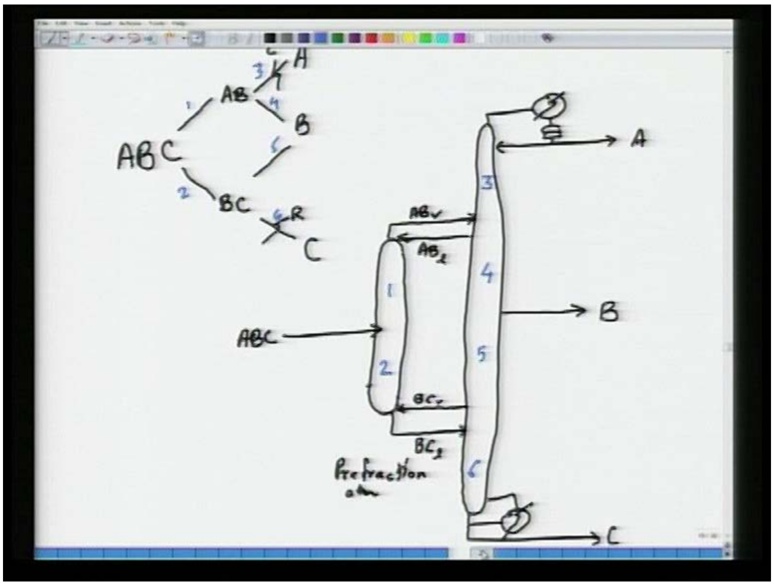
Plantwide Control of Chemical Processes
Prof. Nitin Kaistha
Department of Chemical Engineering
Indian Institute of Technology, Kanpur

Lecture - 18
More on complex columns and reactive distillation

Welcome to this next lecture. Today we are going to talk about control of complex distillation configurations, such as the pet look column and other sequences.

(Refer Slide Time: 00:35)



Consider a ternary mixture ABC; A is the lightest component, B is intermediate boiling, and C is heavy. Each line here denotes a column section; if the line is in the upward direction tilted upwards, then it is a rectifying section. If that line is tilted downwards, it is a striping section. So, AB you can and BC is down in the bottoms. You split the AB again; you get A up the top, B down the bottoms. You split the BC again; you get B up the top, C down the bottoms of that column section. I show a condenser here; let us just call this a condenser and let us just call this a reboiler. This is actually a state-task network representation and it is not necessary to know the details, but I just want to show you how to synthesize these complex column configurations in a systematic way.

So, let me call these 1, 2, 3, 4, 5, 6. So, we have got column sections. Each of the column sections, we will be getting a liquid stream from the top and vapor streams from the bottoms and these we will be contacted on the trays that are there in the column section. So, now let us say I do 1 and 2 in column one; 3, 4, 5 and 6 in a tall column two, and what I mean will be clear when I draw it. So, I have got A B C which is coming in; let us do it here. So, you have got the ABC feed. I have got a small tower, a small column and from the top I take out AB vapor; from the bottoms I take out BC liquid. So, this is AB vapor this is BC liquid.

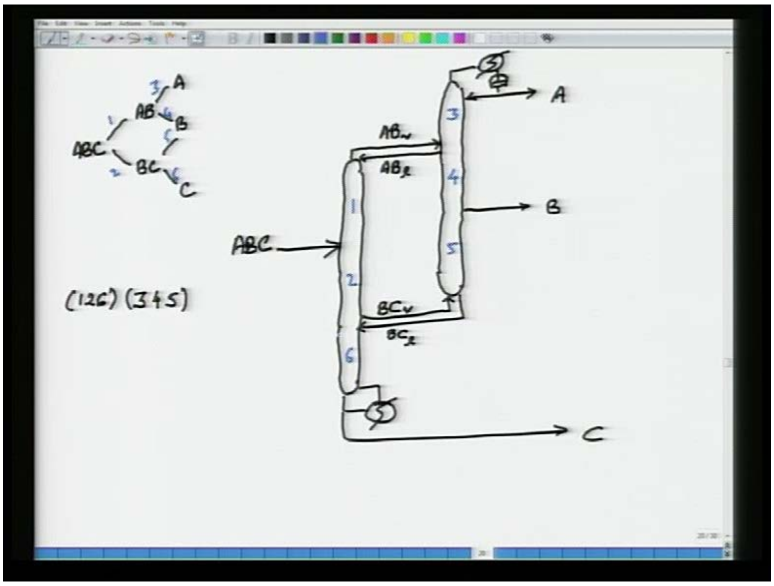
Now these two streams, of course for mass transfer or for distillation or for fractionation to occur in this column section, I need a liquid stream that is going in here and I need a vapor stream, let us say, that is going in here. We will get this from a main column and here is my long main column and what I have in this main column is a condenser, of course a reflux term, etc, etc, a reboiler. And from the vapor liquid traffic this condenser is what is providing the liquid into this column and this reboiler is what is providing vapor into this main column, the tall tower; of that vapor some amount is taken out to provide vapor in this prefractionator. This is called a prefractionator.

Similarly, from the liquid that is dropping down this column, some amount is taken out to provide liquid for fractionation in the prefractionator. So, this condenser in this reboiler; the single condenser in the single reboiler are providing liquid and vapor respectively to all the sections in this column. What are these sections will talk about that a little bit. Now this would be AB liquid, this would be BC vapor. Now if I take this AB vapor stream that is coming up the top and I rectify it; as I go up the column my composition will get richer and richer in A. So, I am taking out pure A up the top. If I start going down here in this direction, what I will find is that because I am going down, my composition will start to get richer if the feed stream is AB; as I go down, composition will get richer and richer in B.

Similarly if I go up in this direction, what I am getting out here is BC. So, composition will get richer and richer in B, the C would not be going up the top. So somewhere, I will be getting a side draw as pure B and if I go down here BC; if I go down, composition will be getting richer and richer in C. So, what I am getting out here is pure C. Now if I look at the column sections, this is one, this is two, this is three, this is four, this is five, and this is six. Compare this with the state-task network that we have here and you see what is going on.

So this is a complex column configuration, where using a single reboiler and a single condenser with different column sections that are coupled in the way shown here, where one and two are done in the prefractionat, three, four, five and six are in the main tower. Using this complex configuration I am getting pure A, pure B, and pure C. Are there other possibilities? Sure. Let us just look at some other possibilities. So, I will draw the state-task network again; this time I would not make it as big.

(Refer Slide Time: 07:39)



So, I have got ABC. Take AB up the top, BC down the bottoms. A at the top, B here, and what we did was call this 1, call this 2, call this 3, 4, 5 and 6. Now I can also do 1, 2, and 6 in one column; 3, 4, and 5 in another column. So earlier what we saw was, I did 1 and 2 in one column; 3, 4, 5, and 6 in the main column. Now what I am going to do is I will do 1, 2, and 6 in one column; 3, 4, and 5 in the other column. So, basically what I am saying is we do this in one column and we do this in another column; so, 3, 4, and 5.

So if we look at this sequence, what will you get; 1, 2, and 6. So, you have got a tower and 6 have got a reboiler with it, 3 have got a condenser with it. So, well forgive my drawing; unfortunately I do not have what should I call, 1, 2, and 6. So, there is feed, 6 has got a reboiler. So, there is a reboiler. You are taking out pure C down here. Then as you move up, you will have to take out a BC stream. So, we take out a BC stream; whether its vapor or liquid we will have to see. Then you move up further. So, we have done 6. We took out BC, then you moved up further. I got to the feed; may be the feed should be down here somewhere slightly, looks slightly better.

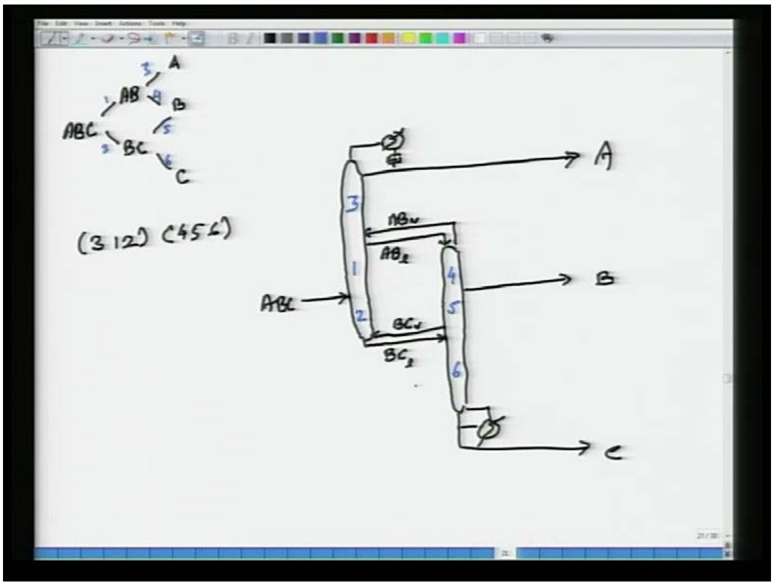
So, this is my ABC feed and then this is section one. From the top of section one which is a rectifier, I will take a vapor stream; that vapor stream is AB vapor. This is sent to a rectifying section. This is my rectifying section. Rectifying section has got its condenser. I would not show the reflux drum; well let us show it anyway. So, this is your rectifying section. It has got its reflux and you are taking out pure A up the top. So, this is section three, this is section one, this is section two, this is section six and what do we have. After three, we have got four. So if I go down, there will be a place where I get to take out pure B. So, this is section four.

And if I go down further, well, this is BC vapor and the BC liquid is sent here. Of course, column section one requires liquid. So, I take out some liquid from here and that is reaching AB. What do we have here? Here we have another complex configuration, where I am doing 1, 2, and 6 in the first column and I am doing 3, 4, and 5 in the next column. How does it work? You have got ABC. If you rectify ABC, you will get richer in AB. So, that AB vapor is taken up the top of this section one. If you go down the feed, you know A cannot go down. So, they will come to a place where your liquid composition is essentially BC; that is where you take out this side draw of a vapor which is BC. If you go further down, the B C, you know B cannot go down because it is lighter than C. So, you take out C here.

Now, since this vapor that is coming in here is essentially is BC. As I go up the top, C will be prevented from going up. So, there will come a location where I can drop your B. If I look at this AB that is coming in, if I rectify this A B stream, I will get pure A because B being heavier cannot go up. If I start going down from the AB wherever A B is drawn and put in, A being lighter cannot go down. So, there comes a location where I have got, where I am drawing off essentially nearly pure B. So, same state-task network but different configuration. How this is different from what we have here; the vapor between the first column, the prefractionator and the second column? Here the vapor is having to flow from the prefractionator to the main tower, to the tall tower; at the bottoms the vapor is flowing from the tall tower.

The direction of flow of the vapor is in opposite directions. So, if I have column the prefractionator at a high pressure, the top stream will go naturally flow naturally into the main tower; however, in order to make this vapor get into the prefractionator, I will have to a the compressor. In this case, the vapor streams are flowing from the column on the left to the column on the right. So therefore, I can operate the column on the left at a slightly higher pressure and the vapor then will naturally flow from the column on the left to the column on the right. So, in this case I do not need a compressor to get the vapor flows that I want. So, I have looked at two possible configurations, let us see. So, we did 1, 2, and 6 and then 3, 4, and 5 in one tower. We may do 3, 1, and 2 in one tower and 4, 5, and 6 in another tower.

(Refer Slide Time: 15:20)

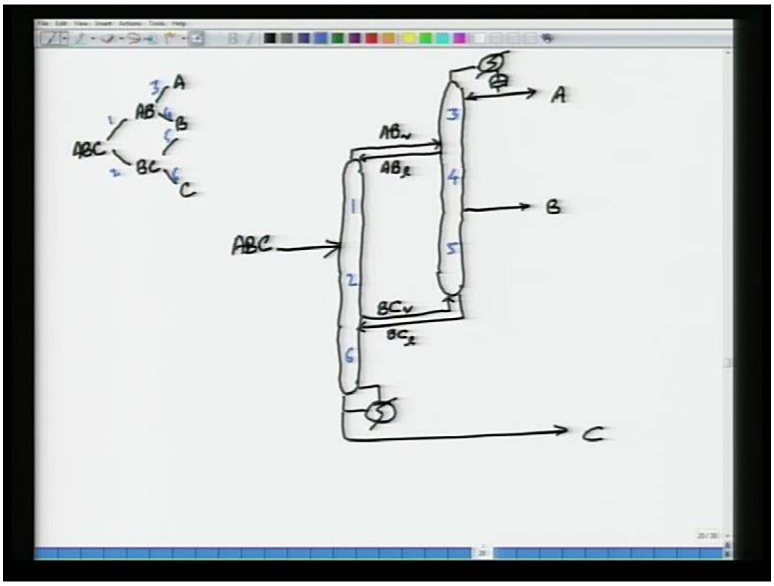


Let us do that. ABC, AB goes up the top, BC on the bottoms. A goes up the top, B goes down the bottoms. B goes up the top, C goes down the bottoms; so, 1, 2, 3, 4, 5, 6. So, now what we are saying is we are going do 3, 1, and 2 in one; that is this right here, this will be done in 1 and then we will do 4, 5, and 6 in the other one. So, let us do it. I have got the first tower which takes in ABC feed. Section three has got a condenser associated with it; taken out pure A out here. As I go up from the feed, there will come a location where there is essentially no C; that is where I take out a side draw and I do not know whether that side draw would be vapor or liquid. We will figure that out in a little bit; I think it will be liquid; so, I m taking out AB.

So, this tower is providing liquid to the other tower. What does the other tower do? It has got its own set of three subsections or tray sections and this is my BC feed. I have got a reboiler there which corresponds to section six. From there I get pure C. So, that all the product streams are aligned. This is pure A. What I am taking out here is AB liquid. So, may be since it is liquid I should write it down here AB liquid. I got a vapor that will be coming out of here; that will probably be AB vapor. The liquid that comes out here is you see if I go down the feed, A being lighter cannot being the lightest cannot go down.

So, what I will get out here is essentially BC liquid and I take a vapor side draw which is essentially BC vapor. So, let me just label the column sections. This is column section two, this is column section one, this is column section three. So if I go down, this is A B. If I go down, A being light cannot go down. There will come a location where I can get pure B. Similarly if I go up, there will come a location C being heavier cannot go up. So, I am taking a side draw which is essentially pure B and so, I label the column sections four, five, six and till now we have done three possibilities.

(Refer Slide Time: 19:51)



There is a forth possibility and we will talk about that. Once again the state-task network and right now what we will do 3, 1, 2, and 6 in one column and we will do this in another column. So, what we are saying is we will do 3, 1, 2, 6 in one column and 4, and 5 in the other column. What happens? What will the configuration look like in this case? Well, let us see. So, there is a tall column which has got 3, 1, 2 and 6. So, that is the tall column.

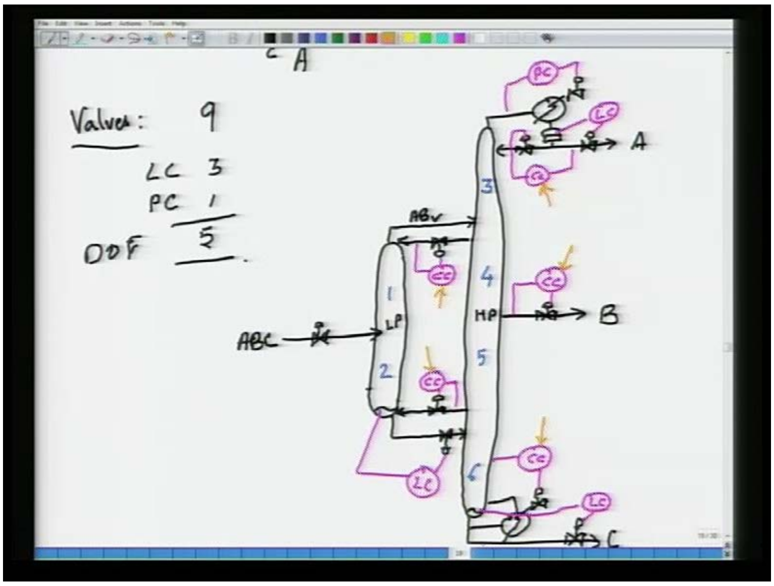
Let me draw the tall column first. This tall column takes in the fresh feed; somewhere in the middle, sought of symmetric. It has got its own condenser and its own reboiler and that will be A, it has got its own reboiler and that will be C. This is ABC the feed. As I go up, concentration of A will go down because A being the lightest component cannot go up. So, there will come a place where you have got essentially rectifying section. So, you will get A. If I go up, C being the heavy component cannot go up. So, there will come a location where you have essentially AB. So, this will be AB liquid, not BC liquid as I have written.

On the other hand if I go down, A being the lightest component will not make its way down. So, there will come a location where you have got essentially BC. So, this is BC vapor. This vapor I will send to A. Well, let me remove the arrows here. This vapor I have sent to A. Let us see; man this looks like a fat woman. Let us see, I draw it properly man. Please forgive my drawing, let us see. And the vapor from here goes out here. The liquid from here goes in here. As I go up in this way, C being the heavy component will not find its way up. There will come a location where I get nearly pure B. Similarly if I go down, A being the light component cannot find its way down and I will get richer and richer in B.

So in this small column section, there will be a location somewhere where I have got essentially pure B, where I will get a pure B stream; that pure B stream is taken out as a side draw. If I label the column sections; well, this is three, this is one, this is two, this is six, this guy is four, this guy is five. Notice that the vapor flow from one column to the other; the two vapor streams are in opposite directions. So, if I operate one of the columns at a high pressure, vapor will flow from the high pressure column to the low pressure column. The other vapor stream will require a compressor.

On the other hand in this scheme, the vapor flow direction for both the streams is from the second column which is the column on the right to the left column. So, if operate the column on the right at a slightly higher pressure, vapor will find its way to the column on the left. Similarly in this case, vapor is flowing from the column on the left to the column on the right; therefore, column on the left should be operated at a higher pressure and vapor will then naturally find its way from the left column to the right column. Again the two vapor streams are flowing in opposite-opposite directions. You will have to use a compressor on one of the streams to achieve the flow that is shown there.

(Refer Slide Time: 25:04)



So now, let us talk about controlling these. Let us draw independent valves, then count and dis-count. Of course, there will be a valve here; of course, there will be a valve here, here, here, here. How much side draw I am taking will again be in my hands. So, let me draw this. How much vapor I am taking will again be in my hands. So, let me draw this. Whatever vapor has been taken out, let us say the column on the right is operating at higher pressure, slightly higher pressure. This column is operating at a lower pressure; of course, I have got a compressor that will make sure, maybe I should show that.

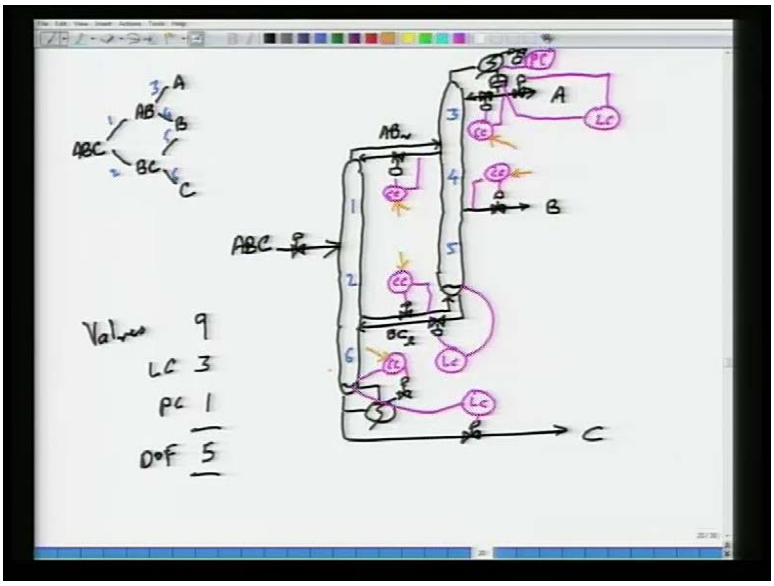
That compressor will make sure that whatever vapor is been fed, they actually find its way to the tall tower. So, I am not showing the compressor here. But even if the compressor is there, it is running all the time. Do I have a valve here? Yeah, I do have a valve here and you can guess what it will be used for. I have got some liquid level here, I have got a liquid level here, I have got some liquid here which is already shown. So, if I look at total number of valves, excluding the feed; because the feed is being set from upstream or by production rate or whatever; so, the feed is specified.

So given the feed, the valves that I have are 1, 2, 3, 4, 5, 6, 7, 8, 9, 9 valves. How many levels do I need to control? 1, 2, and 3; so, three level controllers, one pressure controller anything else that leaves 5 degrees of freedom. What are those 5 degrees of freedom? Well, how much reflux I am putting in; how much side draw I am drawing off, two; how much reboiler steam; how much steam I am putting in the reboiler, three; how much liquid side draw; well, what is it? This is not really a side draw stream. So, what should I call this stream; the liquid being fed to the prefractionator and similarly the vapor being fed to the prefractionator.

So, what do we call it? I do not know, liquid one. So, the liquid being fed to the prefractionator and the vapor; yeah, the vapor being fed to the prefractionator. The other three valves are used for level or the other four valves are used for level control and pressure control. So, let me let me draw a control structure on this. This would be pressure control, this would be level control, this would be level control, this would be a level controller and then what; this would be under composition control, essentially ensuring that there is no amount of C.

This would also be under composition control and what does this composition; this would be again under composition control, this would also be under composition control, and by composition control you can also use temperature controllers. If the pressure is fluctuating, pressure compensated temperature set points, alright. So, when I am saying C C; it may be understood that it is being used interchangeably with temperature controller, with T C with temperature control. Well this would be, alright. So, there you go. Operator would be specifying 1, 2, 3, 4, 5; five things, five set points which correspond to 5 degrees of freedom.

(Refer Slide Time: 30:57)

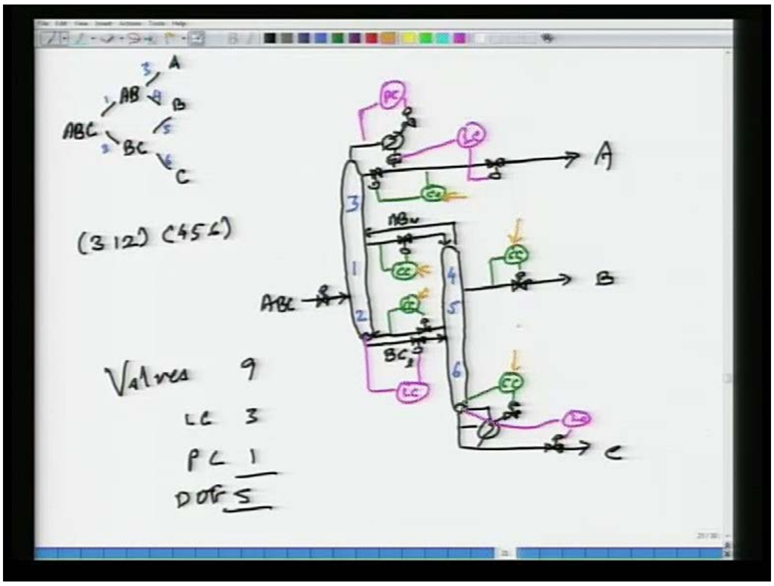


I can similarly proceed on to the next column. Here again let us draw independent valves and then do whatever it is that needs to be done. What do I do? Yes, I just take this off. How much liquid I am taking from the column on the right and putting into the column on the left. Well that is in my hands, that is something that should be adjustable. Therefore, a valve is required there. How much vapor from the column on the left is being taken and put into the column on the right. Well, that is again something that should be in my hands. Yeah and of course, liquid accumulates here.

If the accumulation with level is increasing, I should increase whatever is being drawn off. If the level is decreasing, I should decrease whatever is being drawn off. So, there is a valve here for that increase or decrease. So, no valve is shown on this stream because that will create unnecessary pressure drop; this we have discussed n number of times. So, again if I count; well there is a valve here of course, some sort of dude. There is a valve here for pressure control. So, if I look total number of valves excluding the feed 1, 2, 3, 4, 5, 6, 7, 8, 9; again total number of valves is nine. Three levels are to be controlled, one pressure is to be controlled, degrees of freedom again come out to be five.

Let us just draw those controllers, show it this way. So, these are the three level controllers. Well, here is the pressure controller which is adjusting this valve and its taking the pressure of the condenser. So, pressure controller is doing this. Then again composition and or temperature control, composition and or temperature control, composition and or temperature control composition and or temperature control, composition and or temperature control. What does the operator set? Well, he sets the set point of these 5 composition controllers, 1, 2, 3, 4, and 5. Again notice how degrees of freedom correspond to number of set points that need to be specified.

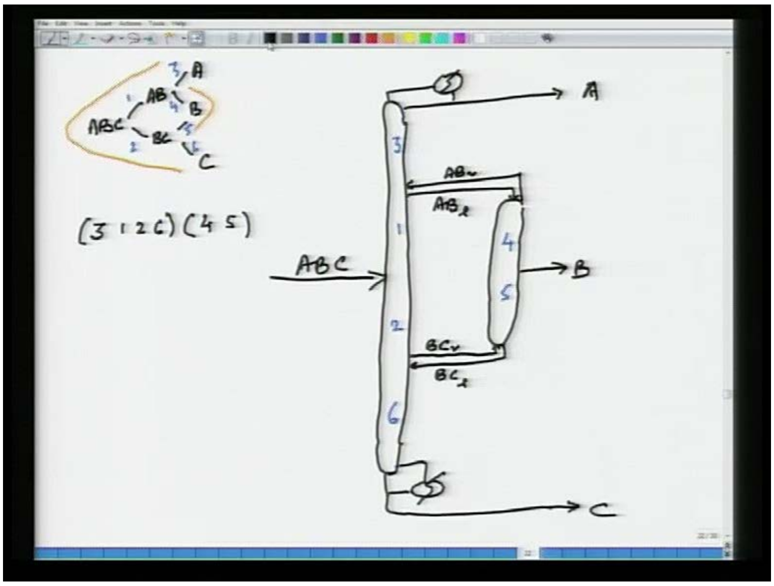
(Refer Slide Time: 34:32)



So, now let us go on to the next column configuration. Is that the last one? Oh, that is the second last one. Independent valves, well, let us get on with it. These are the independent valves and I think it is getting a little boring. So, I think I am going to rush through it; do whatever needs to be done and get it over with. It is going to be a valve here. How much vapor you are putting into it; that is got to be a valve here, here is got to be one. Well, there is no valve here. There is got to be a valve here. Right and again if I look at, well did I miss a few valves here; 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, that is excluding the feed there are. So, excluding the feed there are nine valves. Three levels need to be controlled; 1, 2, 3, level controllers three, one pressure needs to be controlled, degrees of freedom again turns out to be five.

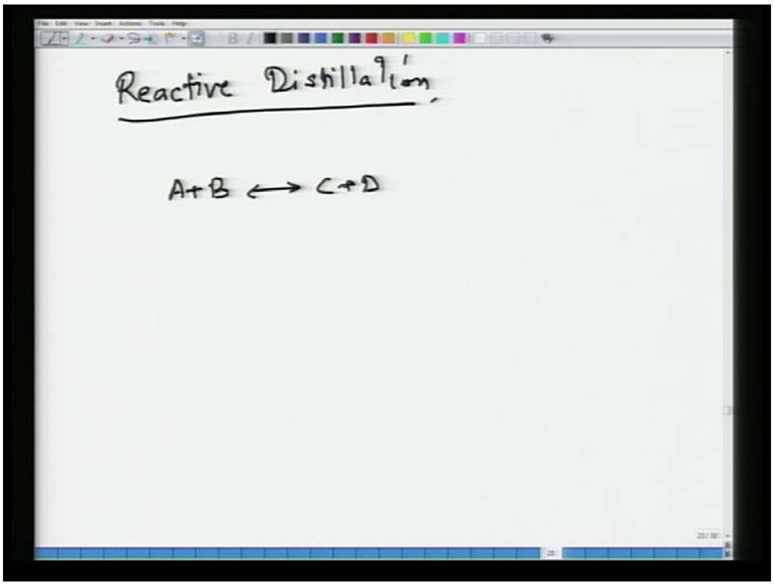
So, let us put in those controllers. So, here is my pressure controller, here is my level controller. This bottoms level is also controlled using a level controller. So, three level controller and one pressure controller. Now we start putting in our composition controllers and let us just use it, here you go; composition controller, composition controller, composition controller, composition controller, did I miss something? Yeah, here is another composition controller here. So, five composition controller set points 1, 2, 3, 4, 5; these are the 5 handles that the operator has in his hands to get the kind of separation that he wants.

(Refer Slide Time: 37:29)



Last, but not least let us just quickly, I think I will leave this as an exercise. Why do not you guys do it, figure it out yourselves. That essentially covers whatever I wanted to do on distillation columns. We have looked at ordinary distillation, complex configurations, we have looked at extractive distillation, we have looked at heat integration.

(Refer Slide Time: 38:01)

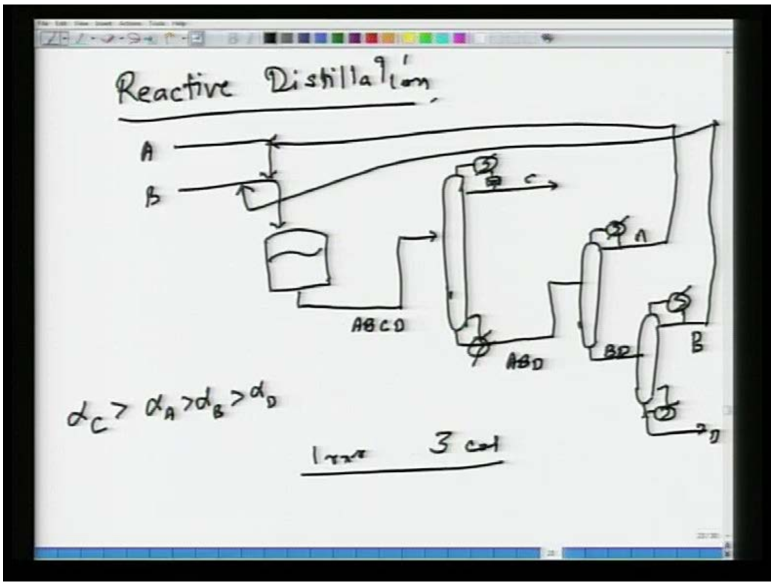


Reactive Distillation

$A+B \longleftrightarrow C+D$

Let me also talk about what has in recent times become popularly known as reactive distillation and just to make a point here. So, you have got A plus B an equilibrium reaction in equilibrium with C plus D. Let us say this is your reaction and C and D are both valuable chemicals that can be sold in the market value added chemicals.

(Refer Slide Time: 38:41)

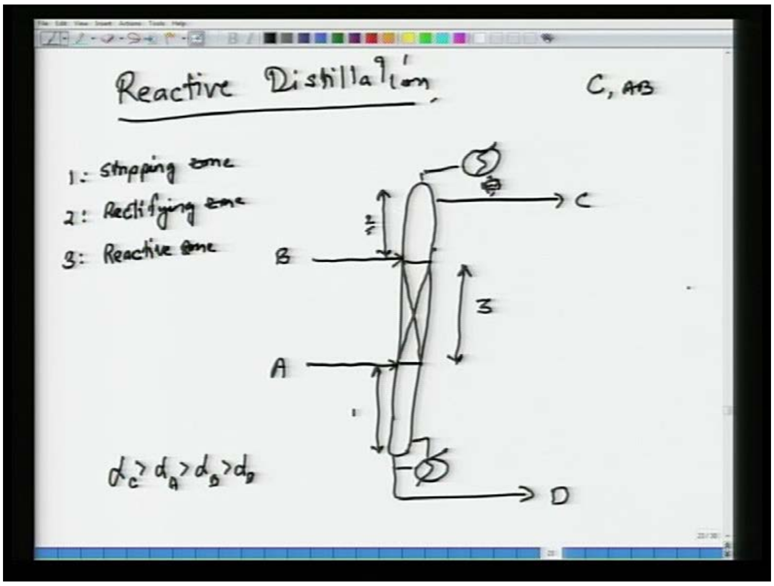


So, one way to do it is the conventional way. What is the conventional way? Conventional way is you put in fresh A, put in fresh B. So, you putting in fresh A, you are putting in fresh B; its reacting in a reactor and let us say the reactor is sized is large enough, so that equilibrium reaction equilibrium is achieved. And then it goes to let us say a distillation column and let us say that alpha A and the reactants are intermediate boiling. Well that means it is let us say C is the lightest; relative volatility of C is greater than that of A is greater than that of B and D is the heaviest. So, when I distill it what I will get is? So, this is an ABCD mixture. Now since A and B are intermediate boiling and C is the lightest, let us say I do a light out first range. So from the first column, I take out C of the top; A B C goes down the bottoms.

This ABC mixture is sent to the next column. What does the next column do? It takes out what? Light out first. So, this is BCD; takes out B up the top. Where the hell did A go? Oh sorry, if you look C up the top, then it takes out A up the top because C is and then you have got BCD. So, A goes and then you have got a CD mixture here. Oh then no, I have made a mistake. Sorry C has gone, ABD this is an ABD mixture. Then I go to the next column. So, this is A and this is BD. D is taken down the bottoms.

A is taken up the top; no B is B is taken up the top. I am sorry about screwing it up so much, but I think you are getting the sense. Now A and B are precious reactants; it does not make sense to dump it. So, A is sent recycled mixed with the fresh A steam. B is also well let us see, anyways let us just do it. So, I go this way and I go this way. The point is this is a one reactor three column scheme to get pure C and pure D as my product and ensure that none of the reactants leave the process. But all of the unreacted reactants are recycled. Let me give you the reactive distillation process that will do the same thing.

(Refer Slide Time: 42:18)



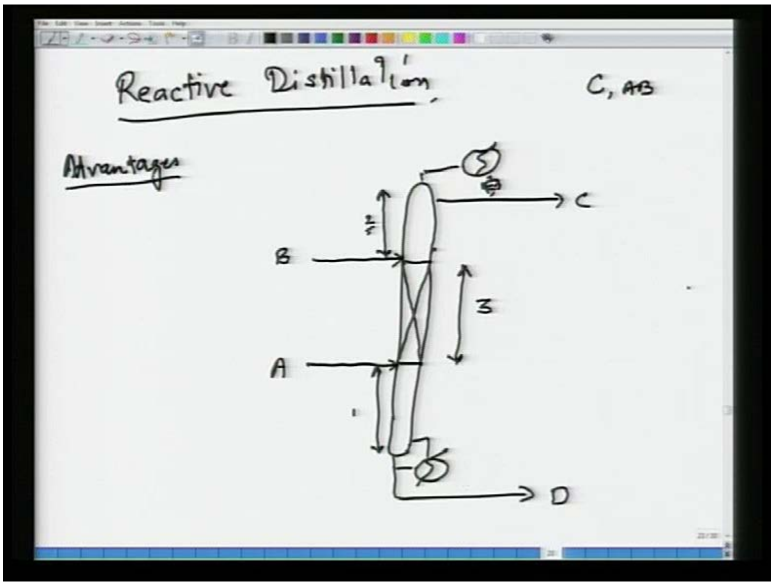
So, here what we have is we got a column and I have got catalyst loaded trays in the middle. Now the way the relative volatilities where alpha C was greater; C was the most volatile, then A, then B and then finally D. I have got a condenser and I have got a reboiler. So, this is the stripping zone; let me call it one. This is rectifying zone, and this is called the reactive zone. So, I have got one is stripping zone, two is rectifying zone as in a conventional column, and those catalyst loaded trays form the reactive zone or the reactive section. Now I have got fresh A and fresh B. What I do is A is light. So, it has got a tendency to rise up the column. So, what I do is I put in A below the reactive zone; this is fresh A. B being heavy has a tendency to go down compared to A; therefore, I put it above the reactive zone, just above the reactive zone.

So, A tends to go up, the B tends to go down. So, you will get a lot of A B reaction in the reactive zone. If you did it the other way, if you had put A up and B down then what would have happened is the A would have escaped up the top, B would have escaped down the bottoms; no reaction. The reactive zone would have been starved of reactants because the reactants escaped. So, it is necessary that B be put up just above the reactive zone and A be put just below the reactive zone. The two feeds have to be in this way. This will ensure that the reactants are seeing the reactive zone and therefore, there will be reaction and whatever C and D get formed, C being the lightest that leaves up the top, D being the heaviest that leaves down the bottoms.

So, what does the rectification zone do? It prevents the unreacted A from leaving up the top; unreacted A and any unreacted B. C is light, A B are heavy. So, what the rectifying zone is doing which is two here? It is preventing the reactants from leaving up the top because the reactants are heavier than C. Similarly what is the stripping section doing? it is preventing the reactants which are escaping the reactive zone from leaking down the bottoms. So, essentially the rectifying and stripping zones are ensuring that the reactants do not escape; they are recycled back to the reactive zone. And well that is it. Here is a single column with a reactive zone that is doing, what the process that I drew previously was doing producing pure C and pure D.

So, a single column is replacing a four unit conventional process which is reaction followed by separation. So, this is in brief where reactive distillation comes from and there are other advantages just like you have in heterogenous azeotropic distillation. There is an azeotropic composition, you add an entrainer. Because of that entrainer, phase separation occur organic rich, water rich and because of that phase separation, the azeotropic composition gets crossed. And then you can get pure A and pure B which otherwise if you had taken it as one, you would not have been able to separate. Here because of reaction, some azeotropes can get reacted away.

(Refer Slide Time: 47:41)



So, let us just before I get into control, advantages. Well, if you have got an equilibrium reaction, notice if the relative volatilities were such that the reactants were not intermediate boiling. Then reactive distillation would not make sense because stripping or enriching would not force the reactants back into the reaction zone. The key is the relative volatilities of the components involved has to be such that you are able to force the reactants to not escape from the reaction zone; that is what requires that the reactants be intermediate boiling. Then reactive distillation makes sense.

So, for reactive distillation to make sense as a reasonable alternative to a conventional process two things; one, the relative volatilities of the components has to follow a certain order which forces that the reactants do not escape the column, which forces the reactants to get back into the column; that is number one. Number two, the temperature inside the column is determined by what pressure you are operating at. If the pressure is higher, boiling temperature will be higher; the operating temperature would be higher.

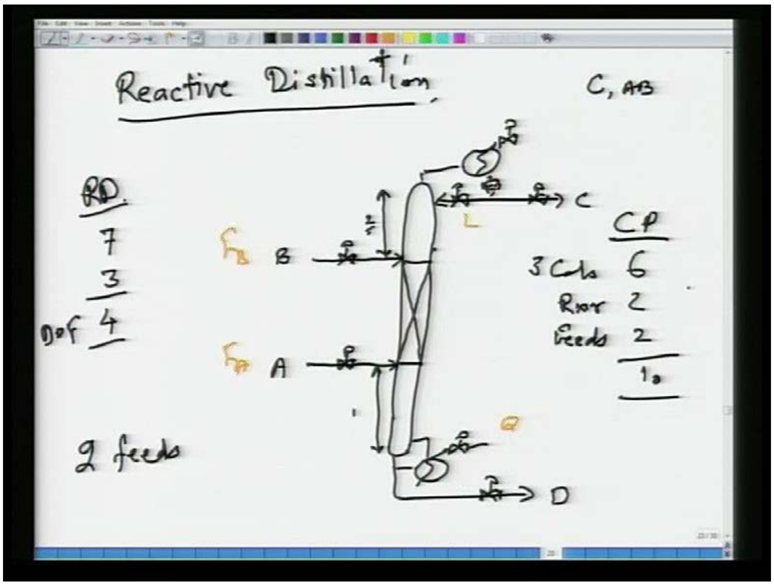
So, let us say you take a pressure that is let us say atmospheric or may be 10 bar that sets what will be the temperature inside the reactive zone. The pressure sets the temperature of the column; higher the pressure more the temperature, lower the pressure lower the temperature. At reasonable pressures, if the temperature inside the reactive zone is not high enough to give sufficient reaction rates, then what you will have to do is, you will have to put and load a lot of catalyst and that may or may not be possible in a column.

You see on a tray, how much catalyst can you load? 500 kilograms, may be 1ton, and may be you can have 5 or 10 trays. So, 10 tons of catalyst loaded, how much more? No more, right. So, the reaction rates at the operating pressure of the column has to be high enough, so that the catalyst loading is feasible.

So, feasibility of reactive distillation as an alternative to a conventional process requires that the relative volatility will follow a certain order, so that the reactants can be recycled. So, that the reactants are prevented from escaping the system. And two, the reaction rates achieved in the reactive zone has to be reasonable; that requires that requires that separation and reaction temperature, there should be some overlap in that. If not, well, you are better off doing a conventional process.

So, advantages. Well, a single column replaces the whole process. It is a one unit process. This is a plant in it. This looks like a single column, but it is a plant in itself. So, capital cost is lower. Typically you will also have energy consumption will also be lower and what else? So, process integration, process intensification, lower capital cost, lower operating cost, and so on and so forth. Disadvantages, well the main disadvantage is I will probably show it to you from degrees of freedom.

(Refer Slide Time: 51:30)



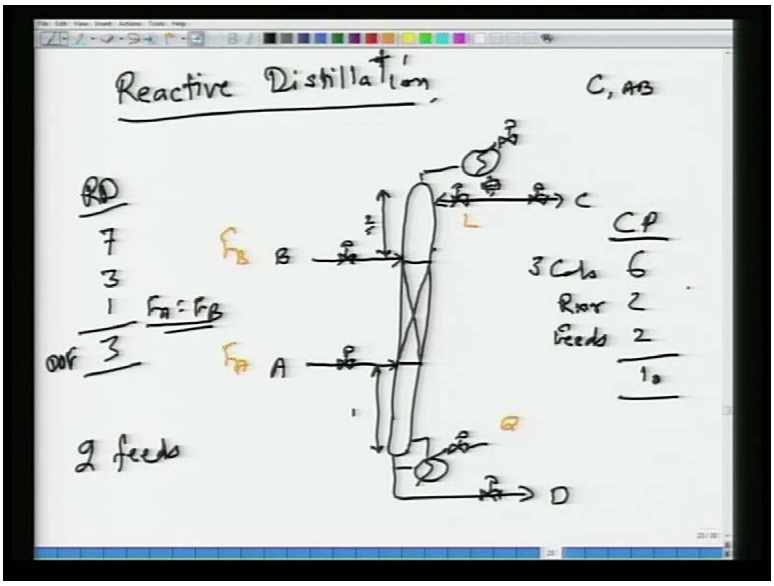
Well I think I have run out of time; that is ok man, we will go five minutes extra. Let me draw the valves, two fresh feeds, what else? Yeah, that is it. What are the degrees of freedom of this process? Well two fresh feeds two levels to be controlled, one pressure.

So, total number of valves is 1, 2, 3, 4, 5, 6, 7 and the feeds are included this time. So, total number of valves is seven; of these seven, two levels and one pressure need to be controlled. So, degrees of freedom is actually four; two for the two fresh feeds, two feeds, and how much reflux you are putting back in and how much steam you are putting back in, L and Q, F A, F B, L and Q. These are the four degrees of freedom that you have for this process.

On the other hand if I looked at the conventional process which unfortunately I have erased, it also had two fresh feeds, it had a reactor and it had three columns and since all of those three columns are ordinary columns, what you have is in terms of degrees of freedom. Let us forget about how many valves, how many this. So, you have got three columns; so, that gives you six degrees of freedom for the three columns. You have got a reactor. What is the operating temperature of the reactor and what is the holed up inside that reactor; that gives you two degrees of freedom for the reactor and you have got two fresh feeds.

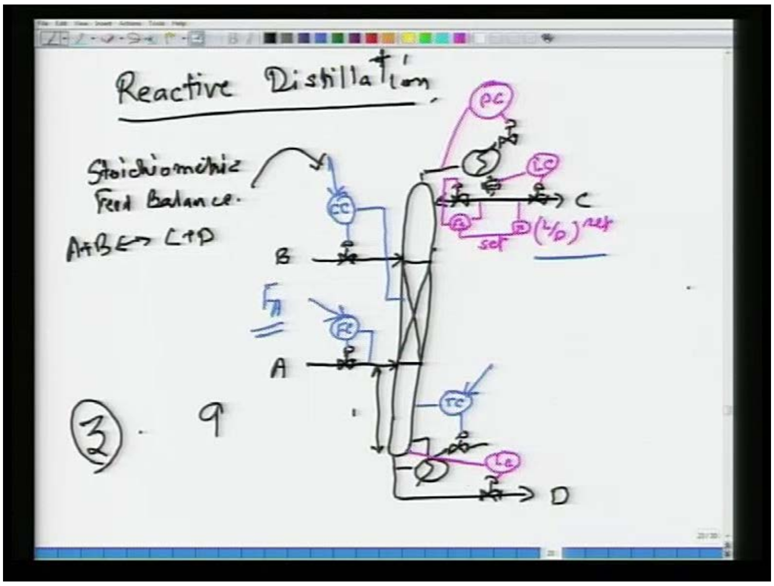
What is the degrees of freedom, ten. Operator has got ten things that he can set to get the kind of reaction and separation that he wants. He can set ten things. So, this is conventional process, this is reactive distillation process. In the reactive distillation process, operator has got what? Only four degrees of freedom, right. So, he has got only four degrees of freedom to regulate the separation as well as the reaction. And this actually four is also improper, it is actually three, because one mole of A reacts with one mole of B and if you are not allowing any A and B to leave the system, if you are setting F A to be 100 kilomoles per hour. Well, F B has to be 100 kilomoles per hour. So, actually degrees of freedom is only three.

(Refer Slide Time: 54:35)



So, I think the degrees of freedom here are wrong; one requires for F A equal to F B. That is something that is dictated by the stoichiometry of the reaction. So, degrees of freedom is actually only three. How much feed you are supposed to process? Let us say F A, then F B has to equal F A and what? How much reflux you are putting in and how much steam you are putting into the system. So, degrees of freedom is you have got only three things and if your throughput is given, that is also gone. So, you have got only the reflux and the reboil to get the kind of separation and the reaction that you want; so, fewer valves to control to regulate the reaction and the separation. That is the problem with reactive distillation; more interaction between reaction and separation, higher non-linearity. The reactive distillation system would be much more difficult to control for large disturbances than a conventional process; that is the major disadvantage.

(Refer Slide Time: 55:46)



So now, let us talk a little bit about control and after that we will end. I am just drawing a possible control structure, pressure control, level control, level control, what else? Let us say I keep reflux in ratio with distillate. So, I take the distillate, I multiply it by L by D set point. There is a flow controller here and that flow controller takes its set point from that, from that multiplication. Let us say I am holding the flow rate of a constant, I do temperature control here to prevent reactants from leaking down the bottoms. So, if the temperature is going down; that means, the light reactants are accumulating in the stripping section.

I need to increase the reboiler duty, so that they are sent back to the reactive zone. What do I do with this valve? Well for every mole of A, I need to put in one mole of B. If I am putting excess B and its not getting out in the distillate or in the bottoms, it is accumulating some place inside the column and therefore, a temperature or a composition inside the column may be going up or down because of accumulation or depletion of B. So, to hold a composition and or a temperature constant typically what you would do is, you will control a reactive tray temperature or a reactive tray composition. Let us just say C C and wherever I write C C it can always be replaced with T C. It should be possible to replace it with T C for reasonably well-designed systems.

So, here you go. What does the operator set? 1, 2, 3, and I am including the feed this time; that is it. So, you have got only four set points that you can adjust and typically this set point, this F A set point will be how much production rate you want the process to have, how much feed you want to process. Well that is it; this is given to you. So, this is actually not in hand and your management will tell you this is how much A I want to process based on market conditions. So given F A, I have got only three things in my hands.

This composition controller that has been drawn here on the fresh feed of B, this composition controller is there to ensure that for every mole of A that I have put in; I have put one mole of B because any excess that I have put must either leave in the distillate or in the bottoms. So, this is called maintaining stoichiometric feed balance. Why stoichiometric? Because the reaction is one mole of A reacts with one mole of B to give one mole of C and one mole of d. That is what this guy does. And then the reflux ratio and temperature set points here are set to ensure that none of the reactants leave up the top, none or the amount of reactants leaving up the top is limited and the amount of reactants leaving down the bottoms is also limited.

Running this process requires much more finance, much more robust control system than running a plant which is where you have got ten things that you can adjust. If you exclude the throughput, then you have got nine things that you can. So, here you have got three things that you can adjust; there you need nine things excluding the feed rate or the throughput. So, regulation of reaction and separation is using three degrees of freedom, regulation of reaction and separation using nine degrees of freedom. Clearly this is much more easier. How to do it? Of course, that that we will be doing; this is more difficult. So, the challenge in reactive distillation process is that the process should be easily controllable and just towards the end I would like to point out that reactive distillation actually came; Eastman chemical company were the first ones to report a commercial reactive Eastman.

Eastman chemical company was the first ones to report a commercial reactive distillation process and their process was esterification to produce methyl acetate. So, you have methanol and acetic acid. They react to produce methyl acetate and I think water. So, there are lots of azeotropes in this system and if you look at a conventional process, the conventional process has got a reaction section followed by nine columns. This was replaced by a single reactive distillation column where some of the azeotropes got reacted away and you have methanol which is light being fed at the bottom of the reactive section. What is the other one? Acetic acid which is heavy is being fed up towards the top of the reactive section.

You have got the rectifying section and a stripping section and you get C is methyl acetate, D is water, A is methanol, B is acetic acid. You have got this simple single column that replaced one reactor nine column process with a single column. That was the first success story and it turns out documentation shows that compared to the conventional process, the reactive distillation process was in terms of capital cost five times cheaper; in terms of operating cost also five times cheaper.

So, when feasible, when reasonable reactive, distillation processes make much more sense than conventional processes, but that does not mean that these are recommended for any and every type of process chemistry. There are certain limitations and I just described them to you; relative volatilities have to be such that reactants can be prevented from escaping the column and the reaction rates at the operating temperature of the column has to be sufficiently high, so that you do not require too much catalyst. With that I would like to end our section on distillation systems of all types, reactive, non-reactive, heat integrated, complex, azeotropic, homogeneous azeotropic, etc, etc.

Thank you.