Plantwide Control of Chemical Processes
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Lecture - 19
Control of reactors

So, welcome to the next lecture. Now, we are going to switch away from distillation columns to reactors and heat exchangers. Reactors are the heart of any given process, because that is where you convert raw materials to the value added chemical that is you are, that you are going to sell in the market. We are going to look at control of reactors. The main issue there is heat management, why is it heat management? It is because the reactions can be exothermic or usually are exothermic sometimes highly exothermic and how do you remove the heat being generated inside the reactor that becomes key to stable effective operation. You, those of you who have gone through a basic chemical engineering under graduate course on reaction engineering or reaction kinetics, and reactor modeling.

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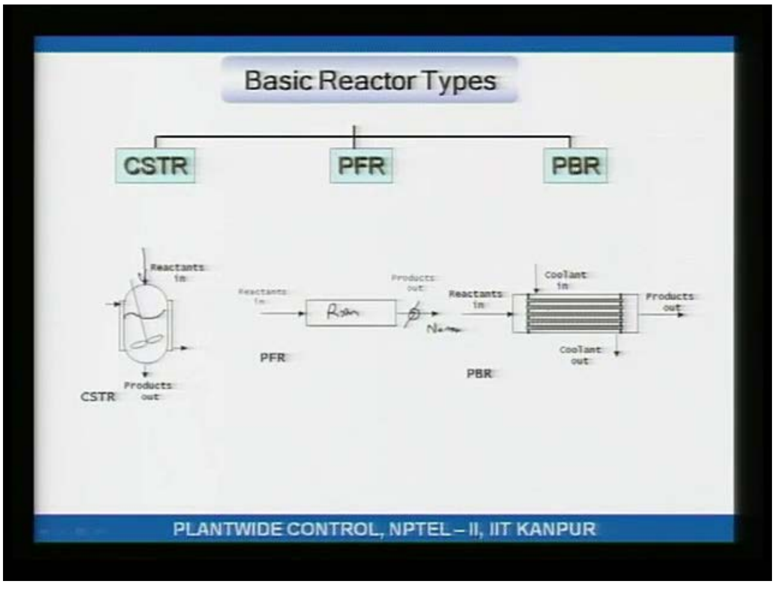

You will know that reactors are actually categorized into three basic types; the CSTR which is the continuously stirred tank reactor, the PFR which is the plug flow reactor, another variant of the PFR is the PBR which is called the packed bed reactor. The difference between PFR and PBR is plug flow reactor is like a hollow tube - a hot hollow tube, because the reactants are hot that is a reaction that occurs inside that hollow tube. Packed bed reactor - well a packed bed reactor has got catalyst loaded tubes, and the material flows through that flows through that catalyst loaded tube, and because the reactants are getting in touch with the catalysts reaction happens, without the catalyst the reaction would not happen.

So, these are the three basic reactor types and any realistic reactor would be a combination of these basic reactor types. So, let us first understand what these basic reactor types are. The continuously stud tank reactor. Well so, you have got reactants coming in. So, the reactants are coming let us see, the reactants are coming in, did not happen. Reaction let us say, is happening in the liquid phase, let us say the reactants are liquid. So, reaction occurs inside the reactor the reactor may be catalyst loaded or it may just be because of the different reactants the reaction happens. Also shown here is a jacket, where you are putting in cooling water in cooling water out, the jacket is has got coolant in it and because the jacket is cold and the reactor is hot, heat transfer occurs across the reactor wall and the CSTR for example, gets cooled.

Alternatively you may have steam going into the jacket and that heats up the reactor so that the reaction kicks off. Both scenarios are possible for an exothermic or an endothermic reaction. Exothermic reaction you got to remove it endothermic reaction you got to give in heat. A PFR like I just said is a is a is a hollow tube, you got material going in and since that material is hot inside the tube reaction occurs and then you you got whatever is going out typically what will happen is you will cool it and once the reactants have been cooled, the reaction does not go any further. So, here there is reaction at the exit there is a cooler and because the hot reactor effluent is cooled, in this stream there is no reaction. Then you also have a packed bed reactor, where you have reactants going in into catalyst loaded tubes, so the tubes are loaded with catalyst and and through the tubes the reactants flow.

On the shell side of this shell in tube heat exchanger you have got coolant going in, that coolant for example, will remove heat from the hot reactor tubes. The reactor tubes are hot because the reaction is exothermic. Alternatively you may have steam going in and the steam will heat up the tubes. So, that if it is an end endothermic reaction you know the the hot steam keeps the tubes hot enough to give the reaction heat that it requires to go on.

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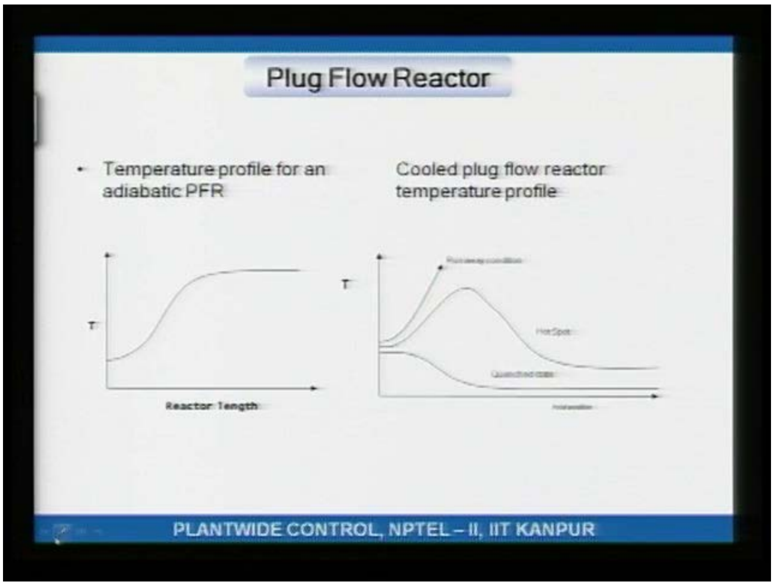

So, this is a pack bed reactor. Now, let us look at the tempera, oh le let me discuss this separately before we do it again. So, let me just discuss all of this so plug flow reactors or PFRs or let us say PFR oblique PBRs. So, let us say here is a tube, you are you know this is the furnace. Of course, you cool it off. So, reactants in the furnace is taking burning fuel and of course, there is air that goes in ratio with the fuel some fuel air mixture, fuel plus air.

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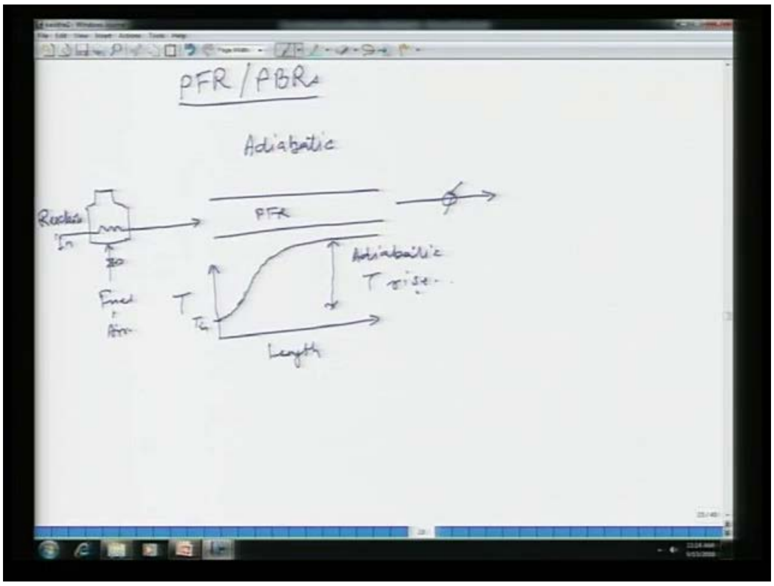

The furnace is burning the fuel so, that heats up the cold reactants to the to the reaction temperature and then one, this hot material reacts inside the plug flow reactor. What do you think, the temperature profile if Ii plot the temperature versus length. So, this is length of the reactor and this is the on the y axis is the temperature of the reactor. What do you think the temperature profile will look like? Well if the reactor is at inlet is at this temperature this is T in and you have got an exothermic reaction going on inside the plug flow reactor, so imagine what is happening in a plug? Initially the plug is reactant rich so, reaction happens because reaction happens the heat of reaction gets released, it is an adiabatic plug flow reactor that means the, that means it does not loose or gain any heat from the environment.

If I adiabatic then what that means is all of that heat that is released in the plug that goes to increase the temperature of that plug, alright. So, as this plug moves ahead, it has gained the reaction heat the reaction heat is converted to sensible heat is to sensible heat. So, the temperature rises because the plug is retaining the heat released by the reaction therefore, its temperature keeps on going up. Now, as you keep moving down the reactor, reactants initially your mixture was reactant rich, as I have move down the reactor now my mixture has got lots of products little bit of reactants. So, what will happen is initially the I have not drawn it properly. Initially the reaction rate will be high, I mean the rate rise in temperature would be high.

You know you will you will have this exponential kick off in reaction, then what will happen is because of depletion in the reactants the amount of heat release will start to go down. So, the rate of temperature rise will go down and ultimately what will happen is all of the reactants would have reacted conversion is complete therefore, there is no reactant left to react and so the temperature profile becomes flat. Does that make sense or no? So, this would be a typical temperature profile inside an adiabatic reactor and this is called the adiabatic temperature rise, temperature in minus temperature out for complete conversion of the reactants. This is the adiabatic temperature rise. Sometimes this is called adiabatic temperature rise. You can also have a plug flow reactor which is a packed bed reactor in the sense you have got a catalyst loaded bed and this is actually very typical you actually have a adiabatic packed bed reactor.

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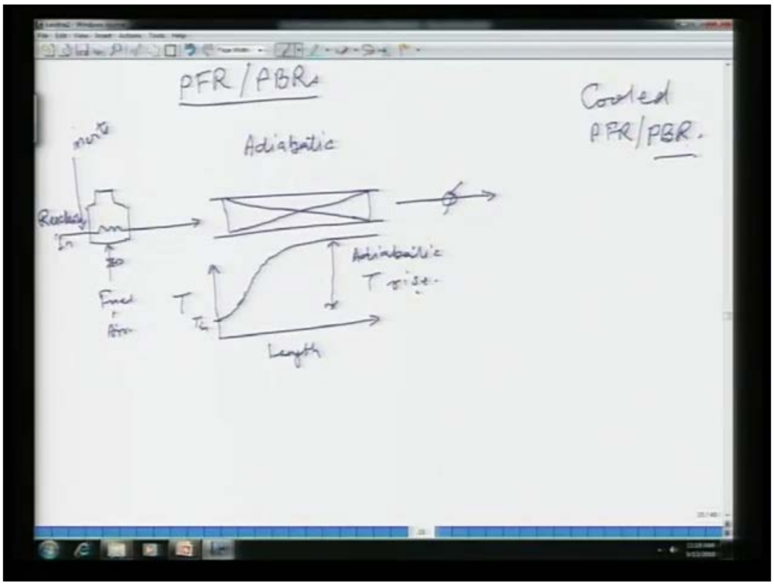

So, there is a catalyst bed, the hot reactants by themselves would not react, but they come in touch with the catalyst because the catalyst reduces the activation barrier reaction takes off, the main reaction takes off accompanied by side reactions as always. It may so happen that this adiabatic temperature rise is too much. Well let us say, inlet temperature is 350 degree Celsius and let us say the adiabatic temperature rise is you know 150 degree Celsius. What that means is the catalyst at the inlet is at temperature x catalyst at the outlet is at temperature x plus 150 degree Celsius. So, if the inlet is 300 degree Celsius the outlet will be 450 degree Celsius.

Now, high temperatures are not good for the catalyst for various reasons one of them being, you know you have you have got coke deposition on the catalyst. The higher the temperature the more the coke deposition onto the catalyst and what that what that coke does is that it blocks the active sides in the catalyst and therefore, slowly but, surely the catalyst activity will go down. Now, in order to ensure that the catalyst can be used for say a year or two years before you take the next shut down, what you then have to ensure is that the temperature rise inside the reactor is not too much. So, if the inlet is if the inlet is 300 degree Celsius and that is desirable because hot you know, too hot if the temp catalyst temperature is too high, it tends to deactivate the catalyst. So, in such situations where the adiabatic temperature rise is too much, there are two options. What are those two options? One is that you start putting in a lot of inerts in your fresh reactants

So, you have got you have got reactants going in, you put a lot of inerts. What that would do is see adiabatic operation is a simplest. You have got no reactor is the simpler it is just a catalyst loaded tube no heat exchange no nothing. However, if the catalyst if the adiabatic temperature rises too much you would like to reduce that adiabatic temperature rise. One way of doing that is to put inerts in the reactants for example, I do not know I do not know know the example so, there may be you would like that the inerts or the non reactive components in the in the feed stream be increased.

What that will do is the presence of the large presence of inerts gives you a gives you capacity to absorb a per unit volume of the reactor, less heat will be released because most of that volume is occupied by that inerts and because most of the most of what is there, most of the comp what should I call it because the inert is in because the inert forms a major fraction of all the components, it does not participate in the reaction so, it suppresses the reaction rate. One because separation rate is suppressed less heat is released, two because less heat is released and you have got so much inert there that inert carries the reaction heat and because there is so much inert the amount of temperature rise is lower.

So, one way to suppress this adiabatic temperature rise is to have you know design your process so that there is lots of inerts going in. When that does not work, even then you know you may have that the adiabatic temperature rise is too much or it may be that putting the inerts in there, you need so much inert that your reactor has to be very big, the tubes have to be very big, you know you require lot of pumping or compression to push the inerts in and then take it out, you know because of all these the cost may blow up. Then what you need is a cooled. So, then what you do is you take a cooled PFR oblique PBR. So, I am not I am not going to show how the cooling is done there are various ways of doing the cooling.

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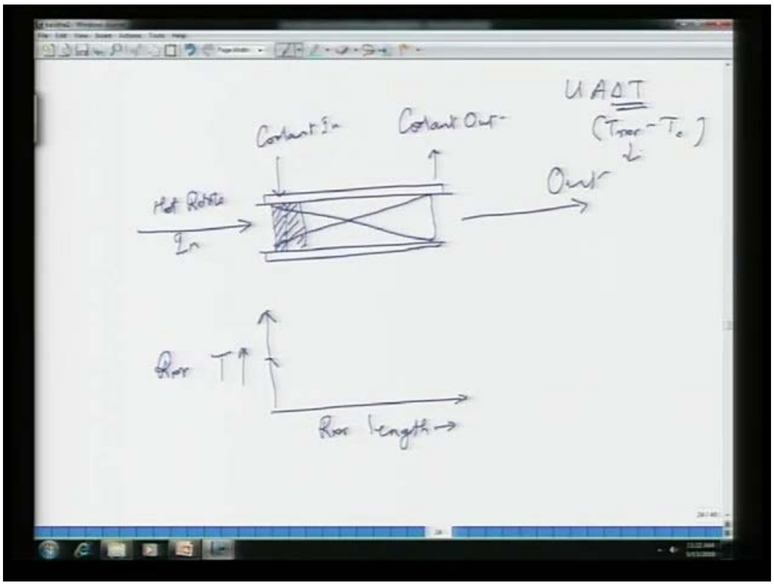

Let us just say you have got a catalyst loaded bed and then you have got material going in hot reactants in. Let us just call it how you are heating it is also not is none of our business, hot reactants in and this is of course, out. You have got some way of and I am just showing a jacket here, how the heat is being removed is separate matter we will discuss that later. You have just got some heat being removed, how do I show it? Well let us just say coolant in coolant out. Now, what would the temperature profile inside the reactor? Now, look like if this is the length of the reactor and this is the temperature inside the reactor reactor temperature, how does the reactor temperature profile vary across the reactor length?

Well there are three possibilities, first possibility is that your coolant is extremely cold when your coolant is extremely cold. What that does is if your reactor inlet temperature is here, coolant is extremely cold or the reactor inlet temperature is not high enough. Then what happens is because the because the reactant is cold and or the reactant is not hot enough, reaction rate is not reaction rate is actually the reaction rate, is the beginning of the plug is actually less than the amount of heat that gets released that gets removed from that plug. So, if I if I if I look at a this initial, let us just focus on this guy, this initial segment. In this segment the react, the reactant is not hot enough therefore, reaction rate is not high enough and the coolant is cold therefore, large amount of heat is getting released removed.

So, what that does is the amount of heat released inside the plug is less than the amount of heat removed by heat transfer. So, temperature will actually go down. Now, because the temperature has gone down if I move to the next plug which is here and I am just blowing it up, the next plug sees lesser amount of reactants because some has reacted and lower temperature amount of heat being transferred will be more because heat transfer is governed by u A delta T. Delta T means, let us assume that the coolant temperature is constant. Let us say that the coolant flow rate is very high so, that you know the the temperature that the tube sees on the coolant side is actually essentially constant. So, delta T is T reactor minus T coolant. Now, your T reactor has gone down what happens is you are removing more heat than is getting produced by the reaction and therefore, temperature actually dies down.

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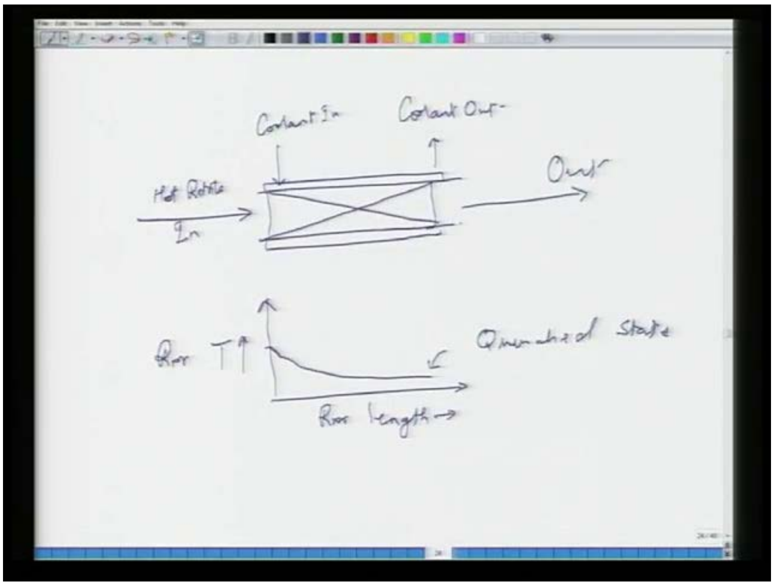

This is called the quenched state. What do you mean by quenched? Your cooling is so high that instead of the reactor taking off, reaction taking off, you actually killed the reaction, the temperature just went down and you ended up at the quenched state. Let us make it again. So, this is my catalyst loaded bed. So, this is called the quenched state. Where what what the quenched state is essentially what you have is the reactor inlet is not hot enough because the reactants coming in are not hot enough, the heat removal actually kills the reaction. If I increase the temperature of the reactor inlet and let me rub this of, you have understood what quenched state is.

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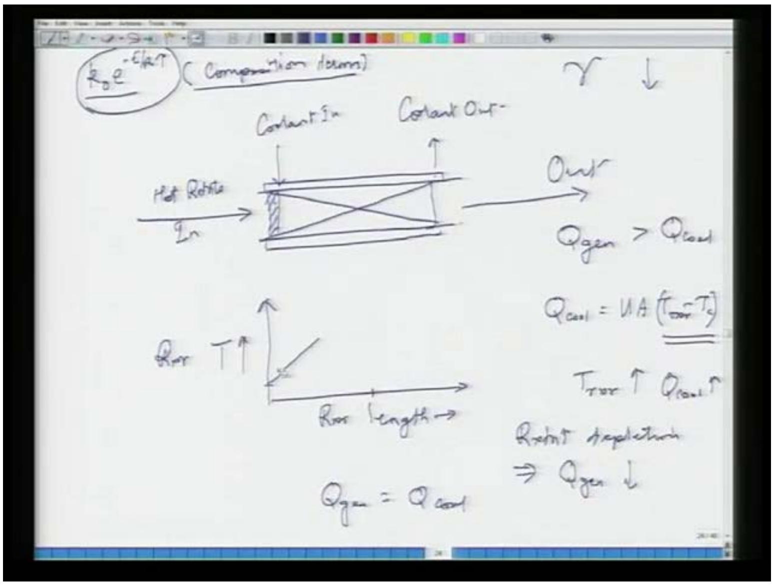

If I increase my temperature, see even though I am drawing it here this is actually more than what it was in the previous one. Now, what happens is reaction rate the heat generated due to reaction in the initial part of the plug, here is more Q gen heat generated due to reaction in the initial part is more than Q cooling, the heat removed. Now the react, you see any reaction the reaction rate will go as k times reaction rate constant which is k not times exponential to the power minus activation energy by R T times you know, essentially composition terms. Compositions or partial fractions or activities or mole fraction composition terms. composition terms.

You will notice that this the reaction rate constant k increases exponentially with. Temperature. So, increases exponentially with temperature. To say exponentially if I increase the temperature reaction rate actually reaction rate constant actually increases much more in fact they say, there is a thumb rule in chemistry which we have read in text books is a reaction rate if the if the temperature goes up by 10 degree Celsius reaction rate doubles or may be 5 degree Celsius. So, well no generalizations can be made, but the point is for a small increase in temperature reaction, rate actually goes up blows up exponentially.

So, earlier I was ending up in the quench state. I increase the temperature of the reactants that are going in, I heat it up more and now, what happens is because the reaction rate is more because of this term the amount of heat generated due to reaction is more than the amount of heat that is getting removed, due to reaction. So, what will happen is temperature will rise because as far as the plug is concerned, the heat that is generated is more than the heat that is removed therefore, the temperature of the plug will actually rise as it moves along. So, temperature continuous to rise. Then what happens is as the plug is moving along the length as we are moving along the length, reaction is happening from the beginning onwards, reactants are getting depleted because they are reacting.

So, as you are moving along the length the composition of the reactants that are available for reaction actually goes down. So, total reaction rate actually ultimately will start to go down due to reaction will start to go down because of depletion in reactants. So, then what happens is as you are moving along the length, temperature is rising because reaction heat generated is is more than the react the the cooling. So, the amount of heat generated in the plug is more than the amount of heat removed from the plug. So, from this segment as I keep moving along, so the temperature is rising, as the temperature is rising notice that Q cool is equal to heat transfer co-efficient times area of that segment times delta T which is T reactor minus T coolant and let us say, T c is constant.

The circulation rate of the coolant is so high, that for all practical reasons you can say the temperature here is the same as the temperature here, even though this temperature may be more by about say 0.12 degree Celsius. So, as t reactor increases as I am going along the length T reactor is increasing because T reactor is increasing this implies Q cool is increasing. Because of depletion reactant depletion if I have gone sufficiently down down the length, this implies Q gen has started to decrease. So, Q cool is increasing because of reactant depletion Q generated or heat generated due to reaction is actually decreasing.

There will come a point in length some place where Q generated is equal to Q cool because Q gen is decreasing because of reaction, reactant depletion. Q cool is increasing because the reactor tubes are getting hotter and as you are moving down the length the temperature is getting hotter and hotter and hotter therefore, driving force is more because the driving force is more, more heat gets removed in a segment alright. So, at some point in length you will have the amount of heat generated in a segment is the same as the amount of heat lost due to cooling. There what you will have is so let me let me draw it.

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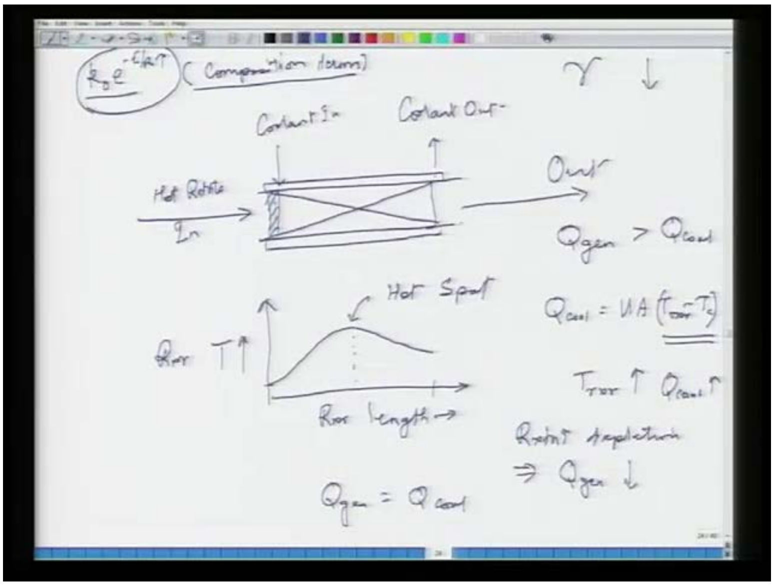

So, initially you got temperature rise then reaction depletion takes over and then you will get an inflection and then what will happen is at some point in length generation is equal to cooling. Let us say, that happens there and there the slope will be 0 and then because of reaction depletion now, amount of heat generated Q gen is less than Q cool therefore, you will start getting temperature decrease. You start getting temperature decrease. Let us say this is where the reactor ends. So, this is called the hottest place inside the reactor, this is called the reactor hotspot. So, I had the quench state where the inlet of the the the inlet feed to the reactor was not hot enough so, cooling was more than the amount of heat that was getting generated and essentially the temperature simply died of.

Then I have this, what I do not know what I call it will see it in the presentation, where you get a hot spot. This is how this is the steady, this is where most this is where industrial reactors are operated where you have industrial cooled reactors are operated where you have a temperature profile and you have got a hotspot. Notice that this hotspot will location will will vary as you vary for example, the feed to the, as you vary the flow rate of the feed to the reactor or as you vary the temperature of the feed into the reactor or if you vary the temperature of the coolant that is going in. You change any of these operating conditions, the location of this hotspot and the magnitude of this hotspot is likely to change.

So, the hotspot actually moves inside the reactor depending on your operating condition. This is something that needs to be known. So, we had the quench state. Now, we have this which I do not know, what I call. Then we also have what is called the, what is called run away condition. You can imagine what happen the temperature essentially runs away as the name suggests suggests run away.

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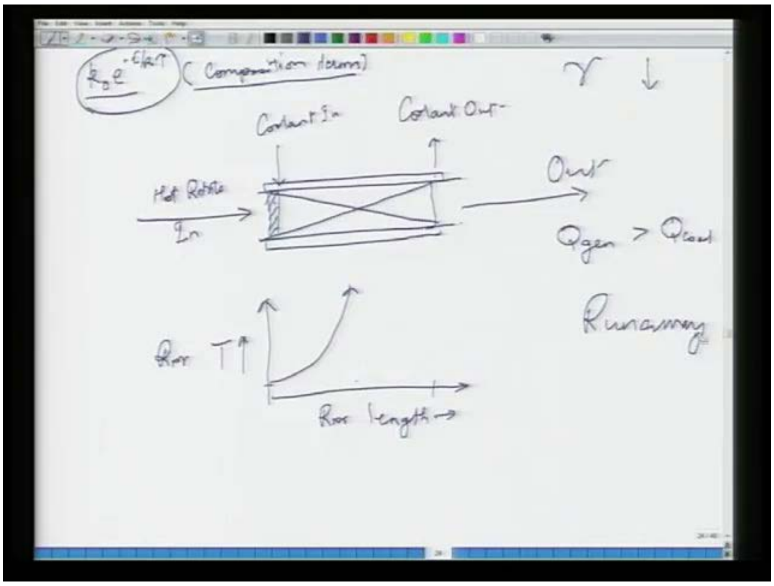

So, in the run away condition the temperature actually just shoots up. Why do you have the runaway condition? Well let us say, you have got a highly exothermic reaction because it is highly exothermic, if you increase the inlet temperature just a little bit reaction rate actually goes up a lot because the reaction rate goes up a lot, the amount of heat that is generated goes up a lot. Amount of heat that is being removed is about the same therefore, what happens is the temperature actually essentially shoots up and before you could get the hotspot where you know amount of cooling is the same as the amount getting generated, the that hotspot temperature is so high essentially what that means is that your reactor is burnt or your catalyst is burnt or let us say some unsafe condition because of such high temperatures has occurred.

So, run away is a condition which is actually a safety concern. So, if you have a highly exothermic reaction I increase the temperature a little bit at the inlet you can have a runaway and that run away is because the tem the the amount of heat that gets generated, as the temperature is the reaction rate actually blows up exponentially with temperature cooling is what it is. So, essentially what it is is essentially your reactor has got caught caught fire so, to speak the quench state is you have put out the fire. The runaway condition is the reactor has caught fire, the hotspot condition that we had you know will like this.

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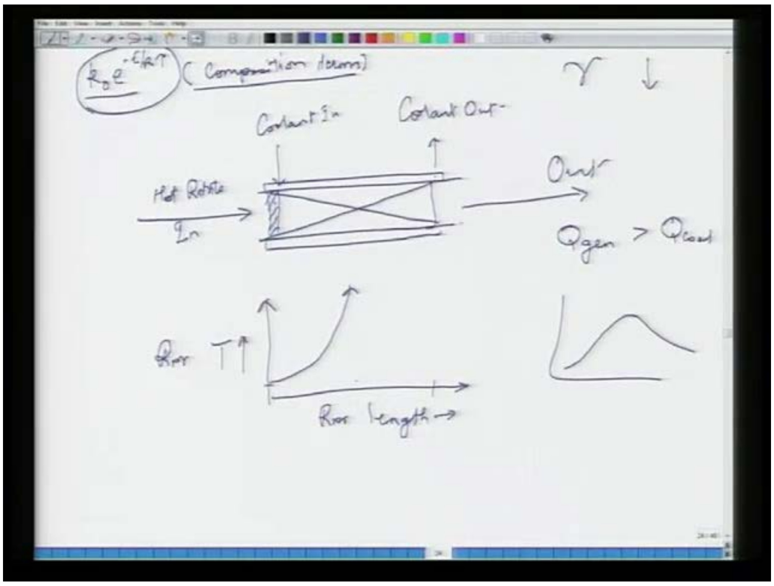

This is where you know the flame is burning in a controlled fashion. So, to speak so, these are the three different states which a packed bed reactor or a plug flow reactor can have.

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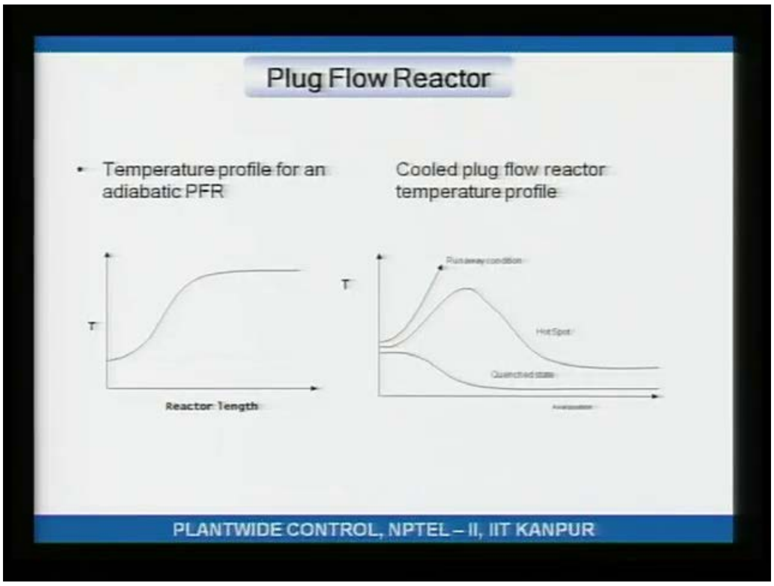

So, the temperature profile for an adiabatic exothermic reaction in a plug flow reactor or a packed bed reactor, you see that the temperature rises and flattens out the flattening out is because there is no more any reactant to burn. Well if the adiabatic temperature rises too much, you will have to have some sort of cooling and if you have a cooling the way I suggested you got three states. The quenched state where the coolant is where the inlet is not hot enough so, essentially a reaction does not take off, and because of cooling the temperature decreases and reaches the coolant temperature.

If you increase the temperature a little bit, then amount of heat generated is more than the cooling therefore, temperature goes up and the reactor is designed or operated in such a way, such that the cooling starts to dominate the amount of heat generated because heat generated cannot go keep on increasing because of reactant depletion. Therefore, you know the temperature profile shows a maxima before coming back down. Then you got the runaway condition where this hotspot essentially moves leftwards and higher and it it actually violates a certain constraint because of either safety considerations because of either catalyst health conditions or whatever else. Essentially what that means is the the hotspot is moving leftwards and higher and it is violating a constraint on the maximum hot spot that is accept the maximum hotspot temperature that is acceptable inside the reactor. So, these are the three quench state hotspot and a runaway condition.

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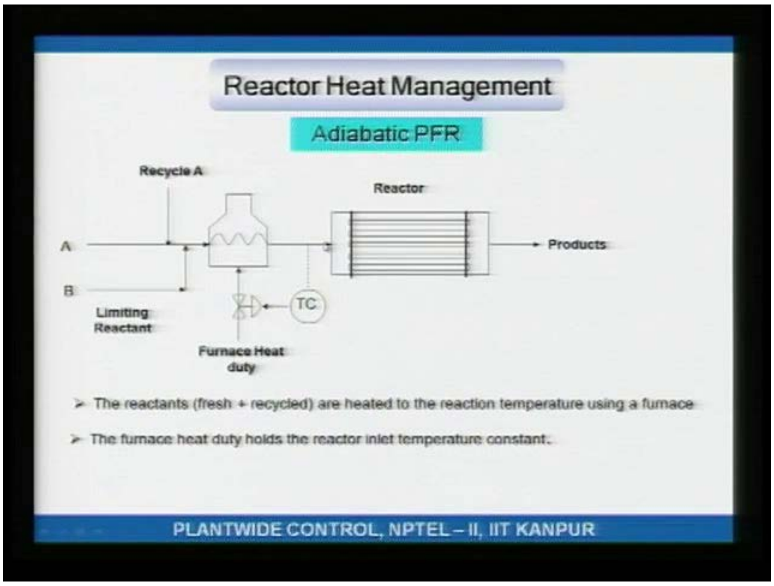

Well so you have got let us say a reaction A plus Bb goes to C so, and let us say B is the limiting reactant. You recover the products are separated downstream you recover the un reacted A all of the B gets reacted inside the reactor the un reacted A is recycled back to the reactor. This mixture of A and B including recycle A is heated inside a furnace. The furnace has got a furnace heat duty which is essentially fuel plus air combination and this furnace is heating the cold feed plus recycle stream to a reactor inlet temperature, the reactor is adiabatic. Adiabatic means no heat is lost no heat is given and the you are getting products on the outlet.

To hold the duty a to hold the temperature at the inlet to the reactor constant you adjust the furnace duty that is what this temperature controller is doing right here so that is what this guy is doing here.

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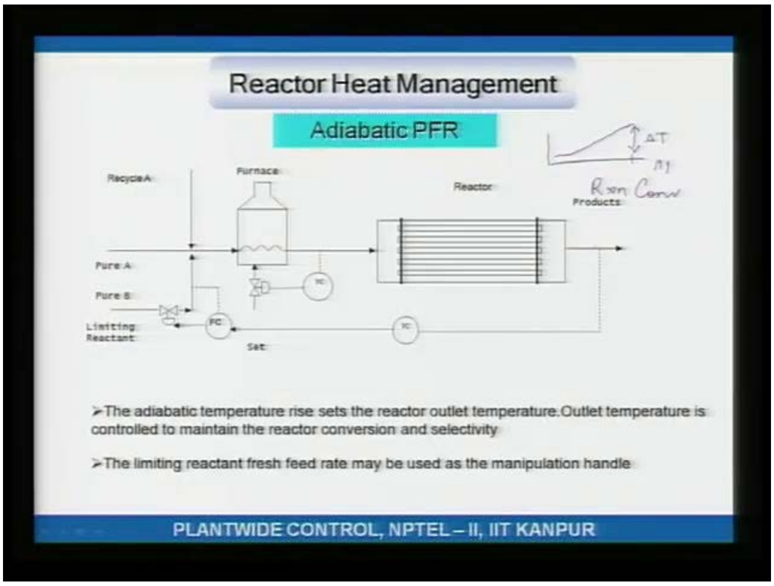

Then what you do is, what is being done here is essentially the following. If you look at the temperature profile inside the reactor, at the exit let us say this is the exit let us say you get a temperature rise and before as it starts to flatten out. You know your temperature profile actually that is that is the end of your reactor. You can see that this temperature rise this delta T the temperature rise, is equivalent to conversion reaction conversion R x n. Now, since your furnace duty is holding the inlet temperature constant you would like to operate the reactor such that the conversion remains constant, Constant conversion means separation load on to the separation section which is downstream that separates the products from the from the reactants remains relatively unchanged.

So, you would like to hold the reaction conversion relatively constant, in order to hold it relatively constant since the temp in in inlet temperature is fixed outlet temperature is essentially a reflection of how much reactant has gotten converted. If the outlet temperature is in increasing that means more is getting converted, if the inlet temperature is decreasing that means less amount of the reactant is getting converted. So, to hold the conversion constant what you do is you essentially set the flow rate of the limiting reactant that is going in. I hope that makes sense. So, if this temperature is increasing I would decrease the amount of reactant that I am putting in.

What that does is the concentration of the limiting reactant going in has gone down because the concentration has gone down reaction rate would go down because the reaction rate goes down amount of heat generated due to reaction goes down because the amount of heat that is generated due to reaction goes down, the temperature goes back to set point. I can have a reverse argument if, I can also have the reverse argument for the for the for the case that the temperature is actually decreasing. If the temperature is decreasing I increase the amount of limiting reactant that I am putting in, that causes the concentration of the limiting reactant going into the reactor to go up because the concentration has gone up.

Reaction rate has gone up reaction rate goes up amount of heat released due to reaction goes up amount of heat released due to reaction goes up implies this temperature at the outlet which was going down comes back up. So, this is a very simple scheme for managing the amount of reaction heat that is released in the reaction or holding the conversion of the react reactor constant alright.

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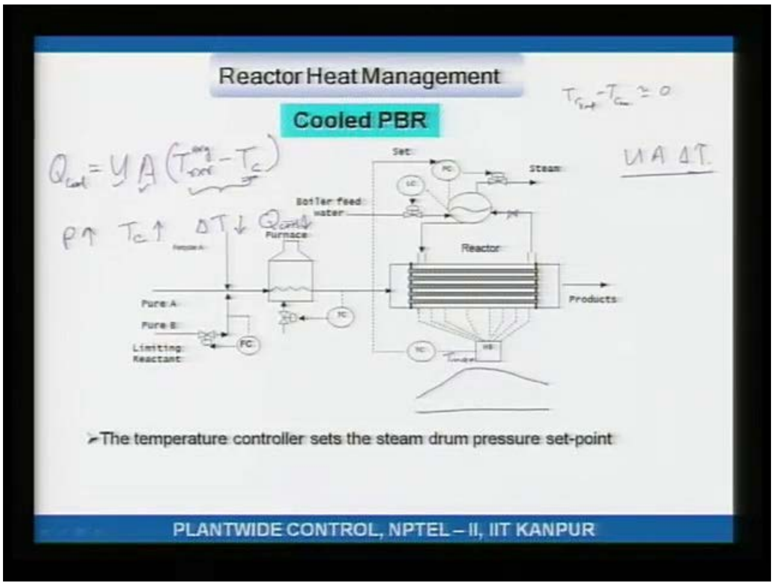

So, now let us take a look at a cooled packed bed reactor. Same situation I have got reactant A reactant B. Reactant A is mixed with recycle A so, the reactor whatever is the stream that is going into the reactor is having excess A, B is the limiting reactant. I have got a furnace that heats up the cold reactor feed stream to the reactor temperature. This is a cooled packed bed reactor. What happens inside the reactor? Let me just explain to you what the how the heat is being removed from the reactor here. What we have is you have got this drum and this drum has got water under pressure, hot water under pressure.

The hot water is circulated on the tube side on the shell side and this circulation rate is very high. Now, because the circulation rate is very high temperature of the hot water going in and temperature of the hot water going out of the reactor is about the same. When I say about the same that means this temperature may be only you know, half a degree celsius or less than half a degree celsius more than what this temperature is. So, T coolant in, this is T coolant out and what we are saying is because the recirculation rate is very high T coolant out minus T coolant in is small. So, small that I can say it is approximately equal to 0. So, as far as the tubes are concerned, they see a shell side at constant temperature. Inside the tubes of course, the temperature rises and then goes back down but on the shell side the temperature of the coolant compared to the changes in the temperature on the tube side relative, relatively speaking is essentially constant.

Because there is a pump this water is under pressure and I guess there will be a valve here which is not shown but this valve takes a pressure drop and this pressure drop causes this hot water to flash and as it flashes steam gets formed and that is what you have here steam is getting removed. Now, because you are losing steam you need to put in some water make up water to ensure that whatever steam is getting lost, that is made up by putting in more boiler feed water. So, that the level inside this drum is maintained. Inside the reactor you have got a a you know for example, a temperature profile that for example, looks like this there is a hot spot. This hotspot like I said moves with operating conditions which changes in the feed conditions which changes in the you know cooling circuit conditions and so on so forth.

Since, it moves what you have is an array of temperature sensors which could be RTDs or thermo thermocouples. RTDs meaning resistance temperature detectors and these array of thermocouples, the temperature reading from this array of thermocouples is sent to a high select. What the high select does is selects the highest of these temperatures. So, you have got a vector going in, which is a bunch of temperature measurements. The highest of those temperature is what passes out here so, this is actually T max. That is what the high select does, this t max goes to a temperature controller and what the way we have shown it here. What this temperature controller does is adjusts the set point of the pressure controller on the drum. Let us forget the temperature controller for a little bit, see what are we doing on the drum?

On the drum what we are doing is you see steam is getting generated let us say, for whatever reason because the tubes were hotter than they were so because the tubes are hotter you know the the water that is circulating will gain more heat because u A delta T and the tube temperature is higher. Since, the tube temperature is higher it gains more heat it gains more heat so, when you flash it out here more steam gets generated now as more steam gets generated if that steam is not being taken out the pressure will go up. If the pressure goes up that tells you look more steam is getting generated I need to take it out. On the other hand if the pressure is going down that means less steam is being generated, I need to close my valve. Reflects the steam inventory or the vapor inventory and this vapor inventory will go up or down depending on whether more heat or less heat is being recovered from the reactor.

So, you have got a pressure controller that manipulates the steam valve to hold the pressure inside that drum constant. Then because you are losing steam you have got a level controller that puts in more or less boiler feed water essentially to hold a level inside the drum constant. So, once you have understood this P C and L C pressure controller and level controller. Now, come lets come to the temperature controller. The temperature controller is getting the hotspot temperature. The maximum temperature from that array of thermocouple or RTD measurements. What it does is, it is essentially adjusting the pressure set point of the pressure controller, the set point of the pressure controller that is what this set indicates.

How will that help in adjusting or let us say my T max is increasing. If my T max is increasing I would like to remove more heat so, that T max comes back my reactor which is getting hotter, my reactor tubes that are getting hotter, I need to remove more heat so, that the temperature of the hotspot or the T max gets back to set point. That is what I need to do. But how would adjusting the pressure of the drum help that. Well it helps as follows it works as follows, you see the amount of heat that is removed is actually u A times delta T, delta T meaning T reactor minus T coolant. Now, T reactor is what it is, it is not in my hands. So, of course, it has to be integrated over the length, but forget the integration let us say I am using some kind of an average in here.

T coolant anyway is constant we discussed that so instead of integrating over the whole length, I am just saying that we are using some kind of an average to get an average reactor temperature. So, Q cool is equal to this. Heat transfer co-efficient is what it is, area available for heat transfer is what it is, I cannot change it because once the heat exchanger is meet, well it has so much area that is what it is. Temperature inside the reactor is what it is. Let us say, it is more than what it should be the only thing that can I can adjust is T c. How do I adjust the T c? I reduce, I change the set point. If I change the set point and this boiler at a higher or a lower pressure then, what that means is if pressure for example, goes up at a higher pressure water boils at a higher temperature.

That is pretty obvious so, for example, water at one atmosphere pressure boils at 100 degree Celsius, water at two atmosphere boils at about 115 120 degree celsius alright similarly, water at four five six atmospheres will boil at 140 150 degree celsius alright. So, as the pressure goes up boiling temperature of water goes up. Therefore, T c goes up because now, I have got hotter water circulating around. If P goes up T c goes up, if T c goes up delta T which is this guy, delta T goes down. If delta T goes down amount of heat removed goes down. Does that make sense?

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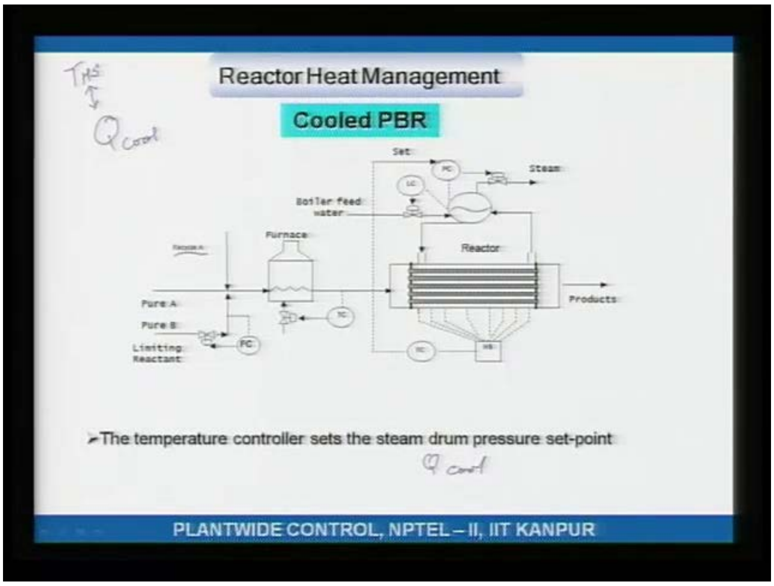

So, now let us see how it works? now let, now let us see how it works If the hotspot temperature is increasing, reduce the pressure set point. The temperature controller would reduce the pressure set point, as the pressure set point is reduced the temperature of the of the water that is circulating around goes down because the temperature of the water circulating in the shell goes down. There is more driving force for heat transfer therefore, the amount of heat removed from the reactor goes up as the amount of heat removed from the reactor goes up, the hotspot which was increasing the temperature that was increasing is brought back.

I hope that makes sense. So, this is how this scheme works and what we are doing is we are adjusting Q cool, to hold T hotspot you are adjusting the cooling rate. The heat removal rate from the reactor. Is this the only way of doing it? Well not. Necessarily there are a couple of other options, which we will talk about right now and I will tell you when it makes sense to use it and when it does not. By the way notice the limiting reactant is under flow control and what I am saying essentially is that all of the limiting reactant for example, is getting consumed inside the reactor. The un reacted a is recovered downstream and it is being recycled here, that is the recycle. Let us just say this is the, this is our process so, the temperature controller sets the steam pressure set point and by doing this you are actually manipulating Q cool the cooling duty is being manipulated.

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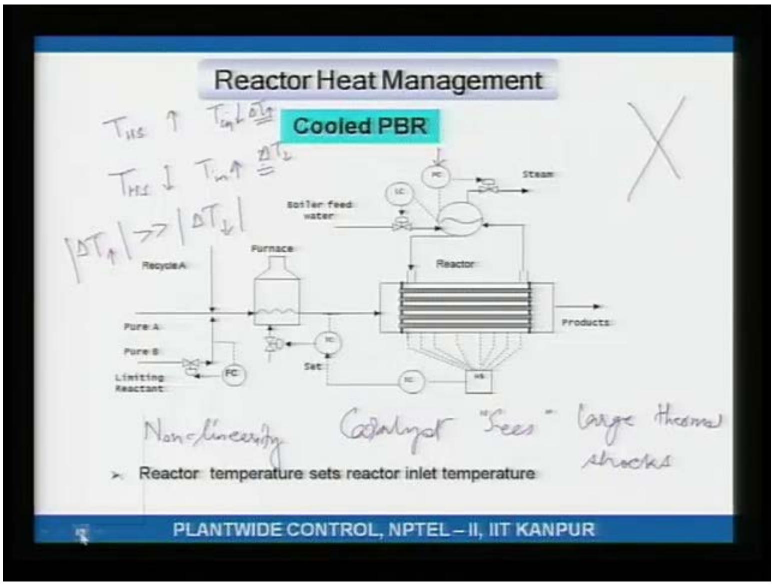

Now, let us say I have got a here is a different scheme. I will hold this pressure set point constant I would not manipulate it. Instead of manipulating the pressure increasing I will reduce the temperature of the inlet. Now, because the temperature is getting reduced reaction rate in the initial parts will get reduced therefore, amount of heat that gets generated gets reduced. Therefore, the hotspot temperature that was going up comes back down and vice versa. This scheme is not recommended in prop even though this is theoretically or whatever conceptually feasible, it is not recommended in practice and the reason for that is as follows you see.

It is so much easier to make a fire than to douse a fire and when I say a fire fire may also be considered as a reaction. So, let us say there is a highly exothermic reaction because the reaction is exothermic enough therefore, I am having this cooling circuit if the reaction was not too exothermic I would have just had an adiabatic packed bed reactor right. So, there is sufficient exothermicity to justify this cooling circuit that is why I have this cooling circuit. Now, what happens is since it is easier to douse a fire no no since it is easier to light a fire than to douse a fire, what that means is if the hotspot temperature is going up let us say T hotspot is going up, that means fire is betting getting caught.

In order to bring this let us say I have to adjust T in, I have to reduce T in whatever may be the amount. Let us say I I will just put a dash there. On the other hand let us say hotspot temperature is decreasing, I will have to increase the T inlet temperature and there will be some amount here. So, let me call this amount delta T in the inlet temperature when hotspot temperature was increasing. Let me call this delta T when hotspot temperature was decreasing. Do you think delta T, do you think the these two changes in opposite directions one case is increase the other case is decrease do you think this will be the same?

You see since intuitively since, it is more difficult to put out a fire than to light a fire, you will find that actually delta T when the hotspot temperature is increasing, the amount of change in the temperature at the reactor inlet that you require, this delta T is actually much much greater than delta T when the hotspot temperature is decreasing magnitude wise. So, what that essentially does is is a hotspot temperature is increasing. I will have to reduce the temperature by a large amount, if the hotspot temperature is decreasing I have to increase the temperature only by a little bit. This large change small versus large change in the in the in the in the reactor inlet temperature this is due to non-linearity. This is a non-linearity and this non-linearity is showing up here. It is showing up the in inlet temperature and what that does is my catalyst sees large thermal shocks.

What that means is that, my catalyst is saying you know the temperature profile of the catalyst is changing a lot. That is not good for the health of the catalyst therefore, this scheme even though conceptually possible feasible is not recommended in in practice another thing that I wanted highlight in this case was that that in this scheme reaction heat, you know in the previous scheme if the temperature is increasing I was adjusting the cooling rate. In this scheme if the temperature is increasing or decreasing I am adjusting the amount of heat that gets generated.

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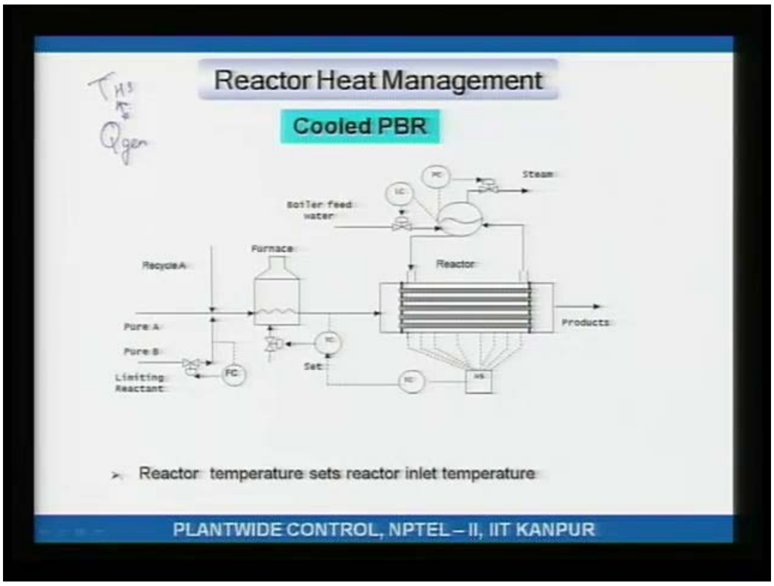

You see. So, in this case works by Q gen so, T hotspot is controlled by adjusting the amount of heat that is getting generated due to reaction Q cool is not getting manipulated I hope this difference is clear. There is a third scheme and here is the third scheme.

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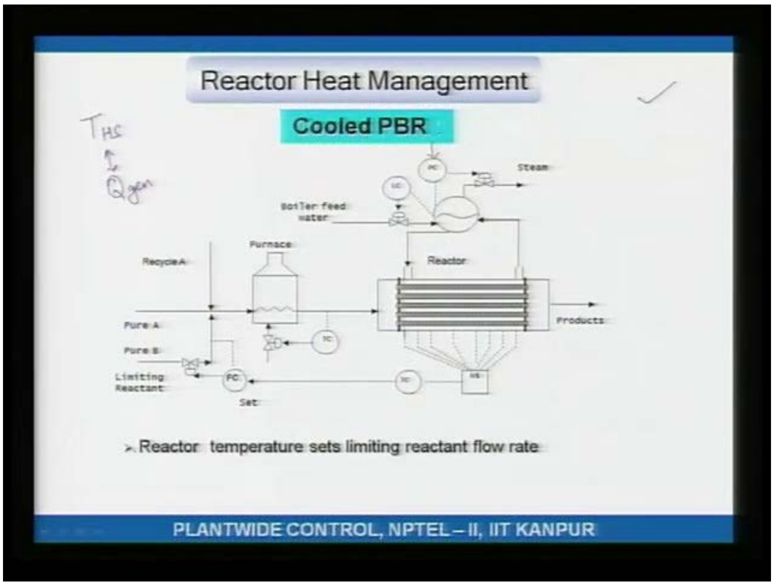

After this I will end alright. In this third scheme everything is the same except that the temperature controller instead of adjusting either the pressure set point or the reactor temperature in is adjusting the limiting reactant flow rate. How does this work? Well this works as follows if the hotspot temperature is increasing, that means you are generating more heat than can be removed and therefore, you need to put in less limiting reactant you need to put in less fuel to burn so, that this increasing hotspot temperature gets back. Visa versa if the hot sport temperature is decreasing, well that means you are removing a lot of heat than you are generating in order to generate more amount of heat, put more fuel more of the limiting reactant, well that is how this works.

Again T hotspot is getting controlled by manipulation of the heat generated due to reaction right alright. Last, but not least I would like to highlight, when would you do this and when would you do that first scheme? So, this is doable in practice. Scheme two which we saw just before this were were you were adjusting T in that is not recommended in practice there was also the other scheme, that we discussed first which was this. Where you are adjusting the pressure set point to hold the hotspot temperature constant, this is also done in practice. When would you recommend this? Well you would recommend conventionally the most common sensical way of controlling the hot spot temperature is, to adjust the amount of heat that is getting removed. But many situations a transfer area that is available.

As you start scaling up things, volume goes up to the power 3 area goes up to the power 2 and soon you reach a you see therefore, the volume blows up much quicker than heat transfer area and therefore, what happens is heat you are typically limited at industrial scales in your ability to remove heat. So many a times it is desirable, many a times it is desirable that you process as much limiting reactant as is possible because that is what gives you maximum production. What limits you from increasing the amount of limiting reactant that you are processing is your ability to remove heat from the reactor.

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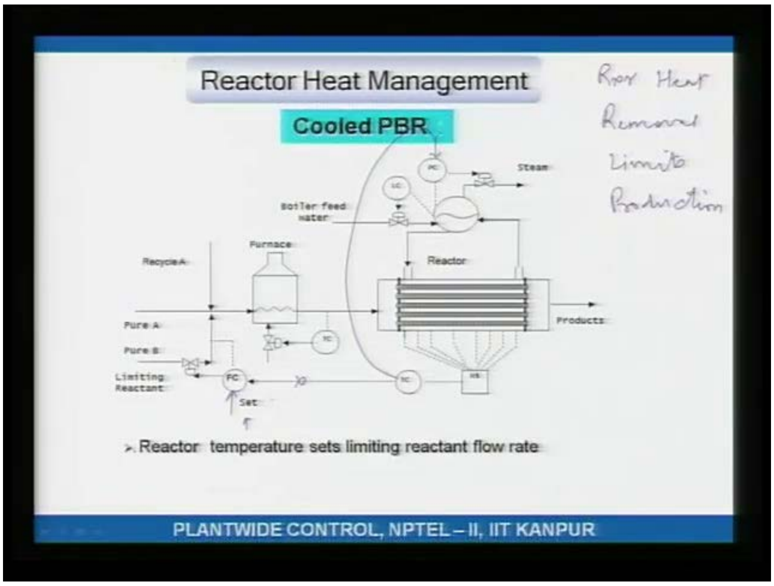

So, then what do you do? You set in that case where reactor heat removal limits production. I would like to maximize my production, I would like to produce as much as I can. I would like to run my car at maximum possible speed on the road so that I get to my destination as quickly as I can. So, I am trying to process as much limiting reactant as I can as as I try to do that what happens is if I was using the other scheme where this guy was being adjusted what would happen is this pressure set point will reach its minimum. Whatever is accept whatever is its minimum acceptable. Then what that means is I so, as I increase this so, I increase this set point. This is not there right now.

As I increase this set point, let us go back to the so, here what I want to do is I want to I want to maximize the amount of limiting reactant, that I want to process. So, what I do is I take this set point, I take this set point and I keep increasing it so, this is F B set point I keep increasing it as I keep increasing it the amount of heat generated inside.

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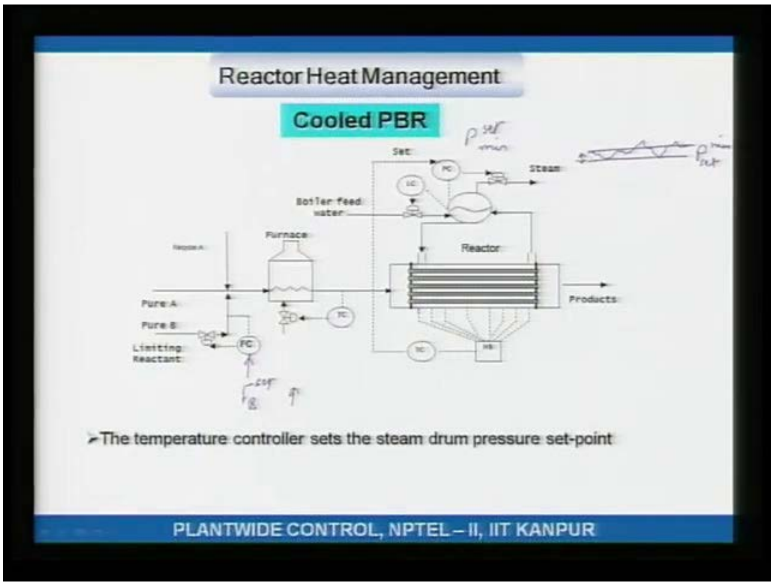

The reactor keeps on going up as because the amount of heat is going up to maintain the hotspot temperature this set point will keep getting reduced until it reaches P min. P set min. What sets P set min is you see this steam will be fed to a certain header that is collecting steam from all locations and depending on whether it is a low pressure steam header or a medium pressure steam header or a high pressure steam header. This steam will have to have at least so much pressure so, that it can get into that header. So, that it can be fed into that header, that minimum pressure that is required that is the limit for this P set min. So, as I keep increasing this P set F B set to maximize my production the pressure set point keeps going down, until it reaches P set min.

So, my pressure set point has reached min. Now, because the temperature can vary due to local disturbances if this is my minimum P, set you see the to to make sure that my hotspot temperature is controlled for local disturbances and because P set is manipulated, it will have some variability. So, on average I will have to operate slightly above P set min to ensure that temperature can be controlled for local disturbances that occur in the reactor.

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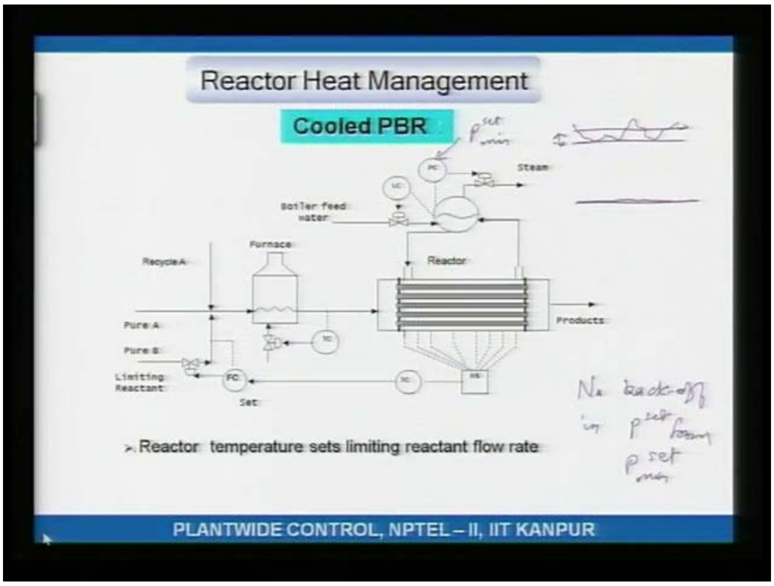

On the other hand if I look at, here what I am doing is this is set at P set min. So, there is no back off I am operating at the lowest possible pressure at all times and to hold the hotspot temperature constant I am putting in as much limiting reactant as is necessary right. So, what this allows me is, in the previous case what I had was if this is the straight line is the P set min, I had to operate away from on average, I had to operate away from that P set min and there was some amount of back off. That means I was not operating at the highest possible cooling late rate, but slightly below that.

That slight below that will correspond to that I am processing slightly less than whatever is the maximum possible processing rate of pure B of the limiting reactant. In this case I am operating at if this is P min well that is where I am, Operating very close to P min no back off. So, in this case there is no back off in P set from P min set and I am putting in as much limiting reactant as can be consumed corresponding to that maximum heat removal rate. So, if if heat transfer is what limits my production, this scheme would give me higher production than the scheme that was shown previously. You see, you may say a big deal 1 percent 2 percent, greater production. Well it is a big deal because chemical processes you know 1 percent or 2 percent of increase in production can actually translate to crores of rupees 100 of crores of rupees in extra revenue.

Millions of dollars in extra revenue. So when do we use this I just gave you an example where it makes sense to use this. Next time we will, Let us see what what there is next

next time around. We will look at some other heat removal schemes or heat management schemes for packed bed reactors and then we will move on to continuous stirred tank reactors.

Thank you.