Cryogenic Engineering
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Lecture No. # 25
Gas Separation

So, welcome to the 25th lecture of we were dealing with gas separation and distillation column; and this will be the last lecture to cover the most of the aspect related to the gas separation and the distillation column designing.

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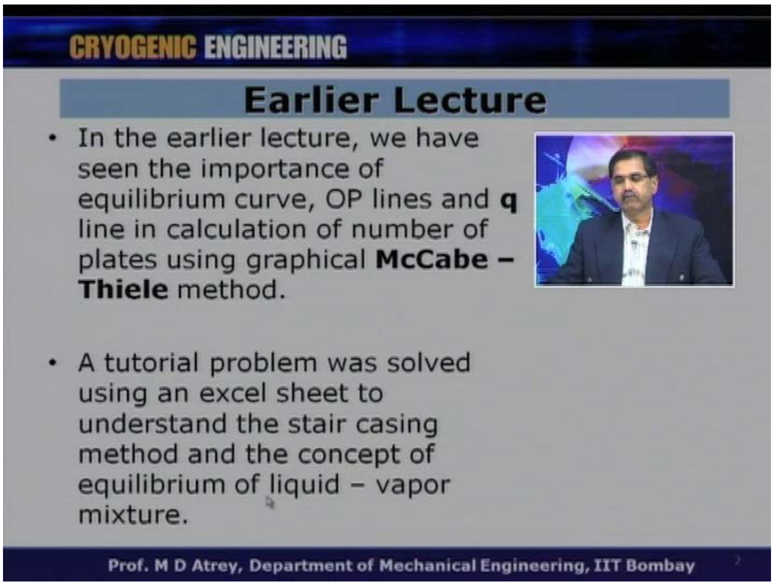

So, in the earlier lecture, we have seen the importance of equilibrium curve, operating lines and q line in the calculation of number of plates using graphical McCabe-Thiele method. As I pointed to you earlier, what is most important is to know the equilibrium curve, which is a given data for a given composition of the field and the pressure. What is important is to calculate the equations of the operating line, plot it properly, and also the q line, and then do the stair casing business, stair casing methodology to calculate the number theoretical plates, both in the enriching section as well as in the stripping section.

So, a tutorial problem was solved using an excel sheet, now when I did excel sheet, I have done lot of work behind that excel sheet, because what I want to do was basically to see the effect of various parameters, which is what will you will see in this lecture. However, you will have to do the same thing on a graph paper and therefore, it needs really a good practice. So, please solve a problem, the same problem you can solve using a graph paper and calculate, show all this curves, show all this lines and calculate the number of plates. So, a tutorial problem was solved using an excel sheet to understand the stair casing method and the concept of equilibrium liquid - vapor mixture.

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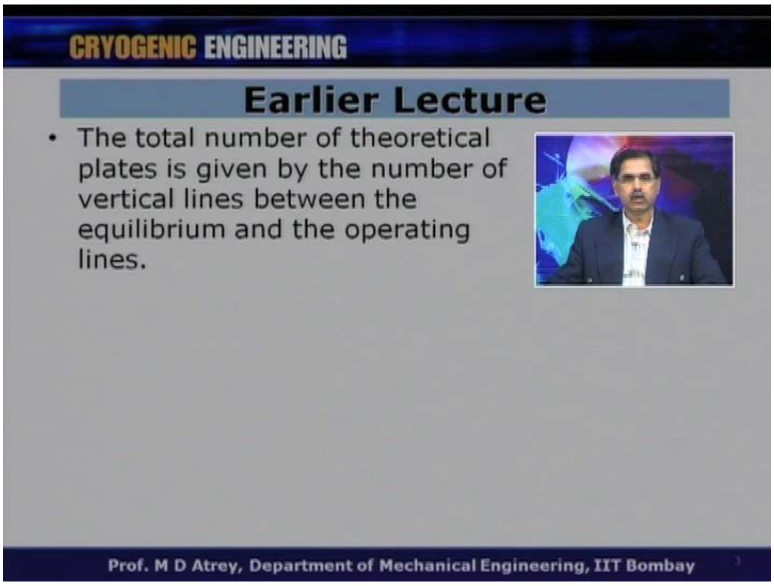

The total number of theoretical plates given by the vertical line between the equilibrium and the operating lines; so the number of theoretical plates in enriching section or in the stripping section is given by the number of vertical lines between the equilibrium line and the operating line. And we have seen, what is the concept behind this? Because on the equilibrium line, when we draw a horizontal line, we find the thermal equilibrium value of the vapor and the liquid, while when we come vertically down we come for the top most plate down, steady down to the lower and lower plates.

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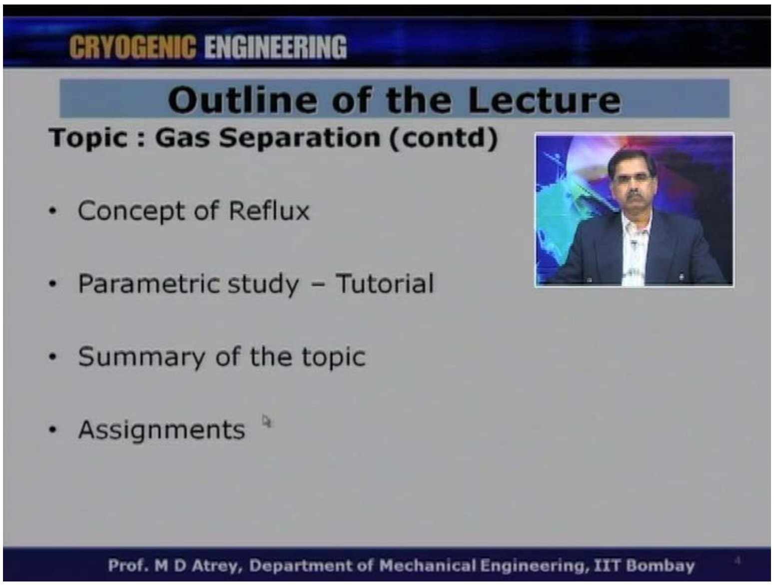

The outline of this lecture is we will talk about concept of reflux; reflux is amount of liquid, when the vapor goes to the top, the liquid comes down after condensation. So, this ratio of liquid, which comes down to the vapor which goes up is called reflux and we will talk about that. And then importantly we will study various parameters using a tutorial, so using problem which we have used earlier, I will extend a same problem using an excel sheet to understand effect of various parameters on the number of theoretical plates that we had calculated. And finally, I will be summarizing entire gas separation topic, which I am covered during last 7 or 8 lectures; and in you got some assignment for you, which I expect that all of you would solve by yourself and compare the results, the solution, which you have also given.

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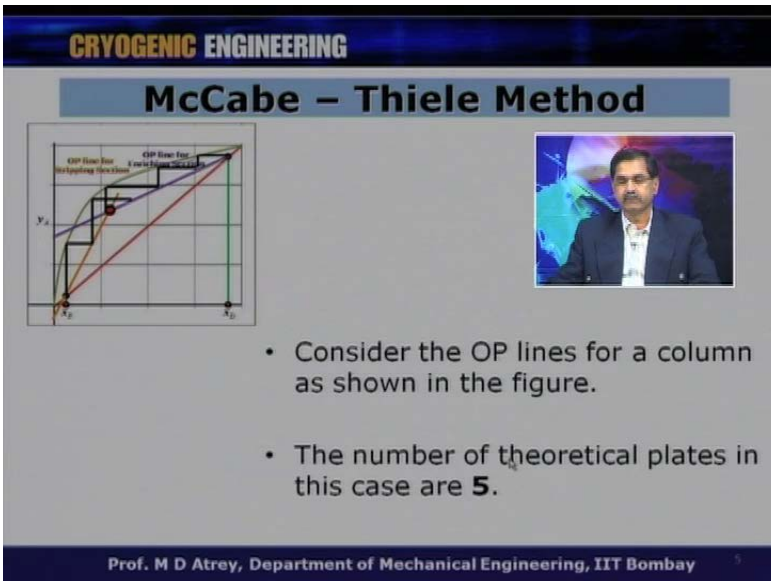

Now, this is what our graphical methodology deals with. What we have is a operating lines enriching section, operating line for the stripping section, and what we have is a equilibrium line; also what we have got a purity on the top, which is given by x d of the low boiling component, and we got a imparity at the bottom or purity of high boiling component, given as x b at this point; and what we have is a diagonal line, which represents y is equal to x line. Also we recall that these two points represent a top most and the bottom most plate in the column, because on this points y is equal to x, as we have found out.

So, consider the operating lines for a column as shown in this figure. So, this basically represents a column, when we want to use McCabe-Thiele methodology. Now we can see that I will just drawn some schismatic line to show that the number of theoretical plates in this case are 5. How did we come to conclusion? We can see vertical lines 1, 2, 3; 3 in the emerging section, and 1 on 2 in the stripping section. So, what you can see here is number of theoretical plates, total are 5.

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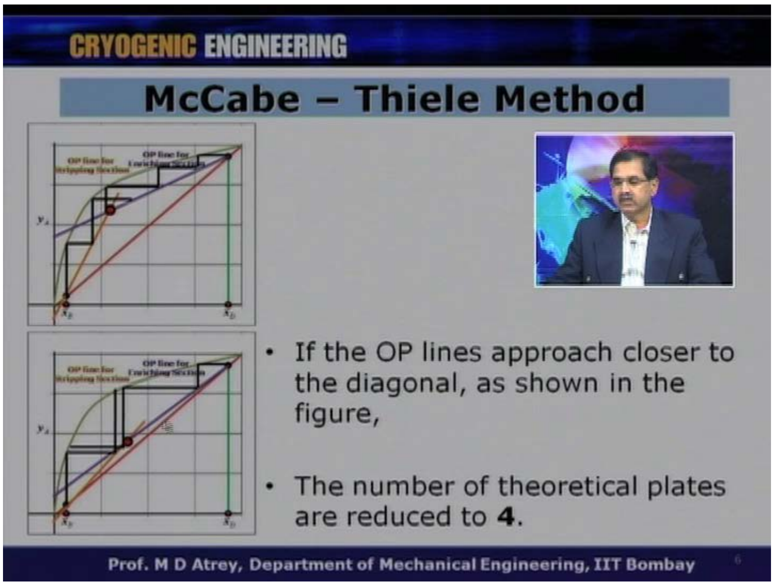

Now, what you can see from this methodology; same thing, I drive these operating lines such a way that they come closer to y is equal to x line. So, if the OP line or the operating line approach closer to the diagonal, which is a y is equal to x line, as shown in this figure, what you can see here? If I draw similar curve over here, the number of plates in the same case will be 1, 2, 3 and 4 only. So, we have come down from so many number of plates to a very small number, the number of theoretical plates are reduced to 4 in this case; what does this mean? This means again from understanding, if the operating line move towards y is equal to x line, the vertical line jumps are going to be very, very high; while if you go towards the equilibrium line, the jumps are going to be smaller and smaller; and therefore, the number of plates in this case very large, where the number of plates, when the operating line move towards y is equal to x line are going to be smaller and smaller; this is what we want to show from here.

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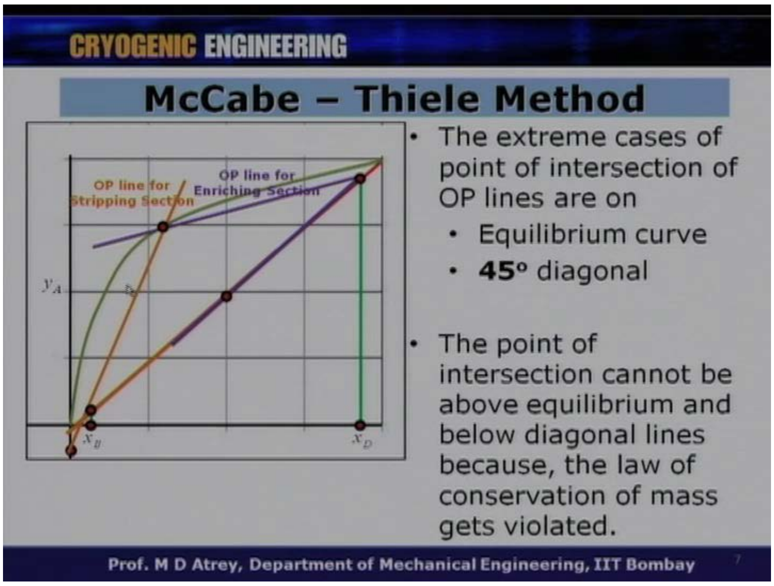

So, the extreme cases now, if I want to talk about two extreme cases, the extreme cases of the point of intersection of operating line are one is the operating lines are very, very close to the equilibrium curve, and this will happen, when the point of intersection of the operating lines is on the equilibrium curve alright; when this is one of the extreme cases that when the operating lines intersect each other on the equilibrium curve, and other case will be the operating lines are line on the diagonal itself; that means, they intersect on the diagonal, which means that the operating lines are on the diagonal itself.

So, you can see that in this case, the operating lines are right on the diagonal, while in other case, the operating lines are very, very close to the equilibrium curve; these are the two extreme cases. In this case as you know, that number plates are going to be very, very large as we just saw earlier; while in this case, when the operating lines intersect on the diagonal, the number of plates are going to be minimum in this case. Also understand that the point of intersection of this lines cannot be beyond the equilibrium section or cannot be below the y is equal to x line.

The point of intersection cannot be above equilibrium and below diagonal lines, because if you understand methodology, in which the way we drawn this operating line, if this happens to be true then the law of conservation of mass gets violated. So, please put in your understanding, the way we derived the equations, if these operating lines goes in this region, above the equilibrium curve, then the relationship between y and x will be violated, the law of mass conservation in this case, will get violated. And therefore, the operating line will always be between the equilibrium curve and diagonal curve, the diagonal.

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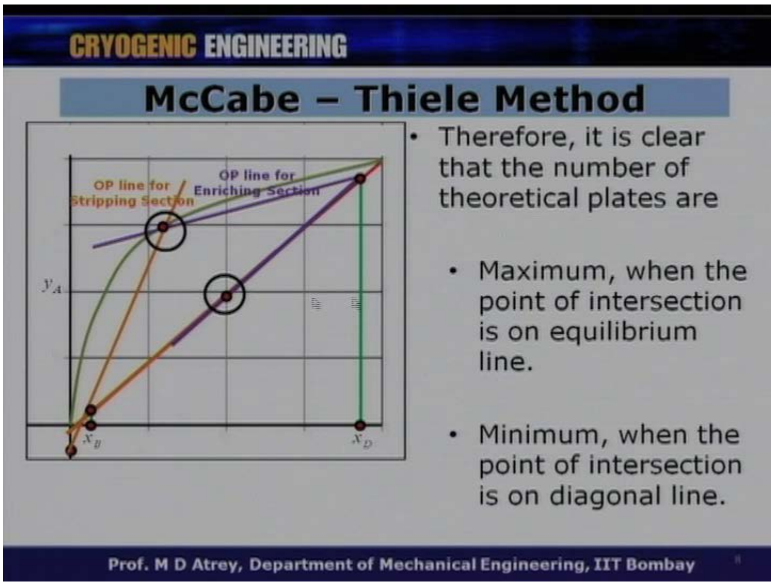

Therefore, it is clear that the number of theoretical plates are maximum, when the point of intersection on the equilibrium curve; as I just said that this is the extreme case now, and in this case, for a given column, for a given mixture, the number of plates in this case going to be maximum, because you can see the vertical lines are going to be very, very smaller over here; I mean the number of vertical lines are going to be large in this case, because of the distance between the equilibrium curve and the operating line is very, very small. While the number of theoretical place will be minimum, when the operating lines are intersecting or they are on the diagonal itself.

Now you can see here that the curve will have a big jumps. So, you can have big jumps and therefore, the number of vertical lines in this case are going to be minimum, if we do the stair casing business. So, the theoretical plates are going to be minimum, when the point of intersection is on the diagonal line, this is very important to understand; these are two extreme cases, the actual case will be somewhere in between; the actual case will be compromise between these two extreme cases.

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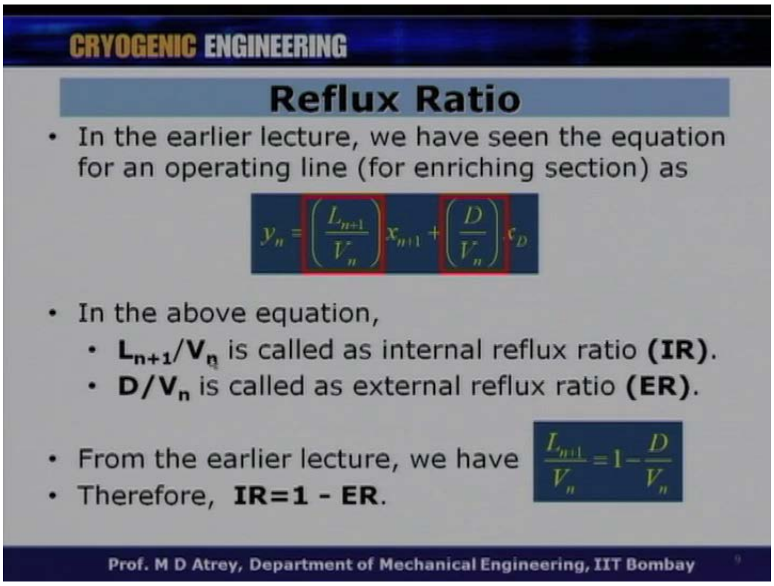

So, let us try to understand this concept of reflux ratio. In the earlier case, we have seen the equation of an operating line for the enriching section given as Y n is equal to L n plus 1 by V n x n plus 1 plus D by V n x D, where L by V or L n plus 1 by V n is a ratio of liquid, which is coming from the top plate to the vapor, which is going up; while D by V n is D is the moles per second leaving the condenser and V n again is the vapor, which is going up, while x D is the purity of the low boiling component. In the above section the L n plus V n that the amount of liquid, which is coming down from the top plate to the vapor, which is moving up is called as internal reflux ratio or IR; this is a reflux ratio we denotes, which indicates how much number of moles are coming down L n plus 1 to the number of moles, which are going up for the condensation V n, which is going up alright, because some of the liquid is taken out as D from this; whatever condensation happens on the top, some of the liquid is taken out as D, remaining liquid will come down as L n plus 1.So, this is very important to understand.

So, L n plus 1 by V n is called as internal reflux ratio; while the D by V n is called as external reflux ratio. So, what is coming out of the column is D; correspondent (( )) this D value will have b and f also, b which is coming out from the bottom or f which is coming from the field, because it will all be governed by the law of conservation of mass. So, D by V n is called as external reflux ratio, and L n plus 1 by V n is called as internal reflux ratio. Now are they related? If you remember earlier expressions they are related; and they are related by this expression L n plus 1 by V n is equal to 1 minus D by V n.

So, one can understand from here that IR is equal to 1 minus ER; what is it mean? If I ER is equal to 0; IR is equal to 1, when ER is equal to 0, when I do not take any D out. So, D by V n if I may is equal to 0; that means, I am not taking any condensate out from the condenser, in that case we reach an a case called IR is equal to 1, which means that the L n plus 1 by V n is equal to 1. Let us see these cases now; in this case, if the ER or the external reflux ratio is 0, then internal reflux ratio becomes is equal to 1.

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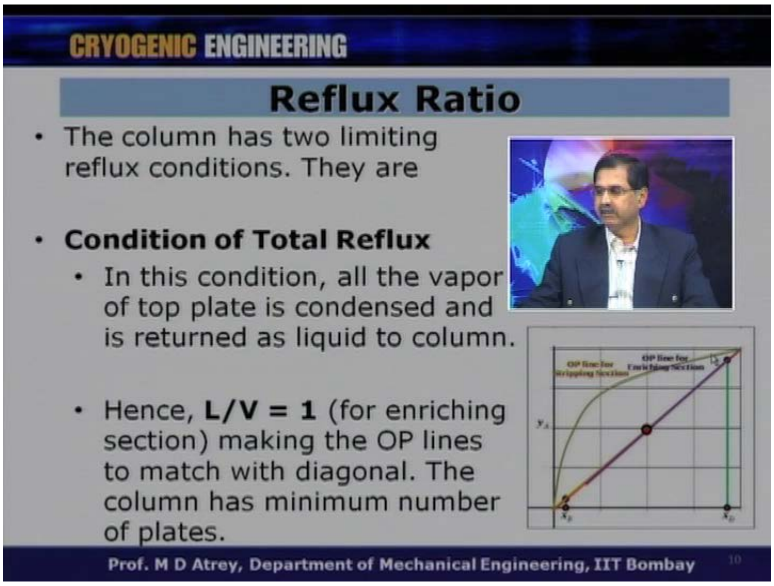

So, the column has two limiting reflux conditions, which is I just showed to you by some mathematical formulation; one condition is called as condition of total reflux, what is the reflux ratio? L n plus 1 by V n is called internal reflux ratio; D by V n is called external reflux ratio. So, condition of total reflux is, in this condition, all the vapor of the top plate is condensed and is returned to liquid as column. So, whatever V goes up, all this v will get condensed, and it comes down in the column itself as L, what is it mean? It means that there is no D, because all which is going up is coming down and this condition is called as total reflux condition.

So, in this case L by V or L n plus 1 by V n is equal to 1 for enriching section; and the moment we do L by V for as equal to 1 for the enriching section, the L by V for the stripping section also would be equal to 1, because D has become equal to 0 in this case.

And by a different calculation, you will find that L by V for the stripping section also become is equal to 1; making the operating lines to match with the diagonal, as you can see here, I got both the lines, operating line for the enriching section, operating line for the stripping section both from the diagonal; and therefore, the intersection can say, we can say that is equal to x is equal to x f point; they are basically intersecting on the same line. The column has minimum number of plates, in this case as we have seen, because if I start stair casing, you can see that I will get a minimum number of plates in this case.

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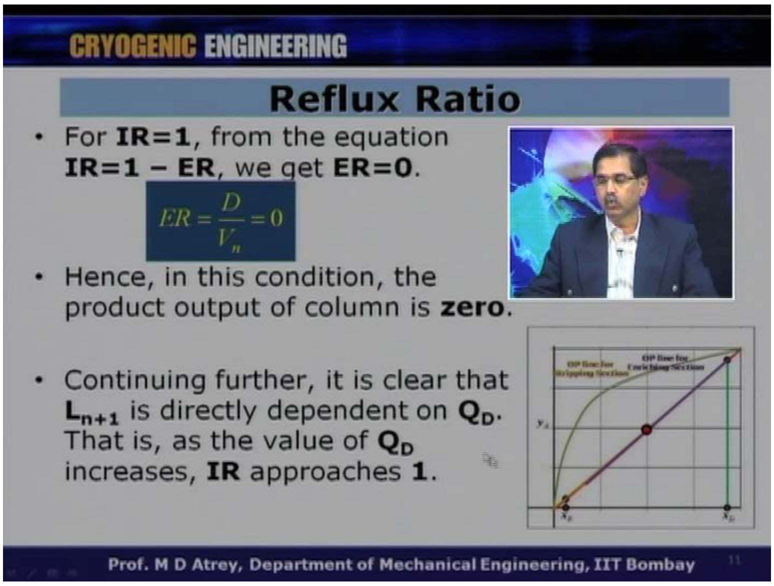

So, for IR is equal to 1; from the equation, we get IR is equal to 1 minus ER, we get ER is equal to 0 this, what I have told you earlier. So, moment I say ER equal to 0, I know D by V n also equal to 0, what is it mean? D is equal to 0. Hence in this condition, when IR is equal to 1, you will get the product output in the column as 0. I can say the other way, if I make D is equal to 0, if I decided that I do not want to take any condensate out; if I make D is equal to 0, then my IR will be equal to 1 in this case alright; when I make D is equal to 0, my IR is going to be 1 in this case, which will approach again in this condition.

So, reverse is also true, if I decide if a do D is equal to 0, I will get L by V is equal to 1, which means I have gone to a condition of total reflux; this is not a admissible case basically, this is such theoretical case; nobody would like to have D is equal to 0, because the whole rectification column is to get some D at the top and b from the bottom; is it not? Therefore, this is the very extreme case, where if D equal to 0, then I is equal 1 or when L by V is equal to 1, D is equal to 0 in this case.

Continuing further, it is clear that L n plus 1 is directly dependent on Q D. How are you again L n plus 1, how do get liquid, the liquid is coming because of condensation; and how does condensate happen; how does condensation happen is because of the cooling effect Q D that is available at low temperature at the top. Now, you see the most important cost of this column is going to be associated with this refrigeration effect or the cooling effect Q D at a particular temperature. If you are talking about the mixture at one bar for nitrogen and oxygen, the Q D has to be coming at 77 kelvin; it has to be kilowatts; 500 kilowatt, which is saw in the last problem, in the last lecture that very high amount or the cost will be involved to generate such a high cooling effect Q D.

If Q D available is less b, if the condensation, if the refrigeration effect is less in that case, my L is going to get decreased; and therefore, in that case, my IR will also get decreased. So, if my condensation effect is less, then my L by V also going to get less. So, if the value of Q D increases, it will increase IR also. So, depending if I got a high value of Q D, I will approach the value of one, if I got a less value of Q D, then I will go away from one, which means that I will go away from this column, and I will try to move towards the equilibrium curve. So, cooling effect available, Q D is very, very important parameter in order to decide, whether we are close to the equilibrium curve or close to the diagonal right; the cooling effect is the most costliest running cost in this case, basically for the column operation.

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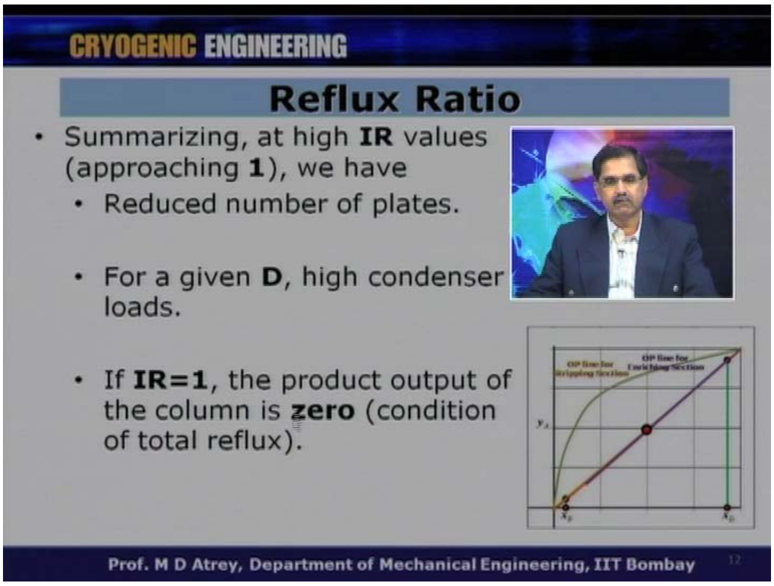

So, summarizing at high IR value; what is the high IR value for the enriching section is 1, and what is the low value? The lowest value will be when this operating line meet or intersect on the equilibrium curve. So, if I got a higher IR value, which is a approaching one, then we have reduced number of plates, which we just saw; then for a given D, suppose I have fixed some value of D, for high condensation loads; for a given D, we have got a high condensation load; if I got a value IR value, which is approaching one; then I will have a high condensation loads; that means, higher cooling effect is going to be required, if I try to move towards the diagonal.

If IR is equal to 1, the product output this is a extreme case, the product output of the column is going to be 0, and this is what we call as condition of total reflux. So, IR is equal to 1 is a condition of total reflux; in this case D is equal to 0, there is no output from the column, and this is the very hypothetical theoretical case.

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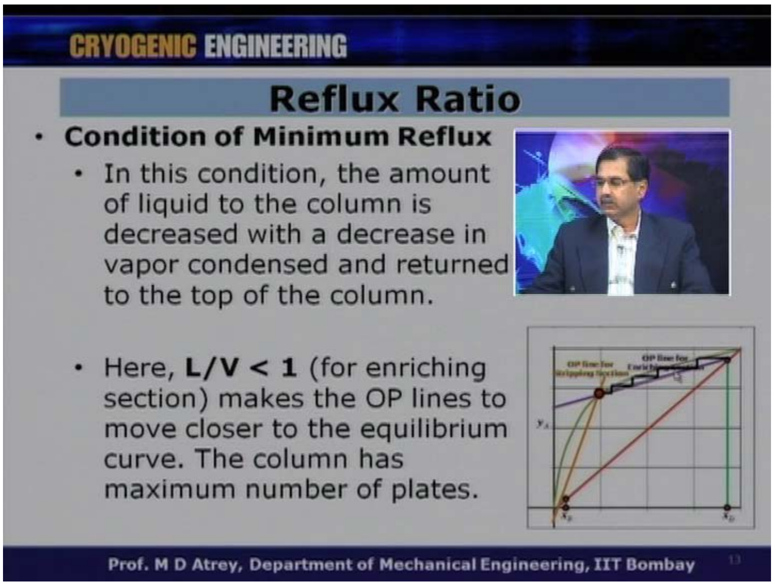

Now, the other condition is condition of minimum reflux; we had earlier condition of total reflux. Now, we have a condition of a minimum reflux, in which minimum L comes down, not maximum value; when the maximum L comes down from condensation, we have got a condition of total reflux, where L by V is equal to 1. However, if I got less number of L coming down, because of whatever other reasons in that case, I call this as a condition of less reflux or minimum reflux in extreme case. So, let us see what it is.

So, I have got a condition of minimum reflux; in this condition, the amount of liquid to the column is decreased. So, liquid which is coming less, which is the decrease in vapor condensed and returned to the top of the column. In the earlier case, what was happening; all the, which goes up, will get condensed. So, L by V was is equal to 1 in that case; but here now, because of whatever reason, I got less liquid coming out from the top and therefore, vapor going up is very high, but I am not able to condense all that into liquid or I am drawing mole D, from whatever condensate is happening on the top, I am taking mole D out, so remaining liquid is coming down as L. So, this could be the two reasons, because of which your L, which is coming down from the condenser is going to get decreased.

So, L by V in this case is going to be less than 1, much less than 1; for enriching section, again correspondingly my L by V also would shift for the stripping section. So, this is a condition, I am talking about; and this is a extreme condition, I am talking about, when both of them meet on the equilibrium curve. So, for L by V less than 1 makes the operating lines to move closer to the equilibrium curve, the column has maximum number of plates in this case. So, the extreme condition, these two operating lines are going to intersect on the equilibrium curve; and in this case, the number of plates are going to be maximum in this case. So, you can see that number of plates in this curve are maximum, because the gap between the equilibrium curve and the operating line is very, very small in this case.

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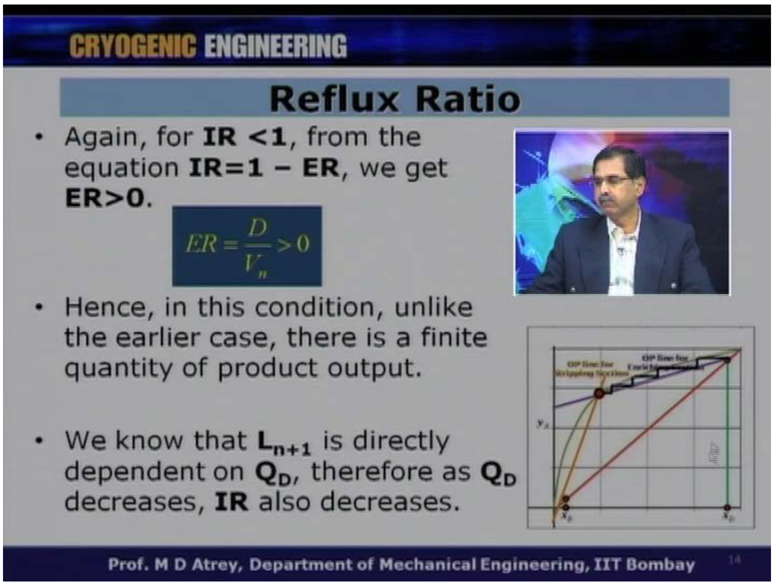

So, again for IR less than 1 from the equli equation IR equal to 1, IR equal to 1 minus ER, we get ER more than 0 in this case. So, I will get, when IR is less than 1, I will have some value of D, because ER is more than 1. Hence in this condition, unlike the earlier case, there is a finite quantity of product output, finite quantity of product output in this case. So, D is not going to be 0, as it was in the earlier condition of total reflux. So, we know that L n plus 1 is directly dependent on Q D again; therefore, as Q D decreases, so this condition can arise, because we have got a cooling effect at 77 kelvin for example, is going to be very, very less.

As I said the major cost is the cooling effect available at 77 kelvin. So, if Q D decreases in this case, here operating lines would shift towards the equilibrium curve. So, as Q D will decrease, IR will decrease; and therefore, your operating line will move towards the equilibrium curve. Meaning which that your number of columns are going to be very high; in order to achieve the kind of purity, which we want to achieve alright; it is also purity dependent, because your point x d and x b have defined the purity requirements from your side.

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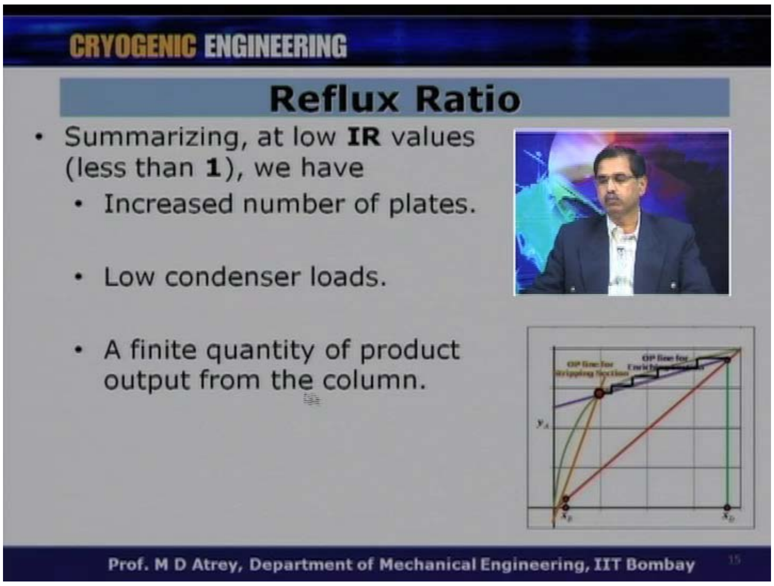

SO summarizing at low IR values that is less than 1, we have increase the number of plates, which is what we see in this case; also we have low condenser load in this case. If the condensation load is less, then we will shift the operating line will shifted towards the equilibrium curve. And in this case, we will get a finite quantity of product output D and V from the column; this is what extreme condition would be.

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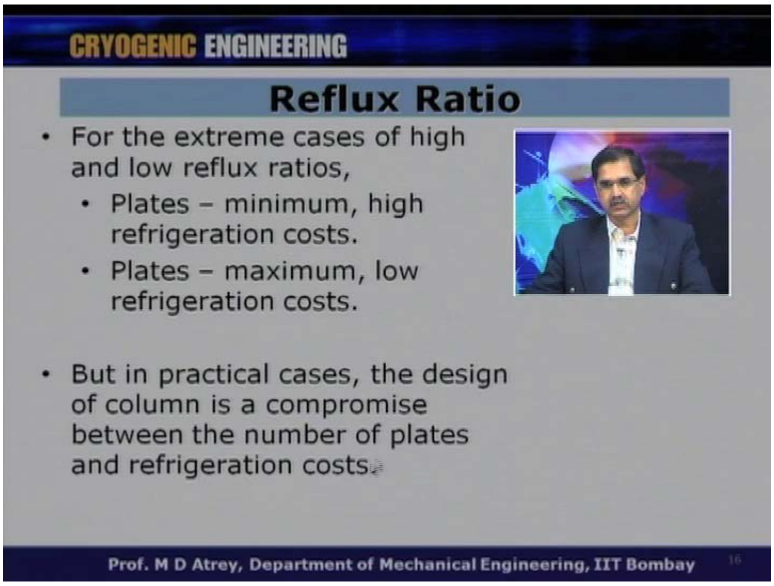

For the extreme case of high and low reflux ratios, we have got plates minimum and high refrigeration cost; if I got IR value to be high equal to 1, I will get plate as minimum, but it would involve a very high refrigeration cost; while the plates will be maximum for low reflux ratio, when IR is less, quite less as compared to 1; the number of plate will maximum, but the refrigerant cost will be minimum. So, these are two extreme cases, this case happen when both lines intersect on the diagonal; this can happens when both line intersect on the equilibrium curve; both these cases are not practical cases and therefore, for practical purpose will be somewhere in between, will be somewhere between the minimum and the maximum reflux ratios.

In practical cases, the design of column is a compromise between the number of plates and refrigeration costs; I cannot have very high number of plate, because my column height will increase this case. At the same time I cannot spend lot of money on the refrigeration cost; the cost of the refrigeration is very, very important. So, I have to really compromise between number of plates and the refrigeration cost in this case.

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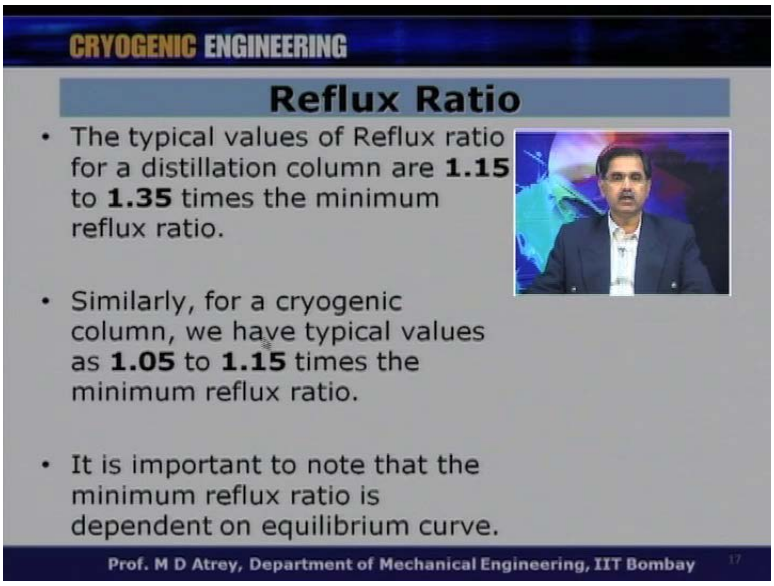

Typically, the typical value of reflux ratio that is IR L by V for the enriching section, for a distillation column are 1.15 or 1.35 times the minimum reflux ratio. So, what is important is find out minimum reflux ratio, which will occur, when both the operating lines intersect on the equilibrium curve. And then multiple it by 1.15 to 1.35 times, depending on again the cooling affect that is available with you; and this could be the typical reflux ratio for a normal operation. For a cryogenic operation, for nitrogen oxygen etcetera, because the condensation load or the cooling load matters a lot, the refrigeration cost is a very important; we keep it to a still a minimum level, and cryogenic condition we have typical value of 1.05 to 1.15 times, the minimum reflux ratio in that case, so that the cost of refrigeration is kept minimum in this case.

It is important to note that the minimum reflux ratio is dependent on equilibrium curve. So, what is the equilibrium curve that decides, what is my minimum reflux ratio? Equilibrium curve depends on what is the composition and what is the pressure of field. So, this will decide, what is my minimum reflux ratio and corresponding to this minimum reflux ratio, you can decide if you want to have a 15 percent more or 35 percent more, depending on the kind of cooling effect that are going to be available to you, throughout the execution, throughout the running of this distillation column and this is going to be very important cost associated with this.

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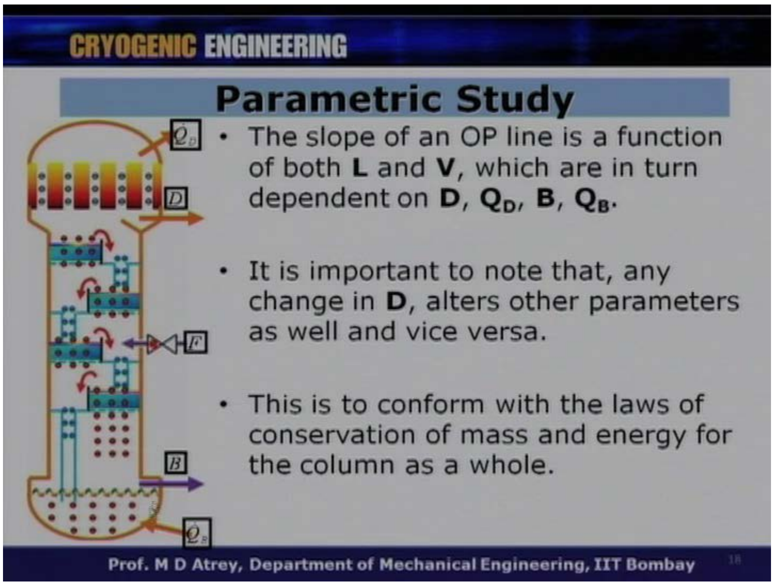

Now, let us see different parameters, which affect the reflux ratio. The slope of the operating line is a function of both L and V; that is L by V is what it is called as reflux ratio, which intern depend on what is your D, what is your Q D, which we just talked about; similarly what is your B and what is your Q B. So, this will decide, in relation it is all related to even feed also. So these are the parameters, which are governed by law of conservation of mass, law of conservation of energy; this is also going to decide, what is L by V of your column? What is the deflux ratio of your column? So, it is important to note that any change in D or any change in B is going to alter other parameters, which will all going to alter the L by V, because they are all related.

So, it is important to note that any change in D alters other parameters as well as vice versa. So, if you change any other parameter, if I change B, if I change Q D, if I change Q B, all other parameter are related and therefore, they are going to change, and this will change the reflux ratio. This is to conform with the laws of conservation of mass and conservation of energy for the column as a whole right. So, what we are going to do now is basically study the effect of different parameters on the theoretical plates of a given column; and therefore, what I am calling this as a parametric study.

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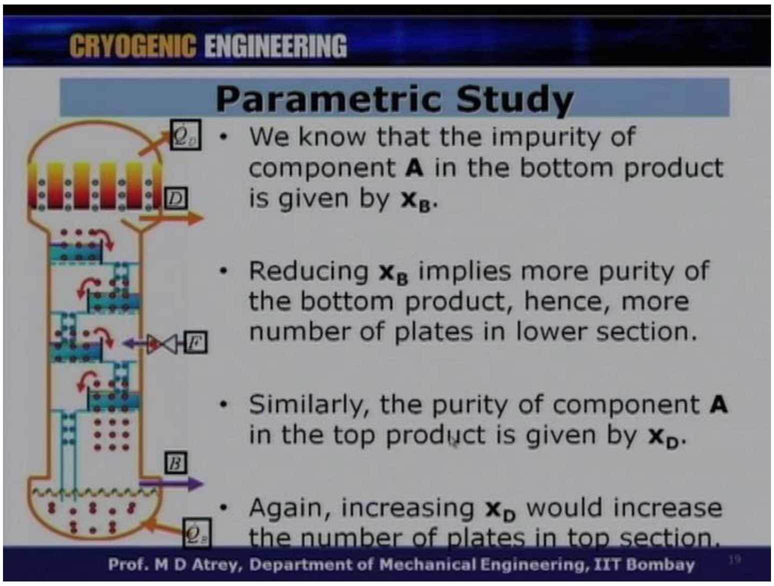

So, we know that also in addition to all this parameters, we know that the impurity of a column A in the bottom is given by X B, and on the top it is X D. So, if I reduce the value of X B or if I increase the value of X D, if I have purity of 98 percent, 99 percent requirement alright 97 percent requirement, I will need to have more number of plates. Similarly, if I want to decrease the value of X B to 0.02, 0.03 alright my number of plates would be required to a more, because I would like to have more heat transfer interaction between the vapor, which is going up; and the liquid, which is going to get coming down; more and more condensation boiling should happen and therefore, this will result in more and more number of plates.

So, the parameter which are affecting the design of column also is the your purity requirement X D and X B requirement; they are also going to decide, what are the number of theoretical plates that are required for a particular column deign. So, reducing X B implies more purity of the bottom product, hence more number of plates in lower section. Similarly, the purity of component A in the top product is given by X D and if I increase the value of X D, I will lead more number of plates for the top column also; again increasing X D would increase the number of plates in the top sections. So, very important parameter X D and X B, they will also determine what is the theoretical number of plates are required.

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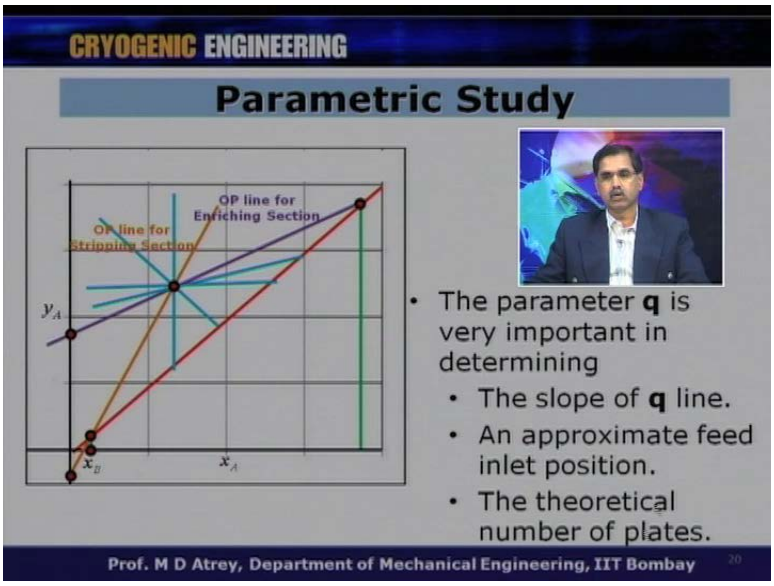

Also what are other parameters? The other parameter is the q line; what is the slope of this q line? When q is equal to 0, you know you got a horizontal line; if the slope of the q line is 0, we got a horizontal line; in the slope of the line is infinite, then it is parallel to y axis and we could be anywhere in between, then we got a two phase flow. So, the parameter q is very important, because it will decide where it intersects here. So, number of plate in emerging section, number of plate in stripping section can change depending on the slope of this q line; and therefore it is very important at this parameter also has to be taken into account, as a very important parameter to decide the number of plates both the emerging as well as in the stripping section; the parameter q is a very important parameter, in determine the slope of the q line, an approximate feed inlet condition and therefore, the number of theoretical plates this is very important parameters. So, let us see the effect of these parameters using the earlier problem, which we have solved.

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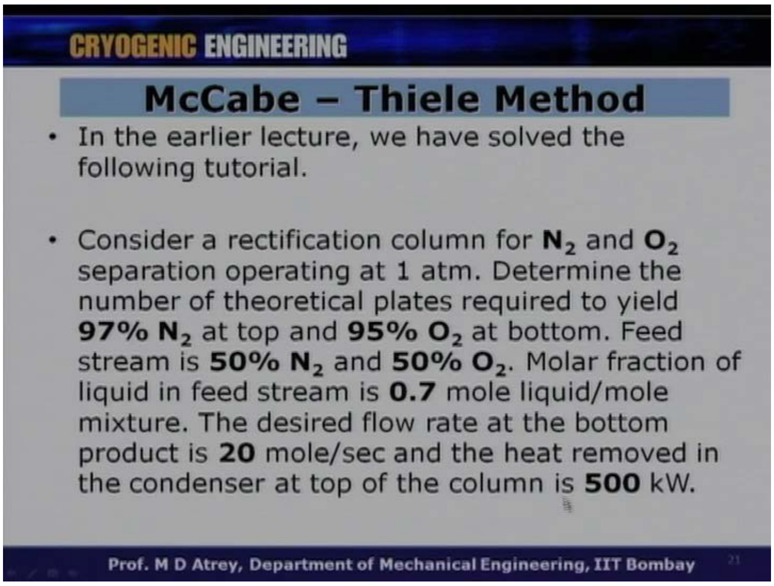

So, in the earlier lecture, we have solved the fallowing tutorial; and I will continue with the same tutorial, in order to understand effect of all this parameters, which we have been talking about; I will do this study, again using a, the graphical method, but again I will use a excel work sheet. So, for example, an excel work sheet is simpler for me, but for you, it will be again you have to use the graph paper to understand effect of these parameters; or also of course, you can develop the your own work sheet, your own excel work sheet. So, you have got a same problem, and I will not going to details of this problem, we got the purity requirement given, we got a feed composition, we have the q value given and also we got a value of B given, and the Q D effect the condensation refrigerant effect available is also given.

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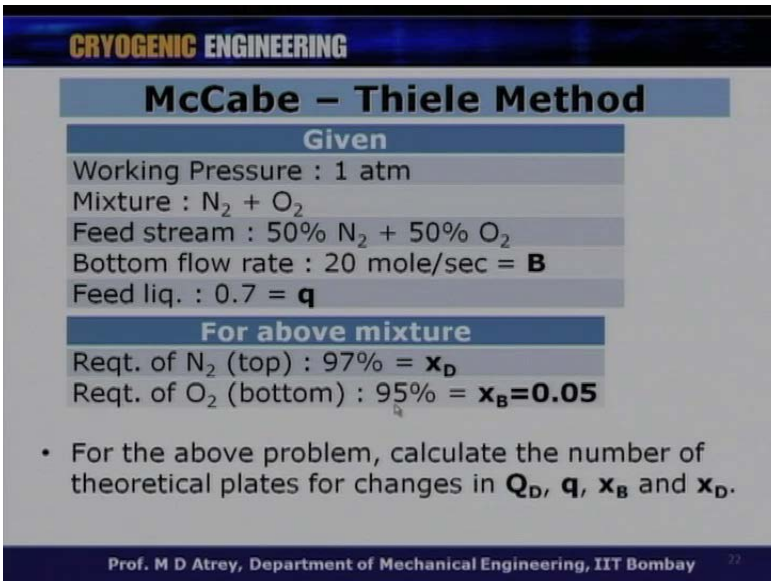

So, these are the parameters which we have been given the composition B feed line equation for the Q, and then we know that the purity requirements are 97 for the top, which is nitrogen and the purity requirement for bottom is 0.05 nitrogen or 95 percent pure oxygen. And what we have to do now, is to understand for the above problem, calculate the number of theoretical plates for changes in value of Q D; I am going to change this value of cooling effect available at top section or the condenser; value of Q, I am going to change; I want to change the value of X B and X D; and correspondingly, we will compare what happens if I increase the value of Q D, what happens if I decrease the value of Q D to the number of theoretical plates that are required for the column design to attain a given purity.

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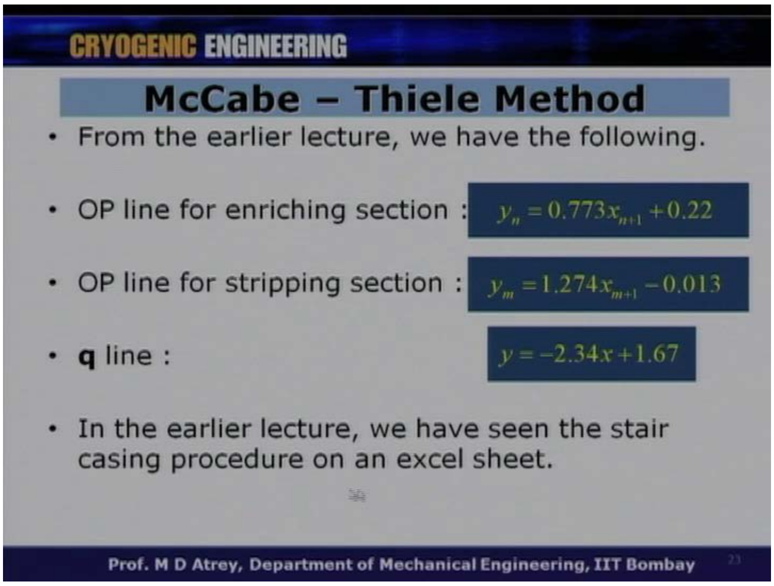

So, let us first see, from the earlier section, what we had seen was the operating line equation, which we had was this; the operating line for the stripping section we had for was this; and we have got a q line equation also as given as this. Based on this, we have already constructed a graphical methodology, we have already plotted; the curves for the given requirement of X D and X B; earlier lectures, we have seen that the stair casing procedure, we had done on the excel sheet.

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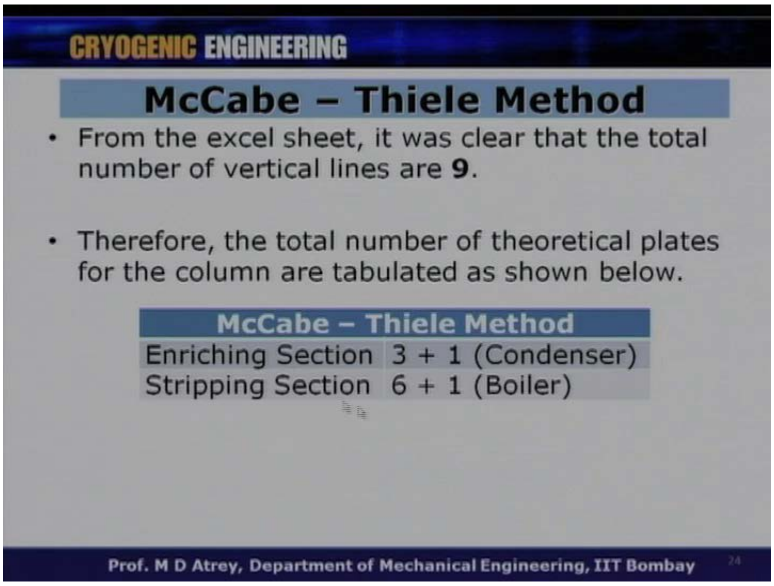

And we have found that the number of total number of vertical lines were 9 in that case; therefore, the total number of theoretical plates for the column are tabulated as below as what we had obtained earlier. So, in the enriching section had 3 number of plates plus condenser; stripping section the bottom section had 6 number of plates plus boiler and this was the case, when whatever was given in the problem as 500 kilowatt; but condensation, cooling effect available and the purity requirement was 97 percent at 0.5 percent respectively, for a top and the bottom section.

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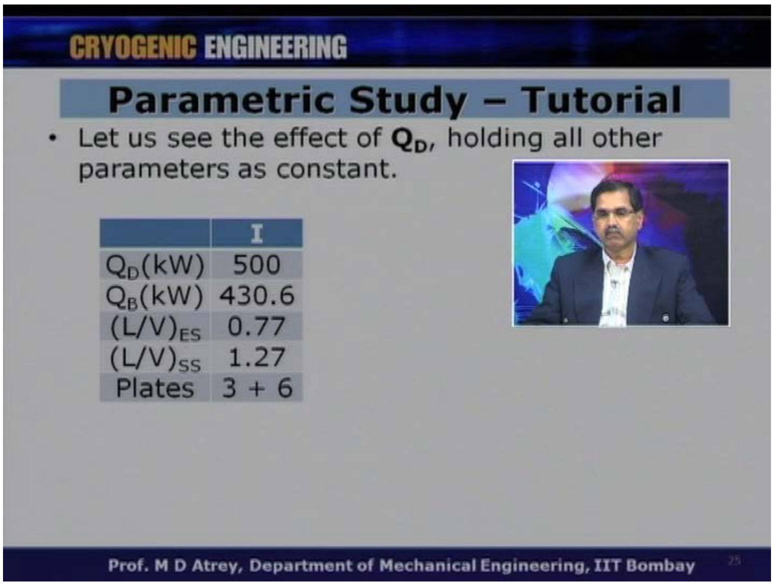

Now, let us take this as a tutorial, when we want to understand what are the defect of effect of different parameters. First parameter is let us see the effect of Q D, which is the condensation cooling effect available on the top, holding all other parameters as constant. So, let us I have just made excel sheet, and we can see that the first column is whatever result we had obtained earlier for 500 kilowatt cooling effect available. So, what for that case, we had got Q D is equal to this value, L by V which is a reflux ratio internal reflux ratio as 0.77 l by V SS for the stripping section as a 1.27 and the number of plates, which we have just seen is 3 in enriching section and 6 in the bottom section or the stripping section. Now, let us go to the excel sheet back, and let us see what happens if I change my Q D from 500 to a different value. So, let us see the excel work sheet.

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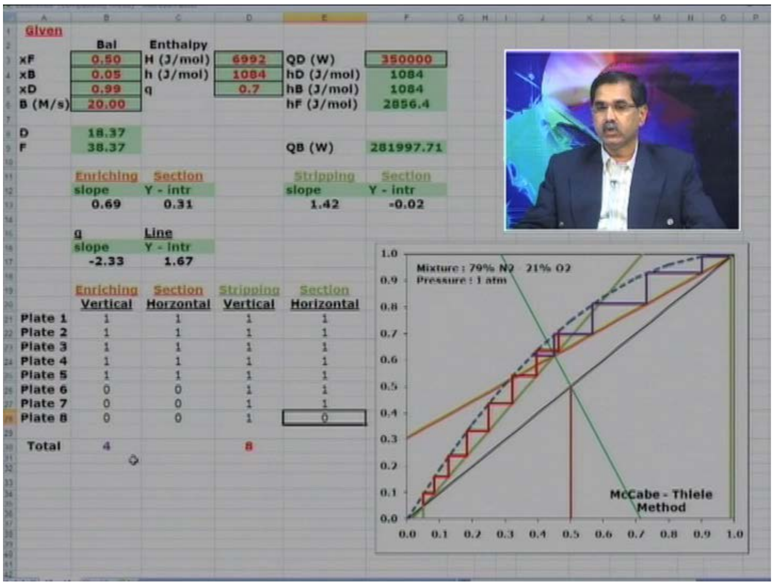

So, here in this case, this is my Q D, which is 500 kilowatt; and now I will change it to the… Let us decrease it to 350 kilowatts 350000 watts; all other parameters will be will be change now and therefore, again my slope has suddenly come down, you see we have now gone to the less L by V; less condensation load that is available; less condensation effects that is available; and therefore, my L by V for emerging section got decrease from 0.77 to 0.69 alright. And correspondingly my stripping section also will change and now, I will see what are the number of plates that could be calculated from this.

So, again you can see that number of plates for the stripping section will be increased to 4. So, the total number of plates will be increased to 4. So, the total number of plates will be now be 6 plus 4, and this is a result if I decrease the cooling effect available from 500 kilowatts to 350 kilowatts and what is happening, because of which my both the lines are shifting toward the equilibrium curve. And now my total number of plates are 1, 2, 3 and 4 for the enriching section; and a total number of plates for the stripping section are 8 over here. So, total number of plates are now, 12 in this case. So, can I just compare this with the earlier case?

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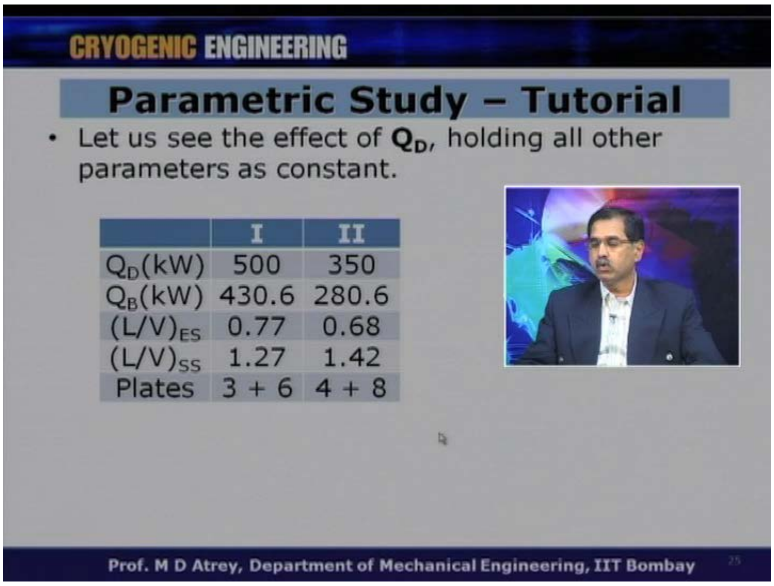

If I see now, this is if I decrease the value of Q D from 500 to 350 kilowatts, my L by V goes from 0.77 to 0.68; that means, it shifts to the equilibrium curve; and therefore, the number of plates have increase from 9 to 12, as we know that as we shift towards the equilibrium curve, the number of plates have increased.

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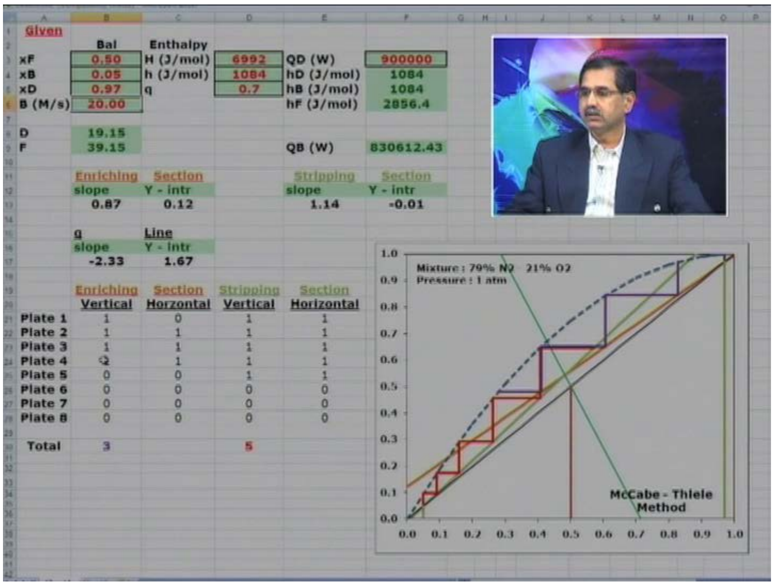

And now let us go to the other case, when I increase the cooling effects from 500 to a higher value, again go to the graphical representation. And now I will increase my cooling effect from 100 kilowatt to 900 kilowatt; and suddenly if I will find all the parameters have changed over here, and my enriching section slope, the operating line for the enriching section has gone to 0.88 that means the slope has increased. So, it has moved towards the diagonal now, it has moved to the y is equal to x line and correspondingly, now number of plates in this case will be less, because I am moving towards the enriching section, this is what we can see from here.

So, here if I draw the number of plates for the enriching section and the number of plates for the stripping section, you can see that this two have decreased. So, my total number of plates have come down to 1, 2 and 3, for the enriching section; and for the stripping section, it has come down to 5; what is it mean? If it means that if I increase the cooling load, if I increase the cooling load, keeping the D as same; keeping the D as same; my L by V as increased to 0.88. Correspondingly my stripping section L by V has moved towards the 1; it has decreased for the stripping section; however, it has increased for the enriching section; what is happen, because of which, I have moved towards the diagonal, I have moved towards the diagonal and therefore, my number of plates have decreased to 5 plus 3 in this case.

So, let us see the condition; now when I increase my kilowatts or the cooling effect from 500 to 900 kilowatt. So, let us see my excel work sheet again. So, here we can see that I have increased my cooling effect form 500 kilowatts to 900 kilowatts; and correspondingly, you will find change in the slopes for the enriching section; in all this cases, I am keeping my B, D and F as the same. So, law of conservation mass remains the same, you can see that my slope has increased from 0.77 for earlier case to 0.87; and correspondingly my stripping operating lines slope has decreased towards 1 - 1.14, which means that I have moved from the equilibrium curve to the diagonal line, which means that the number of plates in this case should decrease. And if I continue on the stair casing, here you can see that the enriching section have got 1, 2 and 3 number of plates; it should have 3 number of plates over here; while for the stripping section, I got 1, 2, 3, 4 and 5 number of plates in the stripping section. So, you can see vertical lines have increased here in the 3 and 5.

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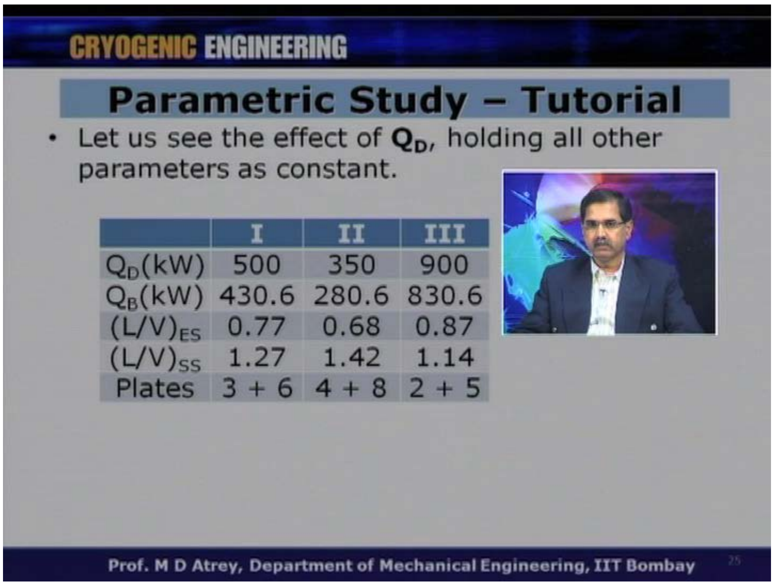

So, if I go back to my earlier case now; I can see now that number of plates here will be 900 kilowatts, corresponding to that L by V has 0.87, which is shifted towards 1; while L by V for the stripping section as 1.14; while you can see that the plates has increased from 3 plus 6 to 3 plus 5 in this case; that means the total number of plates have decreased to 8 in this case as compared to 9 in the earlier case with a given problem, where it was 12 in a lower Q D value.

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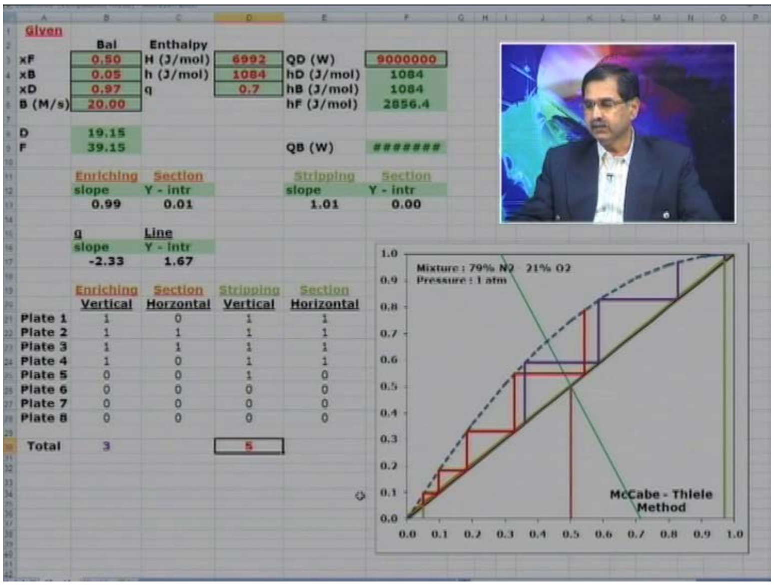

Now, let us go to the next problem, where I would take an extreme case of very high cooling power; you have got a cooling power of let us say 9000 kilowatts; correspondingly, will be lot of changes over here now. So, you can see, I have increased my cooling load to 900000 watts; and suddenly we will find that if you go to enriching section, you can find my slope has come to 0.99. So, I am coming very, very close to y is equal to x line in this case for the enriching section; and also corresponding to that, the stripping section slope also has come to 1 - 1.01; what does it mean? It means that all the lines have shifted very close to y is equal to x.

And therefore, I will have three number of plates in the enriching section; and I will have five number of plates in the stripping section, because you can see now, my number of vertical lines 1, 2, in fact, this is 2.5, but I am completing into 3; and in this case after the stripping section, I got 1, 2, 3, 4 at 4.8, but I will say 5 number of plates in the stripping section. So, total number of plates have come down to 5 plus 3 - 8. So, what does it show?

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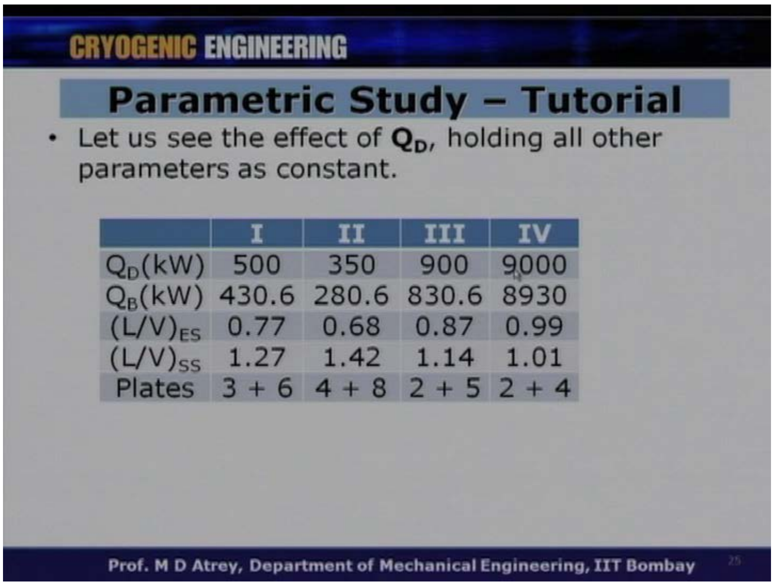

It is a extreme case, very high cooling power is available, I have move towards the y is equal to x line, the slopes have moved towards y is equal to x, which is 1 and correspondingly, if I now go back to comparison, I can see now, my number of you can see for 9000 kilowatts cooling effect available, I have got slope as 0.99 and 1.01; and now if I see number of plates. It will be 5 plus 3 - 8 number of plates, which have got reduced as compared to previous case. So, in extreme case, when I reached to 5 is equal to x line, number of plated have got minimum in this case. Now I also see that if my condensation cooling load is decreased further to let us say 300 kilowatts, then I move towards the equilibrium curve.

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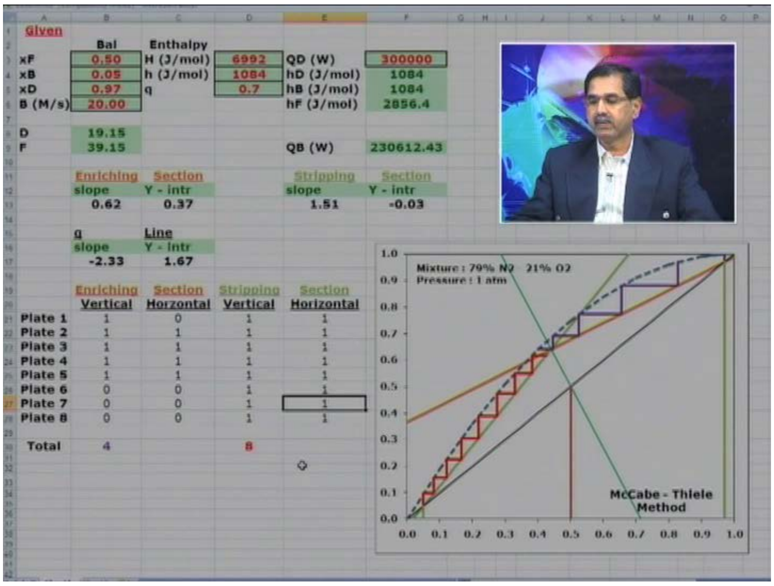

So, if I again play with the excel sheet, and if I now make the cooling load as 300 kilowatts, corresponding to you can see now, when number of plates going to be drastically increased in this case. So, my slope has come down for the enriching section has 0.62, my slope has stripping section has increased to 1.51; that means, I am going now away from the y is equal to x line going towards the equilibrium curve. And correspondingly, I can see now that number of plates in the enriching section has become equal to 4; 1, 2, 3 and 4 are the number of plates in the enriching section, and correspondingly in the stripping section, I have got 8 number of plates.

So, total number of plates have increased to 12 and why did this happen; this happen because my cooling load availability got decreased to 300 kilowatts only; my slope decreased to 0.62, which went to very close value and the point of intersection has come very close to the equilibrium curve; as you remember this is a condition of minimum reflux in this case; and therefore, the number of plates in this case has increased.

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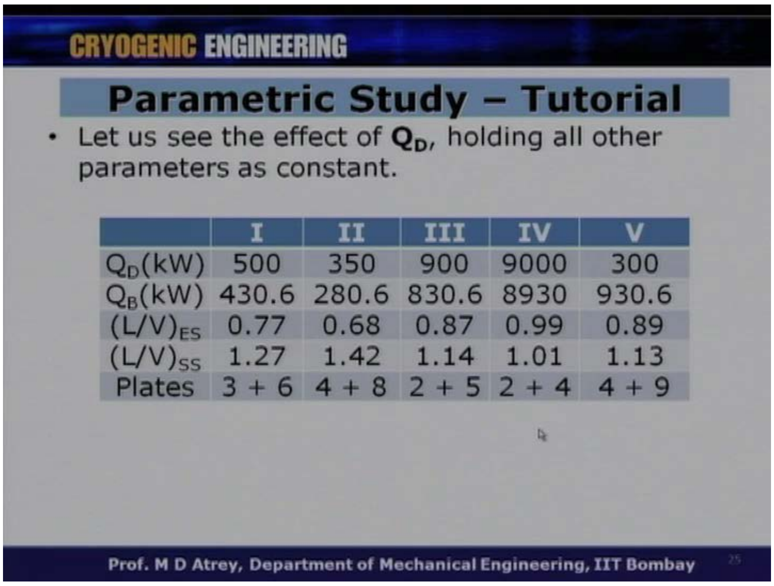

So, let us come back to now comparison curve; and here if I had this 300 thing, I have total number of plates has 13 in this case, which are very high as compared to. So, you can see that lessening the cooling load, moved towards equilibrium curve number of plates gets decreased; and if increase the cooling load, I moved toward y is equal to x line, and the number of plates get decreased in this case.

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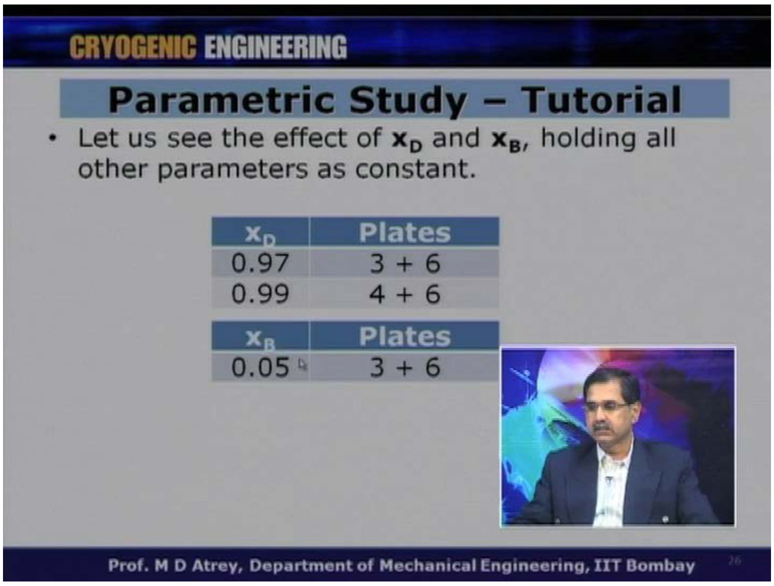

Now, let us go to the next parameter study, which is we want to see the effect of X D and X B, which is the purity level. What happens if I increase the value of X D or X B and corresponding to see, let us see the excel sheet now to this. So, in this case, I go back to my previous case, where my cooling load was 500 kilowatts, my purity was earlier 0.0 0.97, but if I now increase the purity. So, I will increase my purity to 0.97 to 0.99 in this case.

So, correspondingly you can see that enriching section, slope will change and everything will change in this case. So, my slope has increased to 0.78 now, for enriching section the slope has increased to 0.78, corresponding stripping section also has got changed; and here, if I do the stair casing business again 1, 2, 3 and 4; I got 4 plates in enriching section; and I got 6 strips 6 in the stripping section. What is it mean? I have as soon as I increase the purity, I going down from 6 plus 3 to 6 plus 4, my number of plates in the enriching section got increase from 3 to 4 in this case. And this is the effect of basically change of purity or x g parameter from 0.97 to 0.99.

So, you can again I go back to my work sheet. So, here again earlier it was 0.97 - 3 plus 6. And now when I increase to 0.99 plates got increased to 4 plus 6, this is a change of purity for the X D. Similarly, we can see for X B case, where earlier case 0.05 was a purity requirement, we had a 3 plus 6 requirement, and if I change my purity level now, X B level to 0.02 for example or 0.0… So, we will let say (( )) 0.02.

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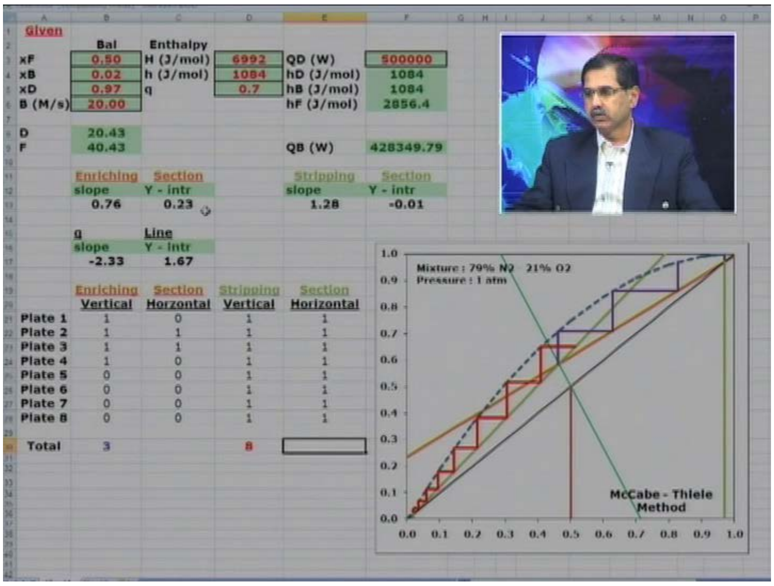

So, my X B requirement has become very stringent on the bottom side, on the stripping side and my X B has decrease from 0.05 to 0.02, corresponding my stair cases feasible change; and the number of line required in the stripping section, number of stripping plates required as increased to 8 now, from 6 it has increased to 8; the slope has come to 0.76, the slope of level stripping section have come to 1.28 in this case. So, you can see that number of plates in the stripping section has increased, just because I made my purity demands from 0.05 to 0.02 or from 95 percent to 98 percent for oxygen purity. This is as you know, is a impurity for nitrogen in the bottom section, which also means the purity for oxygen has become 98 percent in this case.

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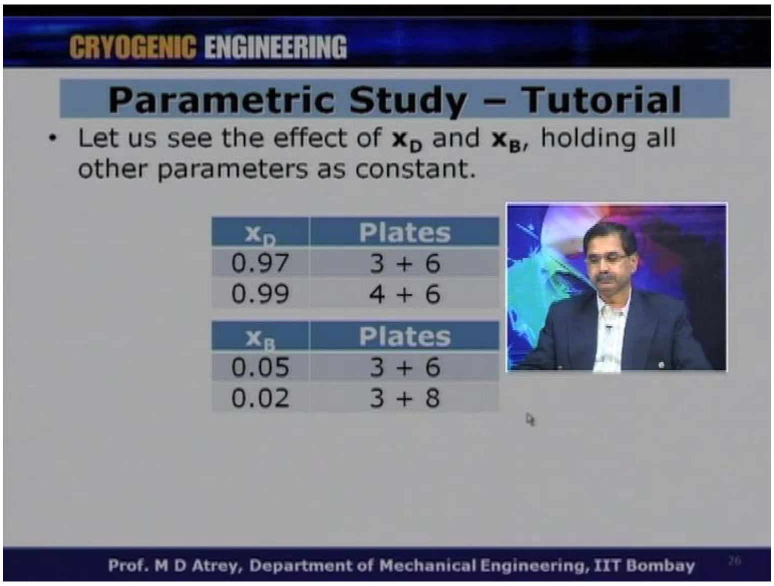

So, let us go back to our slides and see the comparison. So, what is happened; if I go from X B as 0.05 to 0.02, when number of plates have increased from 3 plus 6 to 3 plus 8 number of plates in the stripping section has increased from 6 to 8.

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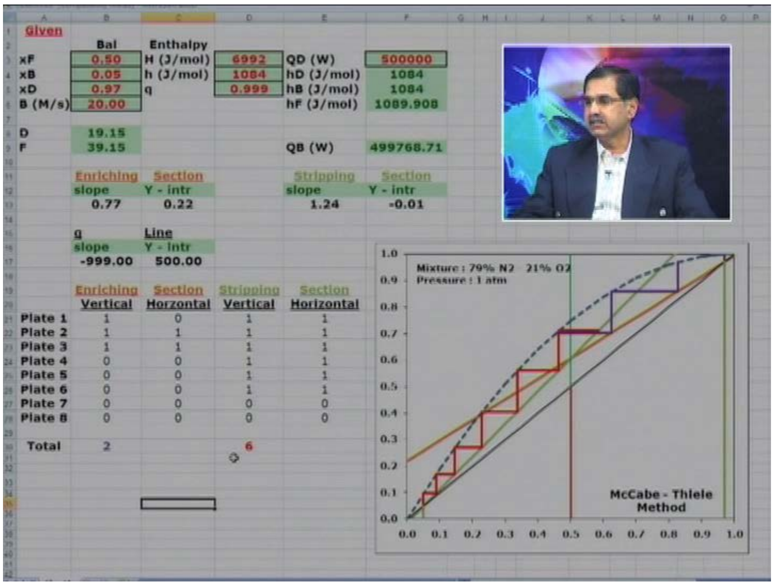

Let us now go to the next parameter; and let us see the effect of Q, what happens, if my Q parameter changes; let us again go to the stripping section. So, here I can change my Q value and let us go to original problem first, and how will you change the value of Q B, Q by changing 0.7 value to 0.8 value or something. Let us go to very high value of 0.999, which is very high value of Q, and you can see that this is Q is 0.99; that means, everything is L basically, everything is L or L by V is almost whatever coming is completely L; that means, my slope has become infinite; Q upon Q minus 1 for the field n has become infinite, and you can see now this is my field line over here, vertical is the feed line. And correspondingly, I got different number of plate in the stripping section as well as in the enriching section here.

What you can see the Q as soon as I change Q to 0.99, my whatever input is happening is now is completely in L, which is the liquid condition - saturated liquid condition in this case. L for the feed is going to be very high is equal to 1, whatever feed is coming is completely 100 percent is liquid in this case; corresponding to this now, I have got a 6 plus 2 or 2 plus 6 as number of plates.

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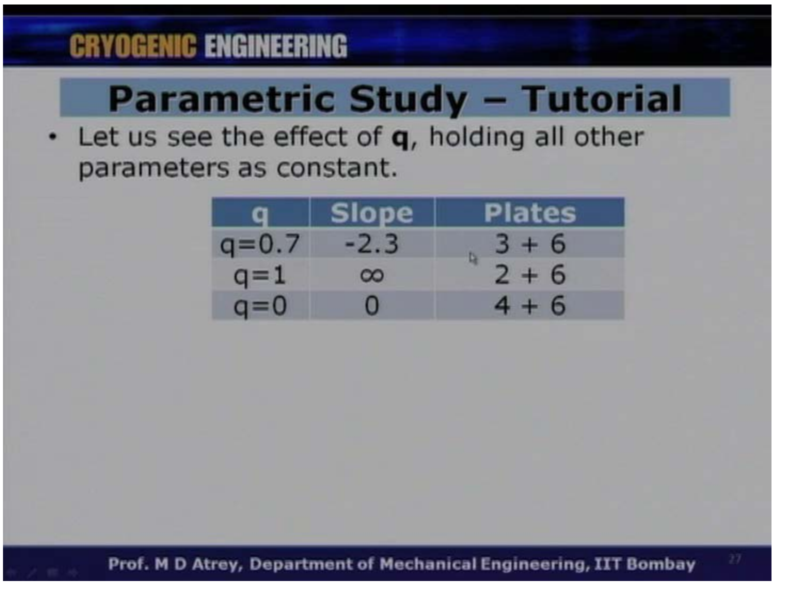

Let us now change the l value to 0; if I change the q value to be equal to 0 in that case. So, q was 0.7 plus and now I add q is equal to 1, which I wrote 0.99 in excel sheet my slope become infinite; and I got number of plates has 2 plus 6 in this case. Now, let us go to the value of q, where q equal to 0; and when I make the value of q to be equal to 0, my number of plates become 6 plus 4; and this can again be seen from the excel work sheet. So, you can see that when I make the value of q is equal to 1, I got all the liquid coming in the thing right, the feed is coming as liquid, if I make q is equal to 0, there is no liquid and the feed is completely vapor; in this case, I need more number of plates and if I put any other q as minus 2.3 for this value of slope, I got number of plates to be in between 2 extreme, all other parameter remaining the same. So, maximum plates will happen, when all the feed is coming in the vapor condition, minimum number of plates, when all the feed is coming in the liquid form, somewhere in between when you got a two phase that is coming in the as a feed in this case.

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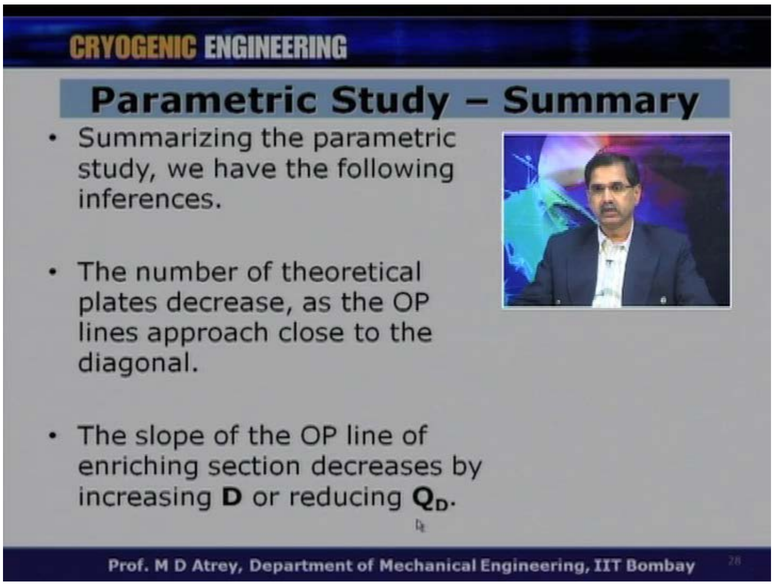

Summarizing these parameters, we have following inferences, the number of theoretical plates decrease as the operating lines approach close to the diagonal, which we know. The slope of the operating lines of enriching section decreases by increasing the value of D or reducing value of Q D, we know this now.

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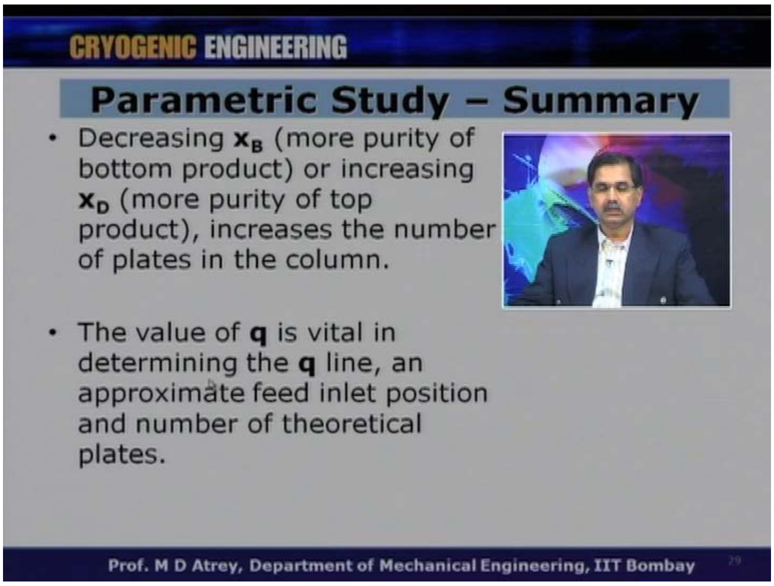

Similarly, decreasing X B or increasing X D, decreasing purity, requirement of purity changes and if we increase this purity requirement, it will increase the number of plates in the column; the value of q is vital in determining the q line, an approximate feed inlet condition and number of theoretical plates of q also dominates the number plates calculations for in this case. With this summary of the different parameters, I would like to summarize the entire gas separation chapter now; this is what we have steadied till now.

So, if I want to summarize all the things, which we have learned in the last 7 or 8 lectures, this is right from the beginning of from the work of separation to different laws; Raoult's law, Dalton's law etcetera, do the number of theoretical plates calculations, and to see the effect of different parameters that effect theoretical number of plates. There are various other thing also to be understood, but I cannot take and that that will go out of the scope of this particular lecture, but there are other thing also to be understood; that means, how much high purity, how to calculate number of plates at very, very high purity requirement and thing like that, but this I will keep you for referring to the different books. Summarizing whatever I have talked to you in this last 7 or 8 lectures on gas separation are fallowing points.

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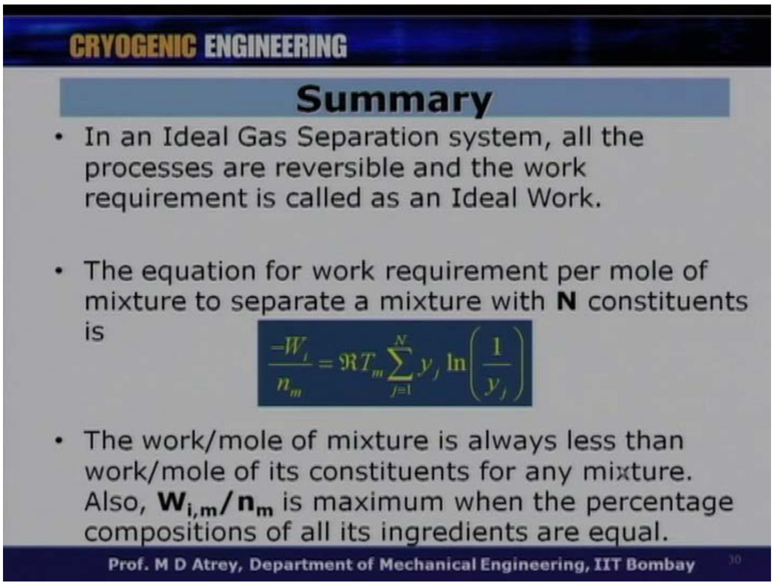

In an ideal gas separation system, all the processes are reversible and the work requirement is called as an ideal work; in this ideal work will be minimum for ideal conditions. The equation for work requirement per mole of mixture to separate a mixture with n constituents is you know this formula, which we have derived, so I will not go this is all sigma depending on number of N components from j is equal to 1 to N y j log of 1 by y j, this is what will determine the work requirement per mole of mixture.

The work per mole of mixture is always less than work per mole of its constituents for any mixture; we have understood this by various problems and tutorials also; also W i m divided by n m is maximum, the ideal of work per mole is maximum, when the percentage composition of all its ingredients are equal; form mathematics we can understand this W i by n m is going to be maximum in this case.

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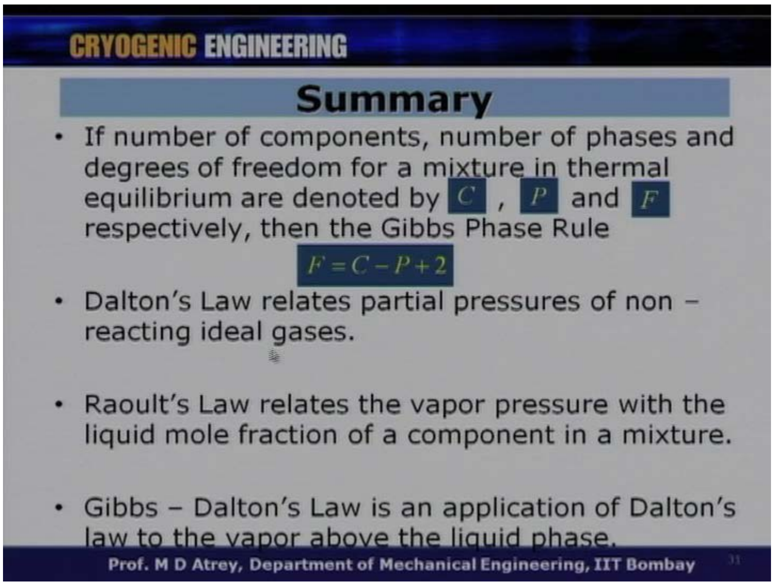

If number of components, number of phases and degrees of freedom of a mixture in thermal equilibrium are denoted by C, P and F; then the Gibbs phase rule gives F is equal to C minus P plus 2; and again we have understood this with various tutorials and problems. Dalton's law relates partial pressures of non reacting ideal gases. Raoult's law relates the vapor pressure with the liquid mole fraction of a component in a mixture, is very important Raoult's law, because of which we could solve problems also. The Gibbs Dalton's law is an application of Dalton's law to the vapor above the liquid phase; in fact, these three laws you know make the basic foundation for the separation column; is it not?

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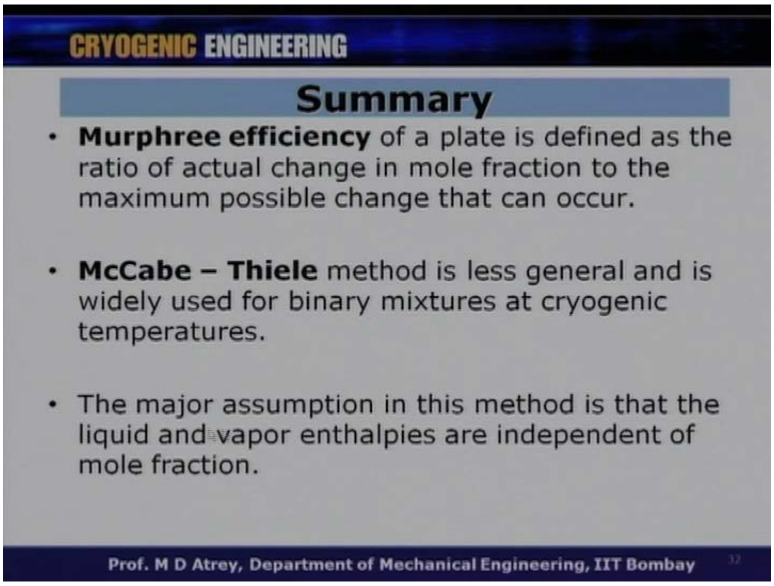

The Murphree efficiency, if you remember Murphree efficiency for a plate is defined as the ratio of actual change in mole fraction to the maximum possible that can happen on each plate. So, Murphree efficiency can be different for each plate also. So, this is actual change of mole fraction to the maximum possible change that can happen, if ideal heat transfer happens you know plate. McCabe-Thiele method is less general and is widely used for binary mixture at cryogenic temperature and this is what we studied; the major assumptions in this method is that the liquid and vapor enthalpies are independent of mole fraction; and this was a reasonable, reasonably good assumptions, in order that we understand the variations of different parameters; if we are otherwise have to calculate the enthalpies for different composition for every plate. So, this is the major assumption, which facilitated the calculations and made it very simple.

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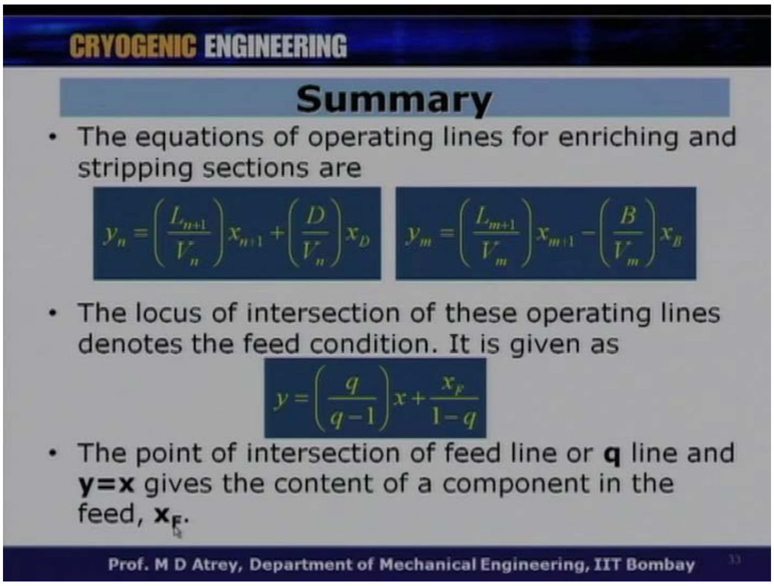

The equations of operating lines for enriching and stripping sections are this and this, you know this very well now; the locus of intersection of these operating lines denote the feed condition, and it is given as y is equal to q upon q minus 1 x plus x f upon 1 minus q, and q upon q minus is the slope of the feed line; the point of intersection of feed line or q line, and y is equal to x gives the content of a component in the feed, which is X F So, X F denotes the composition of low boiling component in the feed in this case.

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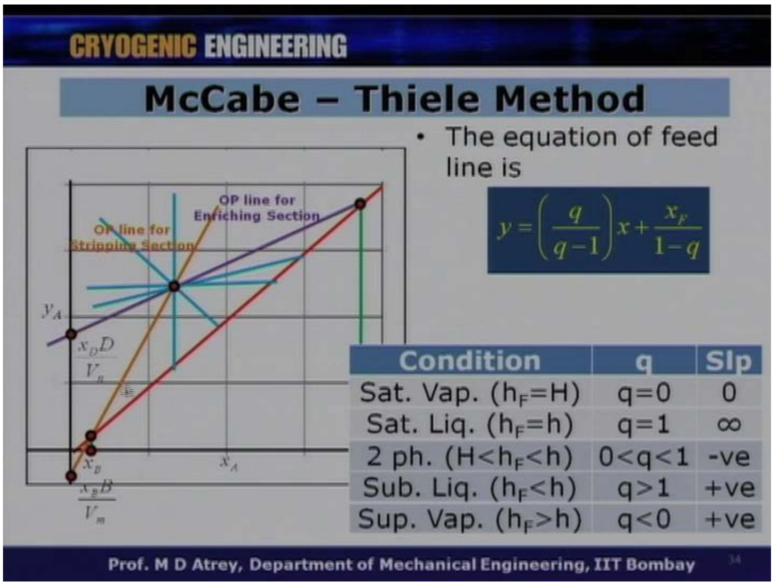

So, this was what our McCabe-Thiele graphical method; and the equation of the feed line is this and different q conditions can be understood, and we had understood for saturated vapor your q is equal to 0, the slope is equal to 0, for saturated liquid, q is equal to 1 and slope is infinite in that case, and you have got two phase, where the q line between 0 and 1, slope is going to be negative, and we got a sub cooled and super cooled condition also. For all this conditions, we got different lines and this is what we going to determine that number of plates in enriching and the stripping sections on top part and bottom part over here.

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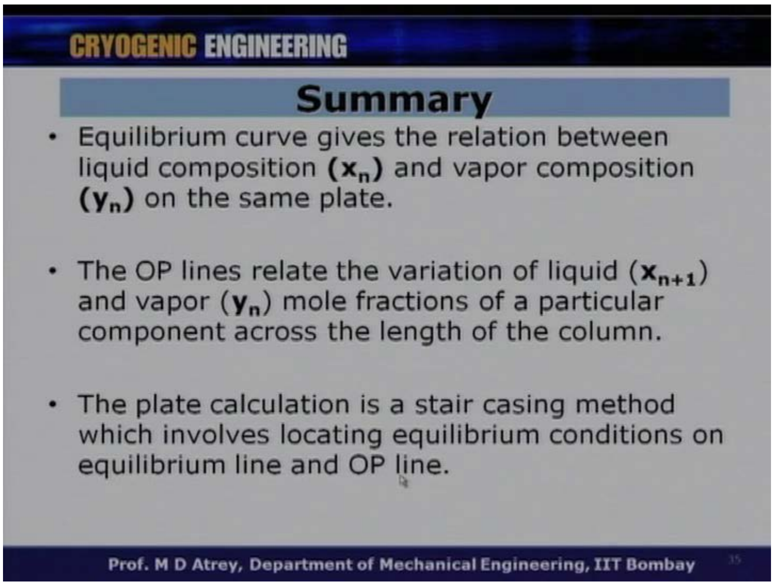

Equilibrium curves gives the relationship between the liquid composition X n and vapor composition Y n on the same plate; it is same, very important this is what facilitated us to go horizontal and vertical on when we wanted to calculate the number of plates in the enriching and the stripping section. The operating line relate the variation of liquid X n plus 1 and vapor Y n, because we got Y n has a function of X n plus 1, these are the mole fraction; liquid and vapor mole fraction of a particular component, across the length of the column. The operating lines gives the operating parameter for every plate, the equilibrium curves gives the operating parameters for each plate, and this is across the plate, because it is X n plus 1 and Y n. The plate calculation is a stair casing method, which involves locating equilibrium conditions on equilibrium line and operating line. So, this is also variable.

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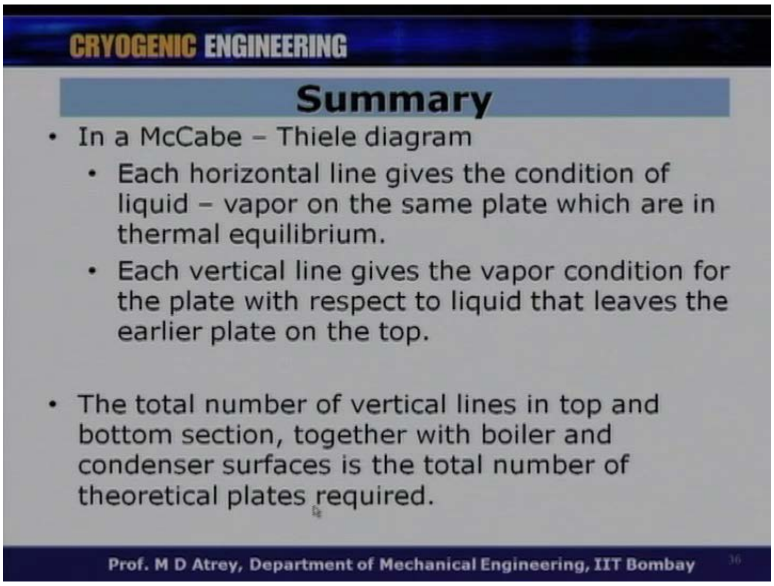

In McCabe-Thiele diagram, each horizontal line give the condition of a liquid vapor on the same plate, which are in thermal equilibrium; each vertical line gives the vapor condition for the plate with respect to liquid that leaves the earlier plate, which is X n plus 1, and this is Y n V n, this is V n for the plate, which is below the top; the total number of vertical line is in top and bottom section together with boiler and condenser surfaces is a total number of theoretical plates required.

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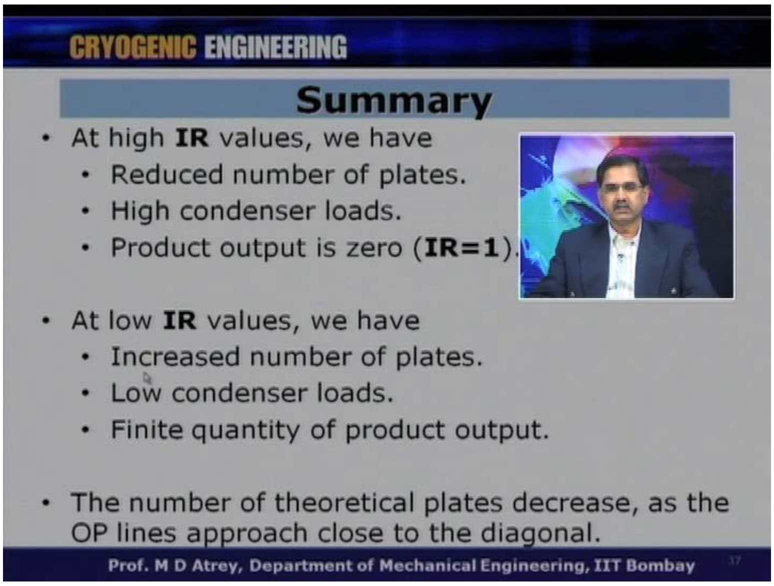

At high IR value, we have reduced number of plates; high condenser loads, product output is 0, which is IR equal to 1 in that case. And at low IR value, we have increased number of plates; low condenser loads finite quantity of product output, this is what we have learnt earlier, IR is equal to 1 and low IR values what happens. The number of theoretical plate decreases as the operating lines approach close to the diagonal; this is what we study from different problems, tutorials, which we took that when the operating lines going toward diagonal, number of plates will decrease, when we reached the IR equal to 1 value.

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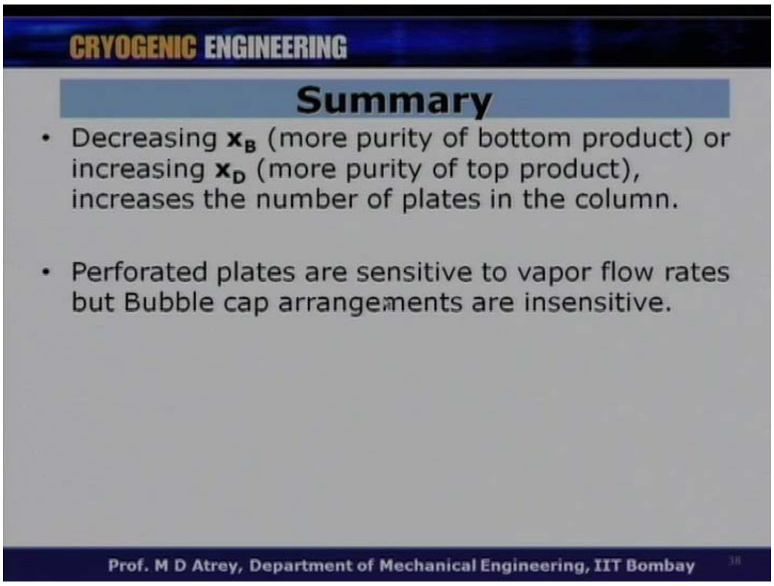

So, high IR value, we are we are very close to diagonal, lower IR value, we are close to equilibrium line, which results in increase number of plates and lower condensation loads. Again the purity requirement, decreasing X B and increasing X D will increase the number of plates in the column. So, purity requirement also dominates the number of plates in the column. The perforated plates are sensitive to vapor flow rates.

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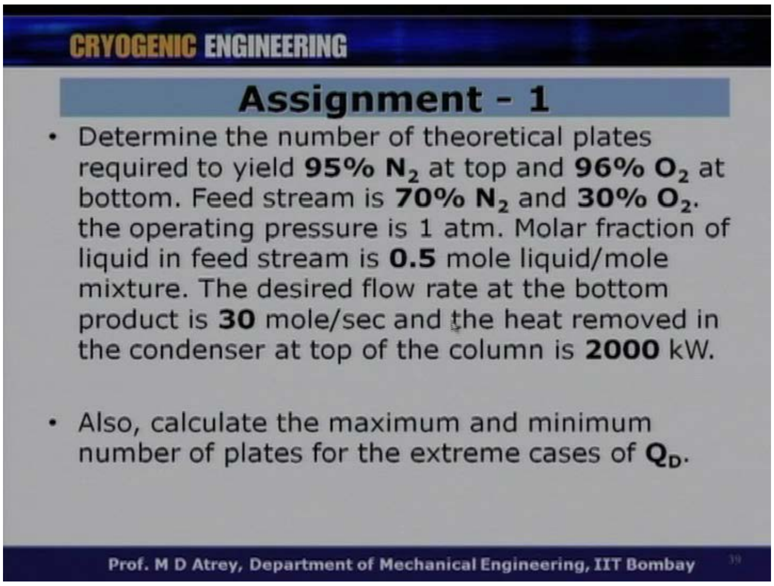

With this now let us come to see the assignments; and please go through the assignment, the problem has been in line with what we have done earlier; and for which, we have got various parameters; please go through this line. And also calculate maximum and minimum number of plates in this case, using a graphical sheet.

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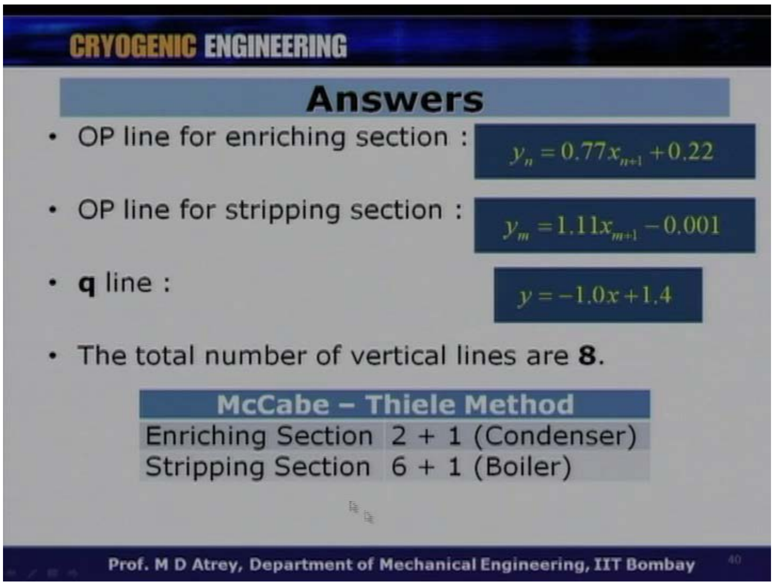

The answers to this are given; please check your answers; and thank you very much.