Cryogenic Engineering
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Lecture No. # 22
Gas Separation

So, welcome to the 22 nd lecture on Cryogenic Engineering, under the NPTEL program. We are talking about Gas Separation, and the earlier lecture give you following points.

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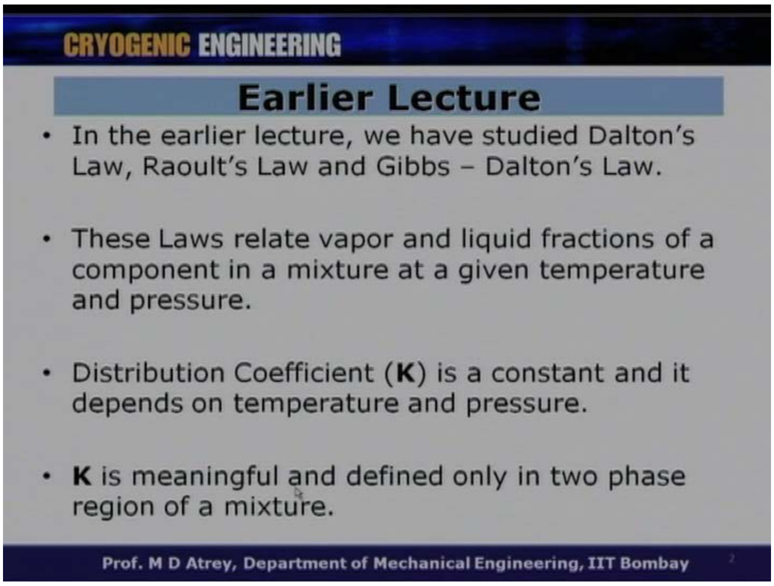

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Earlier Lecture

- In the earlier lecture, we have studied Dalton's Law, Raoult's Law and Gibbs – Dalton's Law.
- These Laws relate vapor and liquid fractions of a component in a mixture at a given temperature and pressure.
- Distribution Coefficient (**K**) is a constant and it depends on temperature and pressure.
- **K** is meaningful and defined only in two phase region of a mixture.

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In the earlier lecture, we studied basic laws which govern the mixture. So, we studied Dalton's law, Raoult's law and Gibbs - Dalton's law. They were all dealt in detail in the earlier lecture. These laws relate vapor and liquid fraction the y and x fraction of a component in a mixture, at a given temperature and pressure.

We also studied about the concept of distribution coefficient, which is K and we found that it is a constant and it depends on temperature and pressure of a mixture. So, what is the temperature of a mixture? What is the pressure of a mixture? According to which one can find out distribution coefficient, which is nothing but y by x or molar fraction divided by the corresponding liquid fraction in a mixture. And this gives a value of distribution coefficient. The K is normally given in a two phase region. So, we were talking about oxygen and nitrogen, the value of K will be given between 90 Kelvin and 77 Kelvin which are happening to the boiling points of nitrogen and oxygen respectively.

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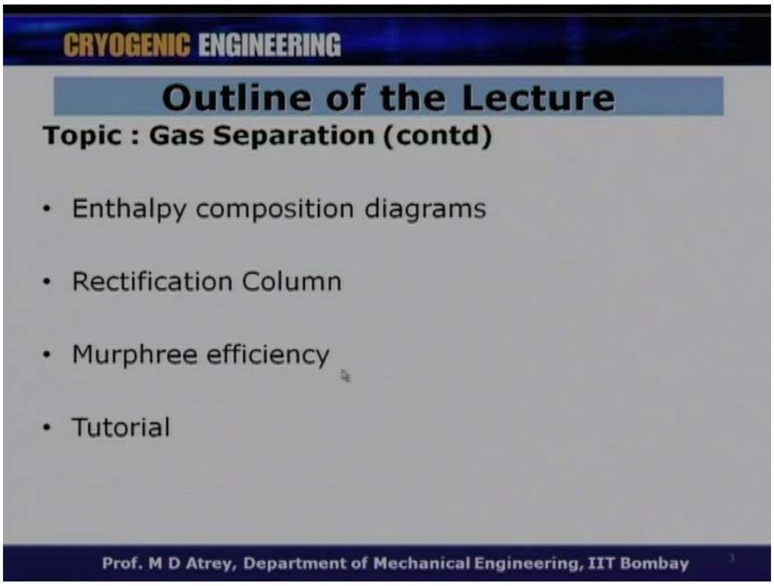

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Outline of the Lecture

Topic : Gas Separation (contd)

- Enthalpy composition diagrams
- Rectification Column
- Murphree efficiency
- Tutorial

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With this background, the outline of today’s lecture is, we will now see Enthalpy Composition Diagram. We have seen earlier, the Temperature Composition Diagram, one of the most important thing is Enthalpy Composition Diagram, then we will see the real Rectification Column where all these gases in a mixture gets separated and see about its working. Then we will define Murphree Efficiency which is with respect to this rectification column functioning and finally, I will take a small tutorial on murphree efficiency. So, that the concept gets cleared.

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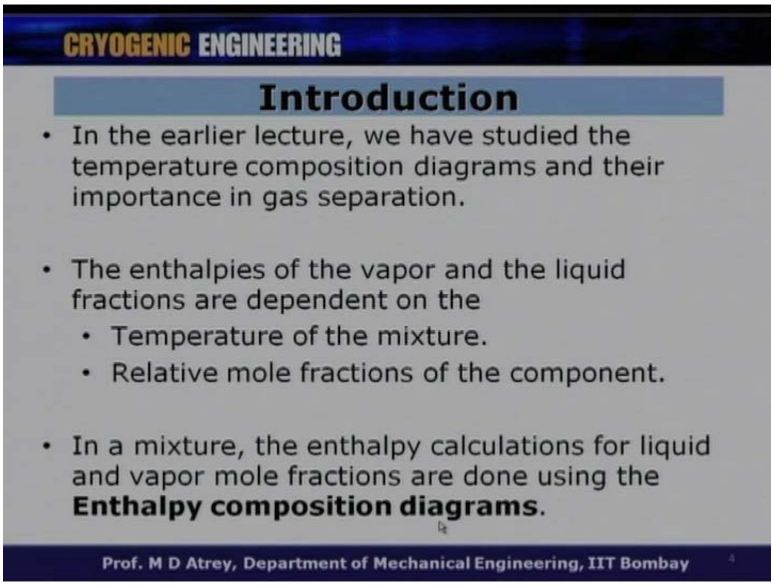

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Introduction

- In the earlier lecture, we have studied the temperature composition diagrams and their importance in gas separation.
- The enthalpies of the vapor and the liquid fractions are dependent on the
  - Temperature of the mixture.
  - Relative mole fractions of the component.
- In a mixture, the enthalpy calculations for liquid and vapor mole fractions are done using the **Enthalpy composition diagrams**.

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To introduce the topic, in the earlier lecture, we've studied the temperature composition diagrams and their importance in gas separation. This is a very important diagram and we've dealt enough in the earlier lecture, how does it look for two different gases and thing like that. The enthalpies of the vapor and the liquid functions are dependent on the temperature of the mixture, the relative mole fractions of the component.

So, if I want to find out now corresponding to given mixture for a given molar composition what is the enthalpy, what is the enthalpy of the vapor, what is the enthalpy of the liquid or what is the enthalpy of a two phase mixture, that is in between the vapor and the liquid, it depends on the temperature and of course, the molar fractions of the component or that is the molar composition. These two parameter will decide for a given pressure. This will decide, what is the enthalpy of a given mixture. In a mixture the enthalpy calculations for a liquid and vapor mole fractions are done using the enthalpy composition diagram and this is the importance of the enthalpy composition diagram. Now let us see how does it look.

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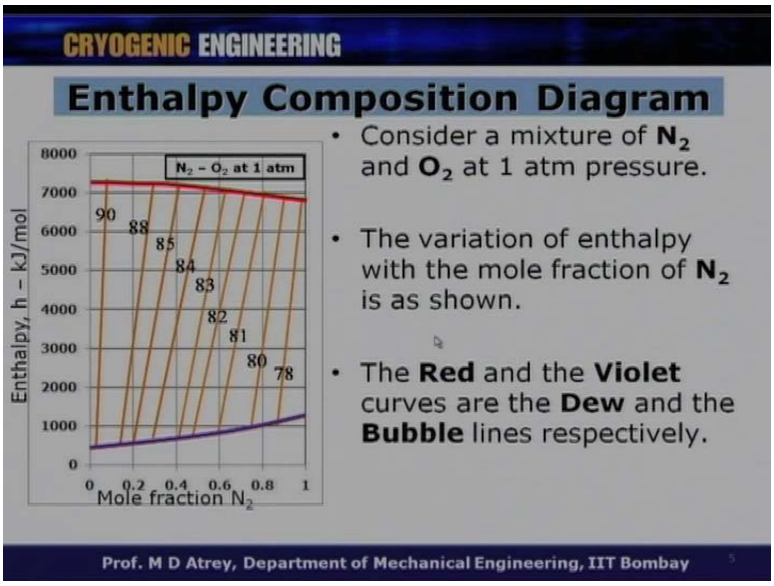

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Enthalpy Composition Diagram

- Consider a mixture of $\mathbf{N_2}$ and $\mathbf{O_2}$ at 1 atm pressure.
- The variation of enthalpy with the mole fraction of $\mathbf{N_2}$ is as shown.
- The **Red** and the **Violet** curves are the **Dew** and the **Bubble** lines respectively.

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The Enthalpy Composition Diagram normally would look like this, on y axis you can find the enthalpy's given as kilo joule per mole. This is given for a nitrogen-oxygen mixture which is at1 atmosphere; that means, all these diagrams are given for a particular component mixture; the mixture is being at a particular pressure, while on the x side you find the mole fraction of the low boiling component that is nitrogen over here. So, nitrogen is 0 percent over here, which means that oxygen is hundred percent, while this nitrogen is 100 percent over here which means that oxygen is 0 percent at this point. Now what you can see is two lines and there are temperature lines across this. So, what are they?

So, let us consider a mixture of nitrogen and oxygen at 1 atmosphere pressure. The variation of enthalpy with the mole fraction of nitrogen is as shown. So, you can see the mole fractions on the x axis and the enthalpy is given on the y axis. Now here what you can see are different colors, one is the red color, one is the violet color here and then there are connecting lines in different color for the temperature. The red and the violet curves are basically the Dew and Bubble lines respectively.

So, whenever we're starting condensation right we will have first the dew line over here and then when the phase change happens, we will have the bubble line as we had seen earlier in a temperature composition diagram. Similar the diagram looks similar as what you've seen earlier.

The figures show the isotherms, that is the constant temperature lines, between the dew and the bubble lines. So, you have got a dew line, the bubble line and we've got a constant temperature line or isotherms as shown in this particular figure. What do you see, what is different in this case, these isotherms have finite slope; that means, these isotherms are not vertical lines, they've got a finite slope, in your vertical line they are parallel to y axis; that means, their slope is infinite; however, they are not vertical lines, but they are having a finite slope, the isotherms have finite slope, specifying that the condensation or boiling of the mixture is a non-isothermal process. This is what we had seen earlier also.

During this phase transformation from vapor to liquid or phase transformation, the temperature decreases and that is what you can see and this happens basically because these isotherm lines are not vertical. Let us see for example now.

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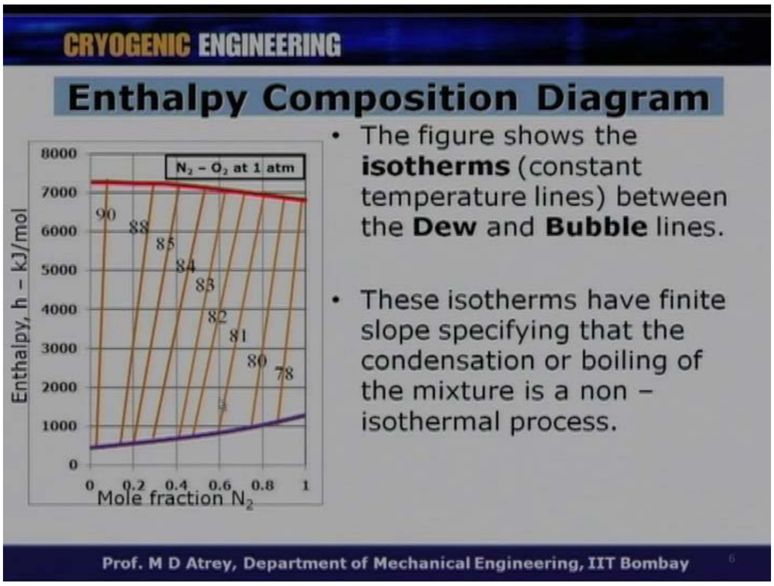

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Enthalpy Composition Diagram

- The figure shows the **isotherms** (constant temperature lines) between the **Dew** and **Bubble** lines.
- These isotherms have finite slope specifying that the condensation or boiling of the mixture is a non – isothermal process.

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Let the state of the mixture be on the dew line at point 1.

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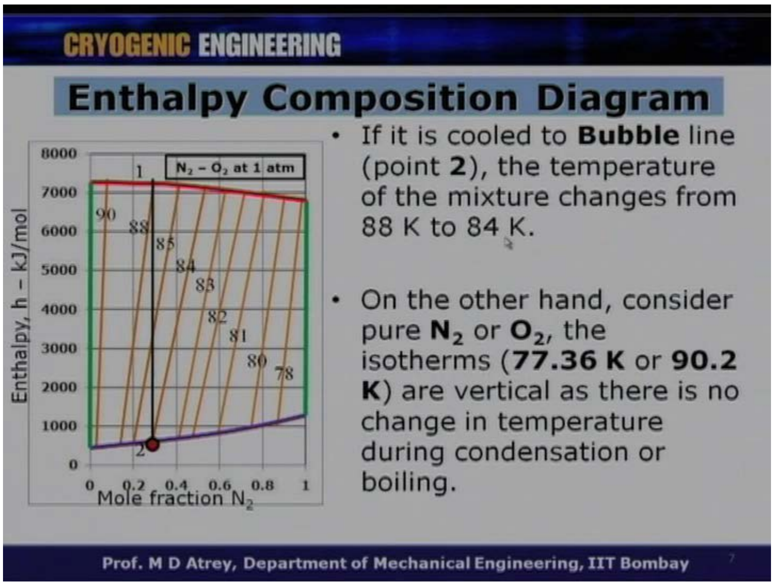

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Enthalpy Composition Diagram

- If it is cooled to **Bubble** line (point **2**), the temperature of the mixture changes from 88 K to 84 K.
- On the other hand, consider pure **N_2** or **O_2**, the isotherms (**77.36 K** or **90.2 K**) are vertical as there is no change in temperature during condensation or boiling.

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So, let us start condensation from this point 1. If it is cooled to bubble line, that is point 2, which is point 2, this is point 2. When then the phase transformations happen, the point 1 will come to point 2, because the molar fraction has to remain the same. Whatever happens, the mixture molar composition remains the same all right.

But, what has happened, at this point 1, what was the temperature of the mixture, it’s around 88 Kelvin. If you see this line which has a having a finite slope is a isotherm, the temperature at point 1 is around 88 Kelvin while, when the mixture gets condensed at this point, the temperature at this point which is point 2, is around 84 Kelvin and that is why the temperature of the mixture changes from 88 Kelvin to 84 Kelvin and that is what you can see.

On the other hand, this is what happens when the phase transformation happens for a given mixture composition, let us say 0.3 nitrogen and 0.7 oxygen. On the other hand, consider pure nitrogen or pure oxygen, where is pure nitrogen, the pure nitrogen is here 100 percent. If you see here from this point for example, if the phase transformation takes place from here, this line is vertical: it has no finite slope: it has got an infinite slope which is parallel to y axis, what does it mean. This 77.36 line is absolutely vertical and same thing can be noticed, if you’ve got 100 percent oxygen which is 0 percent nitrogen.

So, here if you see if I've got a mixture at this point which is 90.2 Kelvin line, we can see that this line is vertical, which means that, whenever there is a single component which is oxygen in this case, nitrogen in this case, this line is not inclined, this line is vertical in that case. Why? Because there is a single component and whenever there is a phase transformation happens for a single component the temperature remains constant. Temperature during the phase transformation remains constant.

So, on the other hand consider pure nitrogen or oxygen. The isotherms are vertical in this case, as there is no change in temperature during condensation or boiling, because it is a one component system. It is not a mixture anymore. I hope this is clear to you. Let's go ahead.

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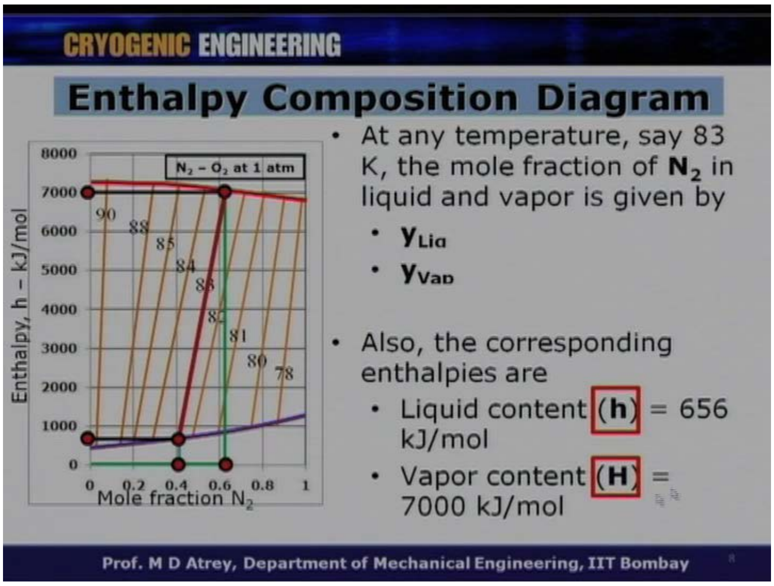

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Enthalpy Composition Diagram

- At any temperature, say 83 K, the mole fraction of $\mathbf{N_2}$ in liquid and vapor is given by
  - $\mathbf{y_{Liq}}$
  - $\mathbf{y_{Vap}}$
- Also, the corresponding enthalpies are
  - Liquid content $\boxed{(\mathbf{h})}$ = 656 kJ/mol
  - Vapor content $\boxed{(\mathbf{H})}$ = 7000 kJ/mol

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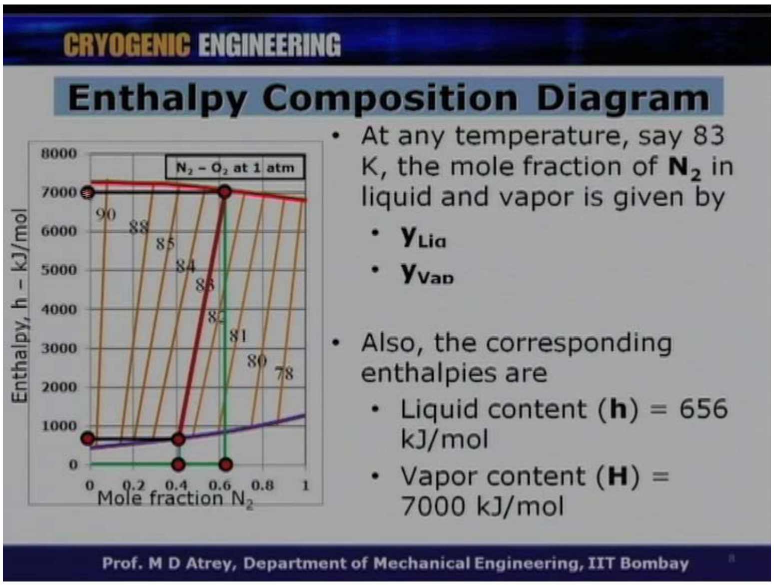

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Enthalpy Composition Diagram

- At any temperature, say 83 K, the mole fraction of $\mathbf{N_2}$ in liquid and vapor is given by
  - y_{Liq}
  - y_{Vap}
- Also, the corresponding enthalpies are
  - Liquid content (**h**) = 656 kJ/mol
  - Vapor content (**H**) = 7000 kJ/mol

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Now let us say at any temperature, say at 83 Kelvin for example, this is 83 Kelvin. The mole fraction of nitrogen in liquid and vapor is given by y liquid. So, the liquid at 83 Kelvin which is a saturated liquid, this is saturated vapor. At this point what is the composition of liquid is y liquid which is around this. all right And what is the vapor at 83 Kelvin, this is this. So, the vapor is around 0.6, just more than 0.6 mole fraction of nitrogen is in vapor condition.

So, from this diagram one can see corresponding to this what is the molar composition corresponding to given temperature if the temperature is given, if you know that it is a saturated vapor or saturated liquid conditions or for that matter anywhere in between one can find out corresponding to this the enthalpy or the mole fraction of nitrogen or a low boiling component.

Also the corresponding enthalpies are… If I want to see the enthalpy, what are the enthalpies at this point, the liquid content that is enthalpy at liquid condition at at this point is 656 kilojoules per mole. So, you can see from here if I draw a horizontal I can grid enthalpy and this enthalpy is given in small h. While if I see the vapor content enthalpy at 83 Kelvin, it is given by this parameter, if we a horizontal line, I can get that the enthalpy is around 7000 kilojoules per mole.

And kindly note the small h for liquid the capital h for the vapor enthalpy. So, this will be used many times in future slides and therefore, please note that the vapor enthalpy’s given by capital h, the small h gives the liquid enthalpy and the vapor enthalpy's much more as compared to the liquid enthalpy all right.

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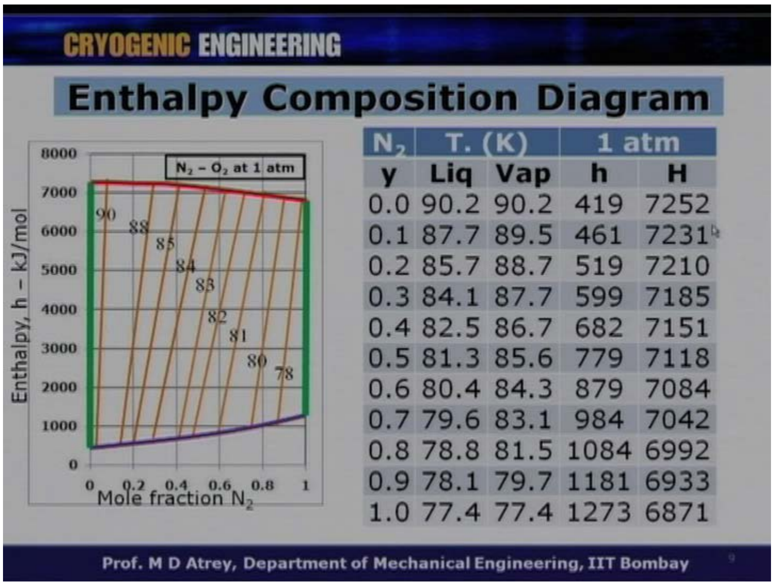

Enthalpy Composition Diagram

N_2	T. (K)		1 atm	
y	Liq	Vap	h	H
0.0	90.2	90.2	419	7252
0.1	87.7	89.5	461	7231
0.2	85.7	88.7	519	7210
0.3	84.1	87.7	599	7185
0.4	82.5	86.7	682	7151
0.5	81.3	85.6	779	7118
0.6	80.4	84.3	879	7084
0.7	79.6	83.1	984	7042
0.8	78.8	81.5	1084	6992
0.9	78.1	79.7	1181	6933
1.0	77.4	77.4	1273	6871

Now, this is a table that also could be given, instead of giving the graphical information one can have the same information given from a table. How does this table convey the same information as given in a graphical form, is you can see here. If I got a 0 y; that means, 0 percent nitrogen, I've got this line, corresponding to this I've got a liquid temperature at this point which is 90.2 vapor 90.2, the temperature remains constant because it is a single component system, it is only 100 percent oxygen system ,because this is 0 percent nitrogen.

The enthalpy h and capital H values are given at this point and this point which can be read from this graphical form also as well as from this table. Now that example is now let us say 0.3, 0.3 nitrogen, 0.7 oxygen, just draw a vertical line, you can get 84.1 as this temperature 87.7 as this, corresponding to this what you get is enthalpy value.

And last, you can see at 100 percent nitrogen, what you see is that both temperatures remaining the same, you got a small h value which is at this point and capital H value which is at this point. So, this is the way the enthalpies can be read for a given molar composition and these enthalpies will further be used for different calculations which we will see in the next lecture also.

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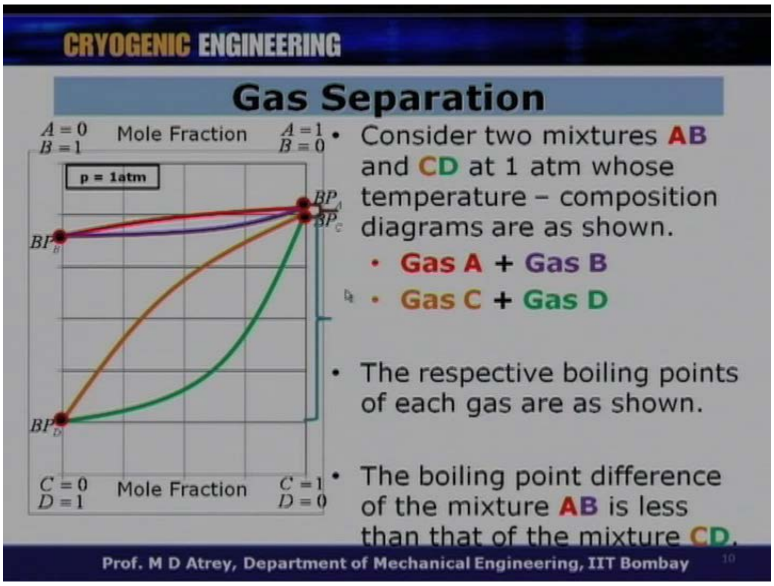

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Gas Separation

- Consider two mixtures **AB** and **CD** at 1 atm whose temperature – composition diagrams are as shown.
  - **Gas A** + **Gas B**
  - **Gas C** + **Gas D**
- The respective boiling points of each gas are as shown.
- The boiling point difference of the mixture **AB** is less than that of the mixture **CD**.

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Having done this now having understood how to get enthalpy, what is the enthalpy concept, what is the enthalpy composition diagram, now let us come to a simple understanding for a gas separation. The gas separation is largely dominated by what is the difference in the boiling point of two components in a mixture all right.

So, let us see this diagram over here, which will show you two mixtures the two mixtures AB and CD at 1 atmosphere whose temperature composition diagrams are shown over here all right. So, you see for AB, you can see the top x axis and for CD, you can see the bottom axis, x axis. Suppose, I got a diagram which is a temperature composition diagram, here you can see a temperature composition diagram for a mixture A and B. And also I've got one more diagram which is for C and D gases mixed together and this is the temperature composition diagram for gas C and D.

What is the difference between the two diagrams; it is the boiling point difference. The boiling point of C is this, the boiling point D is this. Because D is equal to 1 and c is equal to 1 at this point. Similarly, the boiling point of a is this and the boiling point of B is this.

So, what do you see from here. The respective boiling points each of these gases as shown over here. The boiling point difference of the mixture AB is only this much. While, the boiling point difference for the mixture CD is quite large as compared to what it is for A and B. Now what do I want to tell from here that the difference between the two boiling points of A and B, and C and D is a very important because that will determine the separation which happens of A and B and C and D that is how we can see in the next slide.

So, let us consider a mixture with a composition at state 1 at this point and if this mixture is rectified, the first condensation if you can see from 1 to 2, the what you get at this point is the the liquid will be at this point. The mole fraction of a will increase from this point to this. This will be referred to the top x axis and therefore, what you can see here that the fraction of a will increase from this point to this point. So, y liquid will be at 2 f A B. This is what you get at this point, 2 f A B.

Now, if I do the same point, if I come and get the mixture condensed at from the same point, but on CD curve and you can see that as soon as the first condensation happens the liquid will be much richer as compared to 2 f a b and what you can see now, it will have this much mole fraction of C. This essentially can be noted from the diagram itself.

If you've got a boiling point difference from this to this the right in the first condensation you've come very close to 90 percent mole fraction of C. The first condensation itself has separated component C and the liquid has more around 90 percent of component C. While in this case, it was around 75 to 80 percent only. Why did this happen? This is little exaggerated phase just to show the clarity of what happens, when the condensation happens.

What you see here, if you got a difference between the two boiling components the boiling point is quite less, the first condensation will not separate the the high boiling component or low boiling component for that matter while, the first condensation in a for the mixture in which you've got a high boiling point differences, the first condensation maybe sufficient for example, two separate the high boiling component immediately. The liquid is getting richer in high boiling component immediately. If this difference is too large, just from the nature of this curve you can see that this point will come more on the right side immediately right in the first condensation.

The point to be noted is the higher the difference between the two boiling points you will not have to do too many condensations. So,1 or 2 or 3 condensations could be good enough to separate component C and component D while in this case we may have to go for multiple condensations and evaporation in order to separate A and B. Why, because the boiling point difference between the between A and B is not too large is very small.

All right. So, the separation is more effective, when the difference in the boiling point is more this is the point I wanted to stress that right in the first condensation, the separation was very high. While in this case, the separation was not that good for such mixture almost pure product is obtained in one or two condensation all right In this case right in the first condensation you get a pure point and that is the point I wanted to tell you in this case.

In this case, you can see… This is a figure which you've already seen. This is the way we basically do the rectification. As done earlier, the rectification of the mixture at point 3, if you're at point 3 the first condensation would result in this liquid and this much of gas. The subsequent condensation would result from here and march towards that. I just wanted to show this because after this slide I am going to deal with the rectification column itself.

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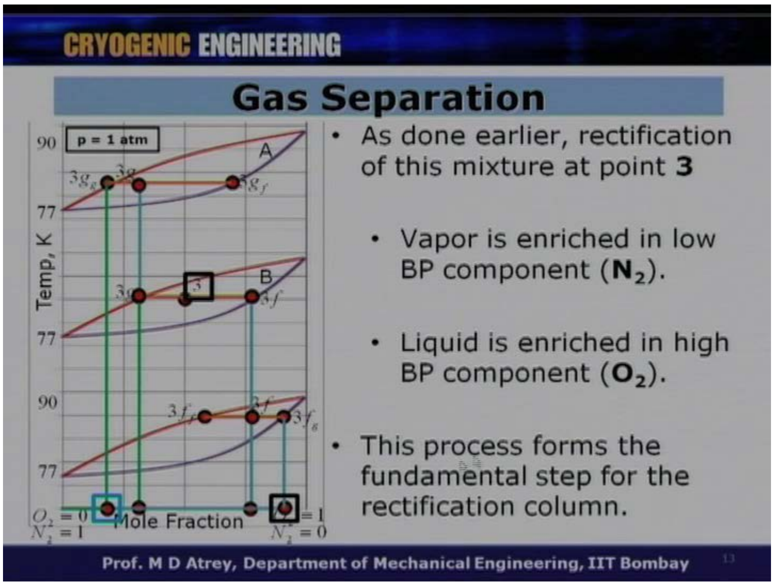

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Gas Separation

- As done earlier, rectification of this mixture at point **3**
  - Vapor is enriched in low BP component (**N_2**).
  - Liquid is enriched in high BP component (**O_2**).
- This process forms the fundamental step for the rectification column.

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So, in a rectification column, right here after first condemnation you'll have go go for subsequent condensation processes in order to reach a right and you'll get high boiling component, you'll move toward the liquid which is richer in high boiling component, while, this vapor will be further evaporated, it will further move towards left and ultimately what you get is a, the low boiling component getting richer and richer into vapor. And ultimately this vapor will get get condensed when you shift toward the left y axis. When the high boiling component in liquid will move to the right axis, which is which is oxygen in this case and nitrogen in this case.

So, as done earlier, rectification of this mixture at point 3, vapor is enriched in low boiling component nitrogen. So, as you go on the left side the vapor is getting enriched enriched in low boiling component which is nitrogen, while the liquid is getting in high boiling component which is oxygen. And this is essentially is the basis of multiple condensations and evaporation which is carried out in a rectification column. This process form the fundamental step for the rectification column. All right.

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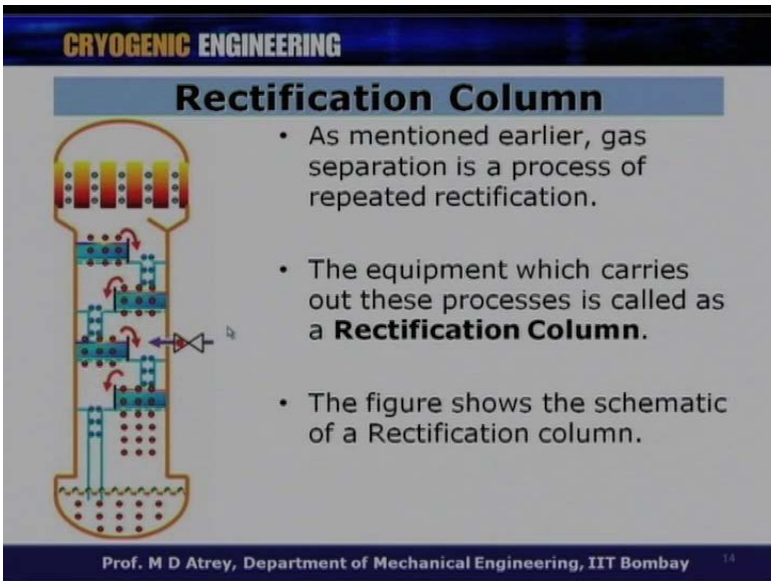

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Rectification Column

- As mentioned earlier, gas separation is a process of repeated rectification.
- The equipment which carries out these processes is called as a **Rectification Column.**
- The figure shows the schematic of a Rectification column.

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Now let us go to the rectification column. With this background whatever we’ve studied, now let us go to the rectification column which, as mentioned earlier, gas separation is a process of repeated rectification or condensation and evaporation. The equipment which carries out these processes is called as Rectification Column and a general schematic is given over here. This structure could be very huge structure; it can have a very high length, also depending on the kind of purity you want and what it consists of is this, we will discuss this structure (( )).

The figure shows the structure of a rectification column. So, the gas which is to be separated, enters at this feed line and ultimately you get the two component to be separated from top and bottom this is the idea. The process of gas separation happens in this column across the height of this column and the height of the column is a very crucial matter because height of column will determine, what is the purity of the gas which is the gas component, which is getting getting separated at the top and at the bottom.

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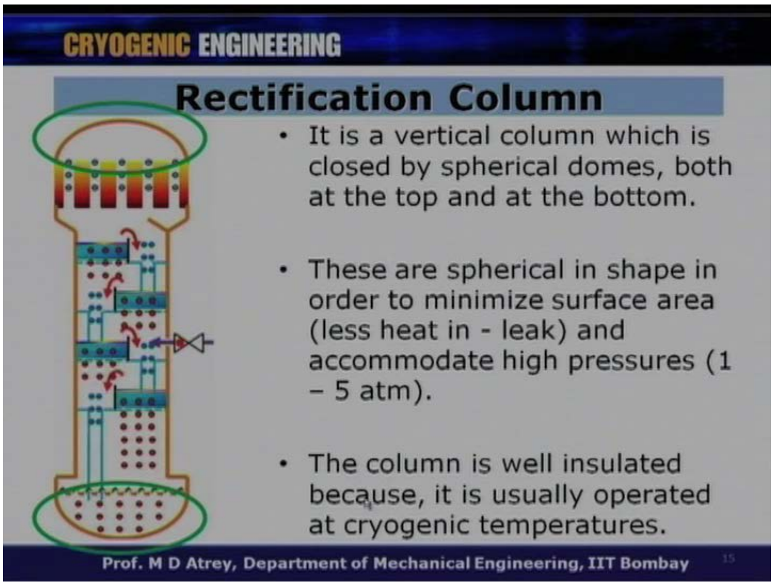

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Rectification Column

- It is a vertical column which is closed by spherical domes, both at the top and at the bottom.
- These are spherical in shape in order to minimize surface area (less heat in - leak) and accommodate high pressures (1 – 5 atm).
- The column is well insulated because, it is usually operated at cryogenic temperatures.

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So, what do you see here. It is a vertical column which is closed by spherical domes both at the top and the bottom. So, what you can see, one dome on the top, one dome at the bottom and a vertical column over here. These are spherical in shape; the domes are spherical in shape in order to minimize the surface area that is the less heat in-leak all right and accommodate high pressure.

Now the whole column or the domes have to stand high pressure. When I say high pressure it could be of the order of 1 or bar 2 bar or 5 bar ,not more than 5 bar normally. The column is well insulated, again the entire column is subjected to cryogenic temperature and therefore, the column has to be well insulated it is usually operated at cryogenic temperature.

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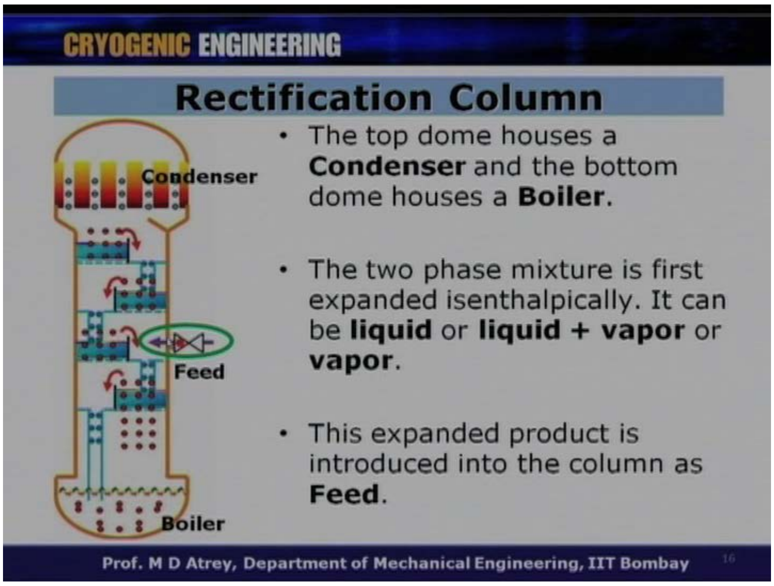

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Rectification Column

- The top dome houses a **Condenser** and the bottom dome houses a **Boiler**.
- The two phase mixture is first expanded isenthalpically. It can be **liquid** or **liquid + vapor** or **vapor**.
- This expanded product is introduced into the column as **Feed**.

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The top dome houses a condenser and the bottom dome houses a boiler. So, what is happening at this point, is the boiler what you collect at this point ultimately is a high boiling component liquid. So, liquid is stored here and the boiler is supplying heat to this liquid while, the enriched vapor of low boiling component comes to the top all right and therefore, this vapor will be ultimately condensed at this point to get liquid of low boiling component which is nitrogen in a nitrogen-oxygen mixture. And this is therefore, called as condenser.

The two phase mixture is first expanded isenthalpically. So, wherever from whichever place the two phase mixture is coming, whatever mixture is coming, is going to be at high pressure the column cannot stand very high pressure. And therefore, this mixture pressure has to be reduced and therefore, one valve is kept at this point, whose essential function basically is to reduce the pressure. So, the pressure is reduced and therefore, the expansion would happen and therefore, this mixture will enter the column as liquid or liquid plus vapor or sometimes as saturated vapor.

So, all three conditions are possible this column, this mixture or the feed can enter this column in all these three forms. And this is a this is the valve where the expansion occurs this expanded product is introduced into the column as feed all right. So, the feed enters the column at this particular point.

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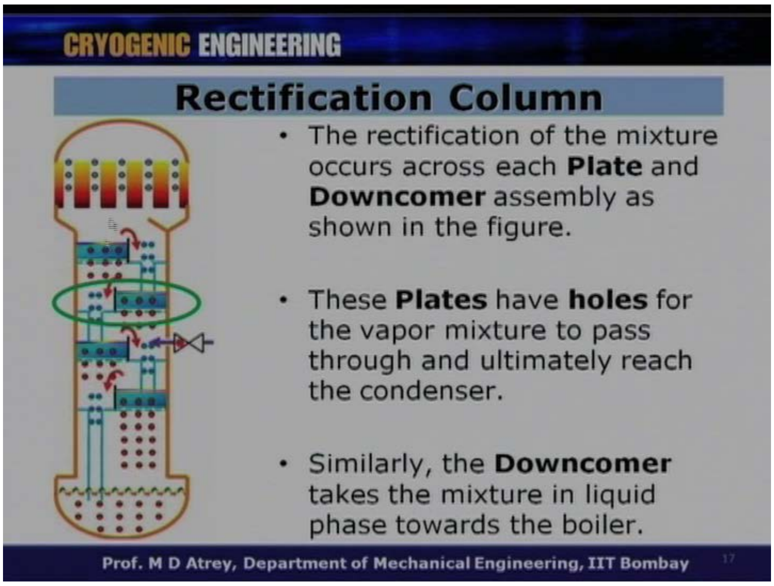

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Rectification Column

- The rectification of the mixture occurs across each **Plate** and **Downcomer** assembly as shown in the figure.
- These **Plates** have **holes** for the vapor mixture to pass through and ultimately reach the condenser.
- Similarly, the **Downcomer** takes the mixture in liquid phase towards the boiler.

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The rectification of the mixture occurs across each plate and the down comer assembly as shown in this figure. So, what we can see in this column is, there are lots of horizontal plates. And on these plates what we can see is a, one particular height which is called ware. As soon as this liquid height increases above a particular ware height the liquid will come down. In in every plate we can see that you got a liquid at this point and this liquid height is governed by the ware height. So, as soon as the liquid height increases or goes beyond a ware it comes down and it comes through this down comer this is what is explained over here.

So, on every plate we’ve got a plate with a down comer. So, with the liquid height increases a particular height of the ware, it comes to the down comer and goes to the plate which is below the top plate. When this height increases, the liquid height increases the liquid will be overflowing across this ware and then comes to the next down comer down to this plate. So that, we can see that the liquid is always flowing down while the vapor will always go up. On a vapor is going up through this plate.

So, let us come to the next discussion. These plates have holes. You can see the plates have holes. So, this vapor whenever the feed comes through, the feed can have vapor, liquid or vapor plus liquid. The vapor will try to go up and it will go through this small small holes which are at the bottom of the plate itself, That means, as soon as the vapor goes up it will go through this liquid. All right And this will go through this liquid and the heat transfer happens between this vapor and the liquid. These plates have holes for the vapor mixture to pass through and ultimately reach the condenser. So, this vapor passes through this liquid.

Now, there is some phase transformation which takes place, but again vapor will leave upper plate this vapor will again pass to the next plate, the liquid on the next plate and ultimately, as you know earlier, that the vapor which is rich in the low boiling component will try to reach on the top, while, this liquid which is flowing down on every plate will try to go to the high boiling component liquid at this point which is nothing but the boiler. Similarly, the down comer takes the mixture in liquid phase towards the boiler. So, the vapor will try to go to the top, but the liquid will try to come to the boiler.

How does it happen? During this motion, vapor is passing through the liquid the vapor and liquid flow in the opposite direction. So, vapor is going up the liquid is coming down. So, it is kind of a counter-flow arrangement basically all right. So, the exchange happens in a counter-flow manner. So, during this motion, vapor and liquid flow in opposite direction and exchange heat in a counter-flow manner. This is what we can see. Now what is happening exactly?

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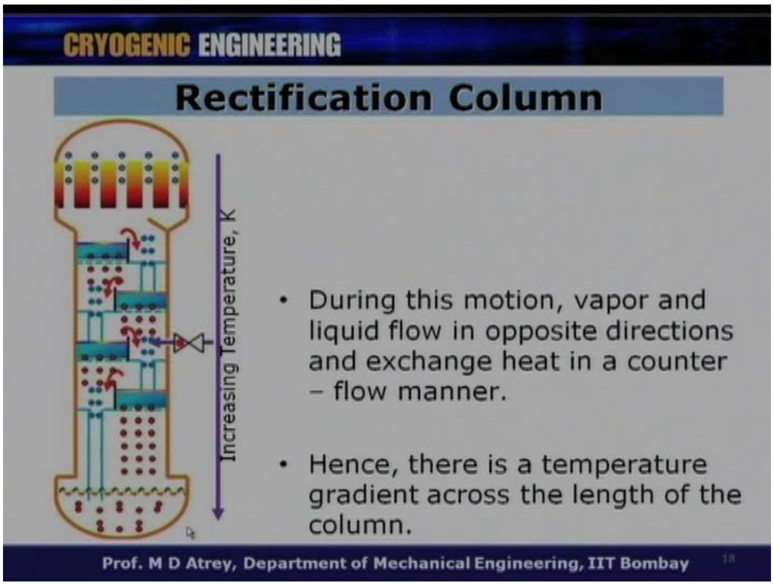

CRYOGENIC ENGINEERING

Rectification Column

- During this motion, vapor and liquid flow in opposite directions and exchange heat in a counter – flow manner.
- Hence, there is a temperature gradient across the length of the column.

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When the vapor or the vapor liquid mixture enters, the vapor passes through the liquid and this liquid above this plate is going to be at a lower temperature. all right And therefore, the heat exchange happen between this vapor and liquid and the vapor will get condensed at this point while, the liquid will get evaporated or the high boiling component of the liquid will get evaporated and ultimately vapor would go to the top. So, the low boiling component vapor will go to the top and again it will get condensed at this point.

So, the temperature at this point, if we talk about nitrogen-oxygen mixture is going to be around 77 Kelvin while, the oxygen will get condensed every time and the liquid will come down and ultimately, we will have a liquid oxygen at this point at o1ne atmosphere; that means, the temperature at this point would be 90 Kelvin.

What does it mean? The temperature is increasing from 77 Kelvin to 90 Kelvin across the height of the column. So, you'll have around 77 Kelvin temperature over here you'll have 90 Kelvin temperature over here while, the temperature at each plate here will be somewhere like 77 in between the 77 Kelvin and 90 Kelvin temperature. So, we got a temperature range will going to be generated across the height of the column. Hence there's a temperature gradient gets developed across the length of the column or height of the column.

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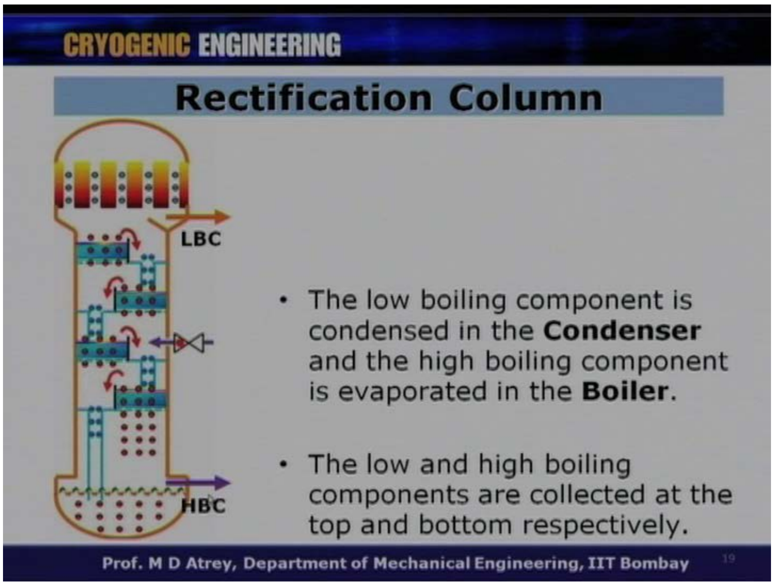

CRYOGENIC ENGINEERING

Rectification Column

- The low boiling component is condensed in the **Condenser** and the high boiling component is evaporated in the **Boiler**.
- The low and high boiling components are collected at the top and bottom respectively.

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The low boiling component is condensed in the condenser. So, ultimately the vapor would reach to the top, the low boiling component will get condensed at this point and the high boiling component is evaporated from the boiler. In order that vapor always goes up and the liquid always ensured to come down, we will have boiler at this point and condenser at this point. This boiler ensures that the high boiling component is always getting evaporated; that means, there’s always a vapor feed of buds condenser ensures that liquid always is flowing down. So, these two ensure that the liquid the counter-flow arrangement of the liquid and the vapor flow is always ensured.

The low boiling components and high boiling components are collected at the top and bottom respectively. So, low boiling component which is the nitrogen it should be connected at this point while the high boiling component which would be oxygen is collected from the boiler.

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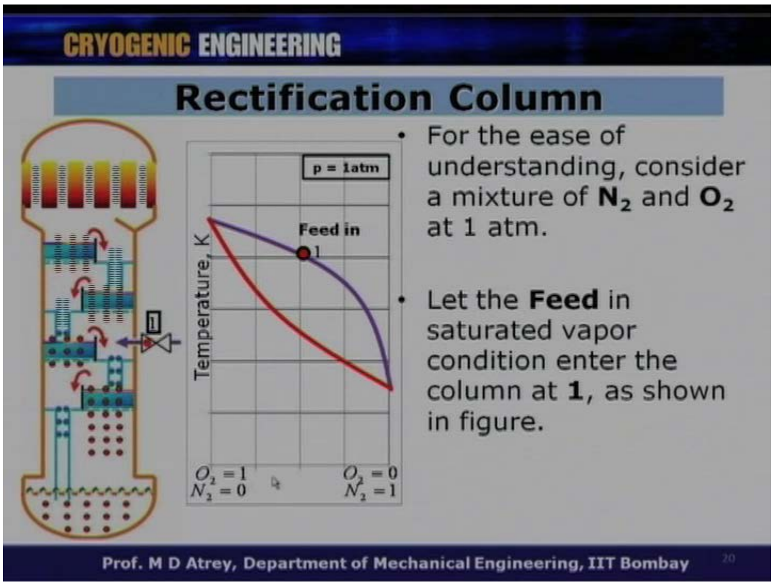

CRYOGENIC ENGINEERING

Rectification Column

- For the ease of understanding, consider a mixture of N_2 and O_2 at 1 atm.
- Let the **Feed** in saturated vapor condition enter the column at **1**, as shown in figure.

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Now, what is happening inside, what is happening inside in a plate, you can see that. For the ease of understanding consider a mixture of nitrogen and oxygen at 1 atmosphere. Let the feed enter at this point 1 which is going to be let us say vapor condition in this case. So, let the feed in the saturated vapor condition enter the column at 1 as shown in figure. So, what you can see is a condition 1 which is at feed at point 1. So, condition after the expansion at 1 atmosphere the feed enters. The feed has a particular composition of oxygen and nitrogen as given in this diagram.

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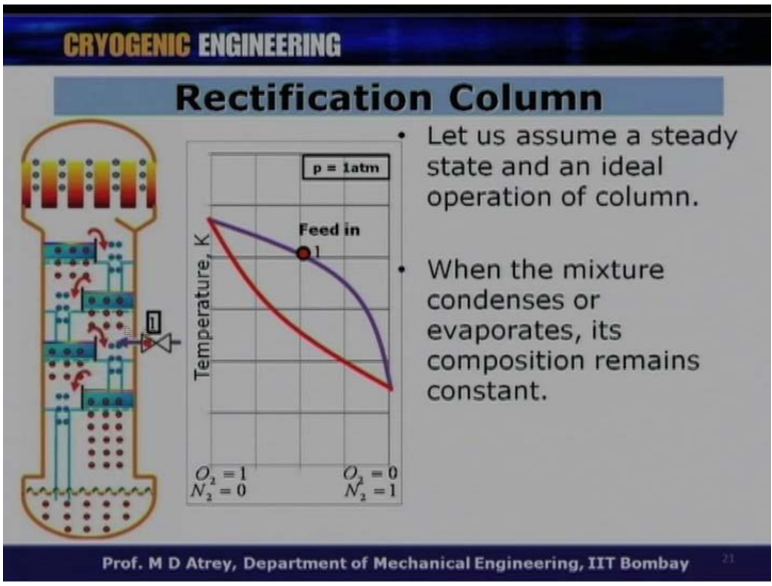

CRYOGENIC ENGINEERING

Rectification Column

- Let us assume a steady state and an ideal operation of column.
- When the mixture condenses or evaporates, its composition remains constant.

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So, what will happen to this feed? Let us assume a steady state and an ideal operation, let us not see any transient operation, let us see that a steady state has got; that means, you’ve got a temperature across the temperature gradient across the column height has already got developed, the temperature at this point around 77 Kelvin while the temperature at the boiler region around 90 Kelvin which is the boiling point of the oxygen.

When the mixture condense, so, what will happen, when the mixture enters at this point or the vapor enters at this point, this vapor will try to go up, through these orifices, through this liquid. And this vapor, because this plate above it, as the temperature has already got developed, that liquid above this vapor is going to be at less temperature than the feed temperature at this point. So, as soon as vapor enters this liquid, the vapor will get condensed all right. That means, a phase transformation will happen and when the phase when the mixture condenses or evaporated its composition remain the same.

So, when the feed will come inside at point 1, when it comes out at point 2, let us say the composition will remain the same; that means, the temperature will come down as it goes up the plate, the composition will remain the same, but its temperature will come down.

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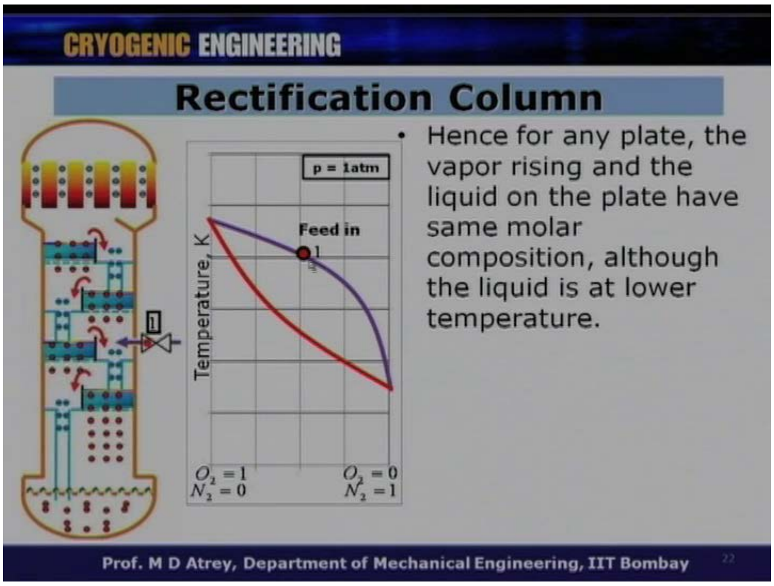
CRYOGENIC ENGINEERING

Rectification Column

- Hence for any plate, the vapor rising and the liquid on the plate have same molar composition, although the liquid is at lower temperature.

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So, what you can see that, hence for any plate the vapor rising and the liquid on the plate have same molar composition. So, when this vapor goes up, condensation will occur, the liquid is going to be there. So, this liquid and the vapor which is coming to pass through it will have the same molar composition all right. That means, this will be a vertical line. It will have same molar composition although the liquid is at the lower temperature. Why this condensation happening, because this liquid is at lower temperature all right.

So, during this phase transformation, we always know that the temperature decreases, the temperature of the liquid above in this plate is going to be less than at, what it is at point 1, but the molar composition of the vapor which is rising and the liquid above it will remain the same. So, we can see that the point 2 which is going to be here at this point will have same molar composition.

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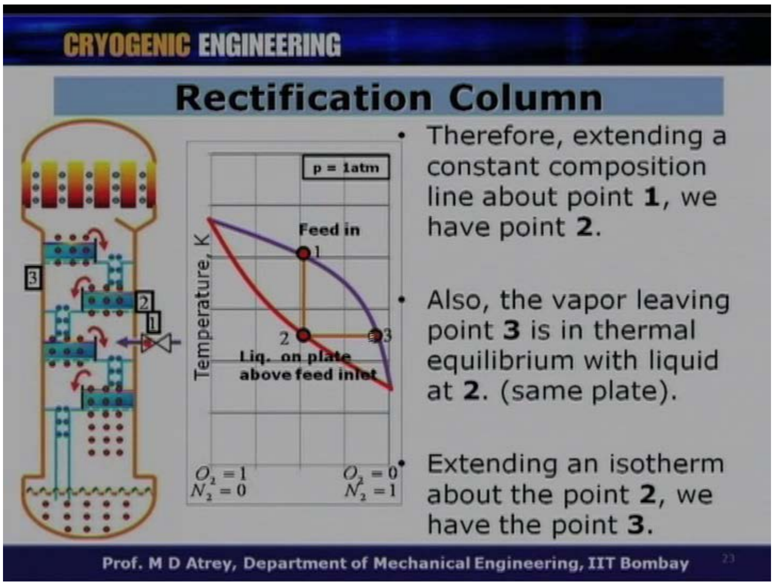

CRYOGENIC ENGINEERING

Rectification Column

- Therefore, extending a constant composition line about point **1**, we have point **2**.
- Also, the vapor leaving point **3** is in thermal equilibrium with liquid at **2**. (same plate).
- Extending an isotherm about the point **2**, we have the point **3**.

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So, now, we can draw the point 2 and point 2 basically denotes the liquid on the plate or a composition of the liquid on the plate above this feed all right. The molar composition remaining the same, the temperature is less than what it is at point 1. So, therefore, extending a constant composition line about point 1, what we have is a point 2.

Now, we've come to this point 2 and this point 2 will get the liquid here will get evaporated, because the high boiling component in this vapor will get condensed and the low boiling component of this liquid will get evaporated over here because of the heat transfer between this vapor and the liquid. So, what the vapor will leave this phase, the vapor which is going to be more in nitrogen content because it is a low boiling component is going to leave this place, but this vapor will going to be in thermal equilibrium with this liquid all right. So, this vapor on the same plate on which the liquid is there, they will be at thermal equilibrium. And therefore, also the vapor leaving the point 3 which is this is in thermal equilibrium with the liquid in point 2. So, the point 2 liquid is this liquid and the 3 vapor is going to be at the same temperature.

So, what do I do, that in thermal equilibrium I draw a horizontal line which is going to be at same temperature and wherever it touches the vapor curve, this is going to be the now composition of the vapor which is leaving all right. You can see this composition is now richer in nitrogen. The vapor is getting richer and richer in nitrogen extending an isotherm about this point 2, we have the point 3 now. all right. This is the point 3 which gives the molar composition of the vapor which is above this plate. Understand that the compositions are different now, but the temperatures are same, because they are in thermal equilibrium with each other.

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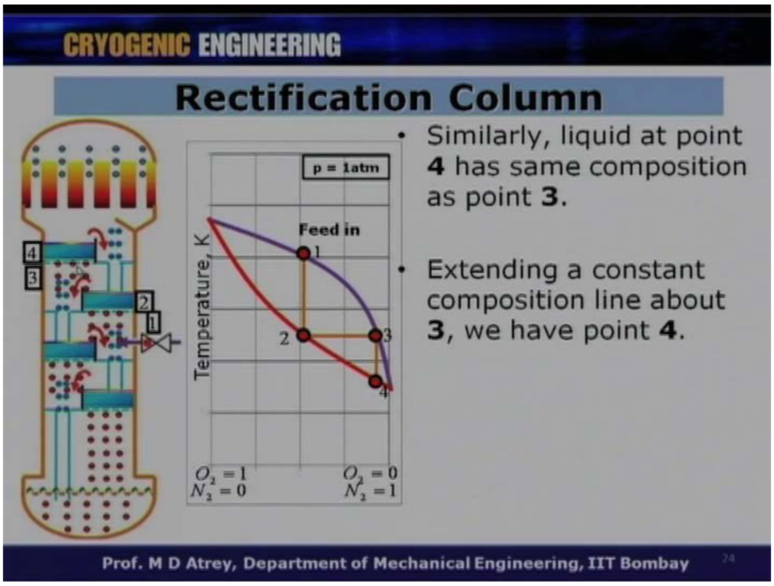

CRYOGENIC ENGINEERING

Rectification Column

- Similarly, liquid at point **4** has same composition as point **3**.
- Extending a constant composition line about **3**, we have point **4**.

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Similarly, liquid at point 4, now if I go ahead, I am going to the next plate again, the same arguments would hold good now which were at 1 and 2. What will happen? The point 4 is going to be at lower temperature, but this vapor will get condensed over here. And therefore, the molar composition of the vapor which is passing through this liquid is going to be the same, but the temperature at point 4 is going to be less than what it is at point 3. So, what is happening to this is a phase transformation again. The vapor will get condensed the molar composition will remain the same, but the temperature will decrease.

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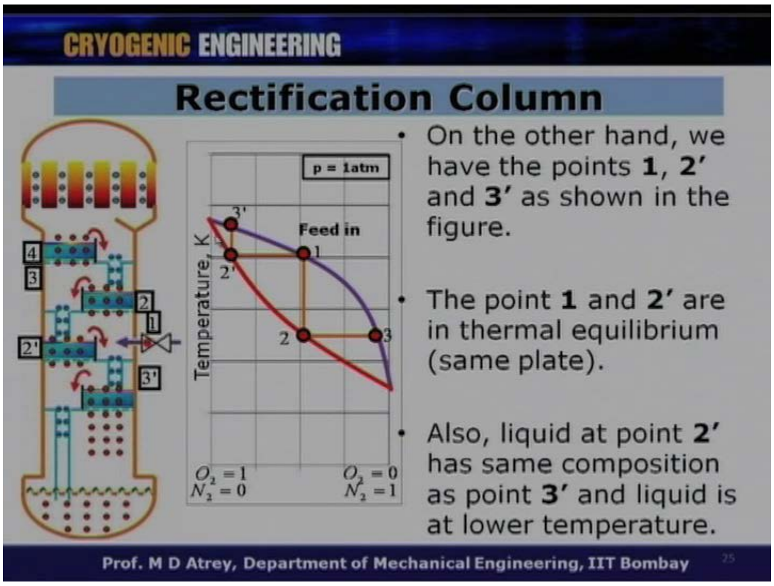

Rectification Column

- On the other hand, we have the points **1**, **2'** and **3'** as shown in the figure.
- The point **1** and **2'** are in thermal equilibrium (same plate).
- Also, liquid at point **2'** has same composition as point **3'** and liquid is at lower temperature.

So, extending a constant composition line about 3 we’ve got a point 4 which now gives the liquid composition at point 4. And also it gives the temperature at point 4. Now this will essentially go on continuing across each plate till we reach the the rightmost place where we want the purity of nitrogen. Similar thing will happen on the opposite side. This is what we’re talking about this, but vapor now, similar thing will happen on the plates below this point all right. The plate will below this point also will show this thing.

On the other hand, we‘ve the points 1, 2 dash 3 dash as shown in this figure. And you can see that at 3 dash will indicate the vapor condition at this point. So, things above from the feed line is going to be shown on the right side of this curve while thing below the the plate, the temperature on composition of the liquid and the vapor below the feed line is going to be shown on the left side of the feed by 1 dash, 2 dash, 3 dash and 4 dash curves. This is very important to understand. What is happening is at some plates, the composition remain the same when the vapor changes the phase while the liquid and the vapor on the same plate are in thermal equilibrium. This is we’re talking about the ideal case right.

The point 1 and 2 dash are in thermal equilibrium for the same plate also liquid at 2 dash has same composition as 3 dash and the liquid at lower temperature. So, we’re talking about the same thing what we talked here for this condition.

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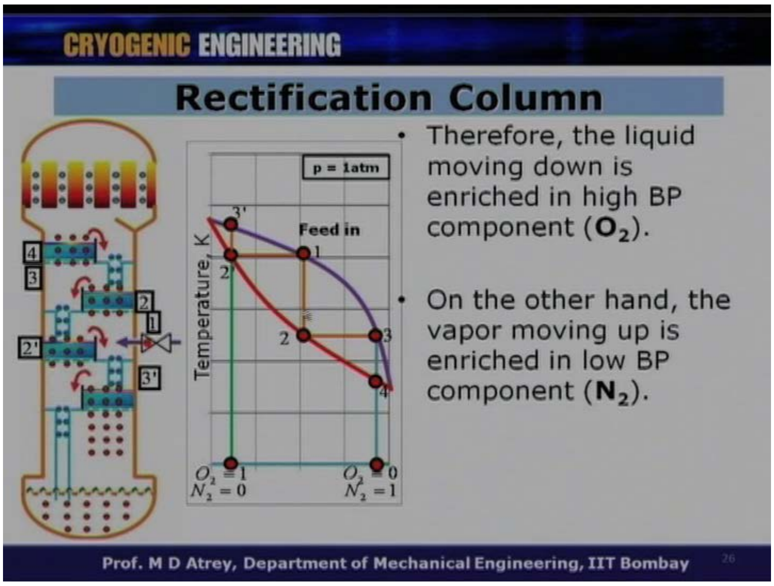

CRYOGENIC ENGINEERING

Rectification Column

- Therefore, the liquid moving down is enriched in high BP component (**O_2**).
- On the other hand, the vapor moving up is enriched in low BP component (**N_2**).

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Therefore, the liquid moving down the liquid moving down is going to be richer in high boiling component. What is happening on the left side is the liquid is getting richer and richer in oxygen all right while the vapor is getting richer and richer in low boiling component which is nitrogen. And ultimately this nitrogen vapor which is richer in nitrogen now, reaches the condenser and what I am going to do at the condenser, I am going to condense all the vapor to get liquid while, all this liquid will get stored at the in the boiler at this point. So, this point therefore, will be at 90 Kelvin as you go up the ladder from the left hand side of the feed while all these vapor conditions is going to be depicted by the right hand side of the feed as shown over here.

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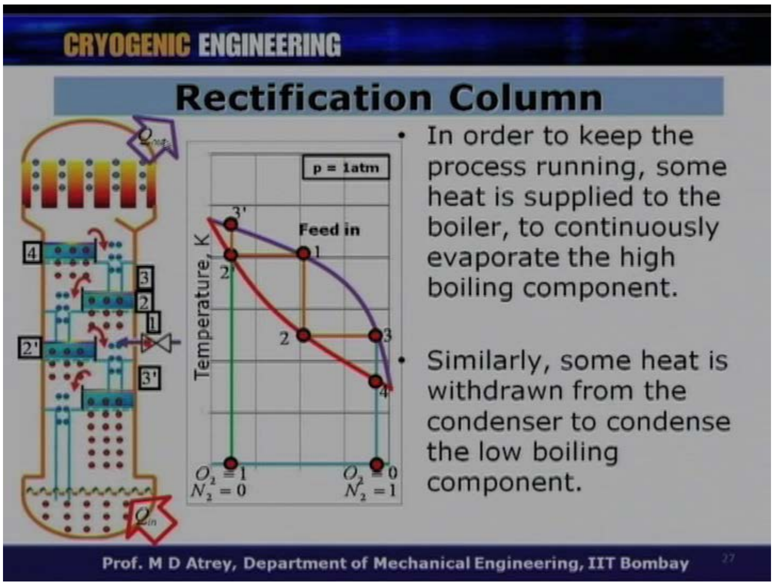

CRYOGENIC ENGINEERING

Rectification Column

- In order to keep the process running, some heat is supplied to the boiler, to continuously evaporate the high boiling component.
- Similarly, some heat is withdrawn from the condenser to condense the low boiling component.

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In order to keep the process running, now ultimately you want this process to happen for years together all right the process is running some heat must be supplied to the boiler. So, I’ve to supply in some heat to ensure that the vapor always is leaving at this point all right. So, some heat has to be supplied to the boiler to continuously evaporate the high boiling component. So, some high boiling component always getting evaporated at this point; it will get combined with the low boiling component vapor essentially later on.

Similarly, what I will have to do, I will have to take heat out from here in order to condense the low boiling component which is nitrogen. So, for condensation to occur effectively, I will have to take some heat out which is q out depicted as this point at the condenser.

So, similarly, some heat is withdrawn from the condenser to condense the low boiling component. And it is in this way that the rectification column would function ideally. Whatever I am showing and depicting in this, please try to understand. These are all the ideal operations. And they’ll go on continuing from the boiling to the condenser and these vertical lines essentially are depicting the operation happening at each plate all right.

When you got a temperature difference from this point to this point, you got a vertical line actually depicting operation at each plate while a horizontal line is depicting when operation happening between the liquid and vapor at each plate. So, basically these are all graphically representation of what is happening in this column right.

Depending on the purity you want at the condenser and at the boiler, you'll have to decide how much do you want to merge on the left side, how much you want merge on the right side and that essentially will decide how many plates this column should have or effectively, what should be the height of this column all right. So, this is what will happen, I've shown you an ideal operation and now in the few slides later, we see that, how these things will be realized in practice, how much away do we go from ideality in that case.

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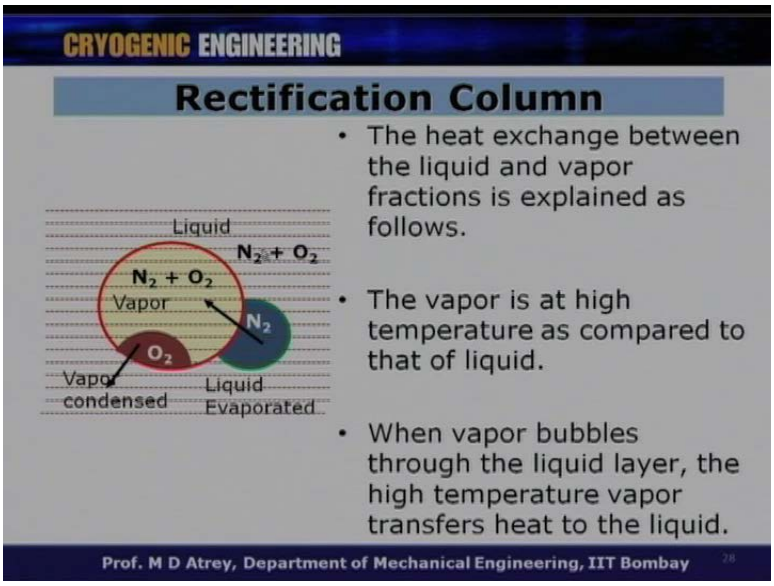

CRYOGENIC ENGINEERING

Rectification Column

- The heat exchange between the liquid and vapor fractions is explained as follows.
- The vapor is at high temperature as compared to that of liquid.
- When vapor bubbles through the liquid layer, the high temperature vapor transfers heat to the liquid.

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So, now in order to understand, what exactly happens in a rectification column or what happens on each plate, let us see this figure. So, here you can see that this is a vapor bubble all right. And let us see now, the heat exchange between the liquid and vapor fractions is explained as follows.

The vapor is at high temperature as compared to that of liquid all right. This vapor which is going up through the liquid, so, this is a vapor, let us say bubble and it is passing through the liquid which is above the plate, which is above the vapor and this liquid around it is going to be at less temperature than that of vapor. This vapor is entering the bubble, vapor is entering the plate through the small holes at the bottom of the plate. And this hole size will decide, what is the diameter of this vapor bubble all right.

So, there are several bubbles which will come through this liquid and the heat transfer between this vapor which is at higher temperature as compared to that of liquid will decide, what is going to be the efficiency of this column all right. So, the vapor is at high temperature as compared to that of the liquid. When the vapor, bubbles through the liquid layer, the high temperature vapor, transfer heat to the liquid. Naturally that, the heat transfer from the high temperature vapor to the low temperature liquid.

Now, this vapor comprises of nitrogen and oxygen vapors both combined together. At the same time the liquid also is going to be comprising of nitrogen and oxygen molar fractions, depending on the mole composition of this liquid at a particular plate and the mole clasps in the vapor below a particular plate.

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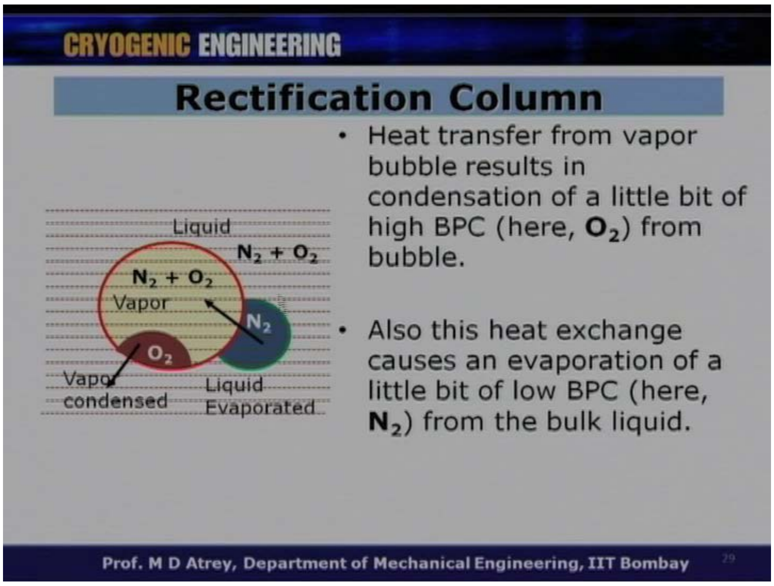

CRYOGENIC ENGINEERING

Rectification Column

- Heat transfer from vapor bubble results in condensation of a little bit of high BPC (here, $\mathbf{O_2}$) from bubble.
- Also this heat exchange causes an evaporation of a little bit of low BPC (here, $\mathbf{N_2}$) from the bulk liquid.

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So, what is going to happen, because of the heat transfer between the vapor and the liquid what is going to happen? The heat transfer from the vapor bubble results in condensation of a little bit of a high boiling component which is oxygen from the bubble. As soon as this vapor gives some amount of heat to the liquid, the part of the high boiling component which is oxygen will get condensed, because it is a high boiling component as soon as the heat is given, this part will be condensed all right. At the same time whatever amount of heat transfer happens between the vapor and the liquid at this point, the low boiling component in this liquid which is nitrogen is going to get evaporated.

So, some part of the liquid which is rich in which is going to be low boiling component it will get evaporated while the high boiling component of the vapor is going to get condensed. So, the condensation will happen of the high boiling component, evaporation will happen of the liquid in the low boiling component.

So, what is happening now, the vapor which is going to leave this particular plate is going to be the nitrogen in the existing vapor plus whatever nitrogen got evaporated from the liquid. So, this vapor will get little bit enriched in the low boiling component or nitrogen, when it will be at this plate while the liquid here will get richer in oxygen, because this vapor got condensed over here and nitrogen has got evaporated from the liquid over here.

So, liquid at this plate is going to get enriched in high boiling component that is oxygen and this liquid will come down, the next plate when its height increases beyond a particular ware height. So, this process will continue on every plate.

So, essentially we’ve to understand that all these condensation-evaporation activities basically depend on the temperature across the column basically all right. So, also the heat exchange causes and evaporation of a little bit of low boiling component from the bulk liquid which is what I just explained all right.

And this is what is going to be get continued across the entire column. So, the success of this column or the efficiency of this column basically depends on the efficient heat transfer between this vapor and the liquid. And therefore, design of each plate is very very critical, design of the hole which is at the bottom of the plate which decide this bubble size is also going to be very very critical.

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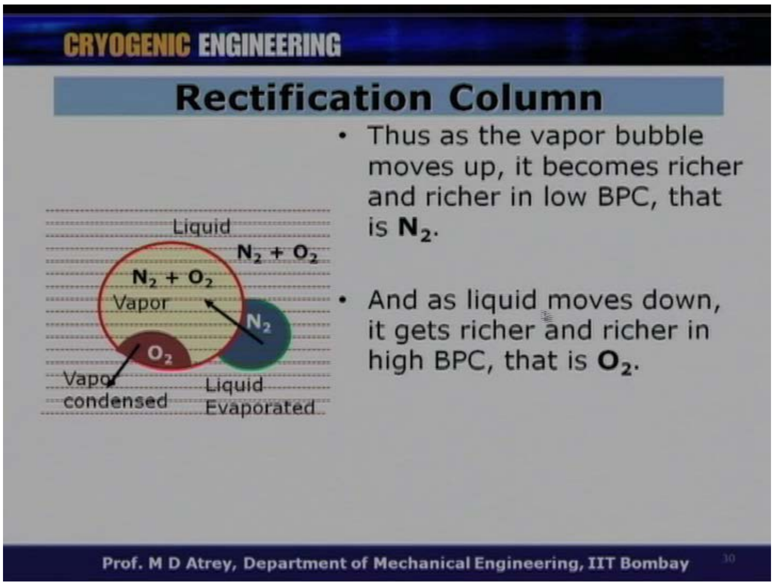

CRYOGENIC ENGINEERING

Rectification Column

- Thus as the vapor bubble moves up, it becomes richer and richer in low BPC, that is N_2.
- And as liquid moves down, it gets richer and richer in high BPC, that is O_2.

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Thus, as the vapor bubble moves up, it becomes richer and richer in low boiling component that is nitrogen in this case. And as the liquid moves down it gets richer and richer in high boiling component which is oxygen in this case.

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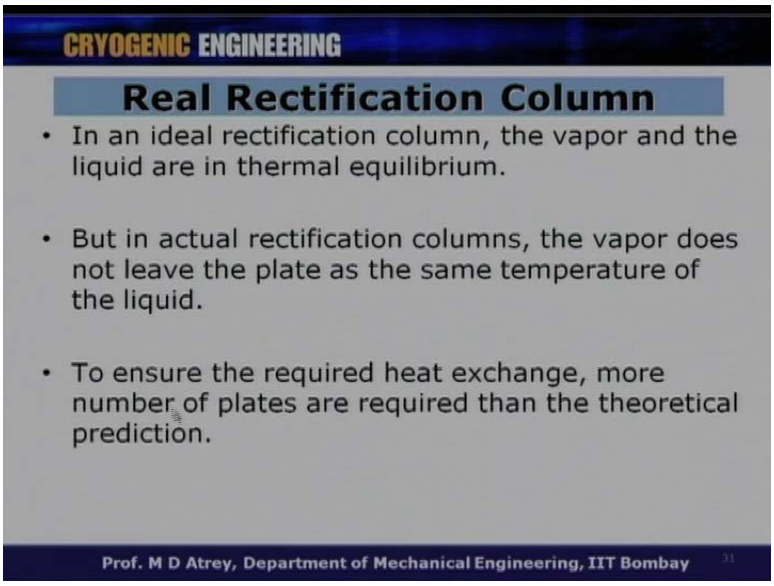

CRYOGENIC ENGINEERING

Real Rectification Column

- In an ideal rectification column, the vapor and the liquid are in thermal equilibrium.
- But in actual rectification columns, the vapor does not leave the plate as the same temperature of the liquid.
- To ensure the required heat exchange, more number of plates are required than the theoretical prediction.

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Now, in an ideal rectification column, the vapor and the liquid are in thermal equilibrium, that is what we just talked about earlier. We showed that a thermal equilibrium basically vapor and the liquid on the same plate will have same temperature all right. Ideally this could be possible, but in actual condition, in actual rectification column the vapor does not leave the plate at the same temperature of that of liquid.

So, in actual case now there’ll be temperature difference. Because the heat transfer between the vapor and the liquid will not be that efficient; it will have some limitation; it will have some efficiency associated with it. And therefore, the vapor is not going to have the liquid, same temperature of the liquid, from which it gets evaporated. There’ll be some delta t across it. And the vapor leaving the liquid will be having some higher temperature than that of liquid.

So, this now we’re talking about the real rectification column. Up till now, we talked about the ideal rectification column and now let us see what are the realities in a real rectification column. So, to ensure the required heat exchange, more number of plates are required than the theoretical prediction. In a theoretical prediction we will assume that the heat transfer is perfect. The molar composition remains the same after condensation or the temperature of the vapor which is leaving the plate is the same.

But, based on this assumption I will calculate the number of plates required in a rectification column. But, in reality these conditions cannot be fulfilled the temperature may not be remaining the same the composition may not remain the same and therefore, the actual number of plates that I would require in a column is going to be more than ideally calculated among and this is basically now shows or indicate the efficiency of the column. Hence there is a need to study the efficiency of an actual system with respect to an ideal system. This is very important thing.

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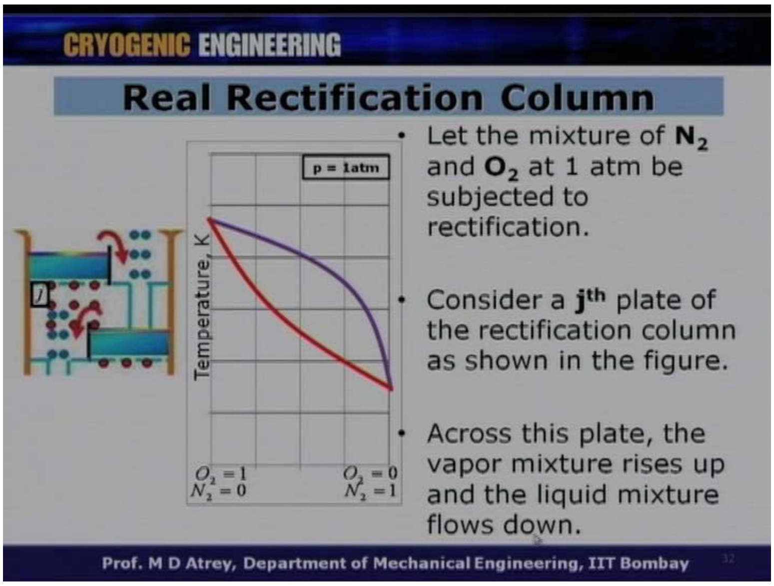

CRYOGENIC ENGINEERING

Real Rectification Column

- Let the mixture of N_2 and O_2 at 1 atm be subjected to rectification.
- Consider a **jth** plate of the rectification column as shown in the figure.
- Across this plate, the vapor mixture rises up and the liquid mixture flows down.

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So, the real rectification column, let us see what happens in one plate and let us whether inefficiency comes into picture. Let the mixture of nitrogen and oxygen at 1 atmosphere be subjected to rectification. Consider a j th plate which is let us say this plate of the rectification column. As shown in the figure, across this plate the vapor mixture rises and the liquid mixture flows down all right. The vapor mixture is going up the liquid is going down ok.

Now, for this j th plate, let y j minus1 is the mole fraction of the low boiling component in vapor phase rising to the j th plate. So, this is the j th plate and y j minus1 gives the molar composition of the vapor which is passing through this j th plate. So, this is a vapor plate, this is a vapor condition of y j minus 1. So, corresponding to this, the composition of the low boiling component that is nitrogen is going to y j minus 1 which is entering through this plate, through this jth plate. The composition of the liquid at this plate is given by x j.

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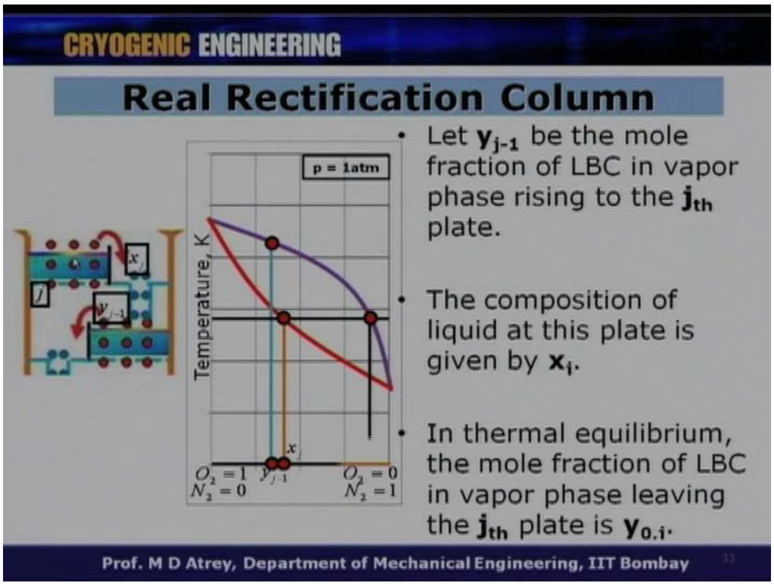

CRYOGENIC ENGINEERING

Real Rectification Column

- Let y_{j-1} be the mole fraction of LBC in vapor phase rising to the j_{th} plate.
- The composition of liquid at this plate is given by x_j.
- In thermal equilibrium, the mole fraction of LBC in vapor phase leaving the j_{th} plate is $y_{o,j}$.

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Now, ideally the composition of the liquid at this point would've been x j, would have been this much isn't it. Because we say the molar composition remains the same, but no/ In actual case the molar composition is going to be of this liquid in this plate, in the j th plate is going to be this. It is going to be x j and not a y j minus 1 all right and therefore, this is a very very essential that that you're going away from ideality when we said earlier that during the phase transformation the molar composition remain the same, but no. Actual molar composition will not remain the same, because all the vapor will not get condensed here, only part of that will get condensed over here and therefore, composition of the liquid in this plate above this vapor is going to be given by this x j parameter.

Now, from this j th plate vapor will leave and we had said that this vapor and this liquid will be at in thermal equilibrium all right. So, the vapor which is leaving this plate j th plate should be in thermal equilibrium and should be given by its composition which could be given by y o j which is y o j.

So, in thermal equilibrium the mole fraction of the liquid low boiling component in vapor phase leaving the j th plate is given by y o j, but no, again this condition is an ideal condition, that the liquid is at this condition, the vapor which is leaving this condition is not going to be at same temperature, but it is going to be at somewhere higher than this. Therefore, real y j which is leaving the j th plate is going to be at a higher temperature.

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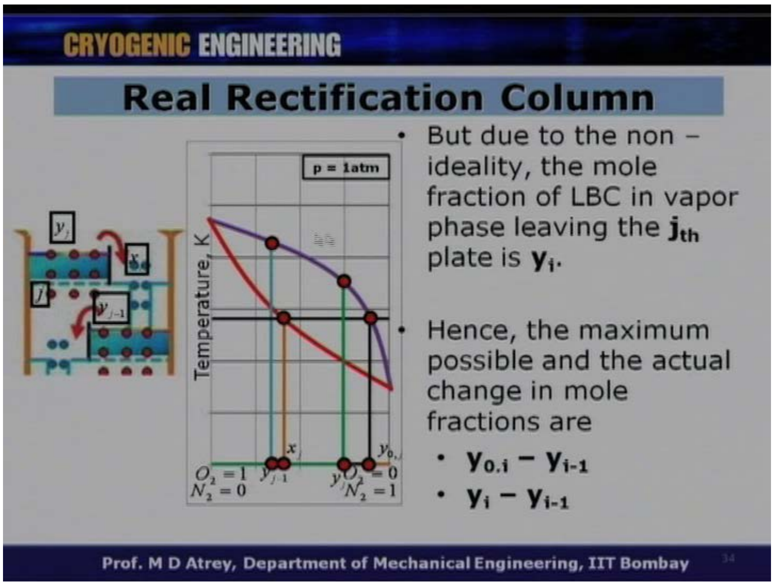

CRYOGENIC ENGINEERING

Real Rectification Column

- But due to the non – ideality, the mole fraction of LBC in vapor phase leaving the $\mathbf{j_{th}}$ plate is $\mathbf{y_i}$.
- Hence, the maximum possible and the actual change in mole fractions are
  - $\mathbf{y_{0.i} - y_{i-1}}$
  - $\mathbf{y_i - y_{i-1}}$

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But due to the non-ideality of the mole fraction of the low boiling component in vapor phase leaving the j th plate is going to be y j and this is my y j. So, what has happened in one plate condition? In one plate y j minus1 entered, vapor enter the plate at y j minus 1 when the vapor left the next plate it left at y j. But, they should’ve actually let at y j 0. So, actual change the vapor got enriched in low boiling component from y j minus1 to y j which is actual change while ideally it should’ve left at y j 0. And this is what is going to basically give the efficiency of this particular plate.

Hence, the maximum possible and the actual change in mole fractions are what were the maximum possible changes, from this to this y o 0 minus y j minus1, but actual one is y j minus y j minus 1. Why did not this actual composition did not change in maximum possible composition change why did not it occur? It it did not occur because the molar composition did not remain the same at the same time the vapor was not in thermal equilibrium with the plate on the same plate, the liquid on the same plate and therefore, we had all these changes that happened and these will determine the efficiency of the plate.

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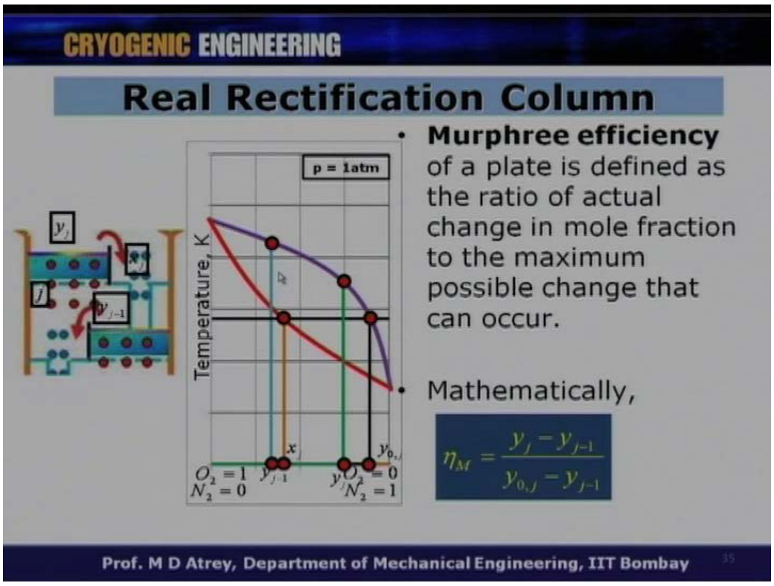

CRYOGENIC ENGINEERING

Real Rectification Column

- **Murphree efficiency** of a plate is defined as the ratio of actual change in mole fraction to the maximum possible change that can occur.
- Mathematically,

$$\eta_M = \frac{y_j - y_{j-1}}{y_{0,j} - y_{j-1}}$$

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So, what we’ve got a term called murphree efficiency. The Murphree Efficiency of a plate is defined as the ratio of actual change in mole fraction to the maximum possible change that can occur. So, actual change in mole fraction is going to be mathematically is going to be y j minus y j minus 1. This is y j minus y j minus 1 is the actual molar transformation that took place when across applied divided by maximum possible mole fraction change which is y o j minus y j minus 1. So, this is basically going to decide how much away from ideality one plate can go when the molar composition and the temperature can change.

All right.

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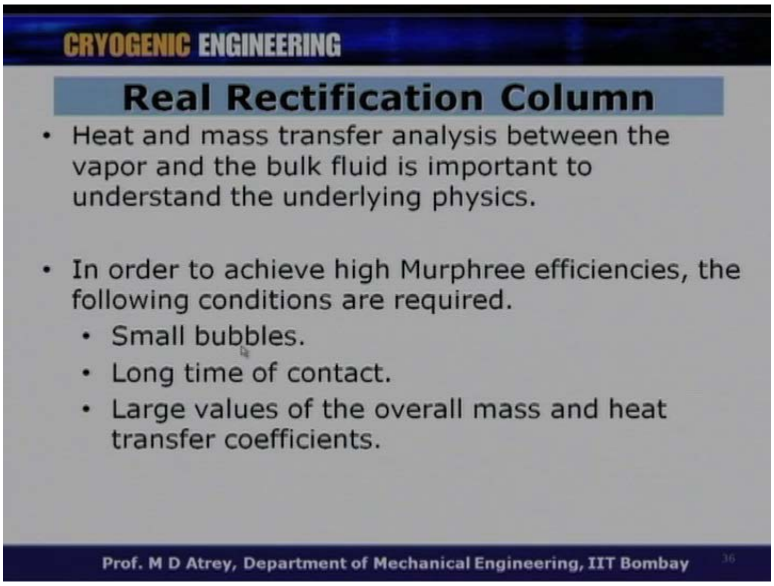

CRYOGENIC ENGINEERING

Real Rectification Column

- Heat and mass transfer analysis between the vapor and the bulk fluid is important to understand the underlying physics.
- In order to achieve high Murphree efficiencies, the following conditions are required.
  - Small bubbles.
  - Long time of contact.
  - Large values of the overall mass and heat transfer coefficients.

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So, the heat and mass transfer, why this happening the what is important for this therefore, in order to have very high murphree efficiency the heat and mass transfer between the vapor and the liquid. The heat and mass transfer analysis between the vapor and the bulk fluid is important and therefore, it is very important to understand the heat and mass transfer between this vapor and the liquid to understand this physics what is happening inside very plate or every liquid and vapor interaction.

So, in order to understand in order to achieve high murphree efficiency, the following conditions are required. Lot of analysis have gone into this, lot of work has gone into it the conclusions are: if you want to have very high murphree efficiency following conditions should be met which will ensure very good heat and mass transfer between the vapor and the bulk fluid.

So, what do they want, small bubbles, long time of contact to ensure good heat transfer and a large value of overall mass and heat and mass transfer coefficient. And this is what we know basically the small bubble will ensure good heat transfer, number of bubbles now will be very important, the long time of contact will ensure that the vapor and the liquid are having good heat transfer for a longer time, longer duration which will ensure good heat transfer while larger value of overall heat and mass transfer coefficient will ensure good heat transfer between the vapor and the bubble, vapor and the liquid basically. So, all these components are basically known in order to achieve the good heat and mass transfer between the vapor and the liquid.

With this background I would now like to solve a small tutorial so that you understand the concept of murphree efficiency. So, let us come to a small tutorial. This tutorial is to calculate the murphree efficiency of a given plate.

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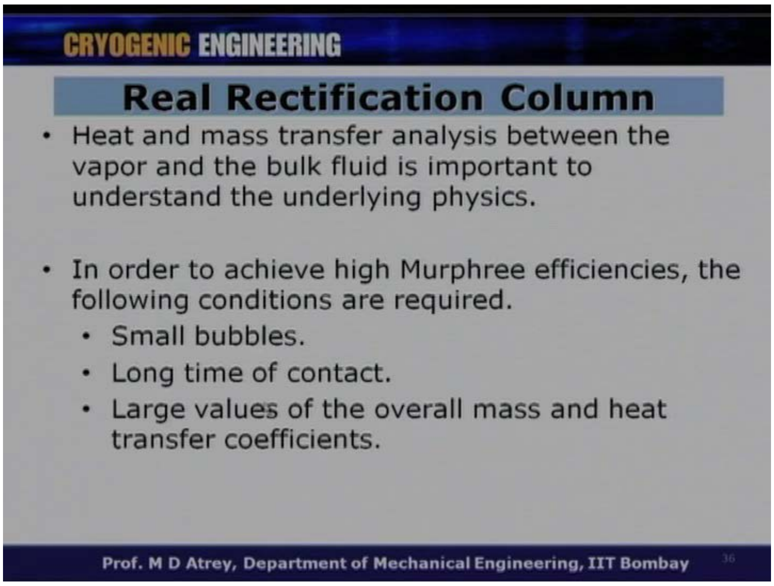

CRYOGENIC ENGINEERING

Real Rectification Column

- Heat and mass transfer analysis between the vapor and the bulk fluid is important to understand the underlying physics.
- In order to achieve high Murphree efficiencies, the following conditions are required.
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So, consider a mixture of nitrogen and oxygen at 1 atmosphere which is entering the plate which entering a column. Calculate the murphree efficiency for a plate with liquid at 80 Kelvin the liquid is going to be at less temperature than at than the vapor. So, liquid at 80 Kelvin and the vapor below this plate is at 85 Kelvin.

So, what is happening? The vapor is entering the plate at 85 Kelvin and merges the phase transformation or the liquid above it has a 80 Kelvin temperature. The heat transfer between this vapor and the liquid and ultimately, the vapor will leave at a temperature actually somewhere between eighty and 85 Kelvin depending on the heat and mass transfer between the vapor and the liquid.

So, what we’ve do is calculate the murphree efficiency for this plate. Also it is given that the mole fraction of nitrogen leaving this plate in vapor phase is 0.84. This is the data which is given. Use the temperature composition diagram given in the earlier lectures.

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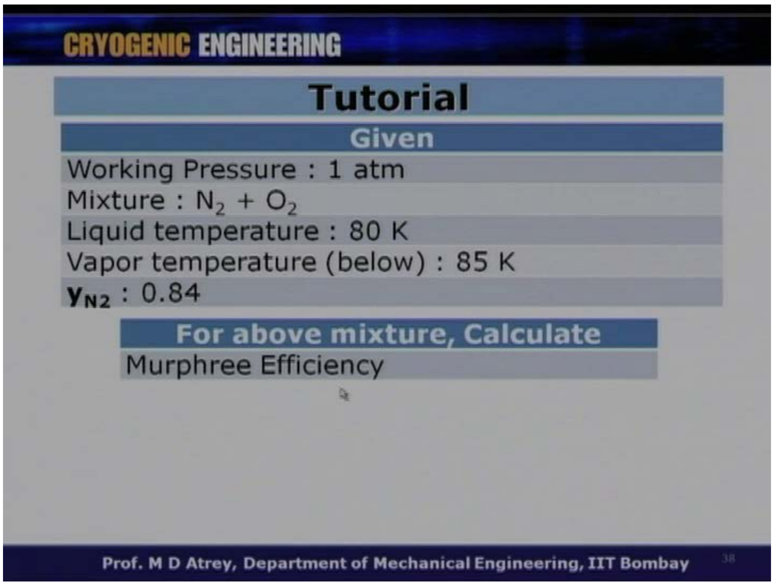

CRYOGENIC ENGINEERING

Tutorial

Given

Working Pressure : 1 atm

Mixture : $N_2 + O_2$

Liquid temperature : 80 K

Vapor temperature (below) : 85 K

$\mathbf{y_{N2}}$: 0.84

For above mixture, Calculate

Murphree Efficiency

So, what is given, the working pressure is 1 atmosphere, the mixture is nitrogen and oxygen, liquid temperature is 80 Kelvin, vapor temperature is 85 Kelvin and y N 2 which is ultimately leaving the plate above is at 0.84 molar composition of the low boiling component is 0.84, calculate the murphree efficiency.

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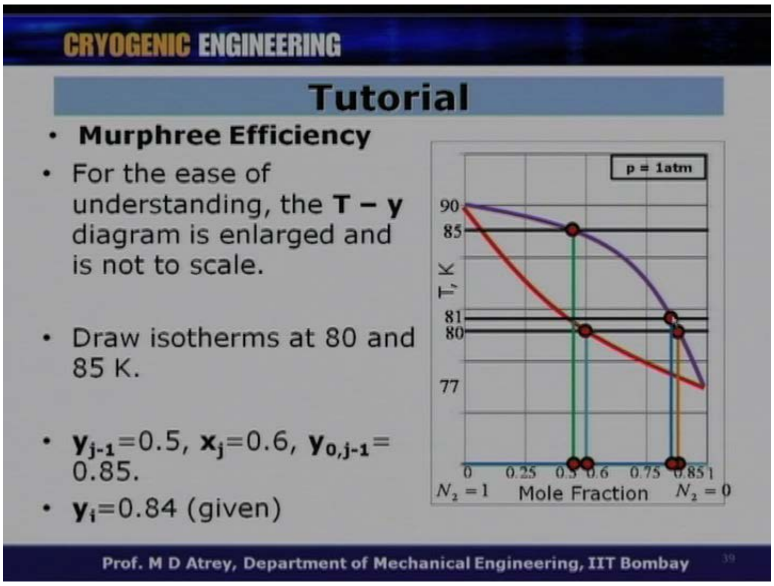

CRYOGENIC ENGINEERING

Tutorial

- **Murphree Efficiency**
- For the ease of understanding, the **T – y** diagram is enlarged and is not to scale.
- Draw isotherms at 80 and 85 K.
- $\mathbf{y_{j-1}}$=0.5, $\mathbf{x_j}$=0.6, $\mathbf{y_{0,j-1}}$= 0.85.
- $\mathbf{y_i}$=0.84 (given)

This is the diagram which is known to us. So, what is known to us is for the ease of understanding the temperature composition diagram T- y diagram is enlarged and is not to the scale. So, what is happening is, the liquid temperature is 80 Kelvin which is drawn horizontal line, the vapor is entering at 85 Kelvin, draw a horizontal line. These two temperatures are known and they are given in a problem all right.

What is known is if I draw horizontal line, wherever it intersects the vapor line is going to give me y j minus 1 that is the molar composition of vapor which is going up the plate. So, corresponding to these for oxygen nitrogen I get y j minus1 is the molar composition of the vapor which enters the plate through the holes. So, it is 0.5.

Correspondent to this, this should’ve been ideal point composition, but no, actually temperature is 80 Kelvin and therefore, wherever it intersects the liquid line, it going to be x j. So, x j is going to be 0.6 and corresponding to this normally vapor would’ve been in thermal equilibrium with this liquid if you see earlier definition of murphree efficiency this interaction, this intersection with the vapor curve is going to be y o j minus 1, that is when the vapor is in thermal equilibrium with the liquid on the same plate. So, y o j minus 1 is going to 0.85 as given over here all right.

So, I know y j minus 1, I know y o j, now actual case is going to be 0.8 because I’ve been told that the vapor which leaves the plate is going to be at 0.8, the molar composition of the low boiling component is 0.8. So, if I draw a vertical line from here it intersect vapor line at this point and corresponding to this the temperature is 81 Kelvin. What does it mean, the vapor is not at 80 Kelvin, but it is at higher temperature of 81 Kelvin at this point; that means, the actual molar change has happened on the low boiling component is this much, this is y j value corresponding to this y j what you got is a 0.84 Kelvin all right.

So, what you get from here is the actual change in the molar composition divided by maximum possible change in a molar composition is going to be this. So, this is the data which is given 0.84 Kelvin, if I draw a vertical line and therefore, I can calculate murphree efficiency as actual change in molar composition divided maximum possible change in molar composition.

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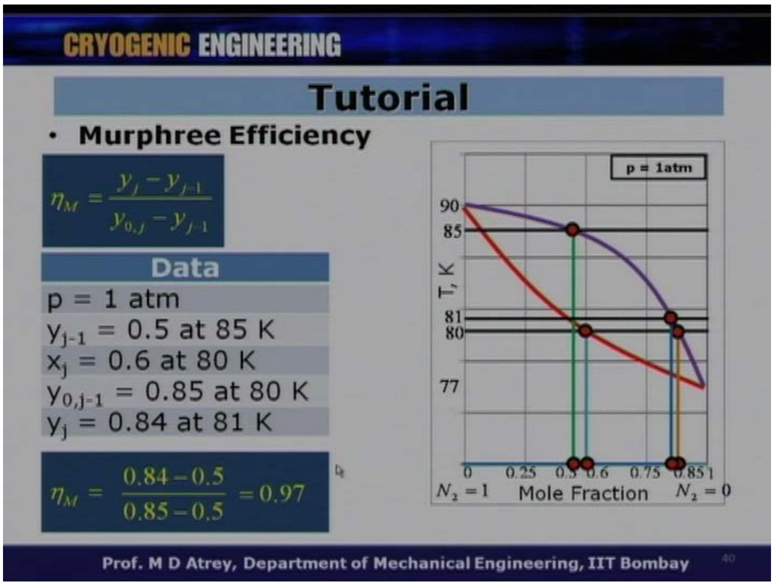

CRYOGENIC ENGINEERING

Tutorial

- **Murphree Efficiency**

$$\eta_M = \frac{y_j - y_{j-1}}{y_{0,j} - y_{j-1}}$$

Data

$p = 1$ atm

$y_{j-1} = 0.5$ at 85 K

$x_j = 0.6$ at 80 K

$y_{0,j-1} = 0.85$ at 80 K

$y_j = 0.84$ at 81 K

$$\eta_M = \frac{0.84 - 0.5}{0.85 - 0.5} = 0.97$$

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So, 1 atmosphere y j minus 1 is 0.5, x j is 0.6, y o j is 0.85 and y j is 0.84 at 81 Kelvin. So, if I put these, I get 97 percent as a murphree efficiency all right. So, this is a simple problem to understand what exactly happened on one plate.

Based on this, I would like to give a small assignment kindly go through this assignment. We’ve given the answers also for the calculations, the efficiency comes to be around 84.3 percent. This is what we have studied here.

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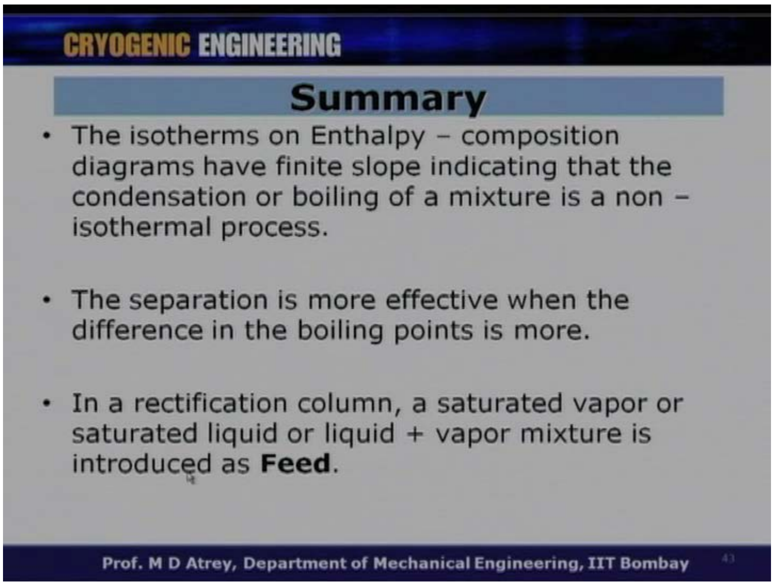

CRYOGENIC ENGINEERING

Summary

- The isotherms on Enthalpy – composition diagrams have finite slope indicating that the condensation or boiling of a mixture is a non – isothermal process.
- The separation is more effective when the difference in the boiling points is more.
- In a rectification column, a saturated vapor or saturated liquid or liquid + vapor mixture is introduced as **Feed**.

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Just to summarize what we did, isotherms on Enthalpy- Composition diagrams have finite slope indicating that the condensation or boiling of a mixture is a non-isothermal process. The separation is more effective when the difference in the boiling point is more. In a rectification column a saturated vapor or saturated liquid or liquid plus vapor mixture is introduced as feed.

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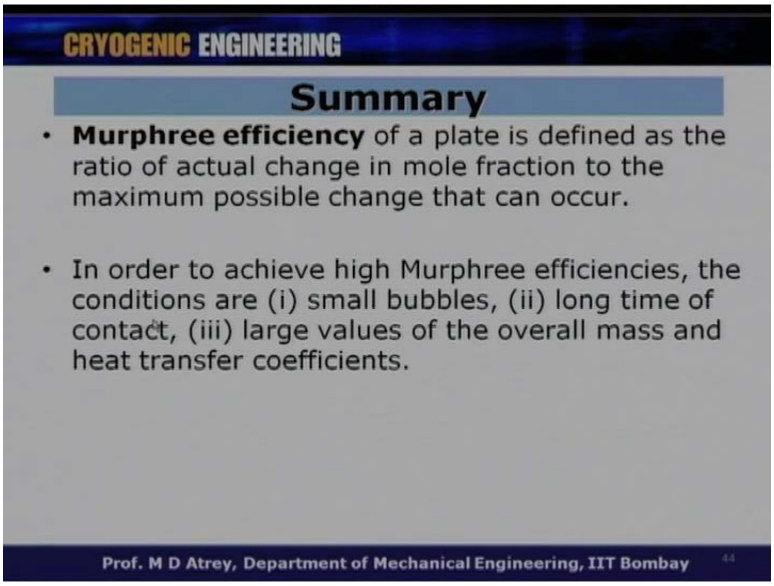

CRYOGENIC ENGINEERING

Summary

- **Murphree efficiency** of a plate is defined as the ratio of actual change in mole fraction to the maximum possible change that can occur.
- In order to achieve high Murphree efficiencies, the conditions are (i) small bubbles, (ii) long time of contact, (iii) large values of the overall mass and heat transfer coefficients.

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Murphree efficiency of a plate is defined as the ratio of actual change in mole fraction to the maximum possible change that can occur. In order to achieve high murphree efficiency, we should ensure good heat transfer. The conditions are small bubbles, long time of contact between the vapor and the liquid, large value of overall mass and heat transfer coefficients. Thank you very much.