

Cryogenic Engineering
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Lecture No. #23
Gas Separation

So, welcome to the 23rd lecture, on Cryogenic Engineering, under the NPTEL program, at IIT Bombay. The earlier lecture, we were talking about Gas Separation Column or Distillation Column.

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Earlier Lecture

- Earlier, we have studied the Temperature composition diagrams, the Enthalpy composition diagrams and their importance in Gas separation.
- The separation of a mixture is more effective when the difference in the boiling points is more.
- In this column, Low and High Boiling components are collected at top and bottom respectively.
- **Murphree efficiency** is the ratio of actual change in mole fraction to the maximum possible change that can occur.

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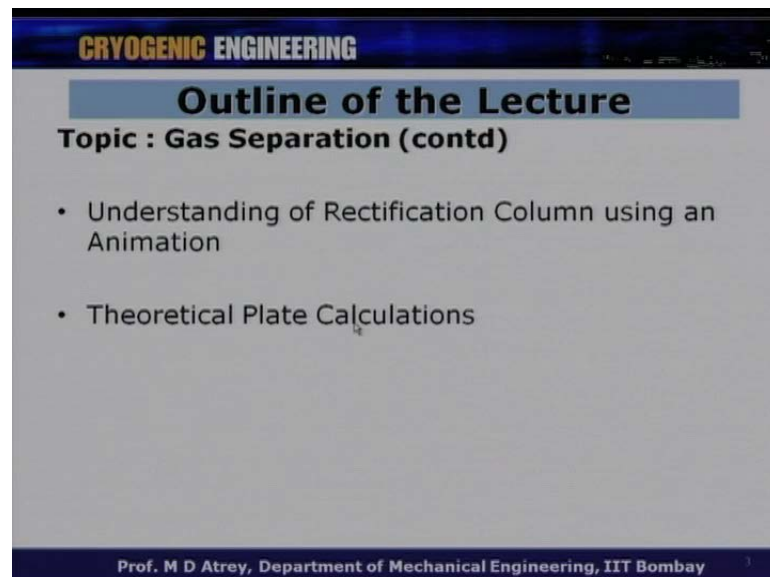
The earlier lecture, we have studied Temperature composition diagram and Enthalpy composition diagrams, and we have understood the importance of these diagrams in gas separation. The separation of a mixture is more effective, when the difference in the boiling points is more, that is also we have understood.

In this column, the distillation column, the low and high boiling components are collected at top and the bottom respectively of the column. For example, in a nitrogen-oxygen you will get liquid nitrogen at the top and you will get oxygen at the bottom of the column. We also define Murphree efficiency which is ratio of actual change in mole fraction to the maximum possible change that can occur in the mole fraction. In a way it actually points at the ineffectiveness of the column. This can help us to calculate the

number of plates or number of processes of condensation and boiling that should occur in the column.

In the today's lecture, I will again continue with the gas separation and what I would like to bring about is a beautiful animation to understand the functioning of rectification column or a distillation column and then from their just given a animation so as to understand what all different processes that happen when a rectification column and then will go ahead to understand the theoretical plate calculation or actually design of a plate column or rectification column.

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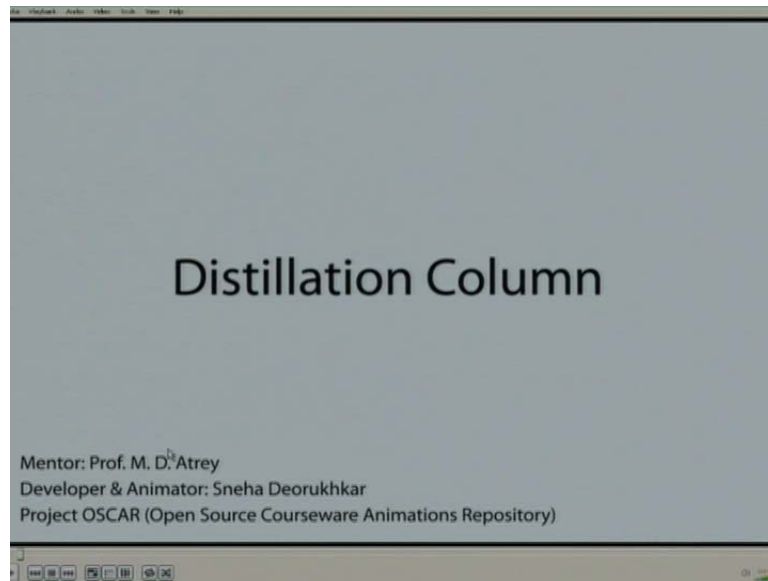
Outline of the Lecture

Topic : Gas Separation (contd)

- Understanding of Rectification Column using an Animation
- Theoretical Plate Calculations

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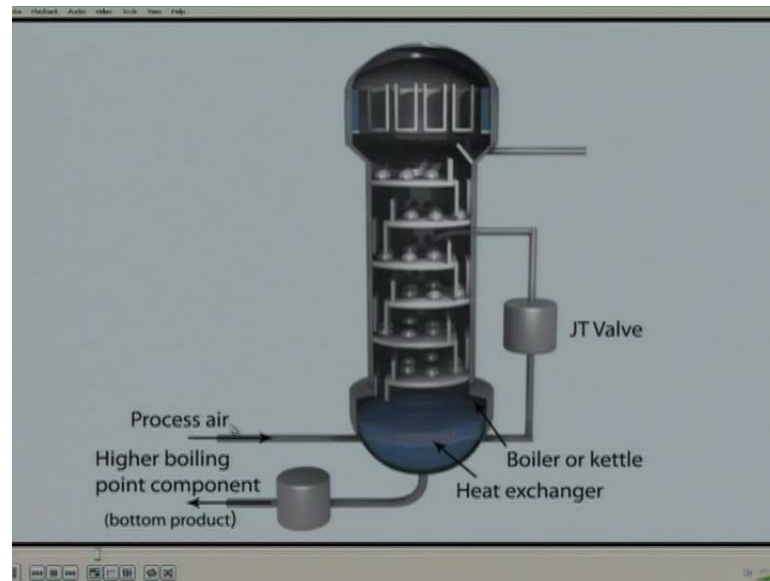


So, let us come to the animation. I am showing you a distillation column. The animation has been done by Sneha Deorukhkar and this animation has been done under the project Oscar, which is Open Source Courseware Animation Repository at IIT Bombay.

Please look at this and possibly you can come to understand different processes that happen when the feed enters the column. Now in this column I have shown **the** not the steady state operation, but I have shown different processes that happen in this column. So, when the gas, when the feed comes, how the feed gets pre-cool first before it enters the column and how the high boiling component and the low boiling component travel up and bottom respectively.

So, please see an each process has been highlighted and at the end what you see is the steady state operation of this column. So, lot many ideas get clear how exactly this process happen because the vapors go up and the liquid comes down.

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So, you can see this is the column and the process gas and let say air, it is coming through this and this process air comes through this and it goes through something called as boiler you know about this. Well (()) I am just saying process by process and assuming that, there is high boiling component sitting over here.

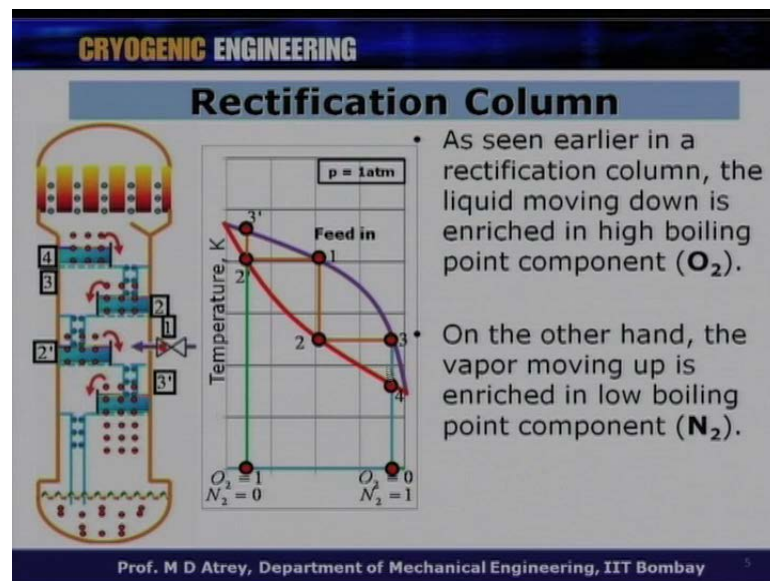
For example, this liquid oxygen already setting over here and this process air will therefore get pre-cooled in this boiler and this pre-cooling sum of the vapors get evaporated and the start coming up and this process gas then gets expanded through a jet evolve and enters over here at the middle of the column. At some location in the column and the liquid starts coming up over here and you can see that on these plates, there are various plates. The liquid starts getting accumulated and once the liquid levels goes to particular level its starts coming down to the next plate which is below it.

So, you can see that as each and every plate gets feed up to the weir height the liquid starts coming down and from the bottom the vapor starts coming up. Because because of this pre-cooling the vapor vaporization happen and this is the heat transfer happens as we have already seen between this vapor which is coming up and you can see this boiling opting over here. So, this is the boiling and condensation that starts happening together, the liquid starts coming down and as the liquid starts coming down, it gets richer in high boiling component and slowly you can see that the vapors are going up.

And this vapor reaches the condenser dome and you can see that the condenser needs to be cooled by some cooling effect which is supplied by an auxiliary circuit. Some cooling effect is offered over here, some heat is taken out from here and whatever vapors come out it gets condensed over here and from here what you get is a low boiling component a liquid form, not all the liquid is taken out. Some liquid starts coming down also. In order to have a steady state you'll have some liquid coming down and what you can see again is heat transfer between the upcoming vapor and the down going liquid.

And you can see that on each plate there small holes or bubble cap through which vapors rises rise up. And the liquid will go down through this weir. So, the beautiful animation to understand, how the vapor starts coming up and how the liquid start going down and a steady state it ultimately reach as shown over here.

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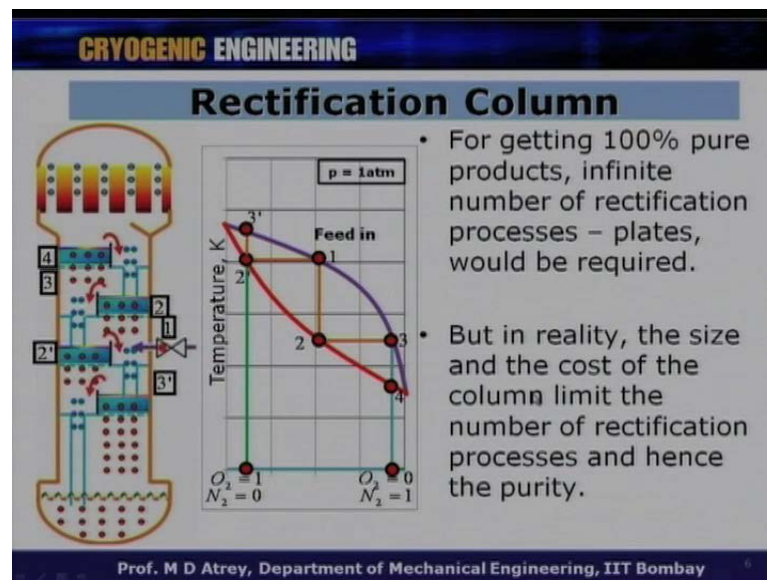
So, ultimately you'll have some liquid and this point and you'll have some liquid on the top of the column. And this is where you understand how this process happens. So, we have seen in the animation of a distillation column, we have understood how the vapors rise up, how the liquid start going down and what is most important is the heat transfer between this vapor which is going up and the liquid which is going down.

This knowledge will help us now to understand how this different process of boiling and condensation happen. That is the most important thing and based on this we do the distillation column design and in this case now we are going to talk about the number of

plate calculations or how many plates will be required. Again coming back to some basics this was the column which we just saw, what you get on the top is a liquid nitrogen or low boiling component, what you get from the down from the boiler over here is liquid oxygen or high boiling component, when we assume that the feed is air.

So, here you can see now, the feed is coming at this point. And as seen earlier in the rectification column the liquid moving down is enrich in high boiling component. So, as the liquid is moving down, the high boiling component means temperature go up and as it goes down from here or as it comes down from here, it will get richer and richer in high boiling component. At the same time, as the vapor is moving up it will get enriched in low boiling component which is nitrogen.

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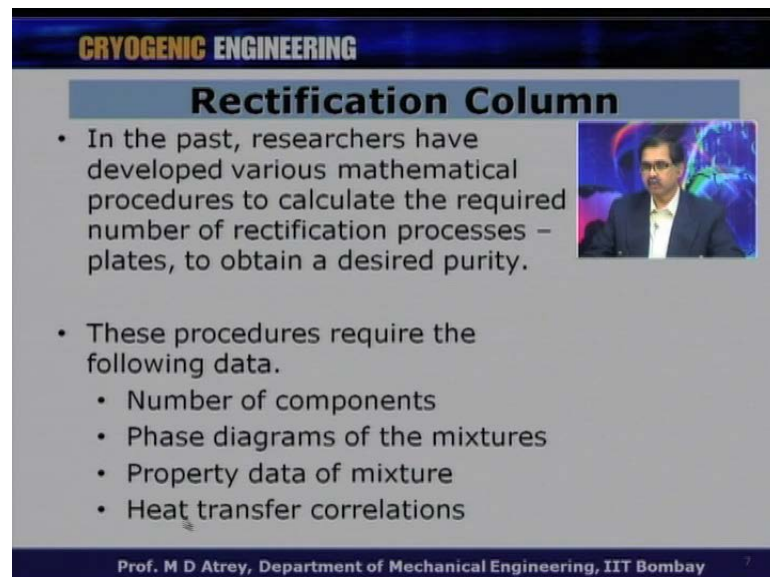
So, as it goes up; that means, it will come down in this temperature concentration diagram **you can** composition diagram you can see here and as it comes down it will get richer and richer in low boiling component. This is the basic which we have studied in earlier lectures also.

What does it mean? It means that for getting 100 percent pure product; that means, if I want 100 percent nitrogen from this mixture or 100 percent oxygen to be separated from this mixture, I would need to have infinite number of rectification processes; that means, I would like to have condensation and boiling which is happening on every plate I will need so many plates to be their and in principal I would require in finite plates because in

a boiling the heat transfer is never perfect it will always have some ineffectiveness associated with it.

So, in principal we need infinite plates, but in reality, the size and the cost of the column limit the number of rectification processes and therefore, the purity. So, I will have to sacrifices some purity that I need not have 100 percent pure nitrogen, I need not have 100 percent pure oxygen, but may be 98 percent may be 97 percent is good enough for me and therefore, a column has to be designed for given purity which is a input data. That is very very important.

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Rectification Column

- In the past, researchers have developed various mathematical procedures to calculate the required number of rectification processes – plates, to obtain a desired purity.
- These procedures require the following data.
 - Number of components
 - Phase diagrams of the mixtures
 - Property data of mixture
 - Heat transfer correlations

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So, in order to calculate the number of place that are required, in order to design this distillation column various researchers have developed various mathematical procedure which are very important to calculate the required number of rectification processes. That means how many plates will be required which will indirectly determine the desired purity for nitrogen as well as for oxygen. And this is what constitutes at a major design of a rectification column.

Now, these procedures require following data, what are number of components. So, your feed should have so many components if the components are many **the** there will be difficult in a separation or even in a calculation. So, how many components are there? Can we have some reasonable assumption for example, air we say that we are got two components. But if I got 4 components, then data for all this four components in a

mixture will be required and what is essential therefore, is a phase diagram of the mixture. So, more the number of components more important will be to have a phase diagram for this mixture.

Also what is important is the property data of mixture at lower and lower temperature which is also very, very difficult to get. And ultimately what is most important is to know the heat transfer correlation because as you know, boiling and condensation heat transfer occurring on every plate. So, one needs to have all this correlations, validated correlations for this data which is very, very difficult.

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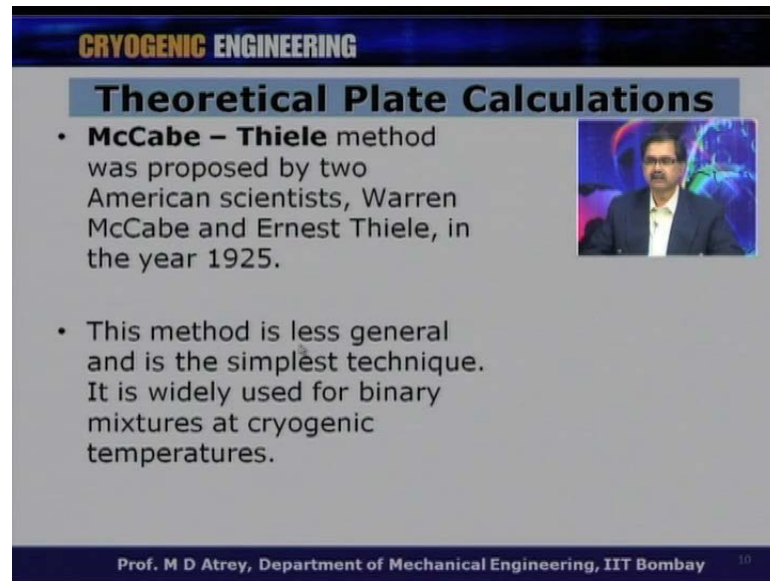
Theoretical Plate Calculations

- The methods of calculation that are used for theoretical plate calculations are
 - Method of Ponchon and Savarit.
 - Method of McCabe and Thiele.
 - Numerical Methods.

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The methods of calculation that are used for theoretical plates are: The methods of calculation that are used for theoretical plates are: So, we have got several methods and we have just naming 3 methods which is called method of Ponchon and Savarit which is a first method, the other method is called method of McCabe and Thiele. It's called McCabe and Thiele method. And third is numerical method. So, these two methods are named after the scientist who developed these concepts or procedures. So, we got Ponchon and Savarit method, we got McCabe and Thiele method and ultimately what we have is a numerical method. Now let us just see, what this method constitute or what are the (()) basically in order to get the distillation column design.

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Theoretical Plate Calculations

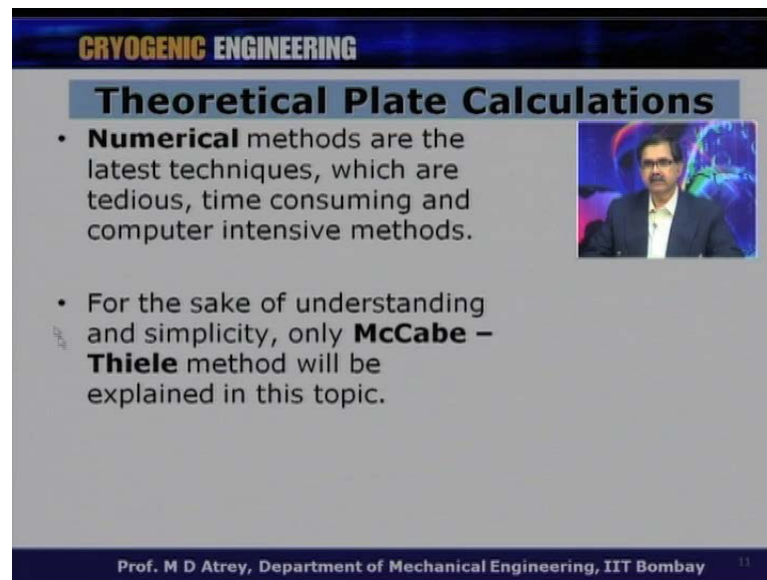
- **McCabe – Thiele** method was proposed by two American scientists, Warren McCabe and Ernest Thiele, in the year 1925.
- This method is less general and is the simplest technique. It is widely used for binary mixtures at cryogenic temperatures.

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The Ponchon - Savarit method is an exact method for plate calculation. It is applicable to any number of components and this method requires detailed data of enthalpy composition diagrams of the mixture. So, I can have 4 component mixture, 5 component mixture, but what I need is correct, detailed data of enthalpy composition which is very very important and which is very difficult to get also.

While, McCabe - Thiele method was proposed **for** by two scientists which is McCabe and Ernest Thiele in 1925 and this method is less general and is the simplest technique. This is very simple technique less general; however, why **why** it is less general because because it is uses widely use for binary mixture; that means, a mixture consisting up two components and at cryogenic temperature. This method for binary mixture has been found a simple technique as well as it validates very well with the cryogenic conditions and cryogenic temperature also.

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Theoretical Plate Calculations

- **Numerical** methods are the latest techniques, which are tedious, time consuming and computer intensive methods.
- For the sake of understanding and simplicity, only **McCabe – Thiele** method will be explained in this topic.

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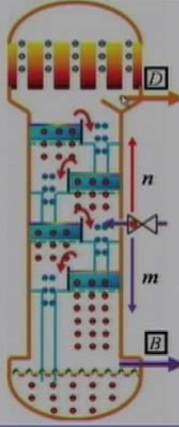
The third is a numerical technique which, as you know, **many of you**, many of you know now, with the mathematical tools, we can have various equations for mass, energy, momentum, etcetera. They would be solved at every point as the vapor moves up and liquid comes down. This methods, as you know are tedious, time consuming and very very computer intensive. So, for the sake of understanding in this lecture and in this course, we are going to concentrate on McCabe - Thiele which as I just told you, its valid for a binary mixture and its relatively simpler and also validated at cryogenic temperature. So, we will now see what is this McCabe-Thiele method comprises of.

So, off all this three techniques we let us go for McCabe - Thiele and understand how do we calculate number of plates that are required to separate a given mixture for given purity; that means, if I want to have 98 percent purity, 95 percent purity, etcetera are the requirement, how do I design a distillation column.

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McCabe – Thiele Method



The diagram shows a distillation column with several trays. A feed stream enters from the side. The top tray is labeled 'D' and the bottom tray is labeled 'B'. The trays above the feed are labeled 'n' and the trays below the feed are labeled 'm'. Arrows indicate the flow of liquid and vapor between trays.

- This method calculates liquid and vapor fractions of each component at every plate and also the number of plates.
- For the sake of understanding, let the plates above the feed be denoted by subscript **n**.
- Similarly, the plates below the feed be denoted by subscript **m**.
- Let the total mole flow rate of top and bottom product be **D** and **B** respectively

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So, this is the distillation column and now let us come to the McCabe - Thiele method. This method calculates liquid and vapor fractions of each component at every plate and also the number of plates. So, what do we basically, we march up or we march down from the feed. This is the feed you go up or you go down and at every plate we calculate what is the liquid and the vapor fraction of each component. And again we are talking about binary mixture over here at every plate and also therefore, we will calculate ultimately the number of plates required for a given purity.


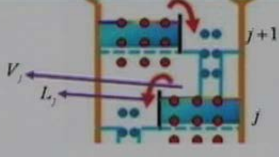
Now, let us come to the mathematics involved in this **right**. There will be various mathematical steps. I've try to go in details, but you will have to go through that many times to understand all the algebraic derivations involved in. What is most important is to understand physics behind a system. For the sake of understanding let the plates above the feed which is called enriching section be labeled as **n**, similarly the plates below the feed which is what we called as stripping section be subscripted as **m** **alright**.

Let the total mole flow rate of top and the bottom products be **D** and **B**. So, whatever moles we get at top as moles per hour, moles per second, whatever and what you get here is a low boiling component, what you get at the bottom is a high boiling component. So, let say we receive **D** moles per hour and when **b** moles per hour at the bottom. So, let the total mole flow rate of top and bottom with **D** and **B** respectively.

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McCabe – Thiele Method



- It is important to understand the indexing pattern of the plate and its corresponding liquid and vapor.
- Let **jth** and **(j+1)th** plate be any intermediate plate as shown in the figure.
- The **liquid** and **vapor** leaving from top of the **jth** plate are **L_j** and **V_j** respectively.

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Now, consider small plate over here and you can see that it is important to understand the indexing pattern of the plate and its corresponding liquid and vapor. So, as you know that for this plate, we have shown just two plates and vapor will leave this plate and it will also receive liquid from the top. So, we have just in two plates there the vapor will go up and liquid will come down.


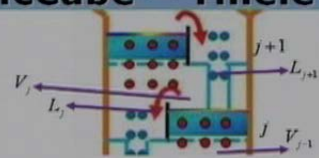
Let us call D as a jth plate, any **any** random plate, in this and this is jth plate and this is a j plus 1th plate **alright**. **So the** let jth and j plus 1th plate be any intermediate plate as shown in this figure. The liquid and the vapor leaving from the top of the jth plate are therefore, called as L_j and V_j respectively.

So, consider any plate, jth plate. The liquid which is leaving this plate is coming down over this weir, as you saw in the animation. Let it be represented as L_j. So, L_j represents the liquid which is leaving this plate and V_j, V_j is going up the vapor which is going up, the vapor which is leaving the jth plate be called as V_j. So, for any plate you got L_j and V_j as liquid leaving the plate and vapor leaving the plate **alright**. Similarly the liquid coming to the jth plate is from the j plus 1th plate.

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McCabe – Thiele Method



- Similarly, the liquid coming to the j^{th} plate is from $(j+1)^{\text{th}}$ plate, therefore it is L_{j+1} .
- Also, the vapor coming to j^{th} plate from bottom is vapor leaving the $(j-1)^{\text{th}}$ plate. It is therefore, V_{j-1} .
- The vapor and liquid on any plate, L_j and V_j , are in thermal equilibrium.

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So, this is the j^{th} plate and it is receiving liquid from the top plate. So, what is the liquid which is leaving the j plus 1 th plate is L_{j+1} . So, therefore, the liquid which is coming to the j^{th} plate is L_{j+1} and liquid which is leaving the j^{th} plate is L_j . Please understand this nomenclature because very important.

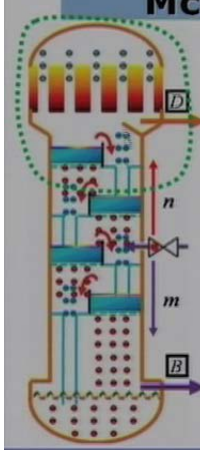
So, j^{th} plate receive the liquid L_{j+1} and which the liquid which leaves the j^{th} plate is called L_j . Also the vapor coming to the j^{th} plate is coming from the bottom. The liquid comes from the top, the vapors come from the bottom. So, what is that vapor which is coming from the bottom is the vapor which is leaving the j minus 1th plate **alright**.

So, vapor coming to the j^{th} plate from bottom is vapor leaving the j minus 1th plate and therefore, it is called as V_{j-1} . So, for any plate, lets suggest **(())** for any plate L_j and V_j are the liquid and the vapor leaving this plate. This plate receives liquid L_{j+1} and this plate receives vapor which is V_{j-1} . **Alright**. The vapor and liquid on any plate L_j and V_j are in thermal equilibrium. We have seen this earlier that for any plate the liquid and the vapor are in thermal equilibrium; that means that temperature will be remaining the same, that is L_j and V_j . Now let us take a control volume as we have done, we will do the mass balance and the energy balance etcetera.

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McCabe – Thiele Method



- Consider a control volume enclosing the condenser and the top section of the n^{th} plate as shown in the figure.
- As explained earlier, for this n^{th} plate, the vapor leaving is V_n and the liquid added is L_{n+1} .
- Applying the mole balance across the control volume per unit time, we have

IN	OUT
V_n	L_{n+1}
	D

$V_n = L_{n+1} + D$

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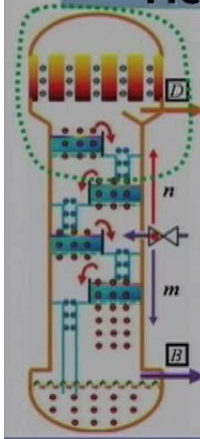
So, consider a control volume enclosing the condenser and top section of the n^{th} plate. So, this is the n^{th} plate and this is the top part. So, this is the condenser on the top and let us have any plate n^{th} plate over here and this is our control volume.

As explain earlier, for this n^{th} plate, the vapor leaving is V_n . So, this is the n^{th} plate and therefore, whatever vapor is leaving up is a V_n and whatever liquid is coming down is L_{n+1} . I think this is very clear now. So, applying the mole balance across the control volume what we get is now, what is coming in **in** the control volume is V_n and what is leaving this control volume is D and L_{n+1} . It is very important to understand again. What is leaving is D and L_{n+1} and if we do the mass balance now, what we get is V_n is equal to $L_{n+1} + D$ **alright**. So, this is the most important. Whatever vapor goes up ultimately, it is equal to whatever condenser it will receive at the top and whatever liquid comes down, very understandable.

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McCabe – Thiele Method



- Multiplying the mole balance equation with mole fraction of a particular component in a mixture, we get mole balance for that component as

$$y_n V_n = x_{n+1} L_{n+1} + x_D D$$

- Where,
 - y_n , x_{n+1} and x_D are mole fractions of a particular component in vapor, liquid and top product respectively.
 - It automatically means that x_D (mole fraction) is the desired purity of the top product.

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Multiplying the mole fractions, a mole balance equation with mole fraction, now this was a molar balance which comprises of both the components (()) moles are going up alright and D moles are received. But all this moles will have both the fractions of let say component a and component b. Now if I want make a molar balance of only one component of let say component a, or let say nitrogen for example, we have to multiply by its mole fraction.

So, what is the mole fraction of nitrogen in a feed mixture? So, multiply the mole balance equation with mole fraction of a particular component in a mixture, we get mole balance for that component. Now we are (()) talking about component balance, component mole balance.

So, therefore, $y_n V_n$ is the mole number of moles of a component which is going up. So, let say nitrogen if I say. So, $y_n V_n$ because I know y_n is fraction of nitrogen in a mixture. So, $y_n V_n$ is going the vapor fraction, $y_n V_n$ gives the vapor fraction of the one component of this mixture and $x_{n+1} L_{n+1}$ is the moles, number of moles of that component which is coming down.

And at the same time $x_D D$ is the moles of that particular component which is leaving this control volume. So, now we are doing a component mole balance from the earlier complete mole balance.

So, where y_{n+1} and x_D are mole fraction of particular component in vapor, liquid and top product respectively **alright**. That means, if I want a component x_D which is leaving over here. So, x_D actually represents amount of nitrogen in D for example, **alright** is very important to understand that x_D therefore, if I say I want D is the top product, if I say that D is D should have 98 percent nitrogen then x_D becomes 98.98 actually, which is what we says. It is automatically means that x_D which is the mole fraction of a particular component is the desired purity of the top product **alright**. So, this is basically desired purity of that component in D.

For control volume taking into account, Q_D watts, now we got a condensation happening what here and refers some refrigerant effect has to be supplied and this is Q_D because some heat has to be taken out from here. So, Q_D has to be taken into account when I do energy balance.

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McCabe - Thiele Method

- For control volume taking into account Q_D (watts) as the heat rejected by the condenser, the enthalpy balance is given by

$$H_n V_n = h_{n+1} L_{n+1} + h_D D + Q_D$$
- Dividing the above equation by D , we have

$$\frac{H_n V_n}{D} = h_{n+1} \frac{L_{n+1}}{D} + h_D + \frac{Q_D}{D}$$
- Rearranging the total mole balance equation, we have

$$L_{n+1} = V_n - D$$

$$\frac{L_{n+1}}{D} = \frac{V_n}{D} - 1$$

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So, Q_D watts as the heat rejected by the condenser, the enthalpy balance is given by now I am doing energy balance **alright**. First we did the molar mass balance, now we do the energy balance and multiply all the component will respective enthalpies and include Q_D in that. So, what is the energy of the molar moles V_n which is coming up $H_n V_n$ is equal to the liquid moles which are coming down and therefore, corresponding enthalpy of small h , we know about this. We have seen in the enthalpy concentration diagram, enthalpy composition diagram.

So, small h denotes the enthalpy associated with liquid, the capital h associates the shows the enthalpy associated with vapors. So, $h_n V_n$ is equal to $h_{n+1} L_{n+1} + h_D D$ which is the enthalpy associated with the top product plus Q_D . So, this is entering and all these are leaving and therefore, the energy balance has been done.

Now, do the mathematical jugglery and therefore, we have some algebraic rearrangements over here. Dividing above equation by D what you get is this. So, you got now D at the bottom over here, rearranging the total mole balance equation we have already got a total mole balance which was these and if I rearrange that or divide that by D I will get expression. So, what is important to see here is you got v_n by D over here, you got $v_n D$ here, you got L_n by D over here, you got L_n by D over here.

So, if I replace this L_n by D by this, we will get a further expression. Just repress, put this values over here and eliminating L_{n+1} by D from the earlier equation what to get is this.

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McCabe – Thiele Method


- Eliminating L_{n+1}/D from the earlier equations, we get

$$\frac{H_n V_n}{D} = h_{n+1} \left(\frac{V_n}{D} - 1 \right) + h_D + \frac{\dot{Q}_D}{D}$$

$$(H_n - h_{n+1}) \frac{V_n}{D} = \frac{\dot{Q}_D}{D} + h_D - h_{n+1}$$

- Rearranging as a ratio of **D** and **V_n**, we have

$$\frac{D}{V_n} = \frac{H_n - h_{n+1}}{\frac{\dot{Q}_D}{D} + h_D - h_{n+1}}$$



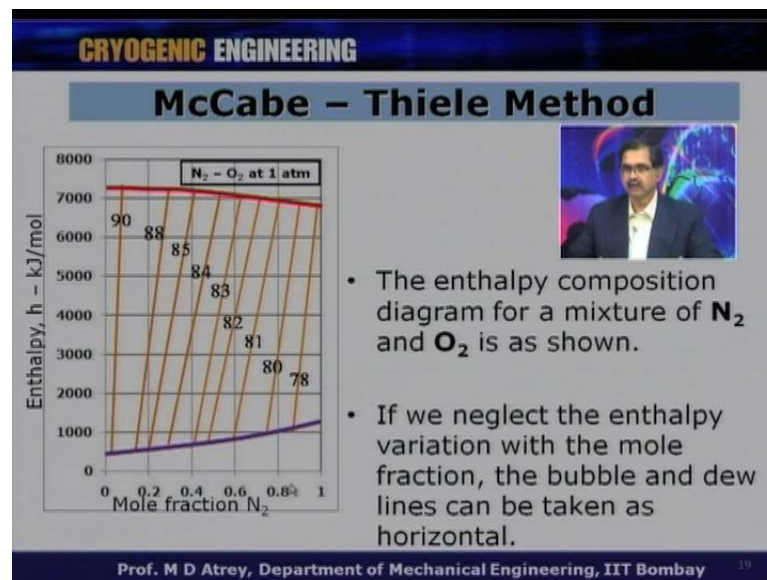
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So, now you got a two terms which has got V_n by D common and doing that I will get an expression like this. Taking capital h and small h difference that is the enthalpies (()) vapor and the liquid V_n by D and you got all energy terms over here. So, here I can rearrange the whole thing and get D by V as this expression. What does it mean, what is D. The mole of a top product coming out and what is V_n , the moles of in vapor form which is entering the control volume.

So, D by V actually represents something. V is entering the control volume, D is leaving the control volume, is a condensed low boiling component which I am getting. So, many moles I am getting at a top and its dependence on the enthalpy difference between the vapor and the liquid and you got all the energy terms coming over here, Q D h D and h n plus 1. So, all the enthalpy terms plus the cooling effect that has been supplied coming over here and this is very important term called D by V n . Now let us see the enthalpies terms. You know the enthalpy composition diagram, enthalpy and mole fraction diagram is shown like this.

The enthalpy composition diagram for a mixture of nitrogen and oxygen, let say at 1 atmosphere is shown over here.

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So, this is vapor and this is liquid and there are different temperatures. Knowing that, we know the change of phase is not at constant temperature **alright**. If we neglect enthalpy variation with the mole fraction, the bubble and dew lines can be taken as horizontal. These are the bubble and dew line and now understand from here you got some inclination over here and can they be approximated, **can they be approximated**? You can see it's an enthalpy changes with mole fraction, but can I say that you can understand that change in enthalpies not so much over here. It's not a very, it's not so much. So, understanding from that, we can see that this is this. If I approximate is a straight line, I

can come to conclusion that now, both the enthalpies are independent of mole fraction. And if I do this, matter became very simple for me.

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CRYOGENIC ENGINEERING

McCabe – Thiele Method

$$\frac{D}{V_n} = \frac{H_n - h_{n+1}}{Q_D + h_D - h_{n+1}}$$

$$\frac{L_{n+1}}{V_n} = 1 - \frac{D}{V_n}$$

- These arguments lead to the fact that liquid (**h**) and vapor (**H**) enthalpies are constant. Hence, **D/V_n** and **L_{n+1}/V_n** are constant.
- Rearranging the molar balance for a component as

$$y_n = \left(\frac{L_{n+1}}{V_n}\right)x_{n+1} + \left(\frac{D}{V_n}\right)x_D$$

- The above equation represents a straight line and is called as **Operating Line** for enriching section.

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So, now coming back to the expression, you have got this. And if I say that and also one more expression and argument which is we just did that, it leads to the fact that liquid enthalpy, vapor enthalpies are constant. They are independent of the mole fractions. And hence we can say that because they are all enthalpy dependent. And if you see that don't change at all, we say that D by V and therefore, L by V is constant. There these terms are constant. They will not change from plate to plate, because because the enthalpies will remain constant. They will not change with molar fraction which is what happens from every plate. **Right.**

Please understand this concept. So, we come to the conclusion therefore, that both D by V and L by V are the terms which are constant and if I rearrange my mass balance expression early, I now get expression which is y is equal to L n plus 1 by V n x n plus 1 plus D by V n x D.

So, here we have got two components which is L by V and D by V and both we have just proved that they are constant. What does it mean, what does this equation tell you? y is equal to n x plus some constant term. So, it is a basically equation of straight line and that is with this assumption, we are leading to this conclusion that these represents an operating line for the top section of a column, which will give me, what is the vapor

fraction at every corresponding to that vapor fraction, I will get what is the liquid fraction.

So, I can now calculate y and x at every location in the top section. And this is what we were aiming for. The above equation represents a straight line and is called as operating line for enriching section gives a relationship between y and x vapor and liquid at every state and this is what we wanted to do basically when I told about what do we basically, I mean for design of a rectification column.

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CRYOGENIC ENGINEERING

McCabe - Thiele Method

$$y_n = \left(\frac{L_{n+1}}{V_n}\right)x_{n+1} + \left(\frac{D}{V_n}\right)x_D$$

- For the top or upper most plate near the condenser, $x_{n+1} = x_D$.
- Substituting, $y_n = \left(\frac{L_{n+1}}{V_n}\right)x_D + \left(\frac{D}{V_n}\right)x_D$
- For y - intercept, $x_{n+1} = 0$. $y_n = x_D$

$$y_n = \left(\frac{D}{V_n}\right)x_D$$

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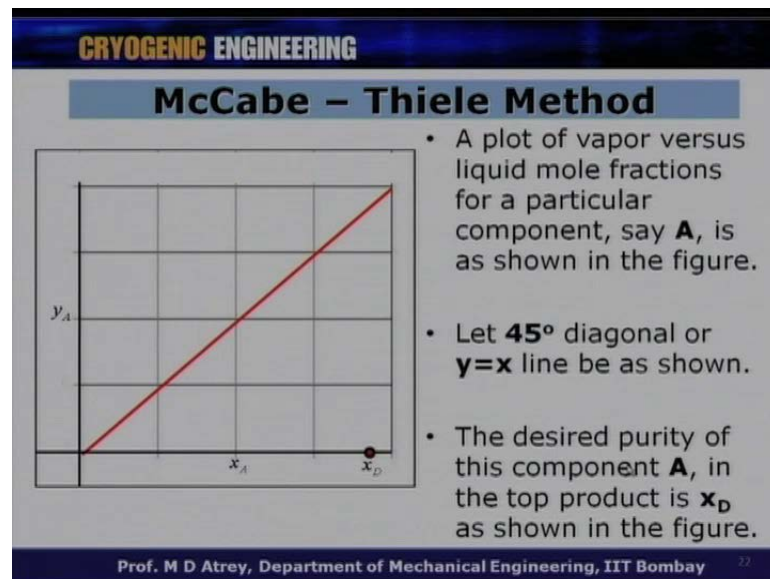
So, this is an (()) which we have just derived. Also understand that at every, at the top most plate I got x n plus 1 is equal to x D at a top most plate. This is x D which is coming at condense set alright. Because there no other plate, at a top most plate, the purity is going to go on increasing and this is equal to x D.

Substituting this value, x n plus 1 is equal to x D at the top plate what do you get? I just replace x the n plus 1 as x D I get, if I put the value of x D taking common and if I put the relationship between this two, this is nothing but equal to 1. So, what do you I get? y n is equal to x D. What does it mean?

For the top most plate y n is equal to x D. Not for any other plates, only for that top most plate I get y is equal to x D. And what is this intercept of the line what. So, we we have located one point of the top which is at the top most plate and other point if I want to

draw this line is the y intercept. And this is nothing but the y-intercept D by V into x_D . And this will happen when x_{n+1} is equal to 0 and that is why it is so called y intercept. So, you got y_n is equal to D by V x_D and therefore, what I can conclude from here, I note two points to draw this operating line for an enriching section, what are these two points? y_n is equal to x_D at x_{n+1} is equal to x_D which we just derive and also the other point is the y intercept which is y_n is equal to D by V x_D at x_{n+1} is equal to 0.

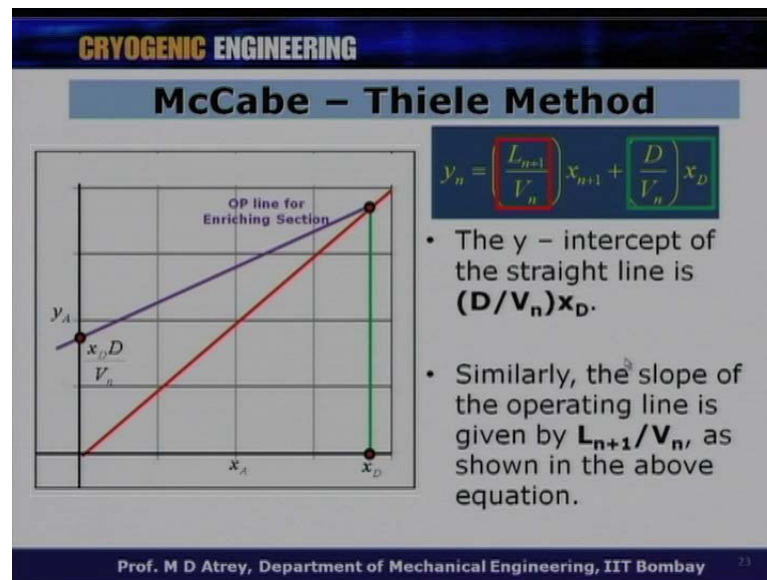
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So, if I know these two points, I can draw the operating line for the enriching section. If I want to do that now, I am plotting y versus x for a component let say A component. So, a plot of vapor versus liquid mole fraction for a particular component say A is as shown in the figure.

What I do first? I will just draw y is equal to x line because because I know that y is equal to x for the top most plate. What I will also know, the desired purity of this component A in the top product is X_D . This is the problem definition for me that I want to design this column for getting a purity of X_D for the top product or for the low boiling component **alright**.

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So, I got I can locate this point which is x_D over here on the x axis. And if I want to locate that point on the on this scale I got this equation and as you know, I got other point which is at x is equal to 0, I got a y intercept.

So, what are these two points? The first point is this y is equal to x. So, y D is equal to x y n is equal to x D, I can locate on this. I am sure because it lies on the y is equal to x line. So, locate this point, the other point is this. And if I join these two points I will get the operating line for the enriching section. I will know the how much y is there for every x at every location in the enriching section. So, if I know my x is this much corresponding to that I can calculate y which is also given by this operating line equation.

For the enriching section what I am doing ultimately with some reasonable assumption I am trying to get the liquid and the vapor at every plate in the enriching section and now I will do the same exercise for stripping section also; that means, for the bottom part of the column also. This is also what we are aiming for basically. Similarly the slope of the operating line is L by V alright slope is basically how much liquid is coming down how much vapor is going up for every plate.

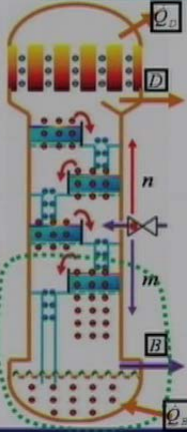
We are saying that the slope of this line is say; that means, what we assume is L by V is common for the entire enriching section. This is what, they are some reasonable

assumption and that is why we say that with enthalpy remaining constant this will automatically come. Now what we are concentrating on is the bottom part.

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CRYOGENIC ENGINEERING

McCabe – Thiele Method



- Similarly, for the analysis of m^{th} plate and boiler in the lower part, we have the following equations.
- Mole Balance: $L_{m+1} = V_m + B$
 $x_{m+1}L_{m+1} = y_mV_m + x_B B$
- Energy Balance: $h_{m+1}L_{m+1} + \dot{Q}_B = H_mV_m + h_B B$
- where, B and Q_B are mole flow rate out at the bottom and heat input to the boiler respectively.

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So, if I take a control volume for now enriching section. Similarly for the analysis of m^{th} plate and boiler in the lower part, we have the following equations. So, what is the mole balance now, L_{m+1} is enriching. So, I got a m^{th} plate over here and I've taken top of the m^{th} plate and the boiler over here. We have got, what is entering is equal to what is leaving. So, mole balance is L_{m+1} is coming down V_m is leaving this plate and B is leaving this control volume.

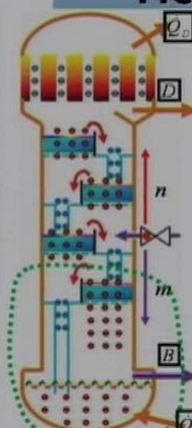
So, if I do mole balance for entire mole balance for both the components, L_{m+1} is equal to V_m plus B . And then if I do component balance as we have done earlier for given component A I will have $x_{m+1}L_{m+1}$ is equal to y_mV_m plus $x_B B$. Again x_B is now denoting how much A is there in bottom. As you know x_D we are assuming to 98 percent, but x_B is now going to be very small because I do not want this nitrogen to be there in oxygen. So, x_B is going to be only 0.02, 0.03 etcetera **right** because the purity of B has to be 97 percent.

And I am talking about component of nitrogen in oxygen here. And that is what x_B will denote because; we are doing mass balance for the same component over here. The third is the energy balance multiply by enthalpies and also I am giving some heat to this boiler that also would figure in this as if I figure Q_D in the condensation in the earlier case.

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CRYOGENIC ENGINEERING

McCabe – Thiele Method



- Rearranging the above equations, we have the following.

$$\frac{B}{V_m} = \frac{H_m - h_{m+1}}{\frac{Q_m}{B} - h_B + h_{m+1}} \quad \frac{L_{m+1}}{V_m} = 1 + \frac{B}{V_m}$$
- Applying the assumption, we have H_m and h_{m+1} as constant, implies B/V_m and L_{m+1}/V_m are constant. The operating line for stripping section is

$$y_m = \left(\frac{L_{m+1}}{V_m} \right) x_{m+1} - \left(\frac{B}{V_m} \right) x_B$$

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So, if I do enthalpy balance $h_m L_{m+1} + Q_B$ which is entering the control volume is equal to $h_m V_m$ which is leaving over here and $h_B B$ which is leaving at less **alright** where B and Q_B are the mole flow rate out of the bottom and heat input to the boiler respectively. And I will do the similar rearrangements as what we have done in the earlier enriching section. Rearranging the above equations we have the following, I will get B/V_m is equal to $h_m - h_{m+1}$ divided by $Q_m/B - h_B + h_{m+1}$ and again we have got a similar assumption that enthalpy values are independent of the molar fractions, we can again show that B/V is constant. And therefore L_m/V_m also will be constant.

Applying the assumption we have capital H_m and small h_{m+1} as constant which implies that B/V_m and L_{m+1}/V_m are constant. The operating line for stripping section therefore, is y_m is equal to L_{m+1}/V_m into x_{m+1} minus B/V_m in to x_B .


So, similarly what we have earlier, I have got an operating line for the enriching section which will be giving me amount of vapor for every x amount of vapor for liquid on every plate as we march down. And this L/V is going to be the slope of that line which is constant throughout and this is the y intercept. So, again if I want to draw this line graphically, I have got two points which is what we will see down.

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CRYOGENIC ENGINEERING

McCabe – Thiele Method

$$y_m = \left(\frac{L_{m+1}}{V_m} \right) x_{m+1} - \left(\frac{B}{V_m} \right) x_B$$

- For the bottom or lower most plate near the boiler,
 $x_{m+1} = x_B$.
- Substituting, $y_m = \left(\frac{L_{m+1}}{V_m} \right) x_B - \left(\frac{B}{V_m} \right) x_B$ 
- For y – intercept, $x_{m+1} = 0$. $y_m = x_B$

Two Points

$y_m = x_B$ @ $x_{m+1} = x_B$
 $y_m = -(B/V_m)x_B$ @ $x_{m+1} = 0$

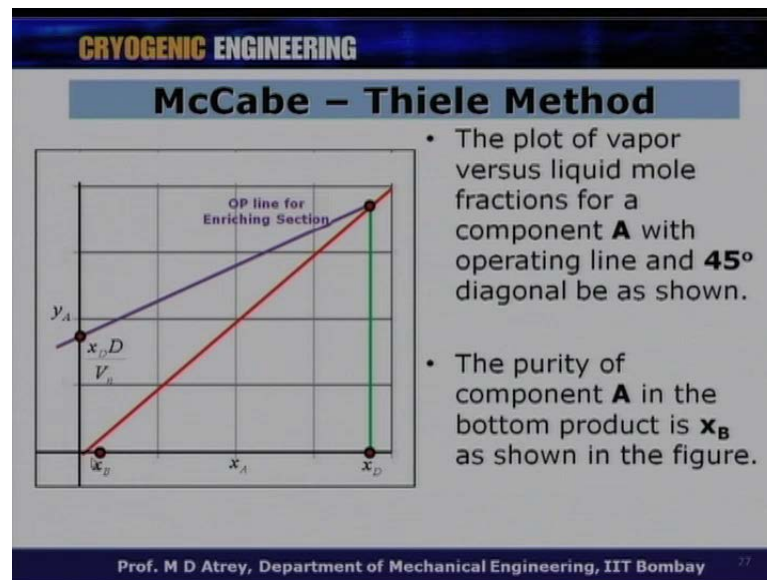
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So, this is my expression for the equation of line for this stripping section again putting the same assumption for the bottom or the lower most plate near the boiler you got x_{m+1} is equal to x_B . It basically shows how much nitrogen is there in oxygen which is going to be very small amount **alright** it going to be 0.02 or 0.03.

It is actually talks about impurity now for the down product and which is the purity for the top product. Substituting this value, so, **if I re** if I line this write this equation only for the bottom most plate, I will get x_{m+1} is equal to x_B in that case putting that I will again get expression as 1 and I will get y_m is equal to x_B ; that means, this line gain has y_m is equal to x_B or y is equal to x at the bottom most plate.

So, again this line will intersect y is equal to x line had the bottom most plate as we saw earlier. This is one point I will get and other point again is y intercept which is minus B by V_m into x_B . So, other point is y intercept which is defiantly going to be at x_{m+1} is equal to 0 which is the y intercept. So, again I've got two points which are y_m is equal to x_B at x_{m+1} is equal to x_B basically the intersection point of the operating line at y equal to x and other point is the y intercept, y_m is equal to minus B by V_m x_B at x_{m+1} is equal to 0. So, now, I have got two line, two operating lines and I will draw those two operating lines graphically.

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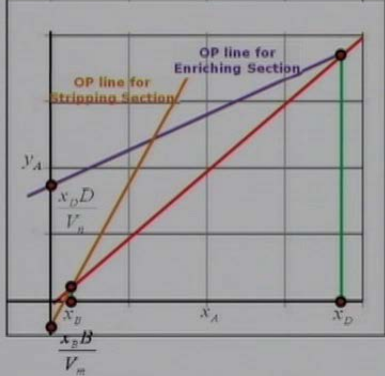
So, this is y earlier line which is operating line enriching section the plot of vapor versus liquid mole fraction for a component A with operating line and 45 degree angle as shown over here.

The purity of the component A in the bottom product is x_B . So, what is the purity now actually is going to impurity for this product, it going to be 0.02. How much of component A exist over here is going to x_B which is very small. So, if I locate that and now locate this point on y is equal to x because at this bottom most plate it going to be with y is going to be equal to x. So, it is going to be on a y is equal to x line **alright**. So, other point is going to be the y intercept which is minus B by V m into x_B this is this. So, one point is going to be here other point is going to be here and I am just going to draw these points. So, this is my one point and other point is this.

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CRYOGENIC ENGINEERING

McCabe – Thiele Method



$$y_m = \frac{L_{m+1}}{V_m} x_{m+1} - \left(\frac{B}{V_m} \right) x_B$$

- The y – intercept of the straight line is $(-B/V_m)x_B$.
- The slope of the operating line is given by L_{m+1}/V_m as shown in the above equation.

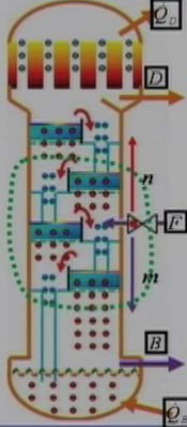
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So, if I draw a line between these two points I will get the operating line for the enriching section. And this is the operating line for it. So, this line gives me what is y for every x up to the stripping section and what does this line give me what is my y for every x in the stripping section. And what does this point indicate, this point indicates where both of them meet and this is called the feed point that the feed inlet happens. The slope of the operating line is given by L_m/V_m as shown in the above equation.

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CRYOGENIC ENGINEERING

McCabe – Thiele Method



- The mixture that is to be separated is called as Feed. It is introduced into the column through an opening called as Feed inlet as shown in the figure.
- Consider a control volume enclosing the n^{th} and m^{th} plates and feed inlet as shown.
- Let F be the total number of moles in the Feed.

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So, now after seeing that how this operating lines for stripping section as well as for enriching sections are drawn, now we will come to the third point, which is third line which is called feed line which will denote the feed condition for the column and this is very important because this is the point at which both this line intersect.

The mixture that is to be separated is called a feed. It is introduced in the column through an opening called as feed inlet as shown in the figure. So, you can see here F. This F denotes this is the feed inlet through which the mixture enters. And this feed point could be anywhere it need not be at the center of this column it can be at **at** this point, at this point depending on the feed condition; this feed inlet can vary **alright**.

Now, let us consider a control volume across this. Till now we had a control volume including the condenser or the other control volume we had including the boiler. And that was above the feed or below the feed. Now let us take a control volume which encloses some part of the some plates in the enriching section and some plates in the stripping section. So, you got some a one n plate and one m plate over there and let's do again the mass balance and the energy balance and difference of this is going to come from the feed because inlet is feed what is leaving here is going to be n, what is leaving here will going to be m.

So, consider a control volume enclosing the nth and mth plates and feed inlets as shown over here. Let F be the number of moles in the feed. The total number of moles that are coming are F. Let see the control volume like this. So, we got a nth plate and you got a mth plate and you got a control volume as shown over here comprising of let say at just two plates above, near this feed.

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CRYOGENIC ENGINEERING

McCabe – Thiele Method

- For the above control volume, we have

IN	OUT
F	
V_m	V_n
L_{n+1}	L_{m+1}

- Applying the molar balance

$$F = V_n - V_m + L_{m+1} - L_{n+1}$$

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So, what is coming in the control volume and what is leaving in the control volume? Have a look at this. So, the above control volume, we have what is in feed inlet which is F what is entering from this m th plate is V_m alright. And also what is entering from the top here is L_{n+1} . This is the n th plate, n th plate. What is entering these n th plate is L_{n+1} liquid.

So, what is entering this control volume is F, V_m and L_{n+1} , F, V_m and L_{n+1} are entering the control volume. And what are leaving control volume what what things are leaving the control volume is V_n which is the vapor which is leaving the n th plate and the liquid L_{n+1} which is leaving are which is entering the m th plate ok.

So, this L_{n+1} over here and this is V_n which is leaving. So, if we do the mass balance of the molar balance of all this components, what you get, applying the molar balance what you get is equal to F is equal to V_n minus V_m plus L_{m+1} minus L_{n+1} . Have a look is a F is a number of moles that are coming in the feed, difference between the vapor component which is V_n minus V_m , difference between the liquid component vertices L_{n+1} minus L_{m+1} alright very important to understand. This is the feed and we can have some the feed can have some vapor component as well as some liquid component.

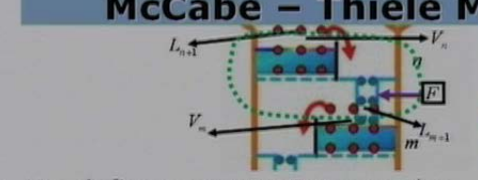
So, what is the vapor component V_n minus V_m , what is the liquid component, L_{m+1} minus L_{n+1} . Sometimes vapor may not be there. So, only liquid component there

will could be there in the frame F that time L_{n+1} minus L_{m+1} is go to 0. Sometimes only vapors can come in the feed and that time L_{n+1} minus L_{m+1} could be equal to 0 **alright**. So, feed conditions will decide, what is the form it has vapor plus liquid, only vapor or only liquid. And that will decide what we call as feed quality **alright**. So, please have look at this things.

(Refer Slide Time: 39:35)

CRYOGENIC ENGINEERING

McCabe – Thiele Method



- We define a parameter **q** as the ratio of liquid moles in the feed to the total number moles in the feed.
- Mathematically,
$$q = \frac{(L_{m+1} - L_{n+1})}{F}$$
- That is for **q=0**, feed is totally vapor and for **q=1**, it is totally liquid.

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So, if we come to the same thing again we define a parameter called q. **alright we define a parameter called q** which can denote a quality of the feed also. q as the ratio **what is** how do you define q, it is the ratio of liquid moles in the feed to the total number of moles in the feed. So, how many liquid moles are there in the feed is called as q or the quality. What does it actually denote; it actually denotes how many liquid moles are there in the feed.

In short it calls, it actually showed the wetness fraction of the feed how much wetness is there, how much liquid is coming with the feed. So, it is the ratio of liquid boils in the feed to the total number of moles in the feed. So, mathematically if I want to write q, q is equal to L_{m+1} minus L_{n+1} upon F. if we just saw the definition earlier, the liquid component are going to be given as L_{n+1} minus L_{n+1} . and therefore, q is equal to what is amount of liquid moles to the feed number of moles coming in the feed.

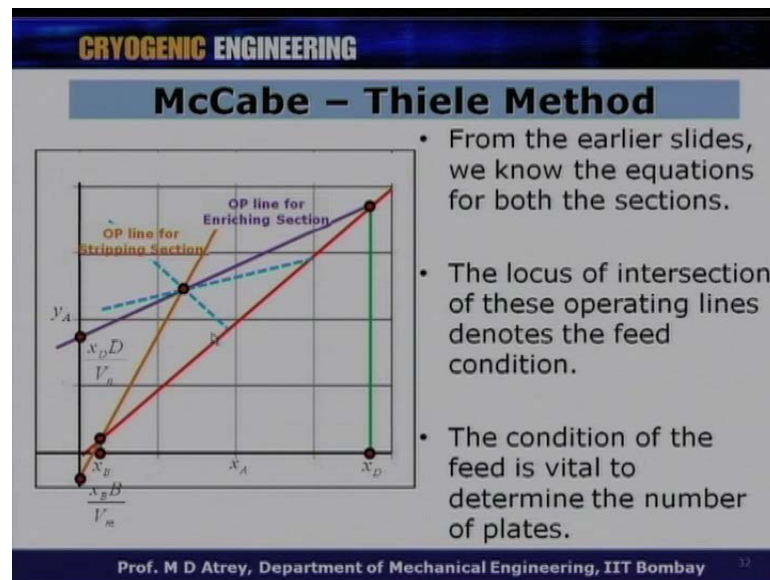
It also denotes something. If I have q is equal to 0; that means, L_{n+1} minus L_{m+1} is equal to 0; that means, there are no liquid component in the feed. What does it

mean? If q is equal to 0, the feed is completely vapor because because your numerator is going to be 0 and no liquid moles are coming in the feed.

So, if q is equal to 0, your feed is completely vapor or if **if** q is equal to 1; that means, L plus 1 minus L plus 1 is equal to F ; that means, feed is 100 percent now liquid. F upon F and therefore, you got q is equal to 1. It means therefore, that the feed is completely liquid. So, go to the meaning to the value of q . If q is equal to 1 it is completely **(())** that means, it's only liquid, it is bringing on the liquid and this liquid could be saturated liquid.

If q is equal to 0, the feed is bringing in only vapor and if something in between when you got some v and some l also; that means, you got a two phase feed now, you got a vapor and liquid component also. We will study that in detail in subsequent slides, but understand the concept of q because very important. So, this is what we have already studied that we have got operating line for the stripping section; we have got operating line for the enriching section.

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From the earlier slides, we know the equations for both the sections. Now you have got a intersection point and the locus of intersection of these operating lines denotes the feed condition. So, where do they meet at this point and they can meet anywhere depending on the slope of these lines and therefore, slope of these lines also play a very crucial role.

The point of intersection however, we denote the feed inlet condition **alright**. The condition of the feed is vital to determine the number of plates. So, what is this locus, this locus could be like this the feed line could be like this, like this or anywhere in whatever direction. And this is very important to understand how many plates are going to be there in enriching section or in stripping section. This plays a very vital role in this and how does it.

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CRYOGENIC ENGINEERING

McCabe - Thiele Method

- Based on feed equation and q definition, we have

$$F = V_n - V_m + L_{m+1} - L_{n+1} \quad q = \frac{L_{m+1} - L_{n+1}}{F} \quad V_n - V_m = (1-q)F$$
- Again, from the operating lines of upper and lower sections, we can rearrange to give V_n and V_m as

$$V_n = \left(\frac{L_{n+1}}{y_n}\right)x_{n+1} + \left(\frac{D}{y_n}\right)x_D \quad V_m = \left(\frac{L_{m+1}}{y_m}\right)x_{m+1} - \left(\frac{B}{y_m}\right)x_B$$
- It is important to note that $V_n - V_m$ is the vapor content in the feed.

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So, let see. Based on feed equation and q definition we have got a feed equation F is equal to something and we have got q definition also which is $L_{m+1} - L_{n+1}$ plus 1 divided by F , what we have is this is my F definition, this is my q definition and if I want to calculate from here $V_n - V_m$ is equal to and putting this value as $L_{n+1} - L_{n+1}$ plus 1 upon F , I get an expression like this which is $V_n - V_m$ the vapor difference vapor mole difference is equal to I am representing this vapor mole difference in terms of q and F . $1 - q$ into F .

Again, from the operating lines of upper and lower sections we can rearrange to get V_n and V_m . So, I can get V_n and V_m from the feed line for the feed expression for the feed and I can also get expression for $V_n - V_m$ as this. Because I have already got a equation as y_n is equal to L_{m+1} by V and etcetera I am just rearing that to get the value of V_n . So, V_n is equal to L_{n+1} by y_n x_{n+1} plus D plus D by x_D . And similarly I get V_m is equal to L_{m+1} by y_m x_{m+1} minus B by y_m x_B . So, I've got two

expressions for V_n and V_m and from here it is very important to note **note** that V_n minus V_m is the vapor content in the feed. We have just seen in that.

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CRYOGENIC ENGINEERING

McCabe – Thiele Method

- In the calculation of point of intersection of operating lines, we choose a common point to both these lines as (x, y) .
- Hence, x_{n+1} , x_{m+1} , y_m and y_n are replaced with this point as shown in the following equation.

$$V_n - V_m = \frac{(L_{n+1} - L_{m+1})x}{y} + \frac{(x_D D + x_B B)}{y} = (1 - q)F$$

- The locus of this point of intersection is the feed line or **q** line and is calculated as explained in the next slide.

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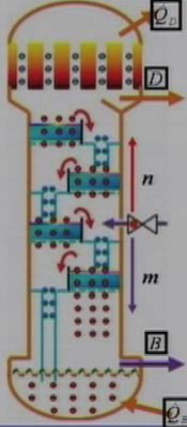
So, V_n minus V_m is going to be the vapor content in the feed if are writing this equation for the n th and m th plate, what we have defined earlier. In the calculation of point of intersection, I am very keen to know my feed inlet condition which is denoted by the point of intersection of this two operating lines. So, operating line will have some coordinate x and y and they should be satisfied by both this equation of operating line for the stripping section and also the operating line for the enriching section.

So, we choose a common point and lets quilter x and y . So, hence now we do not have to write x_{n+1} x_{m+1} y_m and y_n , they will be replaced by x and y over there and now I get V_n minus V_m is equal to L_{n+1} minus L_{m+1} upon y into x plus $x_D D$ plus $x_B B$ by y is equal to 1 minus q into F . The locus of this point of intersection is the feed line or q line and is calculated as explained in the next slide.

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CRYOGENIC ENGINEERING

McCabe – Thiele Method



- For a column as a whole, using the mass balance, we can write

$$x_F F = x_D D + x_B B \quad q = \frac{(L_{m+1} - L_{n+1})}{F}$$

- Rearranging the following equations, we have

$$\frac{(L_{n+1} - L_{m+1})x}{y} + \frac{(x_D D + x_B B)}{y} = (1 - q)F$$

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So, here for a column as a whole using the mass balance, we can now have a entire molar balance for the column which $x_F F$ is equal to $x_D D$ plus $x_B B$ **right**. These are the most coming in; these are the most leaving the column. Again q is equal to L_{m+1} plus 1 minus L_{n+1} of F . Rearranging this term, you get this expression I will replace this by this and this by q , I got this expression and rearranging this expression, I will get expression as y is equal to q upon $q - 1$ x plus x_F $1 - q$. This is also a constant. **This is also a constant.**

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CRYOGENIC ENGINEERING

McCabe – Thiele Method

- Rearranging,

$$y = \left(\frac{q}{q-1} \right) x + \frac{x_F}{1-q}$$

- The above equation represents a straight line with $q/(q-1)$ and $x_F/(1-q)$ as slope and y - intercept respectively.
- More importantly, it is the locus of point of intersection of operating lines. This line is called as **Feed line** or **q line**.



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And this line therefore, is called as feed line actually which as the above equation represents as straight line with q upon $q - 1$ and x_F upon $1 - 1$.

If you got a two phase flow I got a slope which is going to be negative the feed line is going to be posing through this point and in this direction and sub cooled equilibrium will be shown by this and superheated vapor is going to be shown again by a positive slope and therefore, this point or the line makes a very big impact in determine number of plates for the enriching section and for the stripping section which will see in the next lecture also. So, this is the graphical representation of all the possible line stripping section enriching section and one of this line will constitute a q line or a feed line for your problem the point of intersection also what we of in testing is where does the heat line y is equal to x the point of intersection of the feed line or q line and y is equal to x it gives the liquid content of the component a in the feed x_F how do be conclude this. So, let us find mathematically it is calculated by substituting y is equal to x in the feed line. So, if I put x is equal to y is equal to x in this what you get here is nothing, but x is equal to x_F by rearrangement I will get x is equal to x_F .

It means that when this q line wherever it heat by axis y is equal x line you get corresponding to is your x_F ; that means, amount of component a the liquid content of the component a in the feed is given by this. So, I know now to points if I want to draw the feed line I know the liquid content of a component given feed I can locate this point also if I develop equation for the two operating lines I know its **audio is not heard from 47.26 to 54.37.**