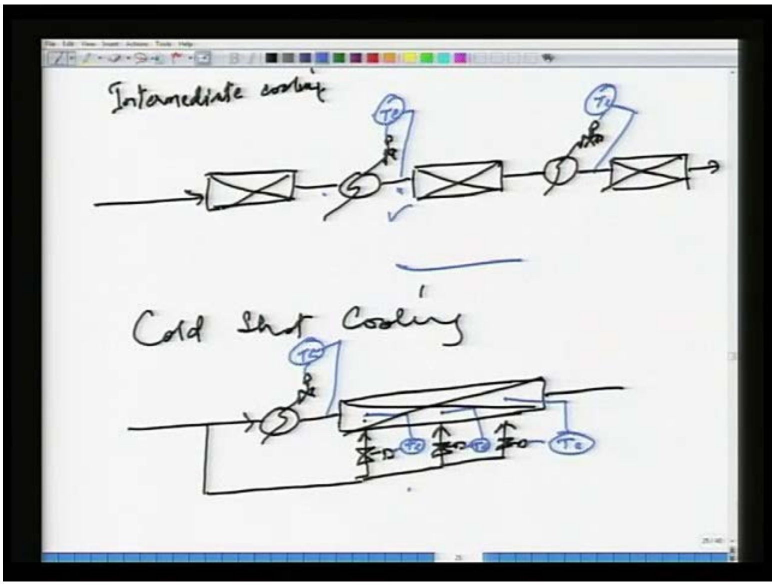
So, for that what we said was instead of doing it this way and let us say you have got you know A plus B and B is the limiting reactant. So, let us say A, B, this is recycle A and what we were saying there was that if you want to maximize you know run the reactor always at maximum heat removal, in that case what you do is, keep this set point at minimum possible that means the coolant is as cold as possible, the water is as cold as possible and therefore, since the water is as cold as possible your are removing as much as much heat as can be removed from the reactor and then what you do is essentially put in as much B as is required to control the hot spot temperature.

So, if the hot spot temperature is increasing you put less fuel to burn less of the limiting reactant. So, B is the limiting reactant here, that is also something, limiting reactant. So, B is the limiting reactant and what we said here was that in this case if I looked at, this is my minimum possible pressure. In the previous case let me call that this is control structure 2, let the previous one that I drew be control structure 1 where I was adjusting the pressure set point.

In the previous case in control structure 1 what I have is this is this is P min set point because pressure set point is being adjusted to control the hot spot temperature. The pressure set point will not be constant it will show some fluctuation because there are always disturbances that are present. And therefore, on average in this case you are operating let us say this is your mean operation. So, this mean operation implies that on average your average pressure is greater than P min that means your average cooling removal is, your average heat removal is less than the maximum maximum possible heat removal. On the other hand in CS 2 what I have is this is P min, then my set point is P min and therefore, in this case there is no back off and therefore, you are always operating at P min set point which is the same as always operating at maximum cooling duty.

Which implies maximum limiting reactant is being put in, limiting reactant is being sucked in which implies maximum production. So, if heat removal is what limits production, here is a very simple way of addressing that. Now, you have, we have adiabatic reactors, we have cool reactors, sometimes what happens is you know a cooled reactor has got a lot of paraphernalia with it. So, it is it is actually easier to have an adiabatic bed.

(Refer Slide Time: 08:37)



So, here is an adiabatic bed. You are, you putting in reactor feed because the reaction is exothermic, but not highly highly exothermic. Therefore, temperature rises, you cool it off, send it again, temperature rises, cool it off again, send it to the next packed bed. Sometimes, this cooling is also necessary to see in equilibrium reactions if you cool the lower the temperature the more the equilibrium conversion, for exothermic equilibrium reactions the lower the temperature the more the equilibrium conversion.

So, you reduce the temperature and then send it again to a reactor in order to drive the equilibrium conversion up. So, this is sometimes also done in equilibrium reactors and what do we have here, what we have here is temperature is controlled, I mean it is very straight forward. So, this is called intermediate cooling, intermediate cooling. So, you have got a bunch of adiabatic beds and in the middle of two beds, in between two beds you have got a cooler, the heating duty or the cooing duty of that that cooler is adjusted to keep the temperature of the feed into the next bed constant. Please, note just I mean, I think it is obvious, but sometime it is good to draw attention. Please note that this will not work, you see when I change the cooling duty it is this temperature that is affected. This is not affected, so, if you draw it like this that is wrong. There is no, got a bad cold so please bear with me, so, there no cause and effect relationship here. You see when you adjust the cooling duty it is this temperature that is affected not this.

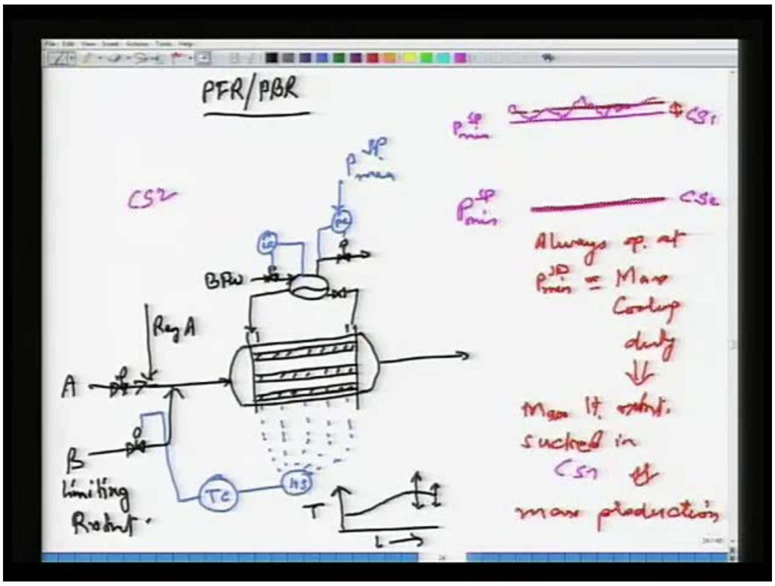
Therefore, it should be drawn this way. So, one has to be cautious what is controlled what is manipulated. Then there is another scheme that is called cold short cooling. Cold short cooling and what you have in cold short cooling is well your your feed is cold or maybe what you have is you take the cold feed, part of it is heated up and then sent to a, to the reactor. This is my reactor and the other part, see these are this is cold feed. So, the temperature as you go from here to here rises because reaction is generating heat to bring that to to keep that temperature down, you put in a shot of cold feed, what that does is brings the temperature down, then again temperature rises, again you put a shot of cold feed, the, it also helps in the sense that you see if all of the fuel is put since you are distributing the reactant across the pack bed reactor, what happens is the concentration of the reactant at the inlet is not as high.

Because all of the reactant is not being put at the at the inlet. So, since that is distributed that also helps, helps to distribute the amount of heat that is released particularly in the initial part of the reactor. So, what do we do here? Well, what we do here is, well what do we do here, well. So, if I increase the flow of this guy what will happen is the temperature here will go down. If I increase the flow of this guy the temperature here will go down, if increase the flow of this guy the temperature here will go down. So, what we essentially have then is temperature control and of course, this heater is for temperature control as before. Notice, in this case that you can hold three temperatures inside your packed bed reactor the way it is drawn, you are actually controlling three temperatures depending on the number of splits, well that many excluding the inlet, excluding the feed to the inlet one, two, three.

So, three temperatures can be controlled. Well, if you looked at the previous case please notice that only one temperature is being controlled that is because you got only one degree of freedom, cooling duty or temperature of the coolant that circulating around. You can use that to control one temperature. In this case sorry in in in this case you got three control degrees of freedom and therefore, you can hold three temperatures inside your reactor constant and what that gives you is tighter temperature profile control. The profile of the the temperature profile inside the reactor because you are controlling three, you are able to control three temperatures instead of only one, the temperature control is more what should I say, is controlled more tightly, let us just put it that way.

An example of this process you know polymerization reactors, where it is very important in order to hold the molecular weight and the and the variability or the, what it is called the polydispersity index, you know, the variation in the molecular weight, to hold these two things constant you require very tight temperate control inside the reactor and therefore, you have this idea of cold shot cooling, it is used in continuous polymerization reactors. Another thing that I wanted to point out here was, let us see 24, I think I forgot to mention this, see it is not always necessary to have an array of thermocouples, there may be some reactors. When do you need an array of thermocouples and when can you get away away with it? Well that depends on the temperature profile inside the reactor and how far is the exit from the hottest spot inside the reactor or from the hot spot of the reactor.

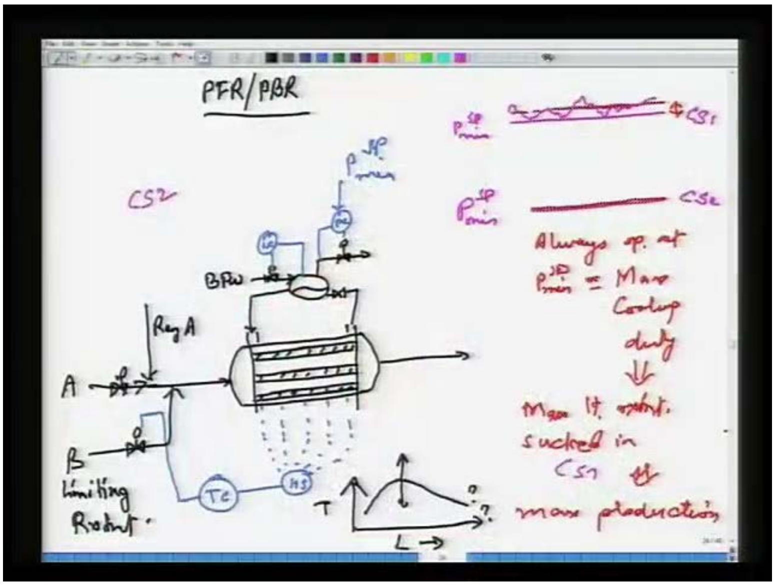
(Refer Slide Time: 16:14)



What I mean is if I look at the length of the reactor let us say this is reactor length and if I plot temperature there may be reactor designs where the temperature rises, hot spot comes and because of various considerations for example, selectivity you know if the reactor is too long the main product actually further reacts to form a side product and since you do not want that to happen you know you essentially have a small length reactor to prevent side product formation because of reason such as these what you will have is that the exit of the reactor is very close to the hottest spot at base case conditions.

What that means is instead of, what that essentially means is if this hot spot temperature is rising most likely this would also be rising, if this temperature is decreasing well this would also be decreasing. So, instead of controlling so, so, the exit temperature an increase or decrease in the exit temperature is a reliable indicator of an increase or decrease in the hot spot temperature. So, in that case you do not need an array of thermocouples inside the reactor, what you can do is just control the exit temperature by adjusting the cooling duty or by adjusting the limiting reactant that you are putting into the reactor CS 1 or CS 2.

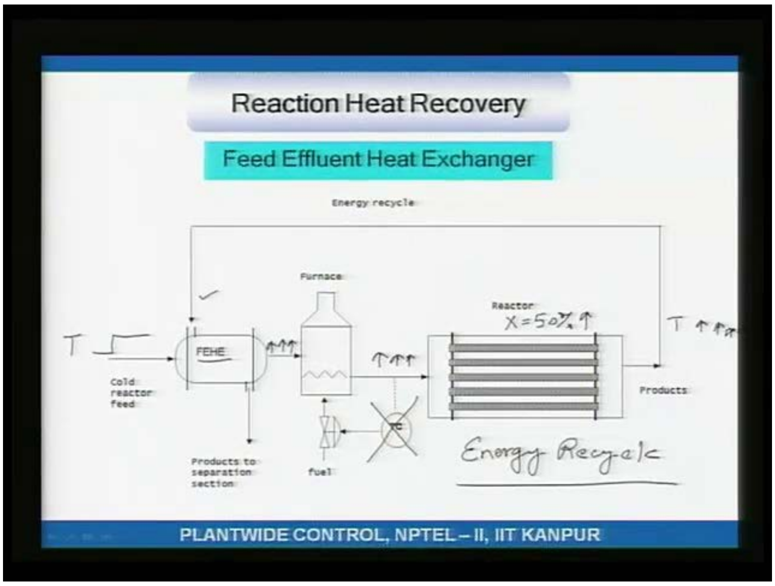
(Refer Slide Time: 17:43)



On the other hand if you got a temperature profile, let us say which looks this is length of the reactor, it is temperature if the hot spot occurs early. In this case if the hot spot temperature is increasing will this temperature increase or decrease? Well, you really cannot say. Even if the hot spot temperature is increasing it may be that the that the exit temperature is decreasing. So, you cannot really say what will happen to the exit temperature.

Similarly, if the hot spot temperature is decreasing you really cannot say what will happen to at the exit of the reactor. So, in this case the exit temperature is not a reliable indicator of whatever is happening to the hot spot temperature and therefore, now since you do not really know where the hot spot is you will have to put an array of thermocouples at least in that portion of the reactor which is closed to the hot spot. So, that you can track you know the hot spot is moving this way or that way. So, there it is necessary to have you know thermocouples inside the reactor that that in itself is a design is not very trivial.

(Refer Slide Time: 19:03)



So, intermediate cooling, cold shot cooling may be this is a goodtime to so that is it, intermediate cooling, cold shot cooling. So, let us say there is an, there is a reactor and let us say it is adiabatic. By the way, the way this this is just an aside thought. The way this reactor is shown there is no cooling circuit that means the reactor is essentially adiabatic, but you got actually a bunch of tubes, why would you do that, why cannot you simply have one big tube with catalyst in it, one large dia tube with catalyst in it instead of n number of tubes of smaller diameter.

It is got to do with dispersion the the thicker, the thicker the diameter the more the radial dispersion that means in the radial direction the thinner the thinner the tube, if the tube is thin aspect ratio is large then radial dispersion at least is negligible and your flow actually gets closer and closer to actually plug flow, but that is just an just an aside, there were a couple of other things that came to my mind, but I seem to forget them. Does not matter let us just let us just stick to stick to whatever is going on here.

You see you got an exothermic reaction that is going on, you first need to preheat the feed and then typically the temperature or the inlet temperature to the reactor is so hot that you cannot by the way, this is something that you know why why a furnace why could not I use a steam generator here for example, why could not I use steam to preheat the feed to the reaction temperature. Now, the answer to that question is very straight forward and its very common (( )), but many of us actually miss it. I do not know what the critical temperature of steam is, but it is I think somewhere in the 300s degrees of Celsius.

So, if your reactor inlet temperature is let us say 350 400 degree Celsius, well phase change in steam cannot happen, you know the the temperature is higher than than the, higher or close to the critical temperature of of water and therefore, phase change is not possible and that precludes the possibility of using steam as a heating fluid. So for example, if the if the if the inlet temperature is 150 200 Celsius steam can be used to heat up, in fact steam will be used up. That is the heating medium of choice, but if the reactor inlet temperature is say 350 degree Celsius, you know 400 degree Celsius steam cannot be used because that temperature is beyond the critical temperature of of of of water.

So, in that case where the temperatures are very high you use a furnace and what is a furnace is essentially a fired up tubes, material is flowing through the tubes because the tubes are extremely hot 800 900 degree Celsius, you get the temperature that you want. So, what we have here is you need to heat up, preheat the cold reactor feed and then you send it to the furnace, the furnace heats it to the desired inlet temperature and let us say the reaction is exothermic. Because it is exothermic therefore, the products or the affluent stream from the reactor is hotter or at least as hot.

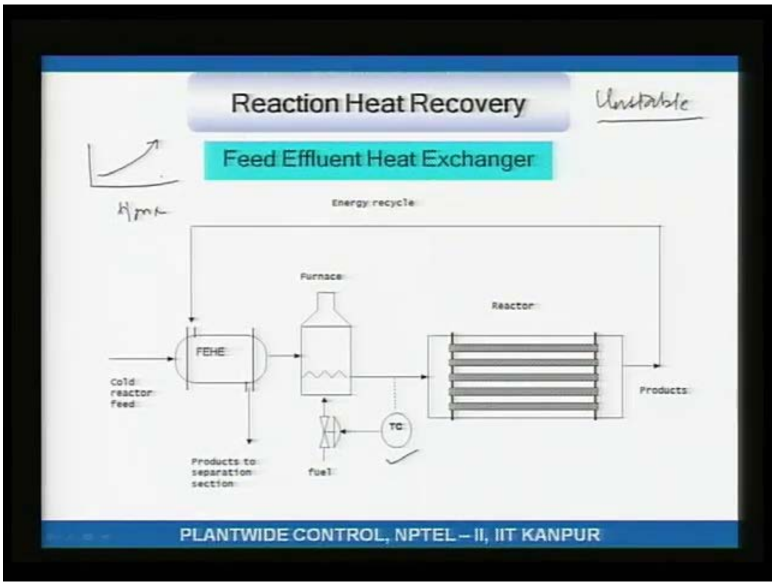
Now, since this is hot and you would like to reduce for example, is you you would like to recover the energy that this hot steam is carrying, what you do is, it is very typical in industry what you have is you preheat the cold feed by making it come into thermal contact with the hot reactor affluent. So, this is called a feed affluent heat exchanger. So, this is a feed affluent heat exchanger.

Why do you want a feed affluent heat exchanger? Well, it eliminates steam consumption, you are recovering heat from the reaction, heat that is generated in the reactor and is being carried with the with the reactor affluent stream, what it also does is the amount of heating load on the furnace actually comes down and and furnace is pretty expensive. I mean for example, you could have had a single furnace here, but that would not be the right way of doing things because furnace with high duties get very expensive, therefore, you would like to make sure that the furnace duty is as low as possible. So, in that sense therefore, you have this feed affluent heat exchanger. What this feed affluent exchanger does feed affluent heat exchanger does is that it introduces energy recycle into the system. Whatever energy is generated by the reactor is being used to heat the feed. So, you can see there is energy being recycled and for the time being let us let us forget this temperature controller. What do I, what are the implications of this energy recycle. Well let us say for what my my process is at at steady state and let us say I took off this temperature controller.

What happen was the reactor you know the feed that was cold actually became hotter. So, temperature of the feed went up because the temperature went up therefore, this temperature went up because this was hotter and now I am putting in as much fuel as I am as before, this temperature goes up. Because this temperature goes up let us say the conversion inside the reactor was I do not know maybe 50 percent. Let us say base case conversion was 50 percent or the, you know when the temperature controller was taken out the conversion was 50 percent. Now, because the temperature is higher more reaction will occur, this conversion will go up because this conversion goes up that means more heat is getting generated because more of the reactants are getting converted to products therefore, this temperature will go up.

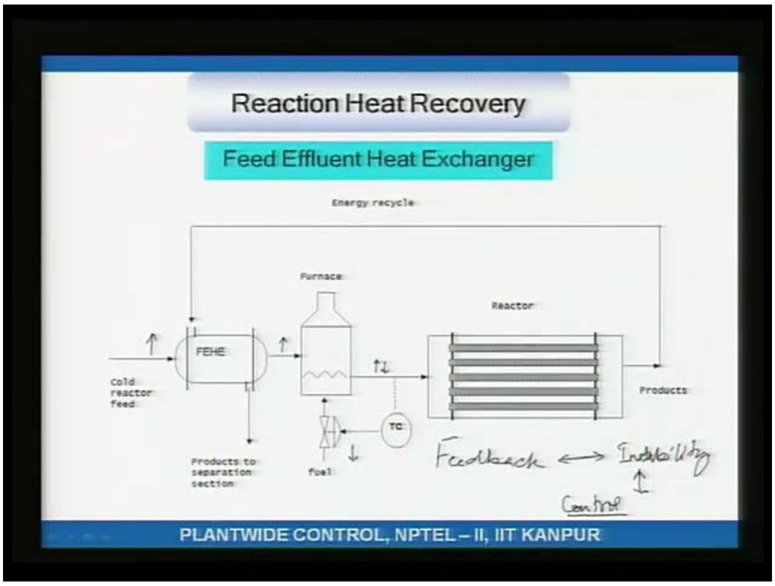
Because this temperature goes up this stream is hotter, because this stream hotter therefore, this temperature goes up, because this temperature goes up this temperature goes up, because this temperature goes up this temperature goes further up and you see you can so what that essentially means is if the reactor feed becomes hotter that temperature of this system will keep on rising that is because the reaction becomes hotter and hotter and hotter. So, this is similar, this is like a reaction run away. How do you take care of that? I have no answers to give. Well, here is here are my answers.

(Refer Slide Time: 26:13)



If you, if you put this temperature controller in then what happens is, so without any temperature controller this system is unstable. What do I mean by unstable, what we mean by unstable is that should the temperature go up so the temperature of the feed which is a disturbance to the process go up, the temperature of inside this reaction loop will actually keep on going up and and what and therefore, the temperature actually if that if that if you look at the temperature across time this actually keeps on going up. So, this is an unstable process, when I put in the temperature controller what happens?

(Refer Slide Time: 27:06)

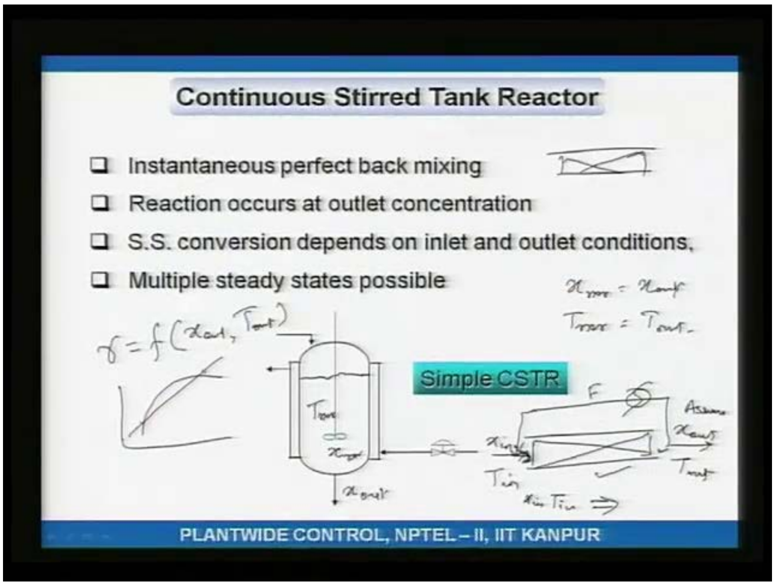


When I put in the temperature controller what happens is if this temperature goes up sure this temperature goes up, but then this temperature goes up therefore, this goes back down and therefore, this temperature goes back to its you see what what that does is the temperature controller essentially stabilizes my system. So, this is an example of a control system stabilizing an open loop unstable system.

So, just to repeat I think my explanation was not that great, if this temperature goes up feed temperature goes up, this temperature goes up, this temperature goes up because this temperature goes up in order to keep it fixed the amount of fuel that is being put in goes down and therefore, this temperature gets back down and that actually breaks the buildup of energy inside this loop, buildup of reaction heat inside the, inside this loop because of energy recycle. So, this is actually an illustration of a very simple thing feedback.

Here I had energy feedback, the energy was being recycled through the feed affluent heat exchanger. Feedback as you would know whether it is positive or negative feedback can create instability and unstable systems can be stabilized by control. This instability can be stabilized using proper control. So, I hope this is reasonably clear to you.

(Refer Slide Time: 28:55)



Now, we get to the other type of idealized reactors that are that are very commonly, that almost all chemical engineer should be familiar with all chemical engineer should be familiar with, it is called the continues stirred tank reactor. Well, I have I have noted a few points here there, there are actually pretty straight forward. This stirrer is essentially saying that everything is well mixed. What does well mixed mean? Well mixed means that whatever is the concentrate that the concentration inside the reactor is uniform. There are no space gradients, derivatives with respect to space variables, radial and whatever as you, whatever that you know the z direction. So, there are no space gradients.

Therefore, temperature inside the reactor at any location is the same, composition inside the reactor at any location is the same and therefore, what we have is this is called prefect mixing, x here and x over x here and x at the exit. So, x inside the reactor and x at the out are equal. x reactor is equal to x out, what you T reactor temperature inside the reactor is equal to T out exit temperature and so on so forth. Now, there is a small point that is written here. Notice, that the reaction rate inside the reactor depends on whatever is being put in plus the reaction rate depends on whatever is the concentration inside the reactor which is the same as the exit concentration.

So, for example, my reaction rate inside the reactor would be a would be a function of x out and T out. So, the steady state conversion depends on both what is coming in, the inlet conditions the temperature and and composition of the feed that is coming in, as well as whatever are the outlet conditions. This is fundamentally different from a packed bed reactor where if I look at a packed bed reactor where the flow is plug flow, if my feed is known and as is showed catalyst bed because most reactors will have a catalyst bed. All I have to do is I know my inlet conditions and I just keep integrating my material and energy balance, energy balance is necessary if it is it is non-isothermal and most reactors are non-isothermal.

So, I have my material and energy balance on the different segments for this reactor and if I just perform my energy balance and material balance and integrate forwards I will know what the outlet condition is. So, if I know x in and T in so here what we have is x in T in implies everything about the reactor is known. The conversation profile, the composition profile, the temperature profile across the reactor all I need to know is what are the inlet conditions and everything about the reactor gets solved once I know the inlet conditions. Suppose, I have something like this which is another way of saying there is some some amount of back mixing, by the way plug flow reactor without this recycle stream if I just, a plug flow reactor like this has has been shown.

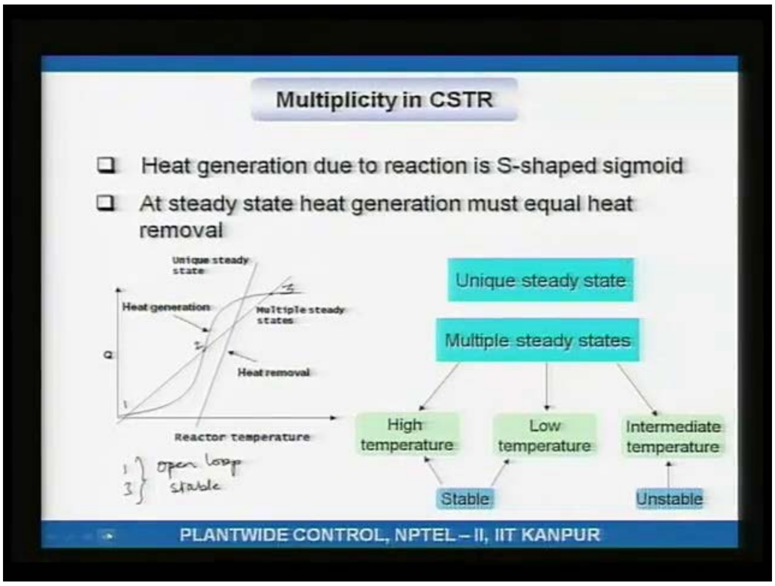
There is no back mixing, a plug just comes in and just keeps flowing ahead that is the ideal flow, idealization of flow, flow condition inside the reactor, the plug just keeps flowing out. No back mixing, on the other hand if I if I for example, take a little bit out and you know maybe cool it a little bit, put it back in. Now, I have introduced back mixing. In this case I cannot solve for the inlet until I know what is the outlet? So, I will have to assume the outlet, solve my material energy balance and then when I get at exit see if whatever is at the exit is the same as the inlet or not as as my assumption or not, if not I will have to iterate until I get convergence. What I am saying is you will have to assume x out T out. So, you assume this, in this case you would assume this, because you have assumed this and let us say the flow rate of this guy is known, that sets how much this is once this guy is set I can integrate forwards then I will know what this is, then I can compare whatever was my calculated x out and T out with my assumed x out and T out and if they do not match, I can keep on adjusting my guess until acceptable match occurs.

So, in this case the conversion or the solution or the reactor profile temperature composition, profile conversation etcetera are depends on not only the inlet conditions as well as the outlet conditions. So, you can see that because of back mixing or because of a recycle, the systems becomes more non-linear because of this greater non-linearity CSTR is an example where there is perfect back mixing, a PFR is an example where there is no back mixing. A PFR with this recycle stream as I have shown, there is some amount of back mixing. What I want to say is that because in a CSTR the solution depend on both the inlet and the outlet conditions.

Therefore, the system is more non-linear and therefore, there is the possibility of multiple steady states and what do I mean by multiple steady states. Essentially, if you are trying to look look for intersection of two lines at best you can have one intersection. The moment your system becomes slightly more non-linear one one is a parabola, the other is for example, a straight line. Well you can have multiple solutions where the two where the two curves intersect. So, the more non-linear the system, there is the possibility of multiple steady states. See, this is a necessary condition it is not a sufficient condition. So, because of so back mixing is a necessary condition for multiplicity or steady state multiplicity. It is not a sufficient condition.

So, multiple steady states in a CSTR are possible, multiple steady states for example, in this case should are also possible, but that does not mean for the, that for the design and operating condition that we have, it does occur, it may be that you still have only one solution, but the possibility exists. Multiple steady states in a packed bed reactor like this not possible. So, I hope these simple things are reasonably clear to you. So, multiplicity or multiple steady states solutions for the same inlet conditions are possible in a study in a CSTR.

(Refer Slide Time: 36:51)



And I think in your under graduate curriculum you would have seen this classic classic picture and what is this classic picture saying. Now, if you take reactor temperature on the on the x axis and Q, Q meaning the amount of heat generated by reaction or the amount of heat removed, then the heat generation curve due to reaction is S shaped and it is got a shape that is looks something like that has been drawn here. The heat transferred across a CSTR wall is actually U A delta T heat transfer coefficient, area for heat transfer times temperature driving force, temperature inside the reactor is constant. Let us the coolant circulation rate on the jacket is really high. So, for all practical reasons the jacket temperature is also constant so, U A delta T that is the heat being transferred across the reactor wall.

Therefore, as the reactor temperature is increased coolant temperature is what it is, delta t goes up and therefore, the heat removal curve is actually a straight line and where the slope is U A. Heat transfer coefficient times area for heat transfer, there you go so that is the heat removal curve and it could have a single solution like has been shown here or if I decrease the slope which means that I am decreasing the U A, if U is constant let us say the A is getting decreased in that case well let us see I could have 1, 2, 3 possible solutions, 1 2 3. So, there is the possibility of a unique steady state and that unique steady state will occur if I have good heat transfer area and coefficient. So, U A is large, slope of that straight line will be high and therefore, I will get only one one intersection. Many a times what happens is because you are working at industrial scales, you do not have a lot of area that is available to you because like I said area goes up as l r square and volume goes up as r cube.

So, volume go blows up much faster than area and therefore, industrial systems many a times you are limited by the area and therefore, U A is not as high as you would like to be and in that case what you will have is 3 possible solutions. So, this is the number 3 is the high temperature solution, number 2 is the intermediate temperature solution and number 1 is the low temperature solution. You can look at the stability of these solutions as as follows. So, let us say my reactor is at this steady state, let us say my reactor is here, if for whatever reason the reactor temperature goes up the heat transfer rate, the heat removal rate grows faster than the heat generation rate.

So, what that will do is the temperature that is going up will come back down because as the temperature of the reactor increases, heat transfer increases more than the generation rate and that brings the temperature back. Similar, logic would apply if the temperature is going down, the heat removal rate goes down faster than the decrease in the heat generation rate and what that does is the decreasing temperature is brought back. Because you are removing now less heat therefore, the temperature that is decreasing goes back up.

So, this steady state is open loop stable. If I do not have a temperature controller, if I am not manipulating the heat removal rate, if I am keeping the cooling water flow rate or the coolant flow rate constant doing nothing, if the temperature disturb gets disturbed a little bit it will get back. Same logic will apply to this steady state number 1, the low temperature steady state here again. If the temperature of the reactor is disturbed and it increases a little bit, if it increases a little bit the heat removal rate grows faster than the heat generation rate. Therefore, the increasing temperature because more heat is being removed is brought back. So, these two steady states 1 and 3 are stable.

So, 1 and 3 are stable steady states or rather open loop stable that means if I am doing nothing to the cooling circuit. If I am making no adjustments it really does not matter, even if the temperature is fluctuating of the reactor it will get back to where it suppose to get back to. On the other hand this solution right here number 2 here you see if the temperature increases a little bit, the generation rate goes up much faster than the removal rate. So, if the temperature grows up goes up heat transfer goes up, but heat generation rate goes up faster than that. The subtraction of the two is net positive therefore, the temperature will grow up further.

So, what that will do is temperature will keep on growing and then you will end up at steady state number 3. A similar logic applies where if the temperature goes down the reaction dies faster than the heat removal and therefore, the reaction will die, reaction will quench and your reactor will end up at steady state 1. So, if you are trying to operate the reactor at steady state 2 well the system is open loop unstable. What that means is if you do not apply control the reactor will either drift to steady state 3 or drift to steady state 1, it will not remain at steady state 2.

Which is where you want to want to operate it and many a times where heat removal is a problem, where you do not have sufficient heat transfer area, many a times you would like to operate at steady state 2, the reason for that being temperature at steady state 1 is extremely low, if the temperature is extremely low a reaction rates will be extremely low. So, get a certain amount of conversation let us say 30 40 50 percent conversion for a given throughput, for a given reaction or product generation rate the size of the reactor will blow up, temperature is too low at steady state 1 and to operate the reactor at that low a temperature and to convert so much and to generate so much of product will require a reactor size, the design reactor size will be very high.

What happens at steady state 3? Well, here the temperature is too high. Probably the catalyst will get damaged or it will get deactivated so fast that every 3 months you got to take a shut down, reload the, regenerate the catalysts and then start up again. Process operation you do not want to take too many shut downs, you want to shut down once in 2 years, maybe 3 years. Once the process is up stream it should keep on flying and and you would not like to take a shut down.

So, at steady state 3 the temperature is too high, not good for the health of the catalyst. So, typical solution where you would like to operate is 2, that is unstable because that is unstable you will have to have a temperature controller that adjusts the cooling rate so that when you are adjusting the cooling rate because of control, the cooling rate can be increased at a faster rate than at which reaction rate increases and that will help bring the temperature back to set point. So, then you operate around steady state 2.

So, well that is that. The high temperature and low temperature steady states are stable, the intermediate temperature steady state is unstable therefore, you will have to have a temperature controller in order to ensure that your reactor, if you are wanting to operate at that unstable steady state. Now, your temperature does not drift to the high to the high conversion or the low conversion steady state, high temperature or low temperature steady state sorry yeah for a given size has the same thing. So, we have talked enough about CSTRs, next time onwards we will look at different heat removal schemes, different design schemes, where you remove heat from a CSTR and see how such schemes are controlled. That will happen next time.

Thank you.