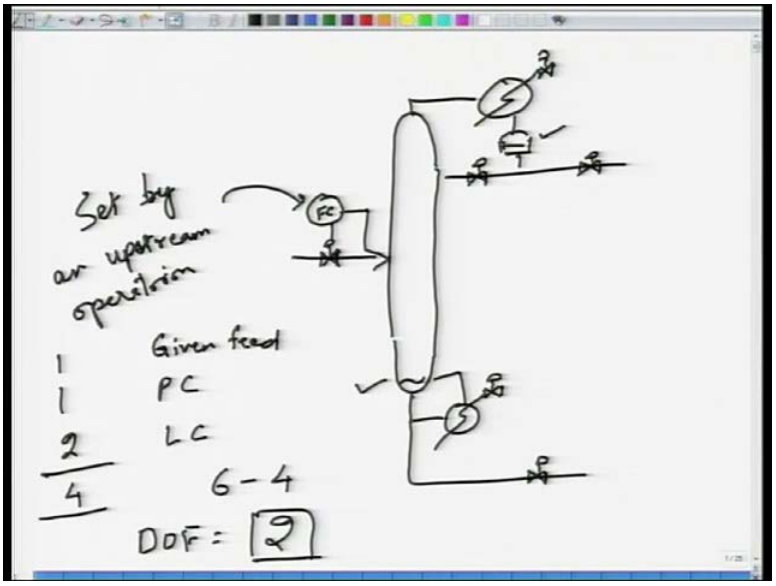
Plantwide Control of Chemical Processes
Prof. Nitin Kaistha
Department of Chemical Engineering
Indian Institute of Technology, Kanpur

Lecture - 13
Temperature inferential distillation control

(Refer Slide Time: 00:28)



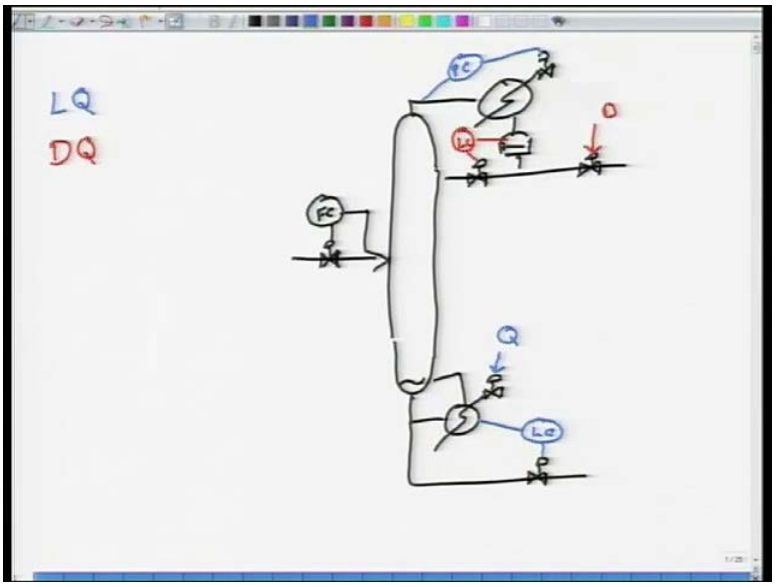
Good morning and welcome to the next lecture. We have been looking at distillation columns and just to recap what we have done, if you look at simple distillation column where the single feed and two product streams. What we saw last time was that there are a total of 1, 2, 3, 4, 5, 6 valves, independent valves on the column, and the feed is typically set from upstream set by an upstream process, an upstream operation typically a reactor.

So, the feed is in not in our hands. We have to control two levels; the top level, the bottom sump level. We also have to control the column pressure; therefore 2 valves go for level control, 1 valve goes for pressure control, feed is set from upstream so that leaves us that is another given feed which has been set by an upstream process or an up operation. So, that way 4 valves get taken away.

Out of a total of 6 independent valves, 4 are taken away that gives us a degrees of freedom. So, given this degrees of freedom what we did last time, degrees of freedom is

2. Therefore, the operator is free to set, two things to get the the separation that he wants and if you control depending on how the level controllers are set.

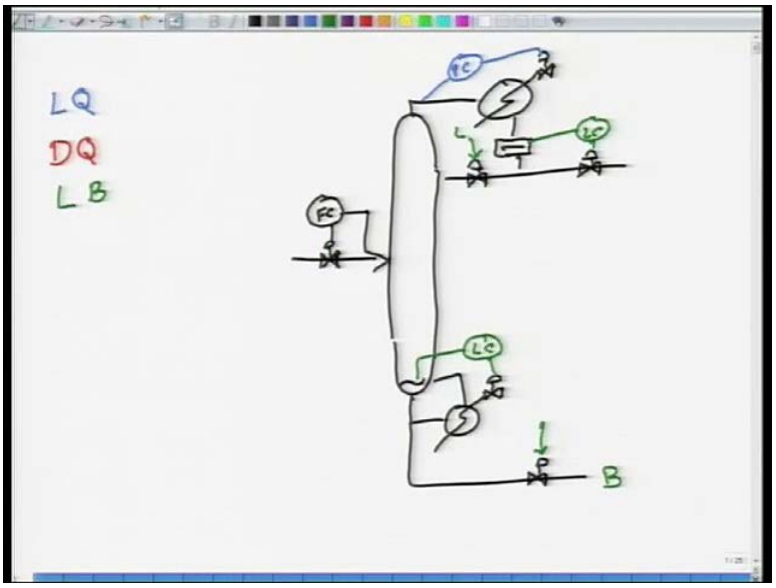
(Refer Slide Time: 02:57)



The level controller may go this way. Maybe I should use a different color for this, the level controller may be set this way, pressure controller typically always is using cooling rate. That leaves the operator to set this and this therefore, it is called, reflux is called L, re-boiler duty is called Q, this is the L Q structure. You may orient the level controller the other way, if the level controller is oriented this way then the operator has to set this stream and therefore, this is called, this is the distillate stream, this is called the operator has to set what is the distillate flow rate and what is the Q or the re-boiler duty.

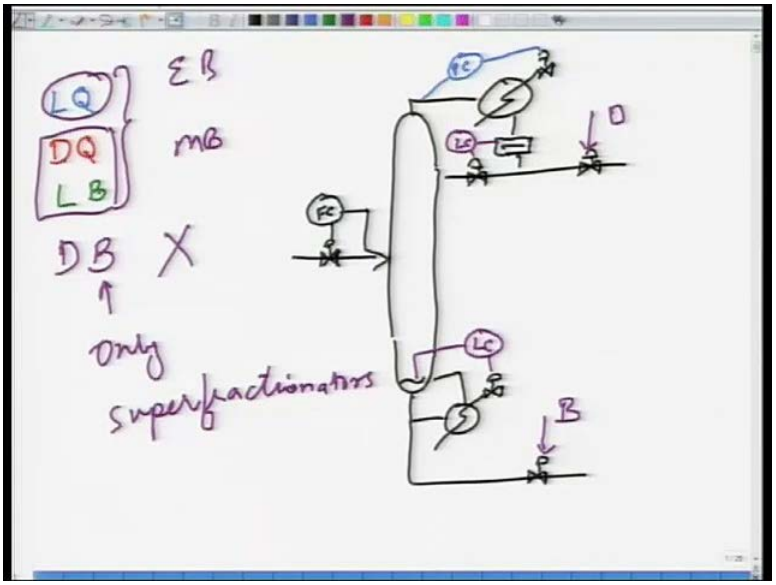
So, this is Q. D Q structure. We may also have a situation. Oh. Everything got erased.

(Refer Slide Time: 04:28)



You may also have a situation where level control on the top is the usual way, in the bottom, because because the bottom stream is the trickle, level cannot be effectively controlled using that trickle therefore, the level in the bottoms has to be controlled using the re-boiler duty. That leaves the bottom stream which is this. So, the operator has to set L and B in order to get the kind of separation that he wants, so that is structure is called L B. We may also have a situation where the distillate is very small compared to the reflux and the bottom is very small compared to the re-boil.

(Refer Slide Time: 05:33)

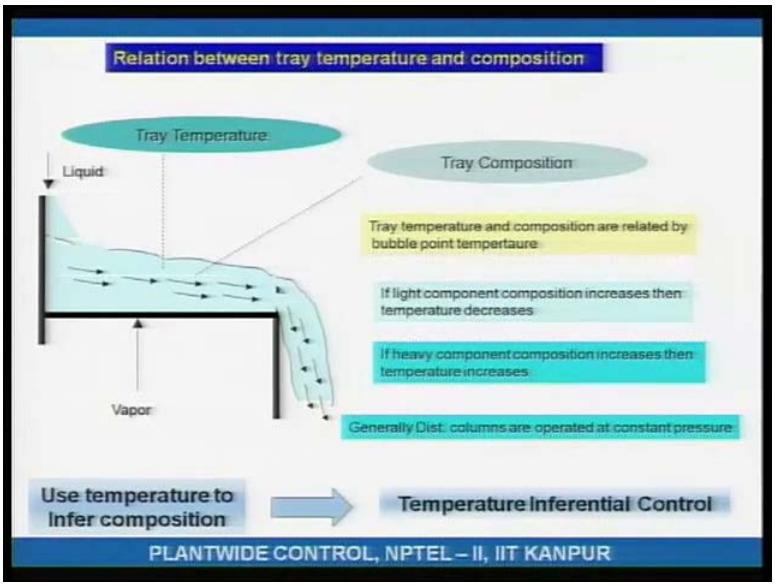


And in that case in that case the level controller at the top has to be oriented this way, level controller in the bottoms has to be oriented this way, and then the operator sets the distillate and the bottoms and this is called the D B structure, it is never used in practice, it is seldom, it is used only in super fractionators and never elsewhere, and that is because this structure valve its material balance in the sense that distillate plus bottoms must always be equal to the feed.

Therefore, you cannot set these two set points independent of the feed therefore these two set points are not independent and therefore, this control structure is quite fragile as has been shown by Luyben and company. So, these are the 4 basic or rather 3 basic control structure types, this is used only in super fractionators, super and what are super fractionators? Super fractionators that are long columns that separate close boiling components, super fractionators L Q is the most natural control structure and it is called an energy balance structure.

These other two structures are called material balance structures because by directly adjusting the distillate or the bottoms rate you are altering the material balance around the column and so on so forth. We saw all these last time now let us continue from where we left.

(Refer Slide Time: 07:04)



All these we have seen. Now, a smart operator would operate the column to keep the distillate purity and the bottoms purity or rather the impurity level in the distillate that is

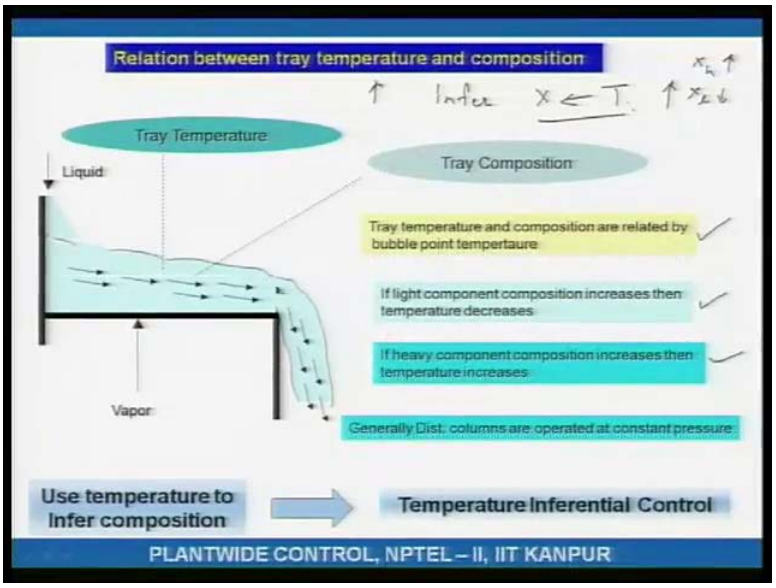
the heavy key impurity in the distillate and the light key impurity in the bottoms to very to reasonable acceptable values. Usually what happens is operators being operators the best way to run a distillation column if you ask an operator he would say is crank up the reflux, crank up the re-boil and you will get product that is you know that just does not have any impurity or very little impurity in it, both the product streams.

That is fine but, the problem there is quality give away, you are using too much energy and you are making too good a product. To conserve energy you have to have in some, you have to have some sort of automation. Why do operators do this because it is convenient just crank up the reflux, crank up the re-boil keep on having your cup of tea and the column will run no matter what. It will give you the kind of purity that you want except that and the operator does not have the liberty to you know keep on adjusting the valves because the feed composition is changed or the feed flow has changed and so on so forth. So, we want some sort of automation and the problem with automation is ultimately you are interested in the composition of the heavy key impurity in the distillate and the light key impurity in the bottoms.

Measuring these compositions in industrial settings can be quite cumbersome and just to give you an example typically what will happen is you will take a sample, send it to your quality control lab, they will do an analysis, a detailed analysis and by the time the shift is over or may be towards the end of the shift you get a reading for what was the quality of the sample that you took in the morning, in the evening you get an answer based on that the operator may adjust the reflux and or the re-boil.

However what that means is for the 8 hours during the shift the operator was running the column essentially blind and the best way to run the column blind is crank up the reflux, crank up the re-boil and then there will be no impurity in the top or the bottom. So, because composition is quite cumbersome you need a measurement that would indicate composition indirectly and it is here that temperatures, this temperature measurement comes in really really handy.

(Refer Slide Time: 10:02)



Most columns you infer composition from X from the temperature and and what is the idea behind this, if on a tray the composition of the heavy component is increasing what do we expect would happen to the boiling temperature of that liquid in which heavy is becoming more and more, you would expect that boiling temperature of that liquid will go up. Similarly, if on that tray the composition of the light component is increasing its boiling temperature will go down.

So, temperature, if the temperature is increasing what that indicates is either composition of the, of a heavy component is increasing or composition of a light component is decreasing, one of the two and and if you look at a distillation column and I do not want to go into it deep into deeper details, but each section of the column if you look it does A type of separation so for example, close to the feed the heavy key is being prevented from going up the top. Towards the top section you will have for example, an A B separation and if you A B C you will have an A B separation towards the top and so on so forth.

So, different zones in the reactive section are essentially performing A A kind of separation, either the heavy key is primarily being removed or light key is primarily being removed or some other set of components are being separated. So, because of that on a particular tray the temperature will rise or go down because a component is increasing or decreasing. Therefore, temperature is a, gives you a pretty good idea if for

example, light material is accumulating in the stripping section. What that would do is the temperature of the stripping stripping trays will start to go down, what that tells you is light material is now coming down, it should be going up, but now it is coming down therefore, what you need to do is crank up the re-boiler duty.

Similarly, if the temperature in the in the enriching section is going up what that tells you is heavy is instead of going down are now accumulating in the top of the column and what that means is your, you will start getting heavy key up the top and therefore, you should increase the reflux so that the heavies are sent back into the column and so on so forth. So, this is refer to as temperature inferential control and let me walk you through. Tray temperature and composition are related by bubble point temperature of the boiling point temperature, if light component composition increases then temperature decreases, if heavy component composition decreases then temperature decreases, if heavy component composition increases then temperature increases, if light component composition decreases then temperature again increases and so on so forth.

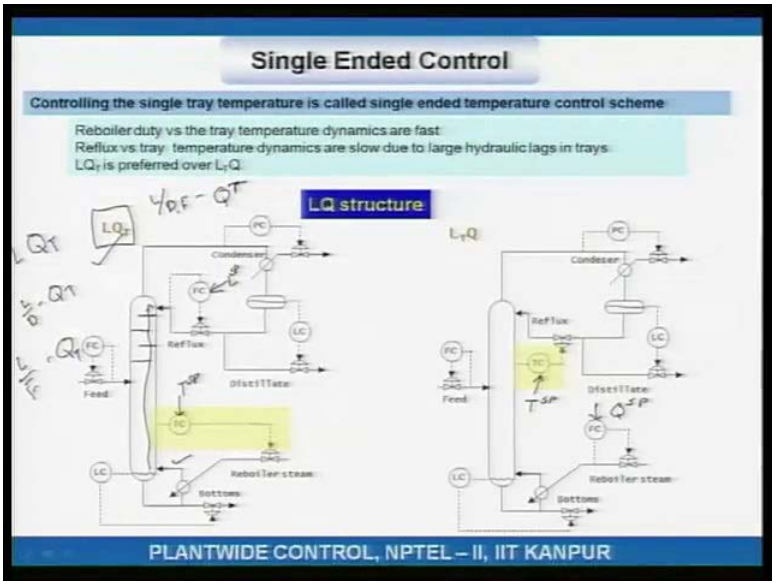
Therefore, what is happening to a tray temperature is a very good indicator of whether the light stuff is going down or going up or the heavy stuff is going down or going up and depending on where that tray temperature is located, where that tray temperature sensor is location it is, it would be an indication of one of the component components or primarily one of the components accumulating or depleting and that would tell you what you should do either the re-boiler duty or to the reflux or the combination of the two.

So, in a sense what we are doing is we are using tray temperature to infer composition or to infer what is going to happen to my product purity and based on those tray temperature measurement I adjust my reflux and re-boil. Notice that tray temperature is a very robust measurement, it is cheap thermocouples and RTDs do not cost much, they can withstand hostile environments or hostile samples, corrosive samples, you can handle hostile environments pretty pretty and also once the sensor is in there the lags are not that great, you know if you put a thermometer in your mouth in about 1 and half minutes or 2 minutes you know you know the the reading and the temp in the thermometer and your body temperature are the same.

So, response time or the lag associated with a temperature sensor is up the order of 30 seconds, 45 seconds may be a minute. So, it is a it is a it is a fast measurement compared

to composition, it is a cheap measurement, it is very reliable, it is quite robust because of these reasons temperature inferential control is the norm in industry. Of course, you always have those composition measurements that are taken by quality assurance labs, but that does have a role to play we would not go into that right now. So, degrees of freedom is 2. Now, in, I could have 1 of the tray temperatures adjusting 1 of those degrees of freedom.

(Refer Slide Time: 15:35)



For example I have an L Q basic structure, let us say my my basic structure is L Q. I can use for example, Q to control a tray temperature, I have fixed the reflux at a reasonably high value so that heavy key does not end up in the distillate no matter for even for the worst case disturbance and then I adjust Q to hold for example, stripping tray temperature constant. Such a structure will be you know I am just putting the subscript T to indicate Q is being used to control temperature and the control structure is drawn here operator is setting L. And operator is setting the temperature set point of the tray that is being controlled, which tray temperature to control well that is another very important issue, we will address that just in a little bit.

Let us now just for the time being focus on the structure. Based on this tray temperature measurement the re-boiler duty is adjusted so if the temperature is increasing that means heavies are accumulating, what does that mean? If the temperature is increasing what you would do is you will reduce the re-boiler duty so that the temperature goes down, if

the temperature is decreasing that mean light that means light stuff is you know coming down which it should not be and therefore, to send lights back up you will increase the re-boiler duty and so on so forth.

So, this is L Q T. By far by far this is the most common control structure that you will find in L Q T or may be L by D or L by F Q T where the reflux in is maintained with in ratio with the distillate or the feed and a tray temperature is controlled by adjusting the re-boiler duty. Why is this by far the most commons, the other possibility is I hold the re-boiler duty fixed, I hold Q fixed, the operator is setting the re-boiler duty and then he adjusts a temperature set point. This is also a set point and to hold this temperature the reflux is being adjusted, the reflux pack into the column. This would be called L T Q because L is being used to hold a tray temperature constant, Q is being set by the operator.

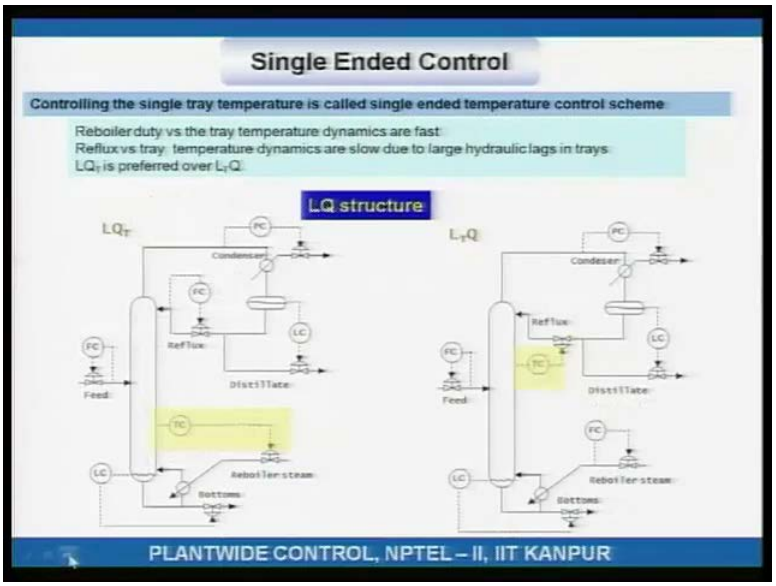
Between these two by far this is the most L Q T you know where a tray temperature is controlled by adjusting the, this is by far the most common structure in in used in industry or L by D Q T or L by F Q T, this by far the most common structure that that you will find in the industry and the reason for preferring to control tray temperature using re-boiler duty instead of the reflux is essentially goes down to dynamics. You see if I change the reflux and if I go back a few figures may be do I show, well I do not think I have it there, well forget it. If I look at my trays you see if I increase the reflux, the reflux first accumulates on tray 1, level on tray 1 goes up then more liquid gets dumped on to the next tray, level on that tray goes up and then more liquid gets dumped on to the next tray and so on so forth. So, there hydraulic lags associated with the liquid flowing by gravity down the column.

On the other hand if I make a change in the re-boiler steam let us say I increased the steam, the boil up which is this stream here, the boil up will go up within let us say half a minute and you see the boil up stream because it is just vapor flowing at a at a velocity let us say 1 meters per second of that order, 1 to 2 meters per second you see the, all trays will see the changed boil up almost immediately. There are no hydraulic lags or let us say that the hydraulic lag associated with the boil up is very small. If I increase the boil up all the trays almost immediately see that increased boil up. On the other hand if I increase the reflux by the time the reflux or the liquid flow rate changes on a tray that is say 10, 15 or 20 trays below, it would take you know 5, 10 minutes because each tray

would have a residence time of the order of 30 seconds to a minute. So, 30 trays is a is a residence time of the order or about what 20 to 30 minute.

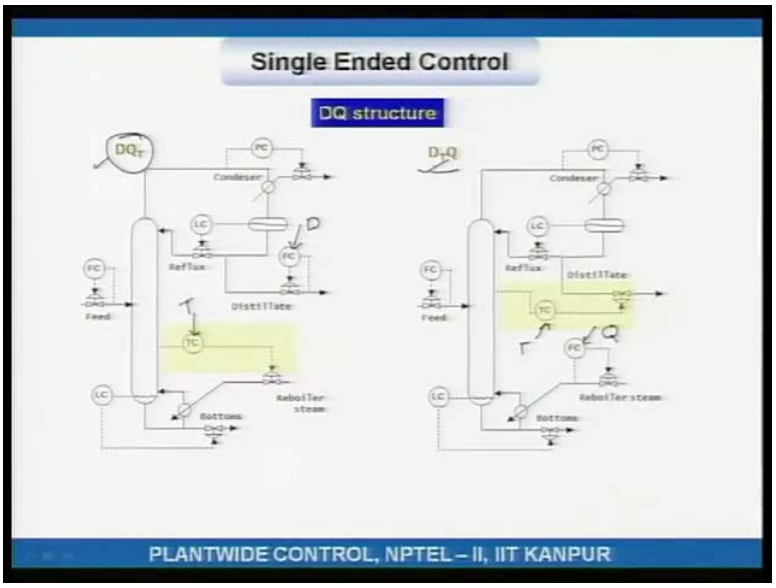
So, because of these hydraulic lags it is usually preferred that we not use the reflux for control instead we use re-boiler duty because I change the re-boiler duty tray temperature almost immediately responds. So, if the response is immediate I can control that tray temperature tightly, tighter the temperature control tighter the product purity control. Therefore, the point that I wanted to make on this slide was that L Q T or its variant meaning L by D Q T or L by F Q T or by far the most common controlled structures used in industry, others may also be seen, but there has to be a very specific reason why you want to use others.

(Refer Slide Time: 21:39)



So, it is written here re-boiler duty versus tray temperature dynamics are fast, reflux versus tray temperature dynamics are slow, therefore L Q T is preferred over L T Q that is usually the norm.

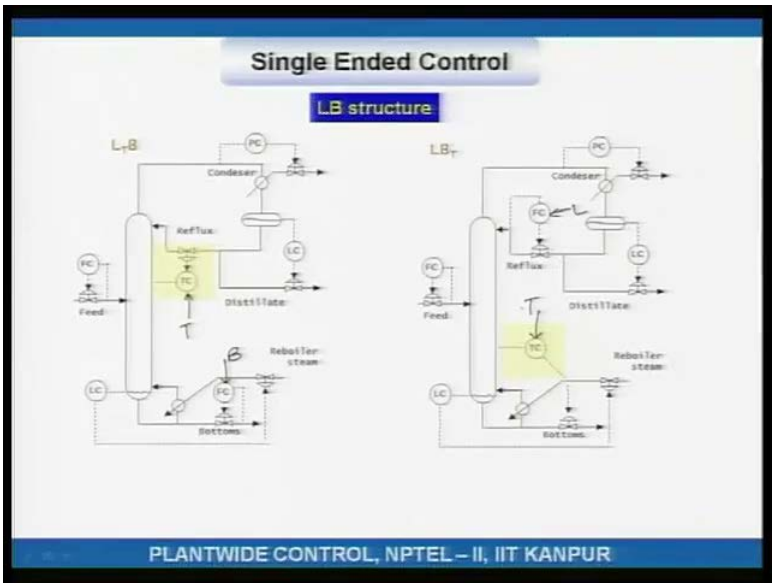
(Refer Slide Time: 21:55)



By the way this single ended control meaning I am, my degrees of freedom is two, I can actually try and maintain two tray temperatures. In over here on what I am trying to do is hold one of the degrees of freedom whether it is Q or L constant and use the other degree of freedom to maintain a tray temperature. So, single ended control that means I am controlling one tray temperature not two tray temperatures. These are variants of the D Q structure in this structure.

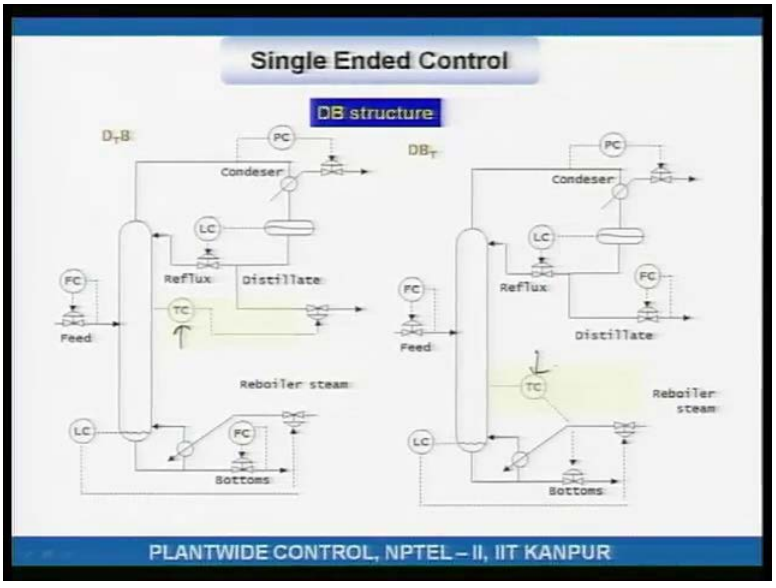
This is being set by the operator this is being set by the operator in the other variant which is over here, this is being set by the operator and this is being set by the operator. No marks for guessing, this would be preferred over this again because effect of change in re-boiler duty a on the tray temperatures will is almost immediate. Therefore, this would be more commonly used than this.

(Refer Slide Time: 23:07)



Keep on going the same way, this tray temperature is being set by the operator in order to maintain this tray temperature the reflux is being adjusted and of course, the bottom steam flow rate is being set by the operator. The other variant reflux is being set by the operator and a tray temperature is controlled by adjusting the bottom stream.

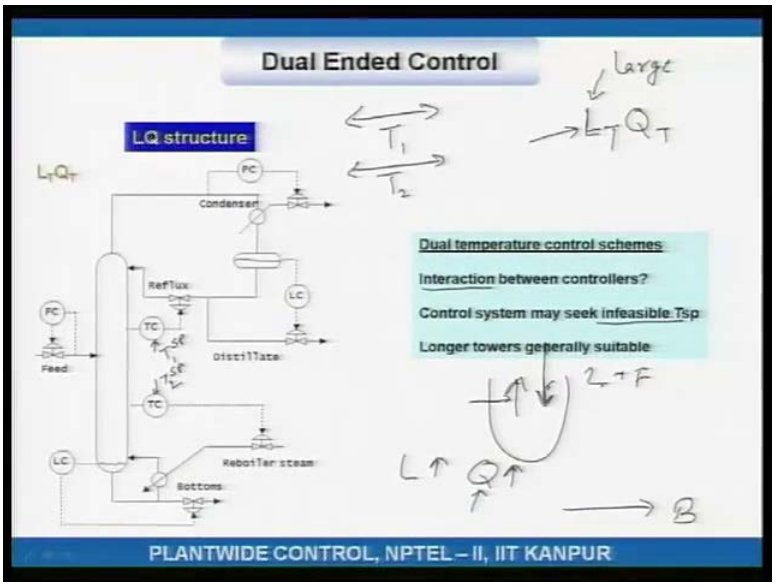
(Refer Slide Time: 23:36)



We keep going ahead D B structure well either you can control a tray temperature by adjusting the distillate or you can control a tray temperature by adjusting the bottoms.

Note, that D B structure violates material balance, so the performance of this structure is going to be fragile recommended only for super fractionators.

(Refer Slide Time: 23:58)



Like I said degrees of freedom is two. I, if I for example, if I am taking the L Q structure, I say that well I choose a large value of reflux and then I adjust the steam or the re-boiler duty to hold a tray temperature constant and I have to chose a large value of reflux because in the worst case disturbance which may be a large change in the feed composition. My L value should be sufficient so that none of the heavy key impurity or so that the the heavy key impurity spec on the distillate does not get violated even for the worst case disturbance. To ensure that the worst case disturbance can be handled L must be high enough.

So, even when the disturbance is not there, L is operating at the same high value and therefore, what that means is my reflux is larger than what it should be, bottoms is about the same as dictated by the split and therefore, my boil up is more because boil up is essentially L minus B, this would be L plus F, if the feed rate is at its whatever this stream is so if L goes up this stream goes up, if this stream goes up, I, what that essentially means is boil up goes up. So, if L goes up Q goes up for the same split. So, if I am using more reflux than necessary when there is no disturbance, what that means is I am operating the column consuming more energy or more steam than is necessary and therefore, my steam consumption per kg product is higher than it should be.

So, smarties would say well instead of holding reflux at a large value, larger than necessary value you have to have it larger than necessary so that the worst case disturbances can be handled. Why don't I control a tray temperature using the reflux and that is what is shown here, you are controlling a tray temperature I will call it T 1 using reflux, you are controlling another tray temperature I will call it T 2 using re-boiler duty. Well, you can imagine if I change the reflux, I am adding more cold material back into the column.

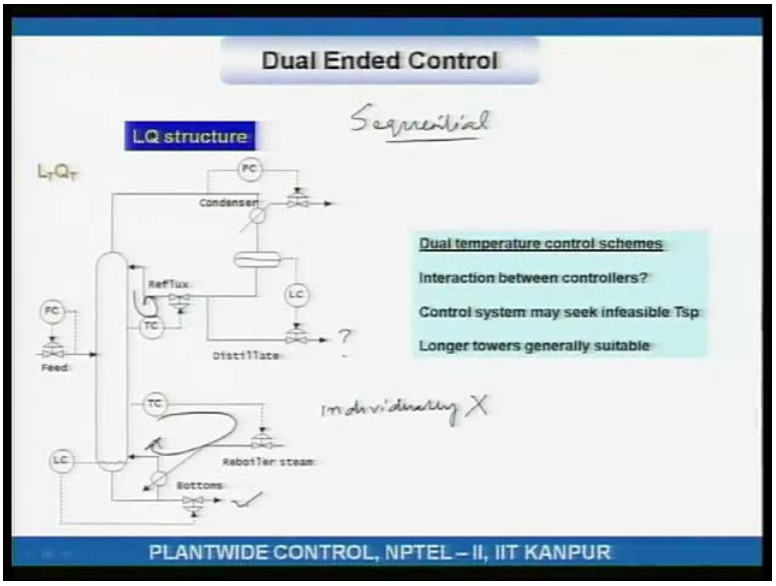
So, essentially what that would do is all the tray temperatures after sometime will go down, the lower temp tray trays will take a long time to respond to that change in the reflux, but they will respond nevertheless. The trays towards the top of the column will respond earlier of course, because the reflux the cold reflux gets there gets there earlier. This brings into the picture the problem of interaction between the two temperature controllers. I change the reflux in order to bring T 1 to set point, that change in reflux causes a change in T 2 and in order to bring T 2 back to set point that the second temperature controller adjusts the re-boiler duty and as I change the re-boiler duty that affects T 1. So, essentially these two controllers can end up fighting with each other.

The second important question is how do I specify T 1 set point and T 2 set point? You see its very easy to give a set point specification for T 1 and T 2 which may actually be infeasible that means there is no solution for which you can get T 1 equal to T 1 set point and T 2 equal to T 2 set point, but it is quite you see the range over which you can vary your reflux rate, you can vary your reflux rate right from 0 to 100 percent full flow, full reflux to no reflux. Similarly, the steam can also be varied from 0 percent to 100 percent. You have the whole span, you can you can set the reflux and the re-boil whatever you want of course, corresponding to that you will get some separation.

In this case where you are trying to control two tray temperatures, it is not very obvious what is the range over T 1 and what is the range over T 2 for which I get a feasible split. So, an operator can end up specifying a split that is infeasible, when you do not have a feasible solution the control system will just try and seek it and some valve will go fully open, another valve may go fully closed, ultimately you will have to shut down the column that is problem number 2. Now, longer towers if your if your towers is long enough problem of interaction problem of interaction is if tray 1 temperature is going up well well likely because of that effect tray 2 temperature is also likely to go up.

If tray temperature tray 2 temperature is going up well tray 1 temperature is also likely to go up. So, there is this problem of co relation between the tray temperature measurements that leads to the ideas that these two, you know the tray temperature measurements need to be sufficiently independent which is related to infeasibility of temperature set points and for two temperature control to generally make sense that means the tray temperatures that you are trying to control are sufficiently independent so that you may try and control them. This happens generally in the case of long towers.

(Refer Slide Time: 30:10)



So, if the towers are sufficiently long you can have two tray temperatures measurements that are sufficiently far apart and then they are relatively independent and then the interaction between them is not as severe and then it makes sense to try and go in for two tray temperature control. So, this is called dual ended control because you are trying to control two tray temperatures not a single tray temperature. So, you have to be aware of the possibility of interaction between the two tray temperature controllers temperature controllers, you have to be aware of the possibility of the control system trying to seek an infeasible set point an infeasible solution and two tray temperature control will generally make sense for columns that are where you get columns that are tall enough.

How much is tall enough? Well that is an art that is not a science so I cannot give a straight forward answer to that. So, this is dual ended control you need to be aware. Let us say distillate is a recycle stream that means the distillate is being recycled back to the

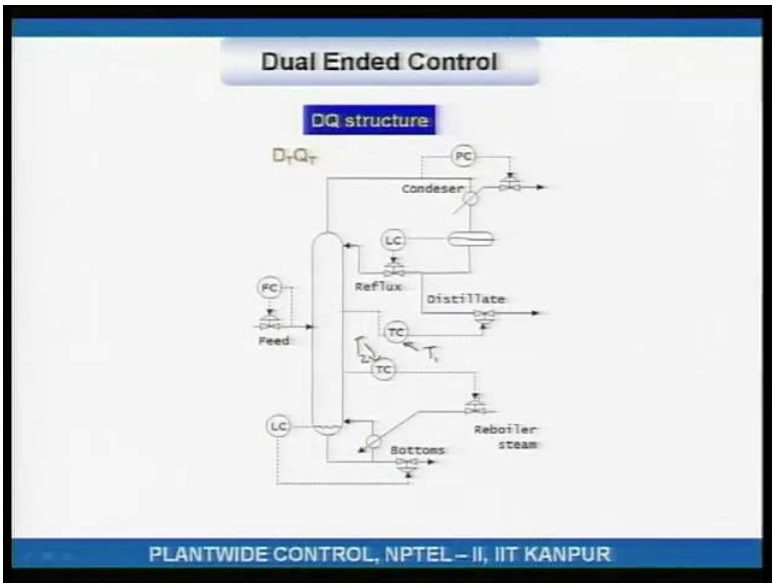
reactor. My main product stream is let us say the bottoms, if that is the processing situation would I be going in for L T Q T? My answer is no. The answer is no because very likely if the heavy key impurity in the distillate goes up all hell is not going to break lose, it is just going to get recycled and come back. A slight increase in heavy key key impurity is acceptable, given that it is acceptable I need not fret about you know trying to control two tray temperatures. Also, notice that because of interaction because this T 1 loop the the reflux loop is going to interact with the re-boiler duty loop.

The control of the temperature on this tray the re-boiler duty loop because of interaction with the reflux loop cannot be as tight. Now, that has implications on tightness of product purity control in the bottoms which is what I am going to sell in the market. So, if I want to tune these two tray temperature loops what I would do if there is a situation that justifies that you are better off controlling two tray temperatures, in that case since the bottom stream is more important what I would do is, I will tune this loop, I will tune this loop to be really tight, this loop would be on manual that means reflux rate is held constant, it is not being adjusted. Once this loop has been tuned with this loop in automatic then I will tune this loop. So, here I will follow a sequential tuning procedure.

Does this make sense or no? I hope it does. This would be called sequential tuning because this is more important. What happens here is important, but not as important. So, in this particular processing situation the way you tune the loops also becomes important because because of interaction if you tune it individually that means this tune, this loop is tuned with this loop off this loop is tuned with the other loop, both loops are tuned with the other loop off. If you do it individually and then take de-tuning what will happen is the temperature control here will not be as tight than if you had tuned this first than if you had done sequential tuning.

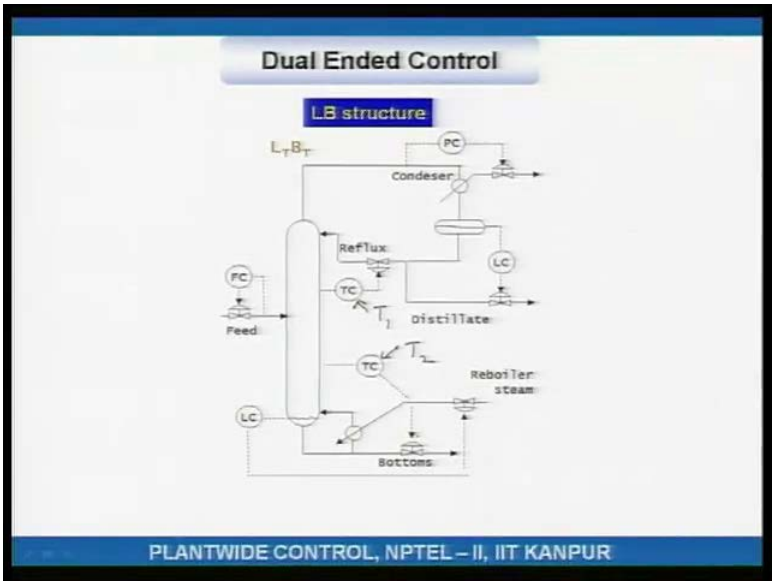
Now, because the temperature controller is not as tight product purity quality variation would be more therefore, you know you will have to operate on average at a at a larger product give product quality give away. What is product quality give away? This was discussed probably I think in the in the first few lectures. So, individually tuning is not recommended here, if this stream is more important than this.

(Refer Slide Time: 34:14)



This is the dual ended temperature control variant of the D Q structure. Well, operator is setting this and this. However, the manipulation handle that is used in this case is distillate rate. In this case it is it is the re-boiler duty. T 2 is controlled as before using the boiler duty.

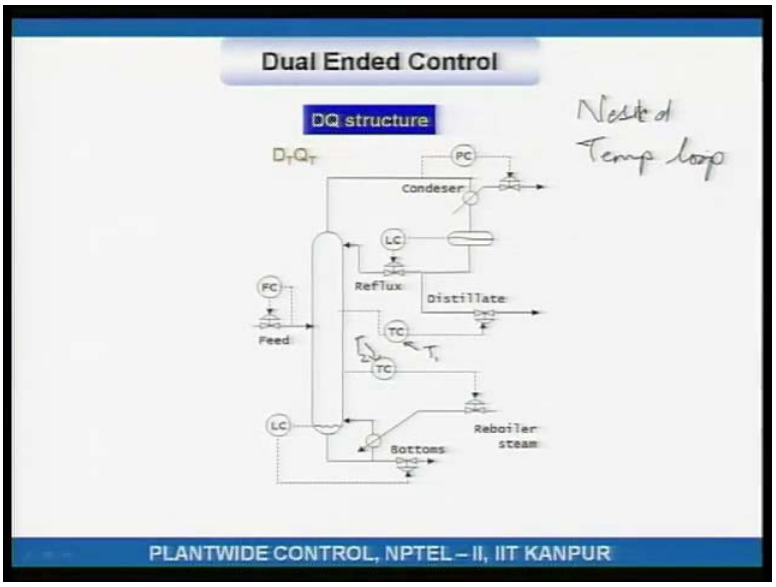
(Refer Slide Time: 34:35)



Here what we have is again two tray temperatures are being set T 1, T 2. T 1 is controlled in the usual way using reflux, T 2 is controlled using bottoms and that is

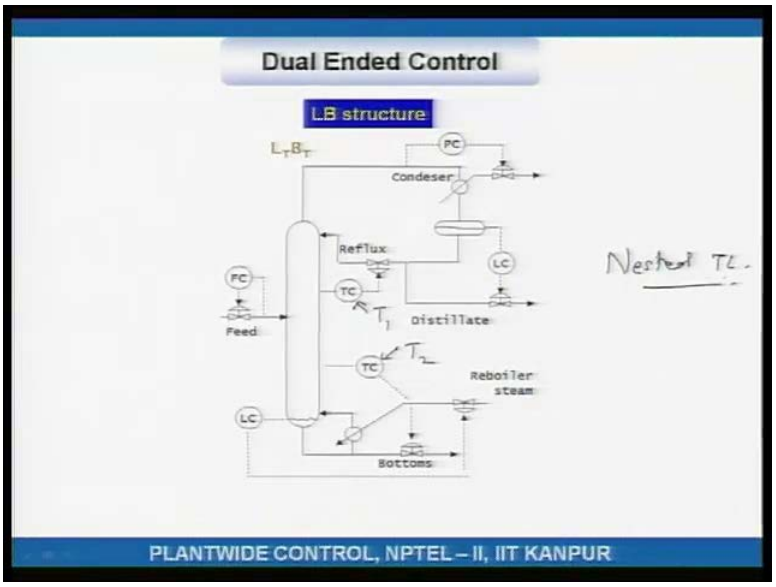
probably because the bottom stream is is very small compared to the total boil up. By the way in both these material balance dual controlled structures for example.

(Refer Slide Time: 34:59)



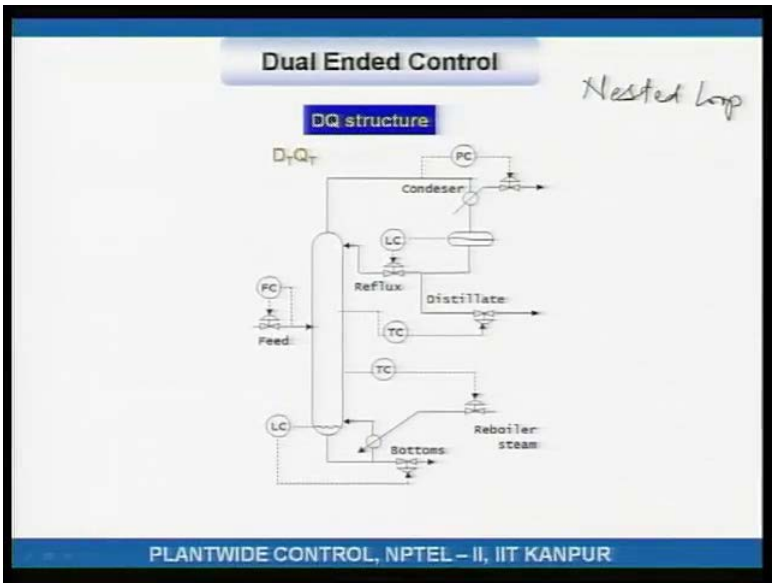
There is what is called a nested temperature loop temperature. What do you mean by the nested temperature loop? May be its better explained here.

(Refer Slide Time: 35:13)



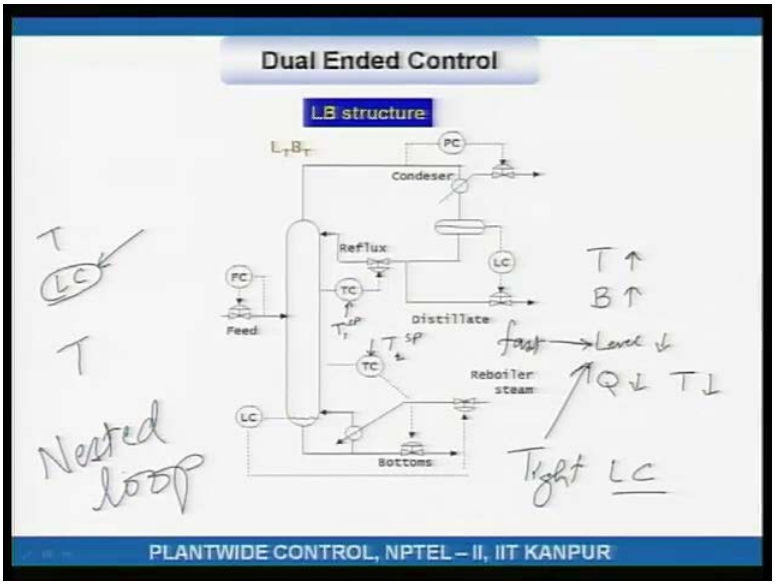
So, this is a, there is a nested temperature loop here. Let us, we were talking about nested loops.

(Refer Slide Time: 35:23)



If you are trying to do dual ended control on a material balance structures that means D Q or L B or even D B that means you are trying to control two tray temperatures in these basic control structures there would be a nested loop and what do I mean by a nested loop?

(Refer Slide Time: 35:44)



Let us look at the nested structures here. Operator sets this set point layer T 2 by convention. Let us say T 2 is increasing, what that means is heavy material is accumulating inside the column. What I would do then I would like that heavy material

because heavy material can only go down the bottoms, I would like that heavy material to find its way out so what what this temperature controller would do is open the bottoms valve. Now, this slow the bottom stream is very small that is when I would use this kind of a basic of of a control structure. Now, since the bottom stream is very small what happens is I open this valve bottom stream is become, is going out, that will take a long time for the tray temperature to get back to set point because whatever material is accumulated for it to flow out would take a long time because the bottom stream by definition is small, by design is small.

In the meanwhile what would happen is if I have opened the bottom stream, the level here will start to go down because more material is flowing out. Now, if the level here is starting to go down what the level controller would do is in order to maintain the level what would the level controller do, level is going down reduce the steam. So, if temperature is going down, if temperature is going up bottoms should go up. As bottoms goes up level goes down, as level goes down in order to bring that level back re-boiler duty goes down. Now, like I said before the moment you change a re-boiler the moment the boil up changes all tray temperatures respond, it is a very fast you know the dynamics is are are quite fast.

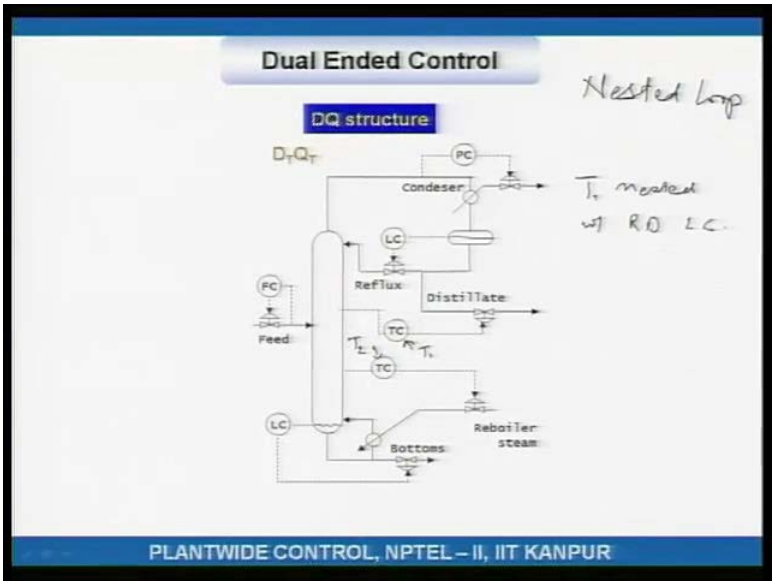
Compare to a change in the reflux for example, so when Q goes down immediately T would go down come back to set point. Now, what that implies is the temperature is essentially getting back because like I discussed a change in bottoms at the same re-boiler duty will take a long long time for the tray temperature to get back, dynamics is very slow. So, if tray temperature goes up I want that tray temperature to get back to set point quickly. What I would like is that this level controller should be fast or fast or rather tight level control. I would like tight level control because a when when my controller gain is large for a small change I will make a large change in the re-boiler duty and that would cause a, an effect on the temperature almost immediate. Is the temperature, is the level controller on the other hand is tuned to be very loose well then the re-boiler duty will change only once the level has changed sufficiently, that again takes a long time.

That is because the bottom stream is small by design. So, here temperature gets controlled because of level control if I if I if my level control is off on the other hand if I have a tightly controlled level control, a tightly tuned level controller my temperature

controller would be much faster, significantly faster. Therefore, it is you know as an approximation you can say temperature is primarily controlled through the action of the level controller. If I switch of the level controller I essentially end up losing temperature control. So, effective temperature control is nested with the level controller being on, if the level controller is off I essentially end up losing temperature control, is this clear or no? I hope it is.

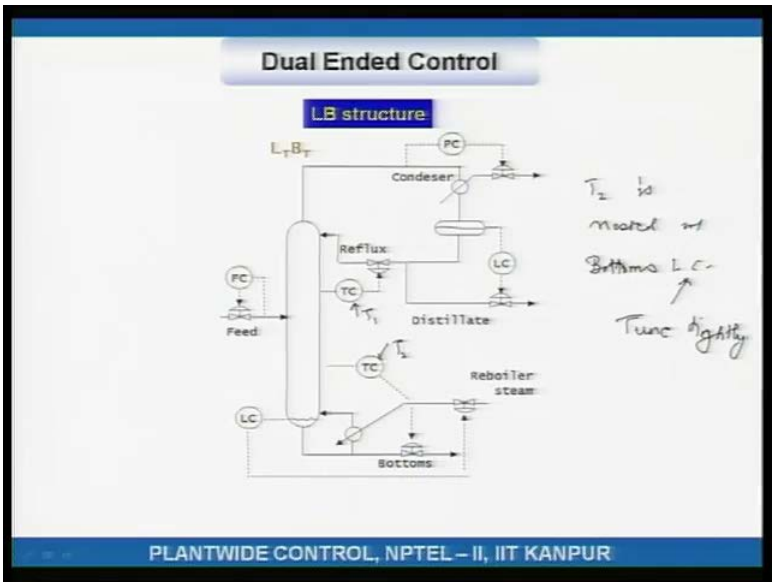
So, this is an example of a nested temperature loop or as a I do not know the convention, maybe it is called a nested level loop, well it is a nested loop nevertheless, the action of the temperature controller depends on whether the level loop is on or not, if it is off you essentially end up losing temperature controller control. This is also an example where you would like the level control to be very tight because the tighter the level control the faster the temperature control, the better the product purity control. So, this is an example of an exception earlier we had discussed surges or surged capacity should be controlled loosely. Well, here you would like the level controller to be actually quite tight in order to get tight temperature control, the tighter the level controller the faster the tighter the temperature control. So, tighter level control will result in tighter temperature control will result in tighter product purity control or rather impurity control in the product. So, this is an example of a nested loop. Here, temperature control is nested with this level control controller I hope you see this.

(Refer Slide Time: 41:39)



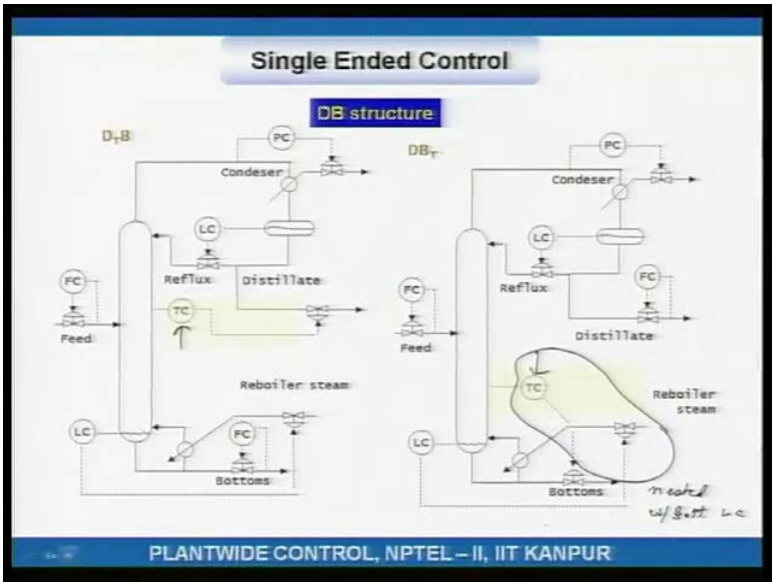
T 1 T 2, so, T 1 is nested with reflux drum level controller. If I call this T 1, if I call this T 2.

(Refer Slide Time: 42:00)



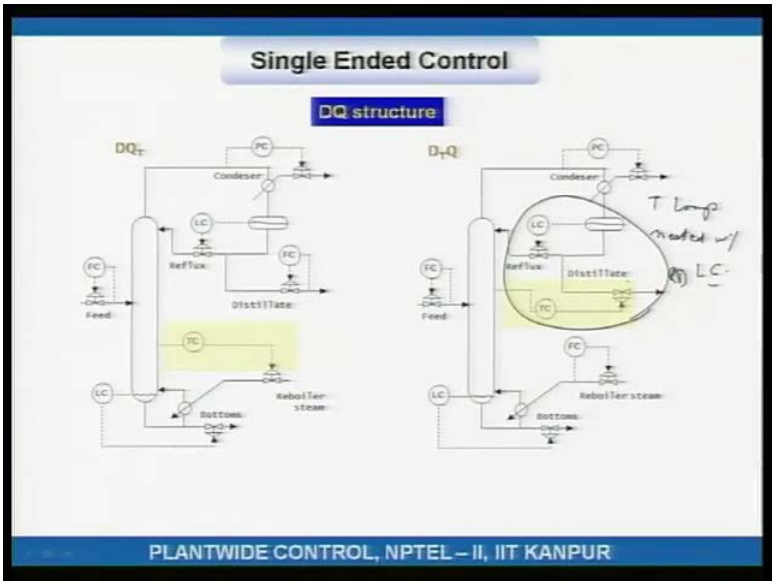
T 2 is nested with bottoms level control. Therefore, this should be tuned tightly, you can also have a nested loop in a in a single ended controlled structure. Let me go back and see if we can, yeah.

(Refer Slide Time: 42:41)



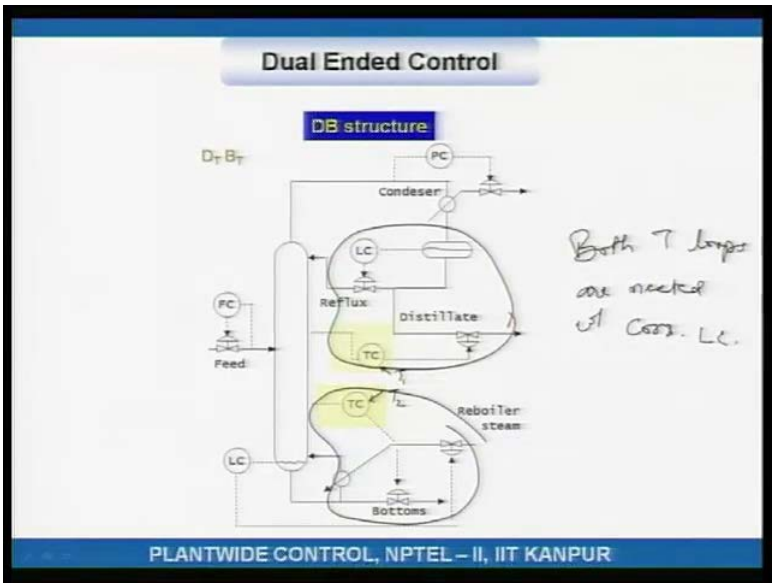
Here it is, is another example of a nested loop, nested with bottoms level controller. Maybe I can get another one L B structure, this is again nested, is that an example of a nested loop here let us see.

(Refer Slide Time: 43:17)



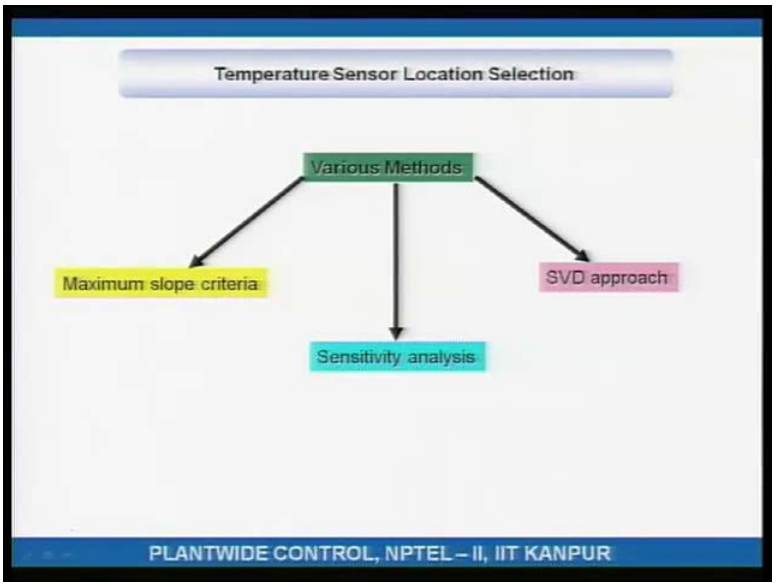
Temperature loop nested with with reflux drum level controller. So, I have a, I hope you see because of the nesting tight level tight tuning or aggressive tuning of the level controller is justified. So, this is the exception to the rule where tight, you know the level controller should not be too aggressive. So, that you know level can can can absorb disturbances in flow, this is an exception to that rule. Another exception that we saw was control of CSTR level. So, we have looked at single ended structures, we have looked at.

(Refer Slide Time: 44:14)



Yeah again here T 1 T 2, notice both loops are nested, both T loops temperature loops are nested with corresponding level controller.

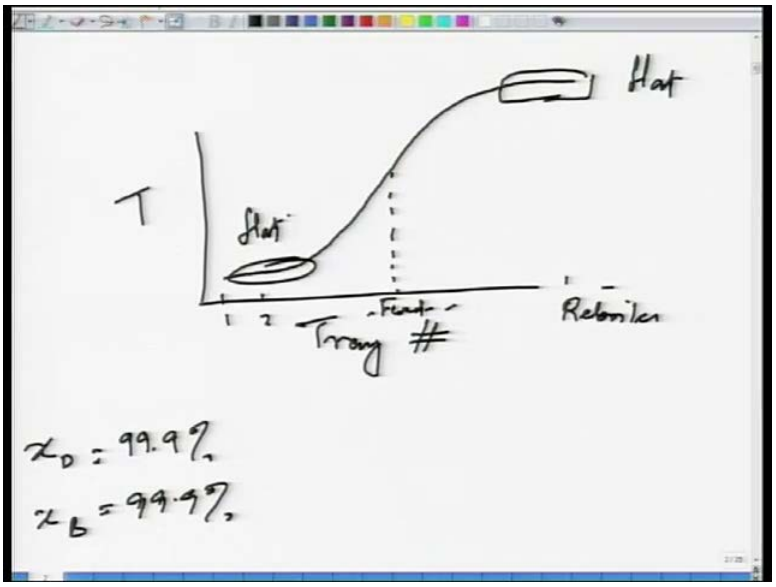
(Refer Slide Time: 44:40)



And another important issue in maybe I should do this, maybe I should not do this. Well, let us I mean let us do it. Now, we have just taken on faith there is some tray temperature that I try and control here, there is some tray temperature that I try and control here, is there a systematic way of figuring out what tray temperature is bay, would be would provide me the most effective quality control. So, there are various methods that have

come into being and I would probably cover there is the maximum slope criteria I will discuss this briefly, there is also sensitivity analysis, there is SVD approach however that require some familiarity with singular value decomposition and and I I may or may not cover that, we will see.

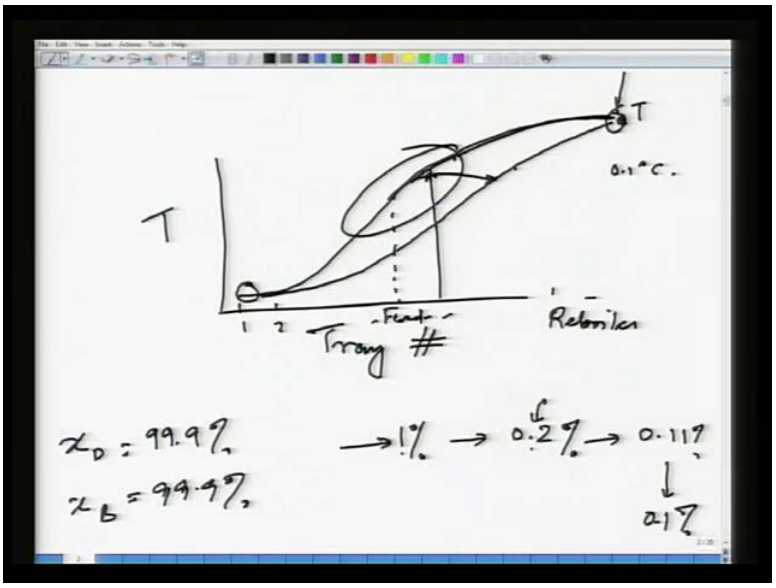
(Refer Slide Time: 45:33)



Maximum slope criteria, if I look at tray temperature so let us say this is tray number and this is the tray temperature and let us say I am doing bottom, top down numbering. So, the top tray is tray number 1, tray 2, tray 3, tray n. So, this is tray number 1, tray number 2 blah, blah, blah. Finally, I have got the re-boiler.

Now, like I discussed, since the light stuff accumulates towards the top of the column, heavy stuff accumulates towards the bottom of the column what we have is the coldest place inside the column will be the top, the hottest place inside the column will be the bottom and I would also like to point out that suppose you want 99.9 percent pure distillate x distillate x bottoms, let us say 99.9 percent. Let us say you want a pure split, you know a sharp split, distillate is pretty pure bottoms is pretty pure. In that case the tray temperature profile would look something like this. Let us say this is the feed tray, this is where I am putting in the feed. Why do I have this flat zones in the temperature profile?

(Refer Slide Time: 47:37)



Well, this flat zones are there because in these few trays towards the top and in these few trays towards the bottom my product purity or rather the impurity level is being decreased from say 1 percent, you go to the next tray the impurity level would be 0.2 percent, then let us say the impurity level goes to point I do not know 0.11 percent and then it goes down to 0.1 percent. You see in these last four trays, here the material or whatever the tray composition is essentially all of the light material plus 1 percent impurity, you go to the next tray it is still mostly light material plus lesser amount of heavy impurity.

You see the tray temperature here and the tray temperature corresponding to this will be very similar and therefore, I get this flat zone here which is indicating that my product or my stream is being purified incrementally. On the other hand when I look towards near the feed tray you know look at this zone tray temperatures changes by a large amount as I go from one tray to the next. What that means is that the tray composition is changing by a large amount as I am moving from one tray to the next, either up or down near the feed tray. So, let us say I want, you know if you ask common sensical or rather non sensical approach would be okay this is where my product is, this is where I should control my temperature.

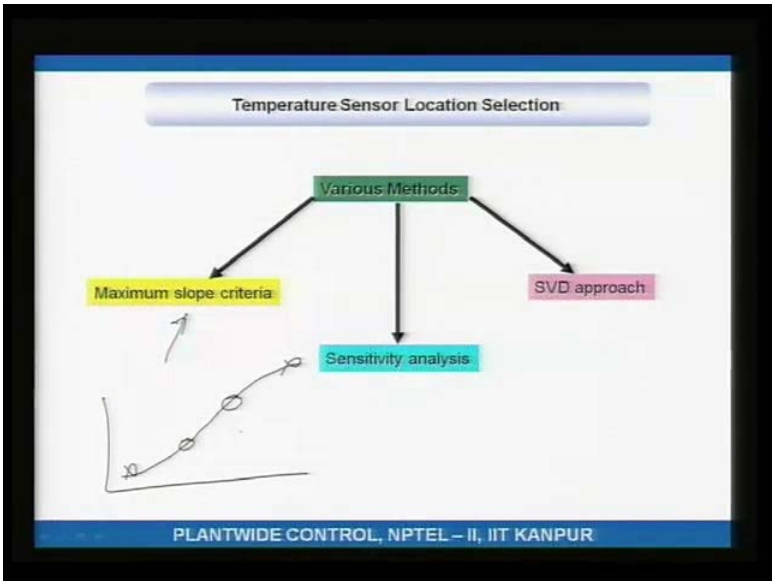
Well guess what if you are controlling this tray temperature the profile may become like this and the change in the tray temperature at the bottom towards the bottom may only be

0.1 0.2 degree Celsius. Your whole separation profile has moved down the column and yet you see only a 0.1 degree Celsius change in the bottom tray temperature. You see all measurements are noisy, tray temperature measurements are also noisy, the noise in the signal itself may be of the order of 0.1 degree Celsius and then you may say well nothing has happened to this tray temperature, well all hell has broken loose, your whole temperature profile has gone from here to here. The separation has changed dramatically, yet if you are trying to control this tray temperature or alternatively by the same logic this tray temperature one would be lead to believe everything is alright. Please note everything is not alright.

So, what this leads to is the simple understanding that you would like to control a tray temperature where the slope with respect to tray number is large. Why do you want that? You want that because a large change in tray temperature when you move from one tray to the next indicates a large amount of separation, you want to hold a separation constant if you hold that tray temperature constant the profile will not be allowed to move the way I have shown here, if you if you hold for example, this tray temperature constant this profile can never drop here.

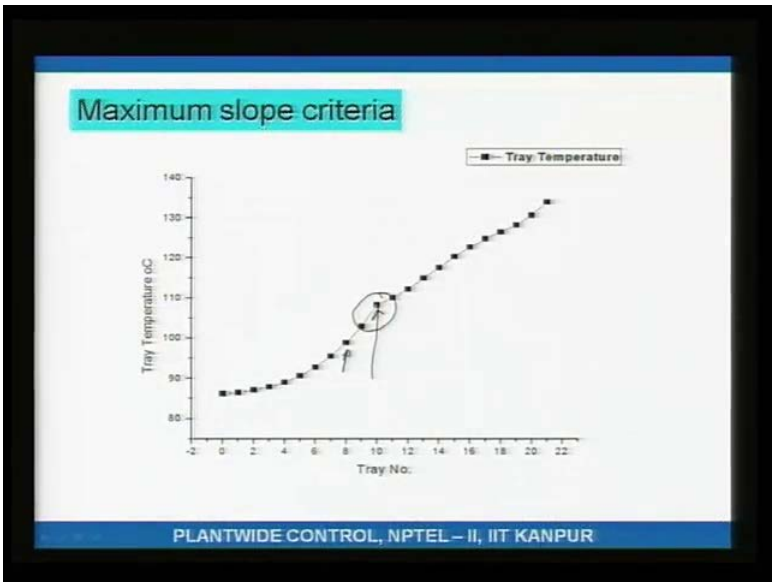
So, this is what is not known as the maximum slope criteria. Maximum separation inside the column is occurring where the tray temperature change as you move from one tray to the next tray is the largest and so we go back to the maximum slope criteria.

(Refer Slide Time: 51:04)



I just discussed with you the maximum slope criteria, what we are trying to do here is look at the profile wherever the slope is maximum or large at least the slope should be large that is a decent location for the tray temperature to be controlled. So, you would like to control a tray temperature for example, here may be here, but certainly not here, certainly not here.

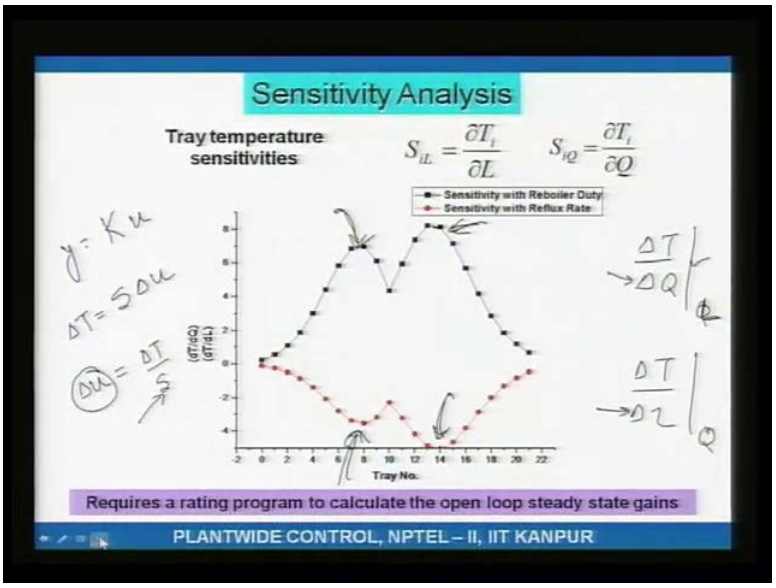
(Refer Slide Time: 51:35)



So, this is the maximum slope criteria if I look at it I may want to control this tray temperature because this is where of course, the feed is here, you never control the feed tray because temperature of the feed tray may change because of two reasons either the condition of the feed is changing that means the feed is hotter or colder, that would cause a change in the temperature on the feed tray or the separation itself is changing.

So, on the feed tray you never know whether temperature change is due to change in separation or due to change in the feed condition. So, feed tray temperature is usually not controlled, but around the feed tray you may I mean you may, you know this would be okay. It appears here that the temperature change is large, but however you would not control this tray because this happens to be the feed tray. So, this is the maximum slope criteria.

(Refer Slide Time: 52:28)



Sensitivity analysis what you do is you take, you got your column it is running at constant reflux some Q, you make a small change in Q all the tray temperatures would increase because you have increased the re-boiler duty by a small amount let us say 1 percent. So, change in temperature over change in Q you can get. Similarly, you can also get change in temperature over change in L note here Q is held constant. Oh sorry L is held constant L is held constant, over here Q is held constant. The, this is called sensitivity. Sensitivities of the tray temperatures to the change in the control input either Q or L. If you plot the sensitivities I know time is up, but nevertheless tape can run run for 40 minutes so will continue. I will finish this topic.

So, if you if you if you make, if you make a plot of this sensitivities you can see that here is a sensitive location, here is another sensitive location, here is a sensitive location, here is a sensitive location. So, I may control a tray temperature which is here let us say this one using re-boiler duty and this tray temperature using reflux. The sensitivities themselves are indicating these are two sensitive locations in this example column where sensitivity is pretty large. Why do you want to control locations with large sensitivity? Well this goes down to you know y is equal to K K u. Change in temperature so delta T is equal to sensitivity times delta u which could be change in Q or change in L. I will just call it delta u. Now, if this sensitivity is large then what that means is delta u for should be delta T over S. Larger the sensitivity smaller the amount of control effort that I have to put to bring that deviating temperature back to set point, the better of I am.

Maximizing the sensitivity in some sense minimizes the control effort that I have to put in in order to bring that deviating temperature back to set point. Therefore, you would like to control tray temperatures that are very sensitive and from that criteria what you get is I may want to control this, this, this or this. There is also also the by the way the one thing the one comment that has come up here is you will you do not have the liberty for example, in an industrial setting to change the tray you know reflux rate and figure out how much the tray temperatures are changing and which is the most sensitive location, probably you will never get to you know have the luxury of doing this kind of an experiment.

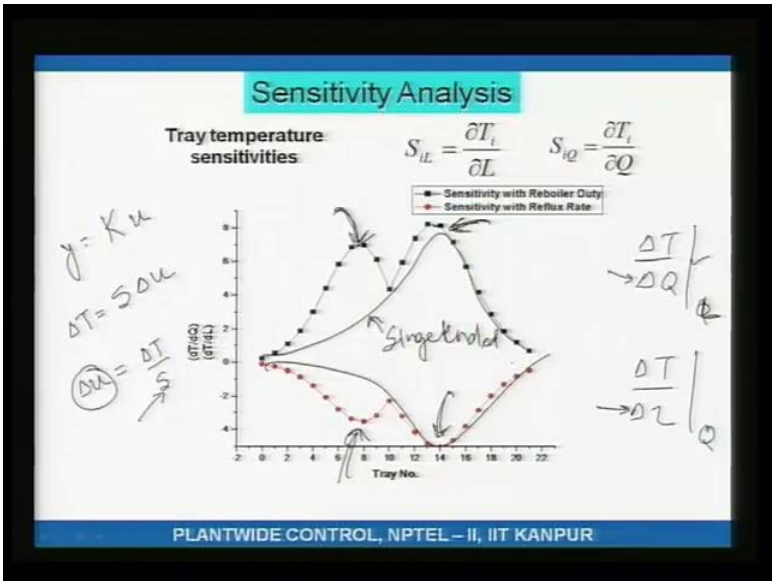
So, to get sensitivities what you would do is you would use a commercial distillation solver, distillation column modular or simulator try and fit your model or your simulation as best as you can with your actual process and then on that program on that simulator do a sensitivity analysis. So, this sensitivity analysis will require a rating program to calculate the sensitivities. So, in in using that rating program, using that simulator you can make a small change in reflux figure out how the tray temperatures are changing, you can make a small change in the Q, figure out how the all the tray temperatures are changing, calculate your sensitivities, plot it, figure out okay this, this, this, this and this.

So, it requires a rating program. On the other hand this maximum slope criteria, I mean typically distillation columns are very instrumented, you will have tray temperatures for a lot many trays in the column and just by looking at that profile you can sort of figure out this seems large slope is here, large slope is here, maybe we should control this tray temperature or this tray temperature.

So, maximum slope criteria is you know very basic, sensitivity criteria is slightly more sophisticated requires a rating program, singular value decomposition criteria which we are not going to talk about it is what you do is you take the sensitivities, perform a since a singular value decomposition of the gain matrix or the sensitivity matrix and from the similar vectors figure out what tray temperature has to be controlled. Well then you need an additional singular value decomposition you know a piece of code that will do the singular value decomposition for you. So, that is slightly furthermore more what should I say, requires a little more sophistication.

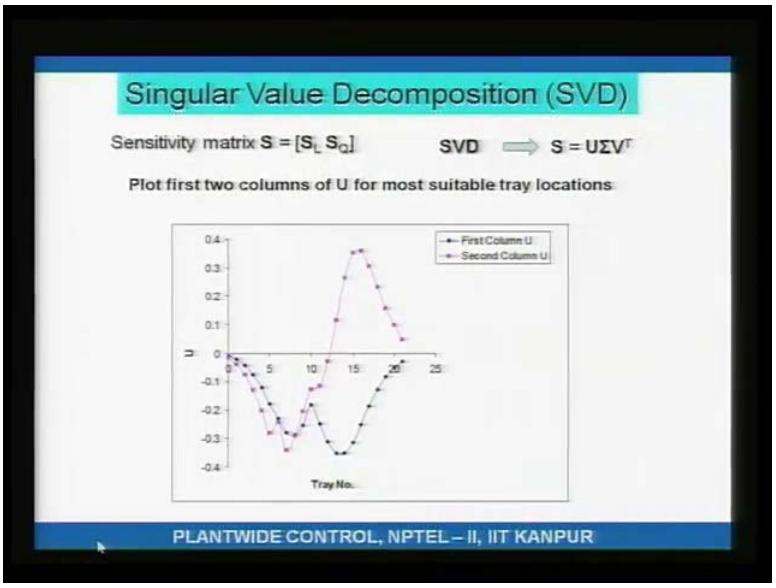
So, how do you select tray temperatures? You do a sensitivity analysis and if you are trying to do single ended control, control the most sensitive tray with Q for example, in an L Q structure, if you are trying to do dual ended temperature control well your sensitivity analysis will show you for example, this sensitivity plot is showing that I can control this and or this. There are two sensitive locations inside my column. So, I can control two tray temperatures. You may have columns that are very short; in those cases what you will find is that getting two getting two locations which are sensitive does not, you know the sensitivity plot may look something like for example like this.

(Refer Slide Time: 58:10)



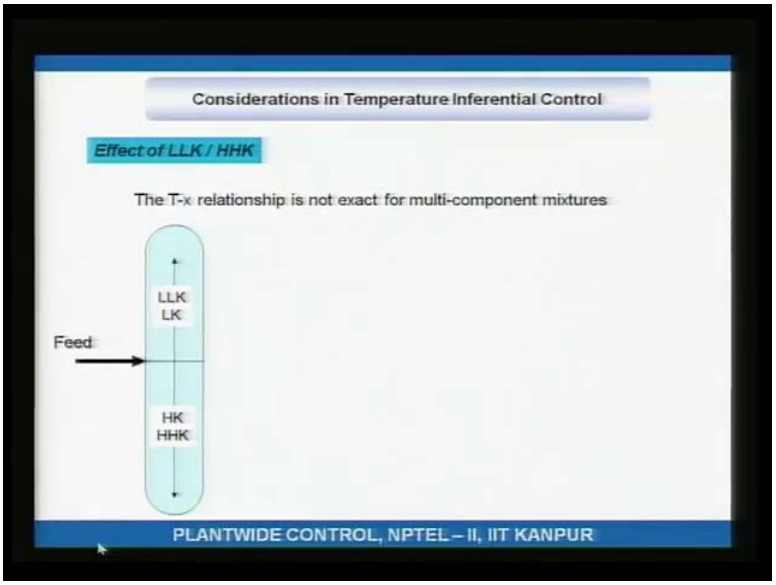
If the sensitivity plot looks like this I would not go for dual ended temperature control. So, on such a column where the sensitivity plot is like this I would recommend single single ended, single ended. If my sensitivity plot is like what it is shown here, well this sensitivity analysis is showing that there are indeed two locations that are highly sensitive and therefore, they should be reasonably independent and I may control this tray temperature and this tray temperature and that tray temperature.

(Refer Slide Time: 58:52)



Singular value decomposition same thing is just that I do not want to discuss it.

(Refer Slide Time: 58:57)



From next time onwards what we will look at is you know we have con, we have covered control structures, we have control you know the basic control structure, single ended control, dual ended control. What other considerations you must be aware of so that you may be able to figure out what is going on when you are operating a column, what is going on. These other considerations which may actually cause you know which will help you troubleshoot operations, this we would cover next time.