Plantwide Control of Chemical Processes
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Lecture - 30
The Luyben Design Procedure

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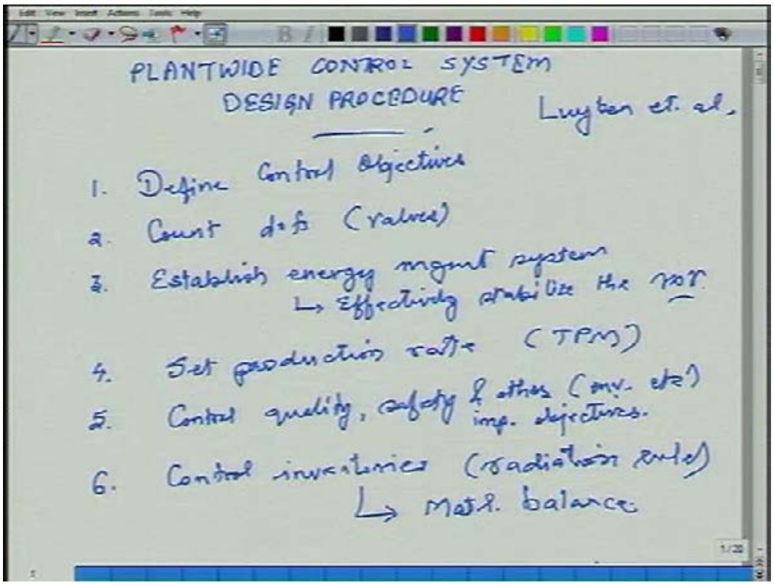

So, welcome to this next class; plant wide control system design procedure. Like I said, we want to refine, whatever we are doing into a systematic procedure, control system design procedure. This was proposed originally by Luyben et al. I think it can be further refined, those refinements, I will talk about later on. Step one; define control objectives, step two; count control degrees of freedom, and once you counted the control degrees of freedom, steady state operating degrees of freedom etcetera, everything comes out from there, number of independent valves, it all comes from valves. Number 3; you see particularly in chemical systems where you have got reactors, and most of the reactions are exothermic, instability in exothermic reaction systems can be quite a big problem. So, you want to make sure, that your reactor is stabilized properly, so this is what they call establish energy management system, this is particularly relevant to energy management.

Basically, done to effectively stabilize the usually exothermic reactor, why is it necessary, because temperature runaway is something that is simply not acceptable, because it can lead to disastrous consequences. So, define control objectives is, straight forward, so we want, what would be your control objectives, what quality grade, any safety considerations, any environmental discharge regulations. You cannot discharge more than this, you know more than this amount of CO 2 or whatever it is H 2 S. All this come under control objectives, you know what do you want to produce, what quality, and what can you discharge and so on so forth, any safety considerations. one of the One of the very crucial safety considerations is particularly systems in which there is oxygen. If you got oxygen, then what happens is, you got hydro carbon, you got oxygen, spark will come from somewhere, and the fire triangle is complete, you can have a an explosion.

Now, what happens is, any mixture will not burn for any composition range. Let us say you got a hydrocarbon fuel oxygen mixture. If there is too little fuel, then obviously the fire would not go, also if there is too much fuel, then you will be oxygen starved. So, you could be in the fuel starved region, or you could be in the oxygen starved region, fuel starved. So, typically any hydrocarbon will have a lower flammability limit and an upper flammability limit, and you must make sure, that if, for example ethylene oxide. So, you are putting in ethylene, and you are putting in oxygen, and you are producing ethylene oxide. This system will have flammability limits, and you have to sure that no where inside the plant, until oxygen is removed, the composition reach is in the flammability limit.

So, that is a very standard safety consideration; that if you are feeding in oxygen, whatever mixture you have, it’s never in the flammable composition region, significantly far away from the flammability region; does that make sense or no. So, control objectives production, how much to produce, product quality, safety consideration, environmental regulation etcetera. Degrees of freedom you know how to count them. Now the next question is, what you do with those degrees of freedom. You see, because stabilization is a fundamental objective, and usually the place where things can go unstable is the exothermic reactor. Therefore, you put in the energy management system in the beginning itself, when you have the maximum freedom in terms of, what you want to pair with what. Once you have paired it, that valve is gone, anything else you will have to use some other valve.

So, therefore, it is a question of prioritization what do I want to prioritize the most, and Luyben and company say that, well to ensure that there is never a possibility of a runaway, no matter what, you first put in a control system that ensures exothermic reaction heat is effectively removed to utilities; therefore, it comes up high up the order. Step number 4; set production rate, this is the same as saying set production rate is the same as saying what, choose the TPM, choose the throughput manipulator. Many a times, because your local plant is operating in an integrated; for example, a refinery complex. Many a times either you will have to process, what the upstream process is feeding, in which case the throughout manipulator is at the process feed, or you will have to supply a downstream process whatever it is demanding, in which case your throughput manipulator is at the product stream. Sometimes you also have large search tanks, so you can operate this plant, without having to worry what the upstream or downstream plant, is wanting or asking you to process.

In that case you can choose the throughput manipulator wherever you want. So, set production rate, choice of throughput manipulator that is a subject in itself, we have dealt with it a little bit, you know if you are free to choose where to put the throughput manipulator, put it at the bottle neck constraint, but if it is been dictated to you, that no; you have to supposed to process to this much, or if it is been dictated to you, well you have to supply this much. Then it’s not a not a choice, that depends on the exact way the operating philosophy of a integrated refinery complex or petrochemical complex or whatever you have, but the point is where do you set the production, is a designed decision. Now number 5 is control quality, safety, and other would include environmental etcetera, and other important objectives, production objectives.

Now you see the way it is being, you know the way things are being prioritize, first thing I want stable operation; therefore, I say well energy management should be done, when I have maximum number of valves available to me, then I can get the best pairing for that; no matter what it’s going to run proper, nice and proper. Then production rate, and if production rate is a degree of freedom or is a designed decision, I will choose it at the bottle neck constraint. So, then, when you are producing, whatever it is you are producing, quality will always be something that you want tight control of, because you do not want to sell anything. If you are saying 99 percent pure, and you are producing 99.5 percent, you are not charging any money for that 0.5 percent, and that 0.5 percent raw material is getting consumed; that is actually is a big loss. So, after setting the throughput manipulator, you want to put in place a control system that will give you what; tight product purity control, or product quality control.

The tighter the control the less the quality give away, the lesser the quality give away, the better of you are, in terms of economics your. Raw material consumption will be that much less. You can always produce 99 percent pure product, and guarantee that it is 99 percent pure, that 0.9 percent is extra loss for you, because you are consuming raw material for that, and not charging anything for it. So, you set your throughput manipulator, or in the operating philosophy of the plant. It is either is being set at the feed or at the product. Then you are you still have lots of valves left, you have only taken valves away for what; react tight reactor temperature control, or removal of reactor heat, production rate you still have lots of valves left, those lots of valves that are still with you, can be used to do what, achieve tight product purity control, because that helps you economically.

Also safety why is safety important, because if an unsafe condition is highlighted and logged, you are duty bound by regulation to; for example, to take a shutdown and then restart or whatever, and a shutdown is century lost production, a loss in production; that is simply no. So, you also want, if there are safety concerns such as you know, ensuring that flammability limits are respected, you are always away from the flammable region, well that has to be. Done real tight, because should it go in that region there is no other option, but to shutdown the process; right that is a big loss. Similarly environmental regulations, because if a an inspector comes, either you have to bribe the chap, which is again a loss or that guy penalizes you, which is again a loss, so you do not want that, so you need to put in.

So, when you have all these degrees of maximum number of valves available, what do you do with them, well you prioritize, so that I always want good quality product, on aim, on target product quality, so let me put in place, when I have maximum available valves; tight quality control, safe operation, zero discharge. Once I have done that then control inventories, when I say inventories I mean search capacities, may be pressures, even component inventories you know you have to make sure, that component inventories do not build up, and we have seen examples of that; control inventories. So, put in place your inventory control system, your level controller, your pressure controller, and it is in this context that the radiation rule becomes important, that we have seen, and this control inventories is essentially ensuring that, material balance is respected; local as well as global. Not only for your local unit, but also overall for the plant.

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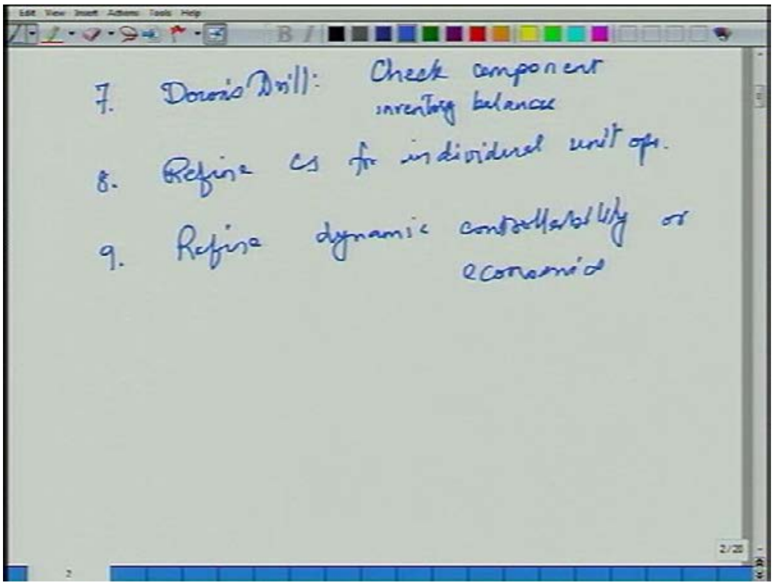

Number 7; is called downs drill, what do you mean by downs drill. You are essentially saying that, make sure that double check, that everything that is coming into the process, has a way out, you have done you have put in place a control system. Now, you want to make sure that everything; that is coming in, has a double check that everything that is coming in is either consumed, or it has a way out. (( )) double checking basically global material balance. So, downs drill is check, component inventory balance. All the species that are that are there in your system, make sure that, they are either consumed or they have a way out. It is a part of control inventory. Yes it is, but you want to double check, you know its suttle, because it is a Suttle you do something, and you double check, so this is essentially a double check. So, check component inventory balances. Number 8; usually after doing all these, you will still have some valves that are left, what do you do with them.

You essentially put in loops, for better control of each of the individual unit operations, whether it's a distillation column, or a reactor, or an extractor, or an observer, or whatever. So, what should I say, what is good English for that; refine control system for individual unit ops. Last but not least; optimize, if you still have valves that are left, well use them for optimizing or refining; I would say refine, further refine, dynamic control ability, or economics. And to improve economics you can also adjust some of the set points; for example, recycled rate can be increased, so that side reaction is suppressed. So, now, you are using the recycle rate degree of freedom to improve yield. This issues are left for the end in this procedure, but philosophically it is a sound procedure in the sense that, you are ensuring that you are reactor can never go unstable, by using the best degree of freedom first.

Then you are doing tight control of everything else that is important; product quality, safety, discharge, environmental discharge. Only after doing that are you controlling inventories, because tight control of inventories is not really important, as long as the level inside the tank is, let’s say between 30 to 70 percent, you are ok. It is only when the level goes beyond 80 percent, or below 20 percent, that some alarm comes, and then you need to make sure that level gets controlled, otherwise the tank will run dry, or it will over flow, some unsafe condition will develop. So, tight control of inventories, is not really important, as long as the inventory is not building up indefinitely, or not depleting indefinitely, you are ok. Therefore, this inventory control is step number 6; low down in the hierarchy of steps.

So, what is most important do it first, next, next, next, next, and therefore inventory is controlled in the end; yes or no, to that end I will also like to point out, for example if you got a distillation column, number of valves is 5, degrees, study state degrees of freedom is only two. No matter what you do, three valves are always going to be available for inventory control, level here, level here, and pressure; yes or no. So, I really do not know if. The philosophy is clear, what is most important do that first; that is the mindset from which this what this procedure has come, what is most important do that first, most important reactor should not run away, well put in place. By the way establishing energy management system. Well it is always, you see this is intimately linked with the way the reactor is designed, so for example, if the reactor is mildly exothermic.

If it is mildly exothermic, you know you have a CSTR let us say, a jacket would be enough to remove the heat. So, for example, fermentation reactors bio chemical reactors are of that type, because the reaction is mildly exothermic, jacket is enough to remove the heat. If exothermicity of the reaction is more, what will happen. You see volume blows up faster than surface area, even though you can remove the heat in a test tube, the moment you want to run it at an industrial scale, well your reactor becomes really big, but surface area does not blow up as much, and now the jacket is not, what test tube you can cool in a bath; that is not enough for an industrial reactor. Then what you have to do is well the heat has to be removed, otherwise the reactor would be unstable.

So, what you do, so you start exploring add-ons, what are those add-ons. Add-ons are alternative designs, so you could have an alternative designs such as; such as a cooling coil. Cooling coil will give you a lot of. Well if it is still much more exothermic, exothermicity is more, and little you know the amount the coil the heat transfer area that you can get, by putting in a coil, is not enough to remove the reaction heat, what do you do then, any idea, what do you do then. Well you can do what you can do is, take the reactor material, send it through an external heat exchanger, you just take the material from the reactor, send it through an external heat exchanger, external heat exchanger does not have any catalyst, so there is no reaction. It's hot, but then the heat shell and tube exchanger has as much area as you want for heat removal. And then that cooled material is send back into the reactor.

This is not a FEHE, FEHE for is for energy recovery, it's for energy efficiency, it's got nothing you know, we will talk, about also like used as a heat removal system. It's not a heat removal system, it actually recycles, it is a it recycles heat, maybe we will discuss it, hold on remind me. The point is depend your reactor system will be designed in a certain way, to remove the reaction heat. So, how would you, for example remove heat if it is a jacket, answer would be obvious. How would you remove heat, if it's for example, an external heat exchanger, answer would again be obvious. How would you remove heat, if it is a cooling coil, answer would again be obvious. Does that make sense or no; maybe I think I need to explain this a little more.

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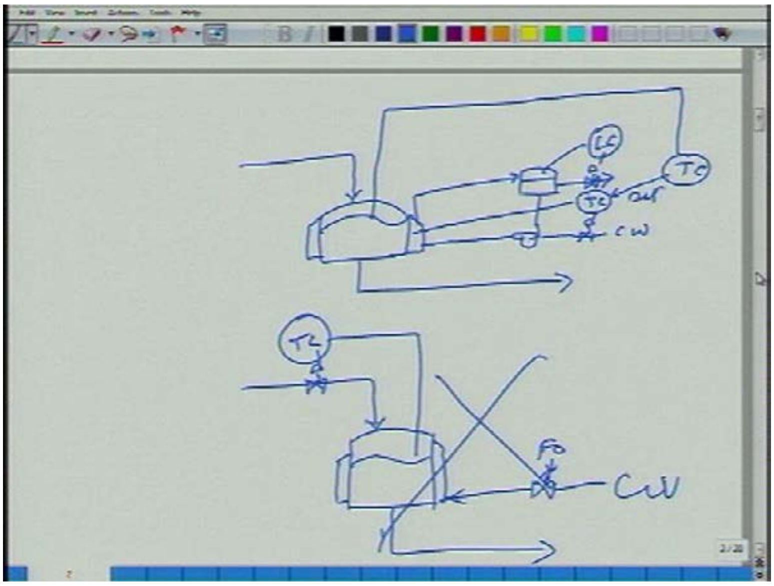

So for example, if you have got a CSTR. man forgive my drawing, it's always pathetic, and I do not have any hopes of it improving. What is usually done in a coiling coil is, you have some amount of storage, of whatever is circulating, let us say cooling water that is circulating inside the cooling coil, inside the jacket, and then what you do is, you have a pump that is taking that water, and circulating it through the. You also have cold water for example, cold cooling water; that is going in. And let us say material is coming out of the jacket here, its going out here, and you have a; is this clear, what is happening. Note that the recirculation rate is high, the pump is ensuring that the recirculation rate is very high. If the recirculation rate is high, what does that mean; that means, the reactor essentially sees a jacket at constant temperature, temperature rises negligible, because the recirculation rate is very high.

So, as far as the reactor is concerned, it is seeing a jacket which is at some temperature. How can you adjust that jacket temperature, how can you adjust that jacket temperature, by putting more or less cold water? If you put less cold water, jacket temperature will go up. Why will it go up, because why will it go up, these things has to be thought through, business time is fixed, recirculation rate is the same, you are not changing the recirculation rate. If I reduce the amount of cooling water going on going in, what will happen to the jacket temperature, why. Jacket temperature will increase, question is why. No, there is less water to absorb the heat that is true, if you look at it as an overall system. Well what is recalculating inside the jacket is the same, it is just that it, it is hotter. If it is hotter, what does it mean, it is because of the delta t, delta t is more.

I think the inverse problem is easier, if the reactor problem is increasing what would you do, you will increase the cooling water. If you increase the cooling water what happens, jacket temperature goes down, delta t goes up, heat removed across the reactor wall goes up, the increasing temperature comes back; yes or no. So, this is what is actually done, what you do is. Of course, now the control system is pretty obvious, you have a jacket temperature controller, and this jacket temperature controller set point, is coming from a master reactor temperature controller; yes or no. So, the point is, if this is the heat transfer arrangement, well this is the control system that is going to get put; yes or no, alright. Somebody may argue, well what I can do is, man this is where I think it is important to think these things true, what I can do is for example, let us say the feed is cold.

Some fellow says, well look my bottle neck is my production capacity is limited by the amount of heat that I can remove in my reactor. So, to maximize production, what I need to do is, make sure that the cooling water flow is maximum, so that heat removal is maximum, and then I will control temperature like this. So, basically what I am saying is, I mean I have removed the rest of the circuit, but basically what I am saying is, cooling water is max. So, basically what I have is, this is a fully open valve, fully open. The valve is fully opened, so you are putting in as much cooling water as possible, and then you are sucking in as much cold material as can be sucked in. What is the problem with this control system, is there a problem with this control system. Throughput is essentially governed by this cooling water, if I reduce the cooling water.

See from a steady state point of view, if I reduce the cooling water, temperature will rise. If temperature rises what do I oh well temperature will low, if I reduce the cooling water temperature, temperature will high, so temperature is rising, so what will I do to the feed, I will reduce the feed. Basically to show that the amount of heat released is less; yes or no; that is what I will do. From a steady state point of view it makes perfect sense, but you will never implement this in practice, why. You will never implement this in practice. Well actually you may implemented, but well I would say do not implemented it any way. The reason is as follows; it is a CSTR, CSTR has got a large holdup. If it is got a large hold up, let’s say reactor temperature was going down.

If reactor temperature is going down, what does it mean. It means that I can add, you know I can add more feed, so I start adding more feed. As I am adding more feed the composition of the reactants starts to go up; that reactant builds up in the composition of the reactants slowly will surely, it will not happen immediately, but the reactant composition will start to go up. 10 minutes 15 minutes down the line, the reaction rate, because of increase in concentration of the reactant. Reaction rate will start, more reaction will start to happen. If more reaction starts to happen what will happen, temperature which was going down will turn around, and now it will start to go up. As temperature starts to go up what happens, you see the rate of reaction increases exponentially, then what happens, temperature has gone up.

Well that feeds the reaction further, temperature has further gone up, and its further gone up, and its further gone up, and then what do you have is a run away. When the temperature starts growing up do not we have a control, but that takes a long time, you see for the feed to effect the concentration, and then for the reaction rate to respond to that, takes a long time; let us say 10 15 minutes. In that 10 15 minutes, once the temperature turns back and starts to rise, it can run away. At least the potential is there for it to runaway. You see what I am saying you could always have. This will not happen in a plug flow reactor for example, because in a plug flow reactor, hold up is not as much, things are flowing it is like flow through a pipe, this is flow through a tank, so this is large hold up.

Because of this hold up, change in feed causes a very slow change in the reaction rate, and therefore temperature control cannot be very tight. And in the exertions where the temperature is rising, you have the potential for runaway. So, this will never be done in practice, exactly. So, your reactor can go unstable, you are using a manipulation handle, which is not tight. You see if something is stable, you want a manipulation handle, you change it and it has an immediate effect, then you can stabilize. It here what is happening is, you are changing the feed, it takes a long time for the reaction rate to respond to that change, in that time dam thing can run away. This is also the classical example. So, you are putting in you are adding fuel in the reactor, when the fuel catches fire; that means, the temperature is turning back.

You cannot put out the fire, you see it is very easy to light a fire, it’s extremely difficult to put it out. So, once that fuel that is accumulated inside the reactor lights up, well a runaway is bound to happen. Therefore, it can never be done in practice. So, that is what is meant by step number three; establish energy management system. You want to make sure that your reactor temperature control is extremely tight. Now we come back here, let’s say economic objectives sill says that, look I want to operate this, so that production is maximized, heat transfer is limiting, what would I do? Heat removal in the reactor is what is limiting production; that is my bottle neck constrain, a great man called Sinsky, what Sinsky says is, take this, this valve should be nearly fully open.

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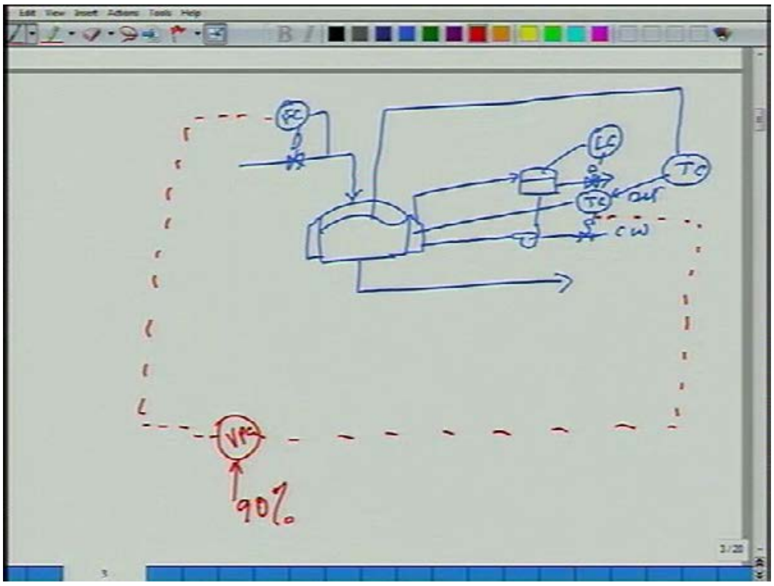

So, I know this valve position, I have got a flow controller on the, let us say the feed. This valve position controller, makes a slow adjustment to the feed set point, and this set point is let us say, I do not know may be 95 percent, may be 90 percent. So, 10 percent trim is there, so there be a disturbance in the temperature, I can still adjust the cooling water valve, I will never input 100 percent, because if then the valve the cooling water valve is 100 percent open, should the temperature rise, I will not be able to bring it back, that again makes it unstable. But in this case, I will be operating my process at on average 90 percent fully open cooling water valve, how does it work.

well if the valve is only 50 percent open ,VPC compares well valve is 50 percent open, I want to be 90 percent open, so what do I do. I need to increase the heat generation inside the reactor. How do I increase the heat generation, by putting in more reactant. So, increase the feed to the reactor; yes or no. And this VPC valve position controller can be a slow one. So, now, I have tight control of the reactor temperature, and the VPC is ensuring that I am processing near max capacity. I am running the process at near max heat removal capacity, which is near max production; yes or no. So, this is one, this is the way it will be done, you won't do it the other way. Why would not do it the other way, where I was controlling the temperature directly by adjusting the feed, because my system is gets my reactor becomes potentially unstable, there is the chance of a thermal runaway; yes or no.

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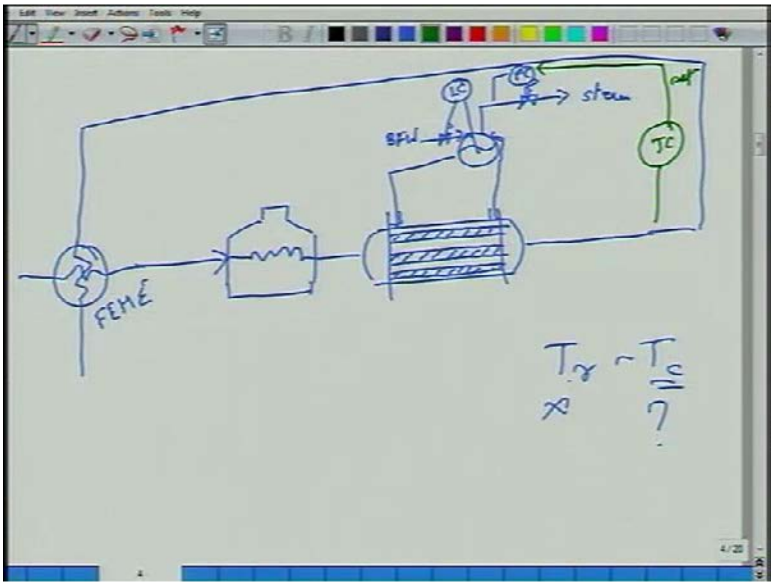

You are taking about feed affluent heat exchanger, see typically what is done is, let us say lets say there is some gas vapor phase reaction ,you are heating it in a furnace, to the reaction temperature, and let's say you are putting it into a packed bed reactor. Let us say it is a cooled packed bed reactor, and well Let me do it the other way, you got a shell and tube heat exchanger, the tubes are catalyst loaded, the tubes are let us say catalyst loaded. So, the hot reactant flows through the tubes, reaction occurs and whatever comes out comes out, whatever comes out is also hot, alright. Then let us say to remove the heat what we are doing is, we are recirculation pressurized water at a very high rate. Since the recirculation rate is very high, very small temperature rise occurs in the water temperature.

So, the tubes, essentials see a shell that is at constant temperature, whatever that temperature may be, u a delta t heat never the less, gets removed from the tubes to the shell, because the shell is colder, tubes are hotter. This goes to this steam drum, and in the stream drum, you see what does a pump do, a pump pressurizes a liquid. So, even if the liquid is at nearly the boiling temperature, under pressure it will not boil, under pressure it won't boil, but the moment it comes into the steam drum, maybe there is a small valve here, near the steam drum there is a pressure reducing valve. So, then the water looses pressure, because it loses pressure at low pressure it flashes. So, you wet steam going out, because steam is getting lost you need to make up, so there is some makeup boiler feed water, so BFW boiler feed water steam.

Why do you want to create steam, why do you want to create steam because this is got some engineering reasons, a you steam is water is available in plenty, so if you want to cool you would rather use water than anything else, anything else will be more expensive. Now because steam and cooling water are the most prevalent utilities, wherever possible you would like to generate steam, where ever possible you would like to consume steam, because anything else is too expensive, is much more expensive. So, heat is being generated in the reactor, it is recovered as steam. Now let us stay the temperature inside the reactor is 400 degree Celsius, then you cannot use steam, you cannot generate steam. Why you cannot you generate steam, because critical temperature of water is 375 degree Celsius, beyond 375 degree Celsius you can do whatever you want to the pressure, it will never condense, you see what I am saying.

So, steam is used, you know from say 100 110 to may be 250 degree Celsius, steam can be used. Higher temperatures you may have to use something like cooking oil, cooking oil won't vaporize even at, I do not know 400 degree Celsius. So, there are these oils which are used as heating media for higher temperatures. If want still higher temperatures, may be 600 700 degree Celsius, then there is no other option, furnace, you just blast the dam thing. So, it depends what is your operating temperature, if your operating temperature is such that steam can be used, or can be generated, dam well you will do it. If your operating temperature is such that steam cannot be used or cannot be generated, well you will do something else then; yes or no. Why do you want to use vaporization, because vaporization uses latent heat.

Latent heat implies your; for example, this line where steam is being generated kilograms per hour will be small, than if you are using let us say no phase change, but a sensible heat effect, then the amount of flow that you would have required to remove the same amount of heat, would have been much more, and then the piping and the valve would have been that much more bigger etcetera. So, it is all for economic reasons, why do you do it this way well, because this is the most economical way of doing it, further to improve the economy what you would do is, well the reactor outlet is hot, reactants are cold, they need to be heated up, you are doing it in a furnish, but you would be a fool if every all of the heating is coming through the furnish. What would you do, you take the hot stuff, pass it through a process to process heat exchanger, so the heat reactor affluent, is heating the cold feed to the reactor. Now what happens? The duty of the furnace goes down. Earlier if all the loads was on the furnace, you would have require this bigger furnace. Now 50 percent of the pre heating load, or 60 percent of the pre heating load, is coming from.

This is the feed affluent heat exchanger. What does that do, furnace heat is expensive, I have reduced the furnished heat, I have also reduced the size of the furnace, furnaces are extremely expensive, as because they operate at 800 900 degree Celsius to the you know, thousands of degrees of Celsius, and then the material that you have to use is expensive, specialized alloys that will not melt that can withstand these temperature etcetera, dam thing is very expensive. So, the smaller the furnish, the more economical, it is the less capital you have to invest right. Therefore, this is what is done; this is a feed affluent heat exchanger. So, how would you remove the reaction heat, well. How would you know more steam is to be removed, or less steam is to be removed, by the pressure inside the steam drum.

If more steam is getting generated, than you are removing the pressure will built up. So, steam rate gets set by the by a pressure controller; that makes sense. How would you figure out whether more boiler feed water is to be put in, or less boiler feed water is to be put in. Well so, you will reshow it. Well what if the rates are not exactly equal, because censors are off, level absolutely. You can have it in ratio, and that ratio set point is adjusted by the level controller. I am just simply drawing it like this, because of lack of space. Essentially how much water you are putting in to the steam drum, is governed by right. How would you decide, or now you put in place this system to remove more or less heat, how would you remove more or less heat. Pressure is what it is, level is what it is. How will I adjust the heat removal rate inside the reactor.

So, for example, let us say I put in more feed, number of passes is fixed. Once you have designed it, and put it in place, if it is two passes two passes, if it is four passes four passes, it cannot be changed on the fly. No, but that is it, it is like flow through a pipe once you set it, you have decided this is the feed rate to the reactor, let us say I increase the feed rate to the reactor. If I increase the feed rate to the reactor more reactant is coming in, more heat will get released, if more heat is getting released, what will happen delta t, think things through. For example, the temperature of the outlet will increase. So, if the temperature of the outlet is increasing, that is telling you that the reactor is heating up.

You need to do what; you need to cool it more, how will you adjust the cooling rate. no What sets, see cooling rate inside the shell, and tube heat exchanger is governed by u a delta t, area is fixed, heat transfer co efficient, flow rate is high circulation rate it is what it is, so you can adjust this. What about delta t, delta t is some average temperature of the reactor minus temperature of the coolant, temperature of the reactor is not in your hands. Can you adjust the temperature of the coolant; that circulating, you know the shell side temperature which is nearly constant, can you adjust that. This is not in your hands, can you adjust t c, how. What sets the temperature of the coolant, of the water. If the pressure is one atmosphere, what will be the temperature, 100 degree Celsius, because steam boils at 100 degree Celsius at one bar.

So, let us say the pressure on average is, I do not know 15 bars, and I find that the reactor exit temperature is increasing, so I need more cooling, what will I do to the pressure set point. I will decrease it, if I decrease it steam will boil at a lower temperature, temperature of the coolant will go down, temperature of the coolant goes down means, u a delta t goes up the temperature of the reactor which was rising, because u a delta t has gone up will come back. So, what you are doing is essentially this, temperature control which is setting this; yes or no. This is got nothing to do with how much feed water you are putting in, you can put more or less feed water, if the pressure remains fixed nothing happens to the temperature in the shell side. Is this clear or no? So, the mechanism has you see once this is the heat transfer system you have put in place, bloody hell this is the control system that you have to put in place, there is no other way.