Plantwide Control of Chemical Processes
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Lecture - 12
Control of Distillation Columns

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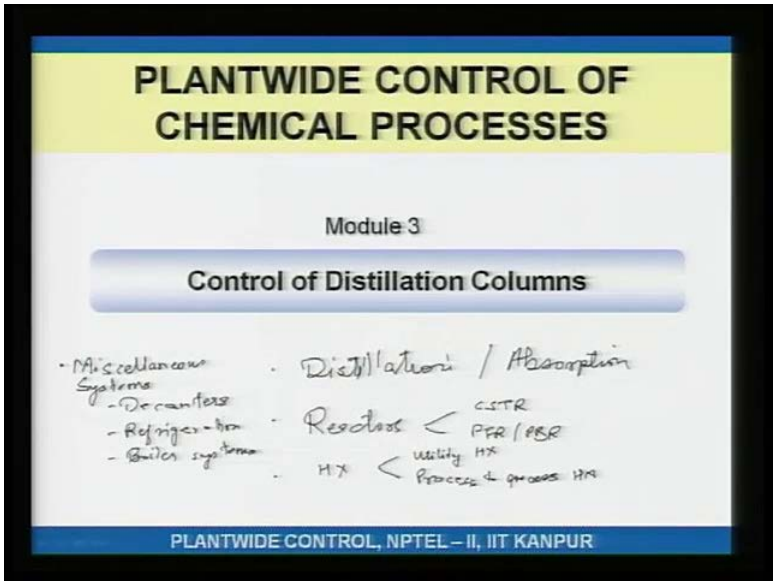

We are going to be looking at common unit operations that are used in chemical processes, their control. So, the most common unit operations that are there in industry are distillation well separation units, distillation columns. We also have absorption towers, then we have reactors which are the heart, which which is where the value added product gets gets produced and reactors basic reactor types you know CSTR, plug flow reactors, packed bed reactors and a combination there off then.

We have got you know heat exchangers, and heat exchangers can be of different types they could be utility heat exchangers. Utility meaning they either use steam or cooling or a coolant such as cooling water for either heating or cooling a fluid, a process fluid, a process stream, utility heat exchangers and there could also be process to process, process to process heat exchangers. Then we have got miscellaneous systems and maybe I should write write miscellaneous systems here.

Miscellaneous systems and in these miscellaneous systems you know we have got decanters, you have got refrigeration systems, you have got boiler systems and so on so

forth. So, these individual units that are quite common, which would which which you would see in a in a chemical process the control of these individual units is what we will cover over the next so many lectures may be 15, 20 lectures and once we have looked at these individual units, then we will consider control of a whole complex plant, which is got all these units which are interconnected to each other and we also have material recycle and or energy recycle, Heat integration. So, that is the plan right now.

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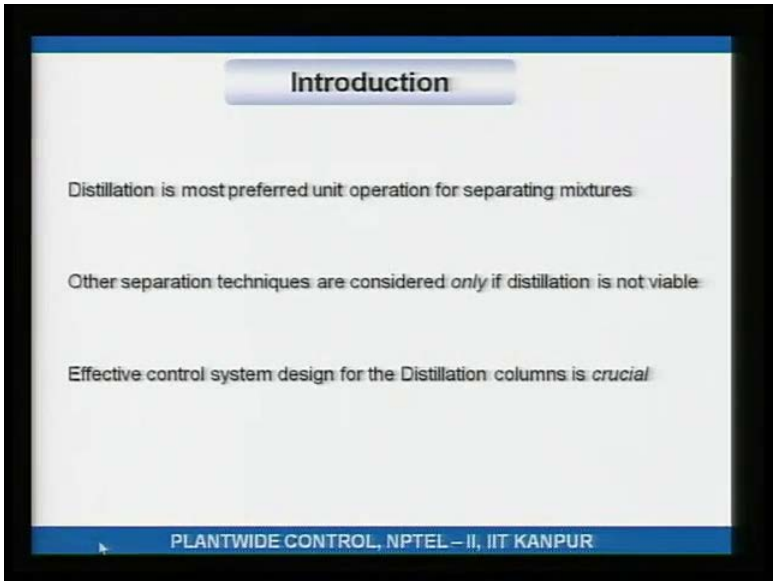

What we are going to do? So, today's next may be 5, 8 lectures would be on the control of distillation columns and why distillation columns because distillation is probably the not probably it is the most preferred unit operation for separating mixtures.

Why do we need to separate mixtures? You see because the effluent from a reactor will always be a mixture of products and un reacted reactants. It will be very rare that you will get complete conversion of the reactants and the and the effluents from the from the reactor is pure stream that can be sold in the market. So, you will have to have some sort of separation of whatever is coming out of the reactor so that you can make pure product, which is that value added chemical which is sold in the market?

Then you also require separation may be because the raw material has got certain sets of impurities that need to be removed and even there probably distillation can be used. Note that other separation techniques such as absorption, liquid liquid extraction, adsorption, pressure swing adsorption etc are considered only if distillation is not viable and what do

we mean by distillation is not viable is, other separation techniques are considered only if distillation is not viable and what do I mean by distillation not being viable is, the volatility of the compounds that are to be separated are are are are similar.

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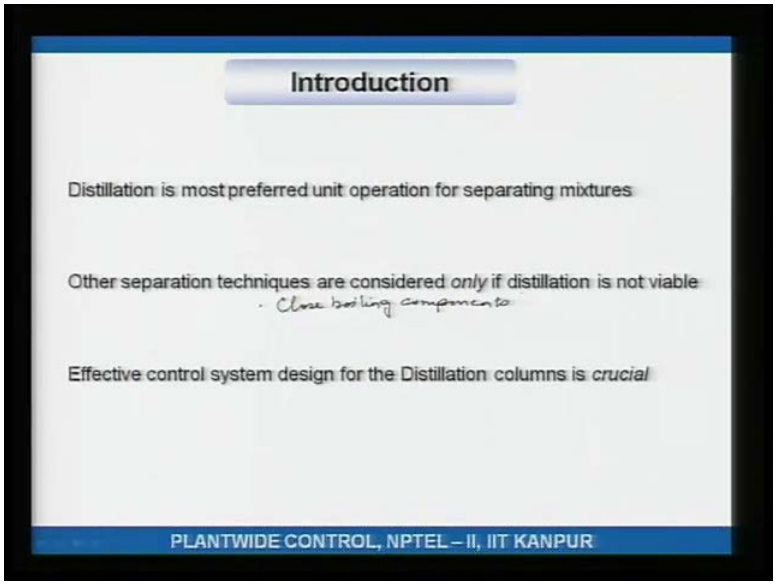

So, that is known as, you have got close boiling components If the close boiling components if the if the components have close boiling points then separation by distillation becomes difficult. You will have a very large tower to get the kind of separation that you want and may be in that case you may consider extraction and or or some other technique. Since distillation is one of the most common unit operation that any plant will have, effective control of distillation columns must be properly understood. It is it is I would say essential so that is what we are going to do distillation basics.

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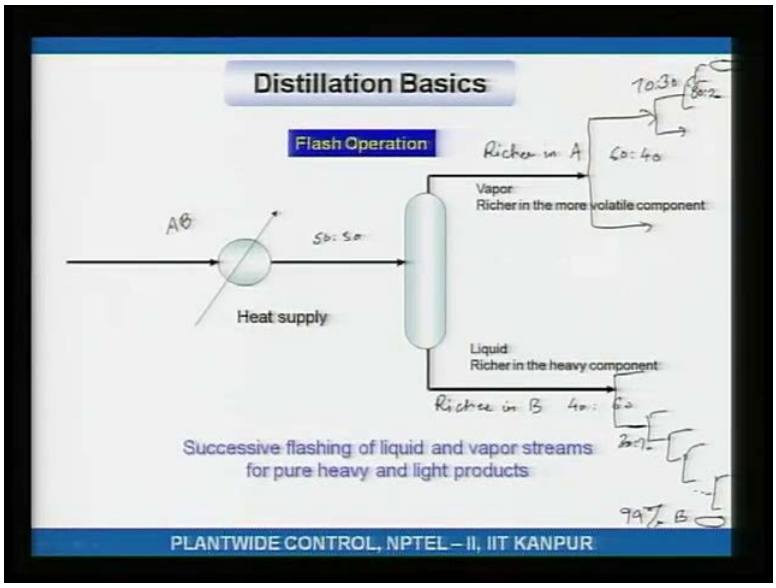

Well let us say you have got a feed stream. It is a mixture of let us say two components A and B. I just say A and B. Let us say A boils at A lower temperatures than B, so A is more volatile than B. B also boils so it is not that B is non volatile both are volatile however, volatility of A is more than that of B. What that means is boiling temperature of pure A is less than boiling temperature of pure B. You heat it up and partially vaporize this stream and then you draw out the vapor and the liquid. So, let us say it is a 50 50 mixture. Now, since A is more volatile than B, what you would get up there is a let us say a 60 40 mixture and let us say here this would be 40 60.

So, the vapor is richer in A which is the more volatile component that is what I have written here and the bottom is richer in B which is the heavy component. So, we have achieved some sort of separation in the sense that what was 50 50. Now, I have got a vapor stream that is richer in A and a liquid stream that is richer in B. Now, imagine if I take this liquid, if I take this vapor liquefy it and partially vaporize it, again that means I do the same flash operation. Again I will get a vapor stream that will probably be 70 30, then I take this vapor stream liquefy it and partially vaporize it again what I will get here? Then probably will be, I do not know 80 20, keep on doing it and so on so forth, up there you will get something that will be nearly pure, nearly pure light component.

Similarly, I can take this bottom stream, liquid stream flash it again. Well the the the liquid that remains would be richer in B again so maybe this will be 30 70, I keep on doing it

again and again and again and hopefully after I have done it enough number of times, what I will get here will be let us say, I do not know may be 99 percent B. So, in distillation what we are want, so so the way to understand distillation is we are trying to do successive flashes so that because of those successive flashes we end up getting nearly pure A and nearly pure B. So that is one way of looking at distillation.

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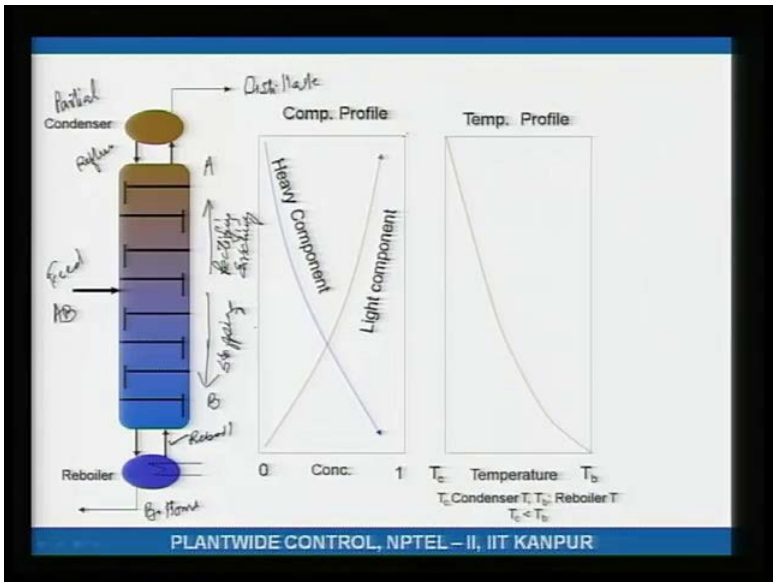

In a column we do not have separate flash tanks, what we have is a bunch of trays and it is, in these trays that you are you are getting successive flashing of the liquid and the vapour. So, you have got a feed, you have got a reboiler and you have got a condenser and the way it is drawn right. Now, the the distillate, which is out here this is the distillate distillate feed and this would be called a bottoms. So, you have got the distillate, you have got the feed, you have got the bottoms. So, imagine the feed is let us say liquid, the liquid will drop onto the trays, the trays will fill up and the liquid will overflow on to the next trays so then you get liquid on all the trays that are below the feed.

Then the reboiler will fill up and then you start putting in steam, what will happen is, you will start getting this. What is called the boil up, liquid will get boiled up, it will rise then you get into the condenser in the condenser you have got cooling water flowing. So, the liquid will condense, part of it gets refluxed back. It is a partial condenser so all of the liquid all of the vapor all of the vapor is not condensed, only part of it is condensed which is refluxed back, this is reflux, this is called reboil, distillate feed, re bottoms reflux and reboil

and this is actually a partial condenser. The way it is drawn, it is a partial condenser. Now, you can see what will happen on each of the trays you have got vapor liquid contact and some of the vapor would condense because it is getting in contact with cold liquid and because the vapor is hot some some of the liquid will get volatilized and the principle of flash is, when liquid vaporizes it will be richer in the lighter component and when vapor condenses partially, it will be richer in the heavier component.

So, you can see what will happen is, as you go down this column the liquid will be progressively richer and richer in B. Let us say this is an A B feed, A being the light component B being the heavier component. This will be progressively richer and richer in B as you go up the column, you will get on the tray the composition of A being progressively more and more. So, if you look at it from the perspective of the more volatile component which is A, this is called a rectifying or the enriching section rectifying or enriching section. Below the feed is what we call the stripping section. Why are they called so is because if I look at my composition on the trays of the more volatile component, which is A, as I go up above the feed I will find that the composition of A in on the liquid trays is getting enriched, the trays are getting enriched in A. That is why it is called the enriching section.

On the other hand if I go down below the feed and I look at the liquid tray composition what I will find is, A is getting depleted. The the composition of A is getting becoming less and less and less. So, A is getting stripped away. Hence, this below the feed section is called the stripping section, alright. If you look at the composition profiles, well this is the top of the column, this is the bottom of the column a mole fraction from 0 to 1, you will find that at towards the top the heavy component composition is very small, light component composition is close to 1 and as you go down towards the bottom of the column, you will have the the light component composition is very small, heavy component composition is nearly 1.

Nearly pure B, nearly pure A nearly pure B at the bottoms nearly pure A at the top, if you look at the temperature profile each of the trays is at its bubble points that means because you have got liquid and vapor it is boiling. So, each of the trays is at its boiling temperature and since A boils at a low being lighter boils at a lower temperature and B being heavier boils at a higher temperature, what you will have is the top of the column will be the coldest place in the column and the bottom of the column will be the most hot place in the column. In between you will have a typically a monotonic rise in temperature as you go down the

column. Lightest place and then as you keep going down and the temperature would keep on increasing.

There are there can be a exceptions to this because of non idealities but typical columns or if you have got a reactive distillation column typical ordinary distillation columns that are separating ideal mixtures temperature would be the coldest at the top highest at the bottom and as you go down the temperature will monotonically increase. So, that is the temperature profile that you have in in most ordinary distillation columns. This is called a simple distillation column. It is a simple distillation column, in the sense that you take one feed and you make two product streams, the distillate and the bottoms. There are no side draws etcetera, etcetera. If you have for example, side draws from a column then what you would call them are complex columns.

So, this is a simple distillation column. Anything beyond this where you are taking a side draw and stripping it or taking a side draw and rectifying it or having a pre fractionators and then male column, main column etc those are called complexed column configuration, this is a simple distillation column configuration. Just, so that we get our nomenclature right. So, this is a simple distillation unit, consists of a rectifying section and a stripping section, two product streams and one feed stream.

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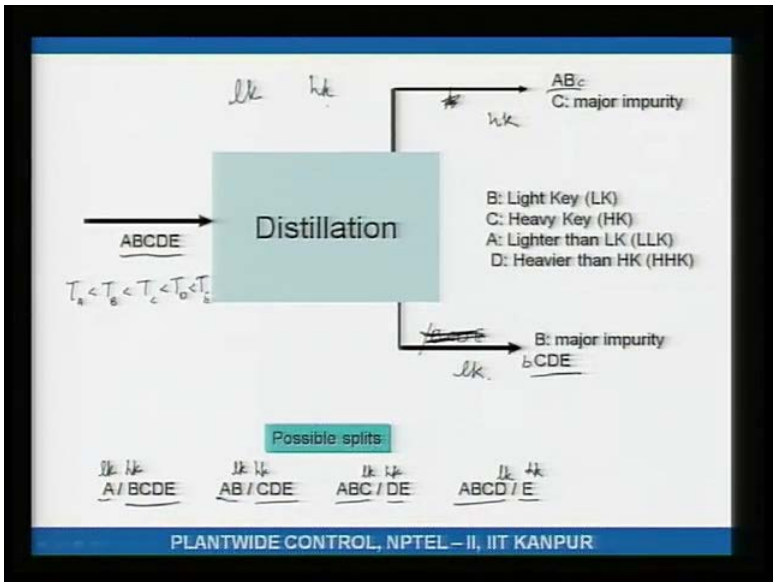

Let us say I have got A B C D E these are my components in the feed stream. I split, I send it to a distillation unit and the volatility of these A B C D E is in decreasing order. What that

means is, A is the most volatile that means it has the lowest boiling temperature, B is next C is heavier than B, D is heavier than C and E is the heaviest component. Temperature boiling of A is less than temperature boiling of B is less than temperature boiling of C is less than. By by definition we will always have A will be the lightest component and whatever is the last component that will be the heaviest and whatever is in between B C D E, the those would be in in decreasing order of volatility by definition by convention.

So, I take A B C D E and I distillate, I can distillate so that I get all of the A going up the top the remainder of the components going down the bottom so B C D E go down of course, some amount of B impurity will be there here, because B is the next most volatile component some amount of a impurity will be here in the bottoms. So, the split is between A and B. A is being sent to the top, B is being sent to the bottom. Some amount of B comes out the top, some amount of A comes down the bottom. So, in this case, the distillate the major impurity in the distillate is B. The major impurity in the bottoms is A. If I do not worry about these things, I could have what is drawn here, I take A B up the top components.

A and B go up the top the remainder of the components C D E A B go up the top C D E go down the bottoms and now the next close boiling component to B is C so C will be the major impurity in the top and the close next, close boiling light impurity to C is small b. So, the major impurity in the bottom will be small b. Well well component b small b big B. So, I can have any number of splits of this type so what I have is, I could have A going up the top B C D E going down the bottoms. I could have a B going up the top C D E going down the bottoms, I could have A B C going up the top D E going down the bottoms. I could have pure E E going down the bottoms everything else going up the top. These are the different types of splits.

And by convention wherever I draw this split line, this is called light key this is called the heavy key. In this split light key would be B heavy key would be C, in this split light key would be C heavy key would be D, in this split heavy key is E light key is. So, the split is between these key components, light key is light key means light key goes essentially to the top everything else goes down the bottoms. Heavy key and any, when I say something is a light key, what that means is all of it is going up the top and everything lighter than this is also going up the top. When I say something is the heavy key what I mean is this component and anything that is heavier than this component is going down the bottoms.

Now, with this convention what I can I I suppose you will see what I am trying to say is that, the principle impurity in the distillate is the heavy key. Principle impurity in the bottoms is the light key. That is another way of saying that what my enriching section is doing I get the distillate after enriching the feed stream, I get the bottoms after stripping the feed stream right. So, what my enriching section is doing is preventing the heavy key from leaking out the top, what my stripping section is doing is preventing the light key from leaking down the bottoms. So, what is the function of the enriching section? Its function is to prevent heavy key from leaving leaking up the top. What is the function of the stripping section? Its function is to prevent the light key component from leaking down the bottoms. I think this is this should be pretty clear in plain English.

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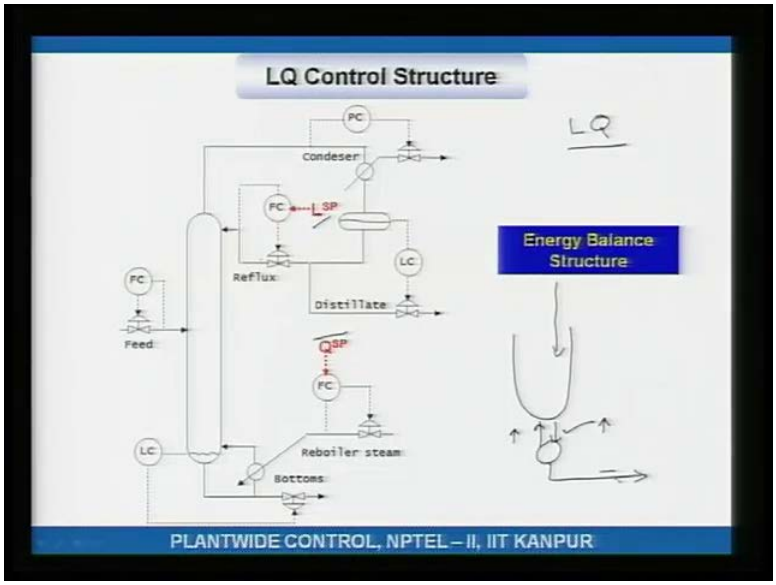

Now, let us start looking at some basic control structure types for a simple distillation column. Like I discussed you need to control at least 3, you need to basically control the pressure and the 2 liquid levels that has to be done Now, the valve or the set of valves that you used to do this, gives certain basic control structure types the first one is called the L Q control structure. In the L Q control structure what we have is, the reflux drum level is controlled by the distillate, the bottom sump level is controlled by the bottoms product stream, the pressure is controlled by adjusting the or the coolant flow rate in the condenser.

Once I have oriented my level and pressure loops like this, what is left then I have got of course, the reflux under flow control and the steam under flow control. The operator can

then adjust the set point of the reflux which is this guy and the set point of the steam flow which is this guy, that determines how much is being re-boiled. So, the operator is then free to adjust L and Q to get the kind of separation that he wants. Ok therefore, it is called the L Q structure when Ii change the Q, I am essentially changing the energy balance around the column. If I increase for example, L then you may appreciate if I this this is what I have in the column. Let us say my L has gone up, the amount that I am taking out the bottoms L has gone up therefore, the amount of liquid that is coming into the re-boiler has gone up.

Since I want all the components that are heavier than the heavy key and the heavy key to get out the bottoms, this flow rate will typically be this flow rate wont vary much, the bottoms flow rate because I I want a certain desired separation. So, if L has gone up this is gone up this is the same as so so reflux has gone up therefore, this stream has gone up. This is the same as before therefore, this must also go up, just by material balance, right. If this is more this is the same as before or nearly the same as before the boil up must be more so what that essentially means is if I reflux more re-boiler has to go up right.

So, no matter what I do when I am changing either L set point or Q set point, I am essentially changing the material adjusting the energy input to the column and hence this is called an energy balance structure. By the way the L Q structure is the most L Q structure and its higher derivatives. This is the most commonly used control structure in distillation columns and you can sort of see it from your text bookish knowledge, that you may have covered in mass transfer etc etc There is what is called the reflux ratio, there is what is called the reboil ratio and really speaking it is the reflux and the reboil, that is giving you the flashing on the trays right. If you have no reboil, the you know the the trays in the stripping section will be essentially pure liquid trays.

Similarly, if you do not have any reflux, the trays if you do not have any liquid reflux, the enriching section would not function because there is no liquid so there will be no flashing on the enriching trays right. So, in the absence of reflux and or reboil, it is essentially reflux and reboil that is giving you the separation and that is what the operator adjusts L or Q the reflux or the reboil to get the kind of separation that he desires this is sort of a natural control structure and most distillation columns usually, will use this type of a control structure. There are exceptions and those exceptions will discuss in just a moment.

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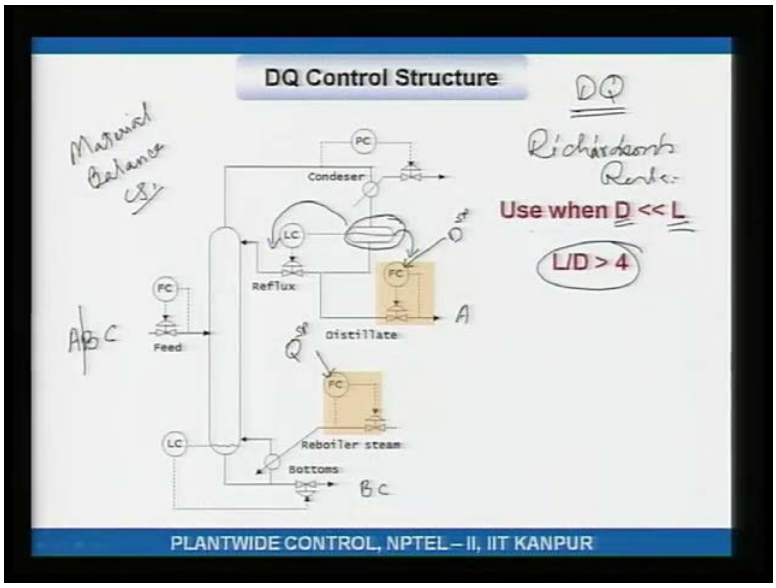

Earlier I had oriented my level controller like this, now my level controller is like this. Let us just say, I have a choice instead of using the distillate to control the level, I am going to use the reflux to control the level. Bottoms is as before, pressure control is again using the cooling water condenser. In this case the two set points that remain for the operator to adjust are these, D set point and Q set point therefore, it is called a D Q structure. My level controllers and pressure controllers have been fixed. After they have been fixed what remains in the hands of the operator to get the kind of separation that he desires, the two things that remain in the hands of the operator are the distillate flow rate, how much distillate is being drawn out? How much steam is being put into the column.

Notice that this is a, this is called a material balance structure. When you change the distillate rate, if you increase or decrease the distillate you are directly changing the material balance around the column, you are directly changing the feed. You see if the feed is 100 earlier you were taking out 50 at the top 50 at the bottom now, let us say 50 goes to 60 you have directly changed the split that is occurring in the column. Therefore, it is called a material balance control structure, material balance control structure Now, why would you choose to control level using reflux and not the distillate?

Well remember the Richardson's rule. Richardson's rule says, Richard Richardson's rule, this essentially says that you should control level using a big handle. Big handle meaning using a large flow stream. Now, consider for a second a case, where the let us say I am I am

having A B C coming in. Let us say A is a you know the component flow rate of A is small a is sort of like an impurity, I take out A up the top and B C down the bottoms. Now, by definition because A is coming in small amounts, the flow rate of this distillate will be small. Reflux is of course, may be 4 or 10 times of of the distillate. So, with respect to the reflux drum, most of the flow from the reflux drum is going back into the column, only a small amount of A is being withdrawn.

So, this a distillate stream this the the distillate stream for the reflux drum is like a leak you cannot control a level using a leak. That controller is unlike will not work. The valve will go fully open nothing will happen to the level, the valve will go fully close nothing will again happen to the level, right. So, trying to control level using a leak is as good as saying that I am not controlling the level and controlling the level is one of my fundamental objectives in order to stabilize the system because levels are non self regulatory right. So, when the distillate flow is much much less than the reflux flow, let us just say L by D reflux ratio is greater than 4 your better of controlling the level using the reflux instead of the distillate. Does that make sense? I hope so.

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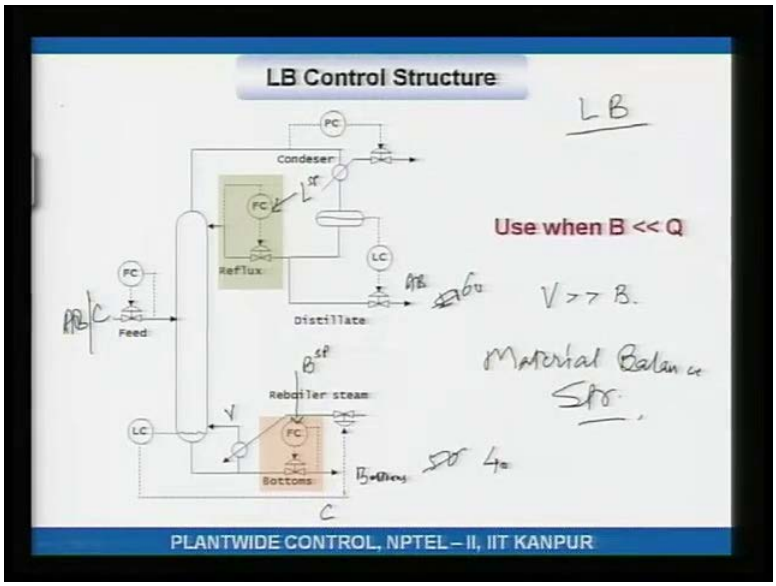

Next L B control structure in this case, distillate is controlled using top level or the reflux drum level is controlled using the distillate flow rate. At the bottoms the same thing happens, you see the bottom stream flow rate is very small and the reboil is much, much larger. So this let me call V this let me call B and what that means is V is much, much

greater than B. So, with respect to the reboiler, the bottom stream is like a leak and you cannot expect a leak to control a level, to give you regulation of a level. Again what would happen is if you are trying to control the bottoms level using a leak, then the valve will go fully open and the level would hardly respond.

The valve will go fully closed and the level would hardly respond right. It is like you got a big tank and you got a small leak whether the leak is plugged or not it does not really matter nothing happens to the level. Since, stabilization is one of the primary objectives of a control system, safe and stable operation like we had discussed in probably the first or the second lecture. Therefore, to ensure that the levels are properly regulated because levels are non self regulatory, in this case what I will have to do is I will have to control the level using the steam flow rate, the steam to the column using the reboiler duty. Then the operator can adjust the bottom set point, the operator can adjust the reflux set point to get the kind of separation that he wants and therefore, it is called the L Bstructure L B meaning operator is L and B himself.

Again, this is a material balance structure. Why is it a material balance structure, that is because when you are when the operator increases or decreases the bottoms set point, is directly adjusting the material balance across the across the across the column. Let us say, initially the feed is 50 50 or you got total of 100 kilo moles per hour coming in and you are taking out 50 up the top 50 down the bottoms. If you make this 50 40 well then 60 has to go up the top right. So, by adjusting the set point of the bottom stream, you are directly affecting the material balance around the column the hence it is called again a material balance structure. When would you use it again, say I would use a similar example A B C, C is very small compare to A B, I am taking out C down the bottoms, component C down the bottoms AB up the top.

Well since by definition the bottom stream would be very small compare to the boil up and therefore, trying to control the level using this bottom stream does not make sense. You will have to use the reboiler duty, does that make sense? I hope so. In all these material balance structures, there is what is called the nested loop I think we will talk about it later when we start considering temperature control. This will be discussed later.

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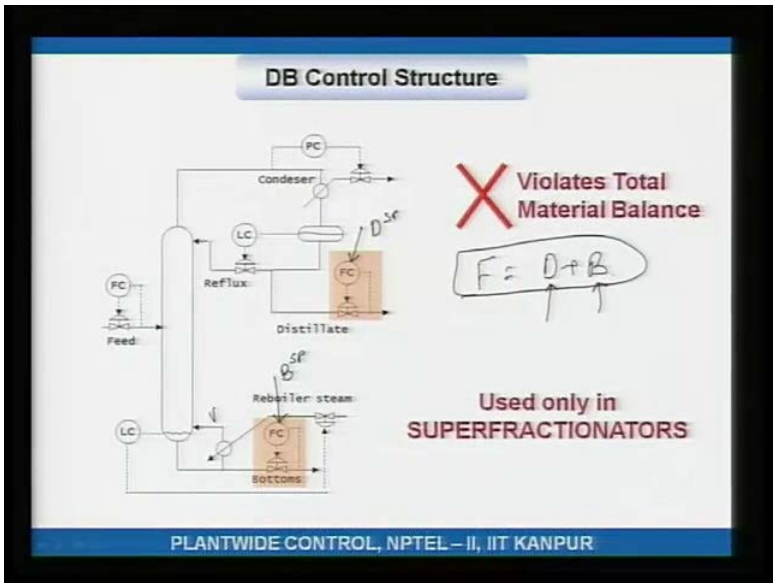

I may also have a situation, where the distillate rate is small compared to the reflux, bottoms rate is small compare to the re-boil. When does this happen? This happens in super fractionators. What are super fractionators? Super fractionators are distillation columns that are trying to separate close boiling components, by definition because the components are close boiling it requires a long tower to do it and also to get the separation you will have to have, more reflux and more reboil. The the minimum reflux ratio will be pretty large and corresponding reboil will also be pretty large.

So, this is now the distillate is much, much smaller than the reflux, the bottoms is much, much smaller than the re-boil and therefore, level controllers have to be oriented as shown here, reflux is used to control reflux drum level, the re-boiler duty is used to control the bottoms level. What that leaves is the bottom set point and the distillate set point in the hands of the operator to get the kind of separation that he wants. Well this is used only in the case of super fractionators and otherwise it is never used and the reason why this is never used is because at steady state feed should be equal to distillate plus bottoms. No matter how much reflux you are putting in how much reboil you are putting in ultimately this has to be satisfied all the time.

In this control structure you are going trying to independently set this and this. This is very similar to what we were doing to the tank trying to independently set inflow and the outflow wont you know not done. So, this control structure is never use, the only exception is super

fractionators. There have been some studies in the literature by Luyben and Schogistas and company and all of them report that even though this structure can be used it is actually very fragile. For our purposes we just need to know that this kind of control structure must only be considered in the case of super fractionators, otherwise not it is a strict no no. There is also you know, sometimes it is not sometimes many a times you would have L by D being the reflux ratio being set by the operator.

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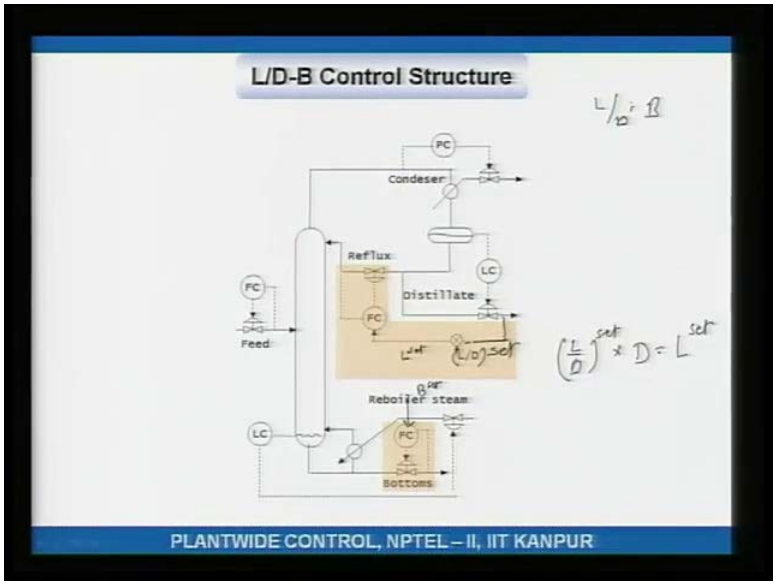

What do you mean by L by D? That means the reflux is maintained in ratio with the distillate. So, the level control is this way. Then I have, I measure the level over here. Level is controlled using the distillate the flow rate of the distillate which is this signal is multiplied by the reflux ratio, so this gives me L set point, L by D, so L by D set this is the set point multiplied by whatever is my measured distillate rate this gives me whatever should be my reflux set point.

So, this reflux set point is sent to the flow controller that is controlling the reflux reflux flow alright. So, in this way reflux is maintained in ratio with the distillate and in this case this L by D set this guy, is what the operator sets to get the kind of separation that he wants. Of course, at the bottoms what is this L by D B. So, at the bottoms the level control bottoms, level control is using re-boiler duty therefore, the operator is setting B set point and L by D set point to get the kind of separation, that he wants. Hence, this is called an L by D B structure.

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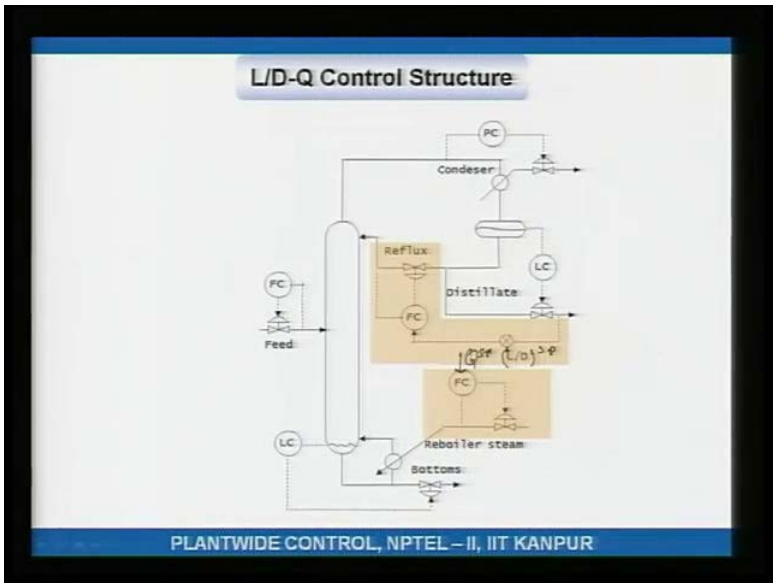

Similarly, we have got this L by D Q structure. I think this should be obvious again operator is setting the Q set point and the L by D set point to get the kind of separation that he wants.

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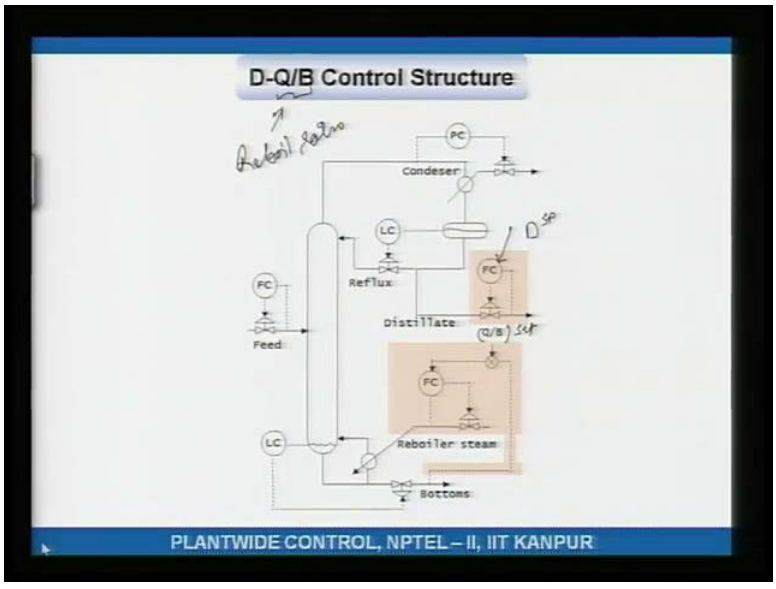

I can also show you D and Q by B set point, Q by B is actually called the re-boil ratio, this is called the re-boil ratio. We talked about the reflux ratio this is called the re-boil ratio and in this case the operator is setting the distillate and the reboil ratio. What we have here is you are measuring the bottoms multiplying it by Q by B set and that gives you the steam flow set point and the steam flow controller essentially moves this valve to get the steam

flow rate, that is desired. Think this is a good place to stop. Next lecture we will talk about temperature inferential control of distillation columns.

How do you, in all these structures the operator is supposed to adjust the two things that he is supposed to adjust to get the kind of separation he wants. Can we free the operator and do it in an automatic way, so that the quality is always controlled regardless of disturbances that are coming in? What are the control structures to do that; that is what we will take up next time.

Thank you.