Plant Design and Economics
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Lecture No -42
Distillation Sequencing using Columns with Sidestreams

Welcome to lecture 42 of plant design and economics. In this module, we have been talking about separation system synthesis part 2. In the previous lecture we have started our discussion on distillation sequencing and we have been looking at nearly ideal liquid mixture separation. We will continue with our discussion on distillation sequencing, and in this lecture we will focus our attention on distillation sequencing using columns with sidestreams.

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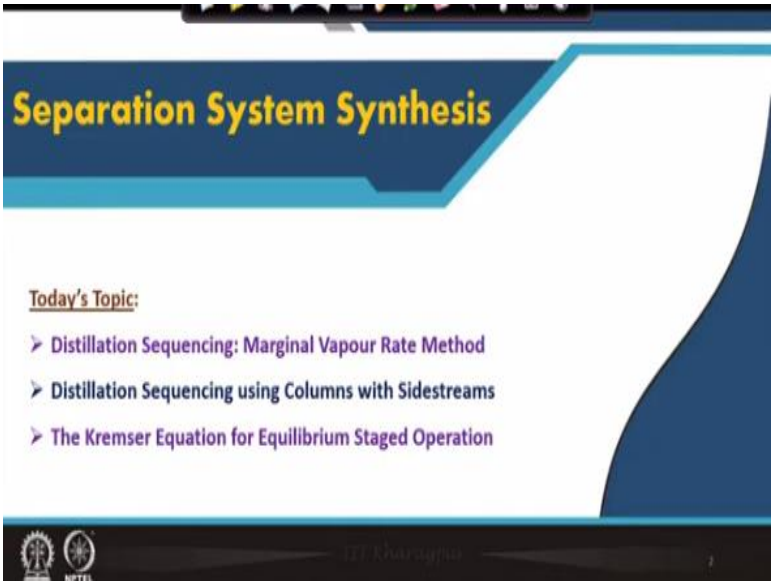

So today we will first talk about distillation sequencing using marginal vapour rate method. Then we will talk about displacement sequencing using columns with side steps and finally we will briefly touch upon the Kremser equation, which is an analytical expression for determination of theoretical number of plates for equilibrium stage operation.

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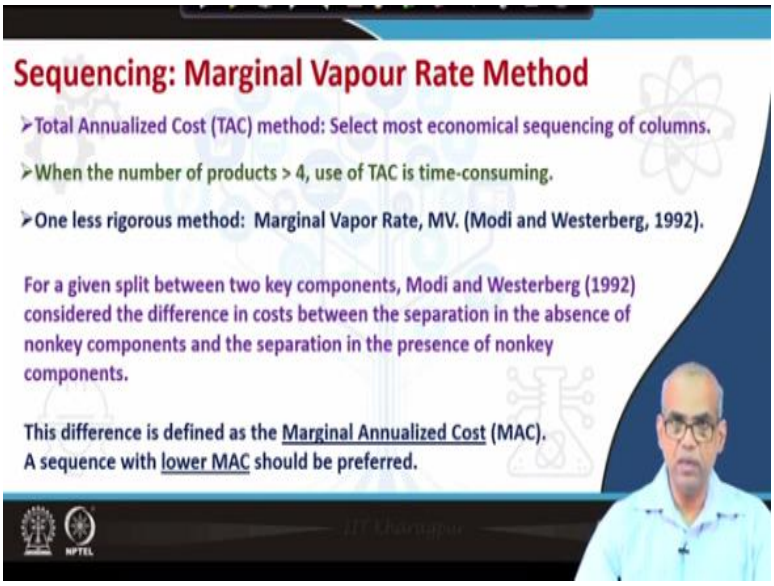

Now we have talked about certain heuristics, for distillation sequencing we have seen that depending on the number of components present in the liquid mixture. A large number of sequences are possible we can always select the most economical sequencing of columns based on total annualized cost. However when the number of products is fewer, use of total annualized cost may be convenient.

But when the number of products is large, when it is more than 4 the use of total annualized cost is time consuming because the number of possible sequences will be quite large. Under such circumstances there is one less rigorous method available proposed by Modi and Westerberg for a given split between two key components, Modi and Westerberg considered the difference in costs between the in absence of non-key components.

And in the separation in the presence of non-key components. So this cost between two operations; one in the presence of non-key components and other in the absence of non-key components. This difference is defined as the marginal annualized cost, and it is recommended that we should select the sequence with lower value of marginal annualized cost.

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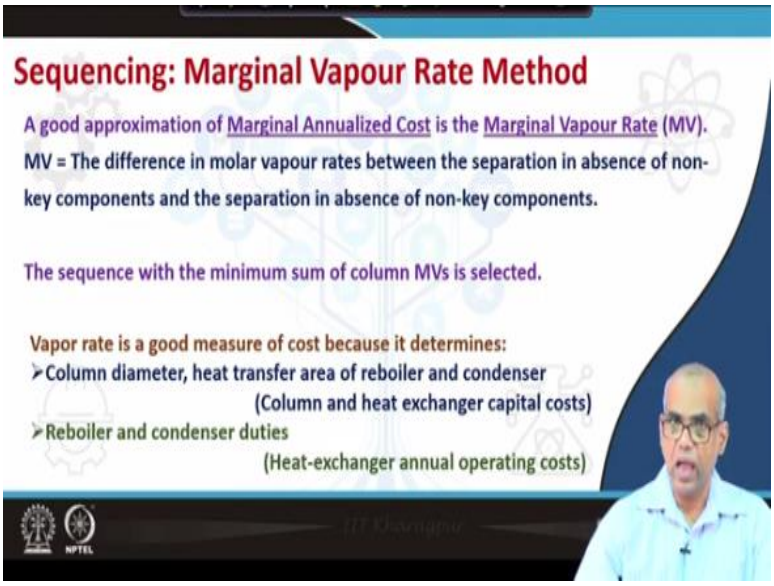

Now a good approximation of marginal annualized cost is the marginal vapour rate, note that to compute marginal annualized cost we require the cost data for separations under two conditions; one is the presence of non-key components, the other is absence of non key components. So to make it simpler a good approximation or marginal annualized cost is used which is the marginal vapour rate.

The marginal vapour rate is the difference in molar vapour rates between the separation in absence of non-key components and the separation in presence of non-key components. The sequence with the minimum sum of column marginal vapour rate is selected. So the marginal vapour rate is the difference in molar vapourized between the separation in presence of non-key components and in absence of non-key components and the sequence with the minimum sum of columns, Marginal vapour rate is selected as the preferred sequence.

So here also we are using vapour rate as measure of cost and this is quite justifiable because, the vapour rate determines the column diameter, heat transfer area of the reboiler and condenser. So all these reflect the column and heat exchanger capital cost. The vapour rate also determines the reboiler and condenser duties, which reflect heat exchanger annual operating cost, so both capital cost and operating cost are taken care of by user vapour rate.

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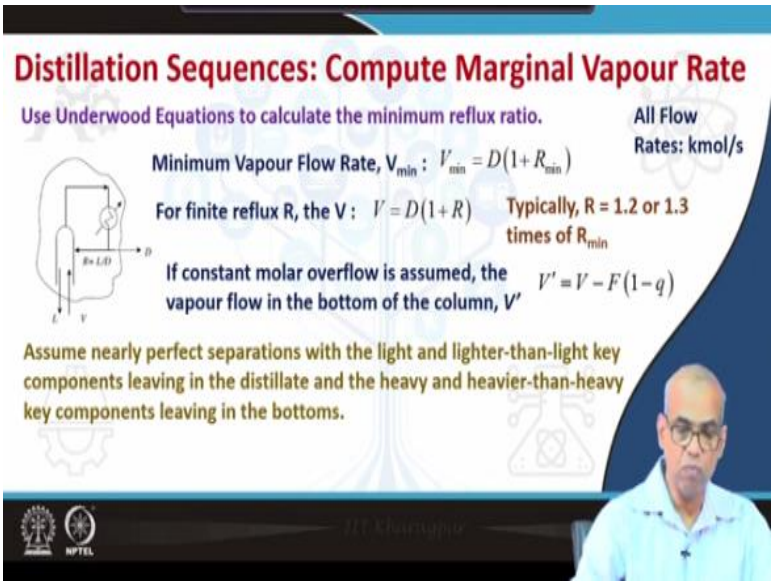

Now to compute the marginal vapour rate you can do a mass balance considering the same envelopes around the top of the distillation column, and you can see that, according to this envelope V equal to l plus D and you know l is R into D. So under minimum refresh condition the minimum vapour flow rate is obtained as V minimum is equal to D into 1 plus D minimum for finite plus R, which is usually considered as 1.2 to 1.3 times of minimum reflux, R minimum we can compute V equal to D into 1 plus R.

Now if constant molar overflow is assumed the vapour flow in the stripping of the distillation column can also be computed from the knowledge of feed condition q, we assume nearly perfect separations with the light and the lighter then light key components living in the display and the heavy and heavier then heavy key components living in the bottoms. Column top and bottom pressures can be estimated the column feed pressure is taken as the average of the top and bottom pressures.

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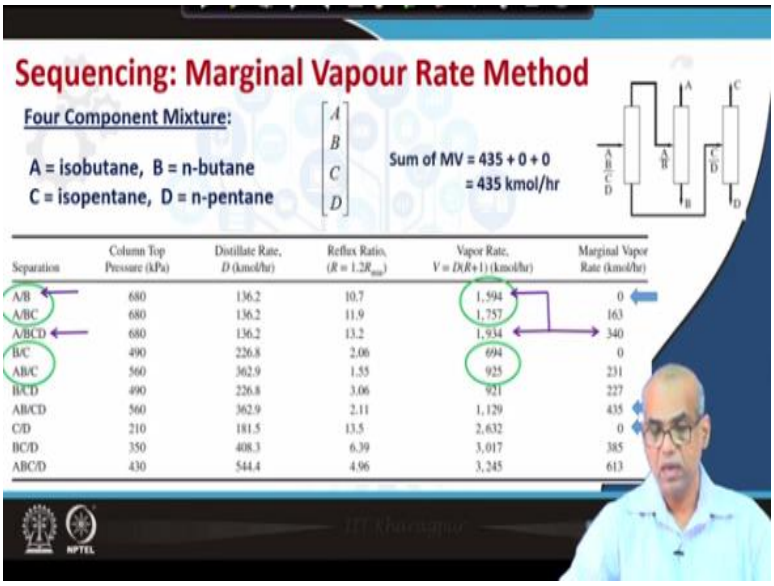

Now let us consider an example, we are separating a 4 component mixture A B C and D isobutane, n-butane, isopentane, and n-pentane. Now A is most volatile then comes B then comes C and finally D is the less volatile. So the table, all the required data column temperature distillation rate, reflux ratio, which has been taken as 1.2 times the minimum reflux ratio and the vapour rate computed as V equal to D into R plus 1.

Now all possible splits between along these four components are given, so you consider two key components and consider a split and all possible splits are shown. Now from the table we have to compute the marginal vapour rate, so how is termed? Let us take an example. So let us consider this separation in the first the split is between A and B, so there is no non key so marginal vapour rate is 0

The vapour rate for this is 1.594 marginal vapour it is 0 because there is no non-key components, so next one is there is a presence of non-key components with this split A B for which the vapour is 1.757, So marginal vapour rate for this one will be 1.757 minus 1.594, which is 163 kilo mole per hour the same way, these two peers can be taken and the marginal vapour rate of this split can be obtained.

Note that splits like AB, BC, CD will all have 0 marginal vapour rate, because there is no presence of non-key components. Now let us consider this one: we are making a split between A

and B and there is CD as non-key components. So to find out the marginal vapour rate for this one, I have to subtract the vapour rate of this one; this gives me 340, note 1.934 kilo mole per hour minus 1.594 kilo mole per hour gives you 340 kilo mole per hour as marginal vapour rate.

So this way we can compute the marginal vapour rate for all and we will select the minimum one, for example consider this particular sequence. So, note down the splits and there marginal vapour, rate. So, three marginal vapour rates for three different columns, so; for delta sequence, let us sum up these marginal vapour and I get 435 kilo mole per hour.

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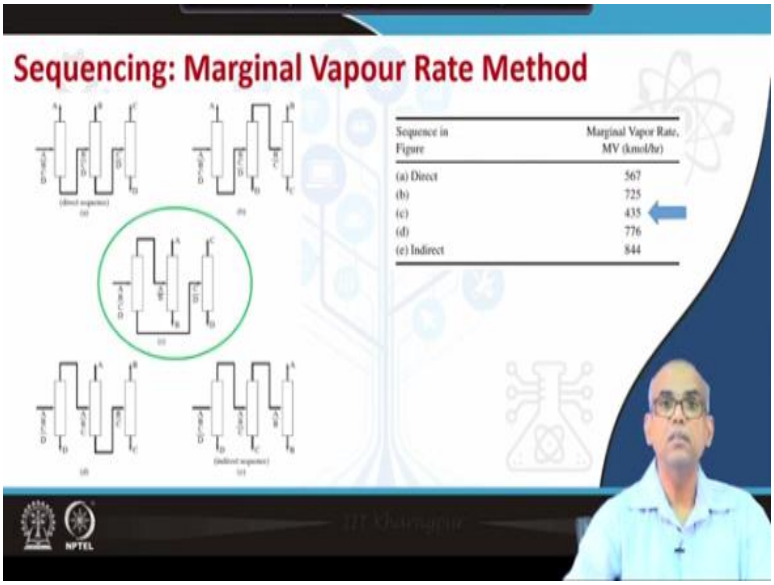

So this way we have to compute for all possible scenarios. So these five sequences are possible for that particular separation, so the marginal vapour rate for all these five sequences are put in the table and the one with 435 kilo mole per hour, is the minimum marginal vapour rate, so this particular sequence will be vapour.

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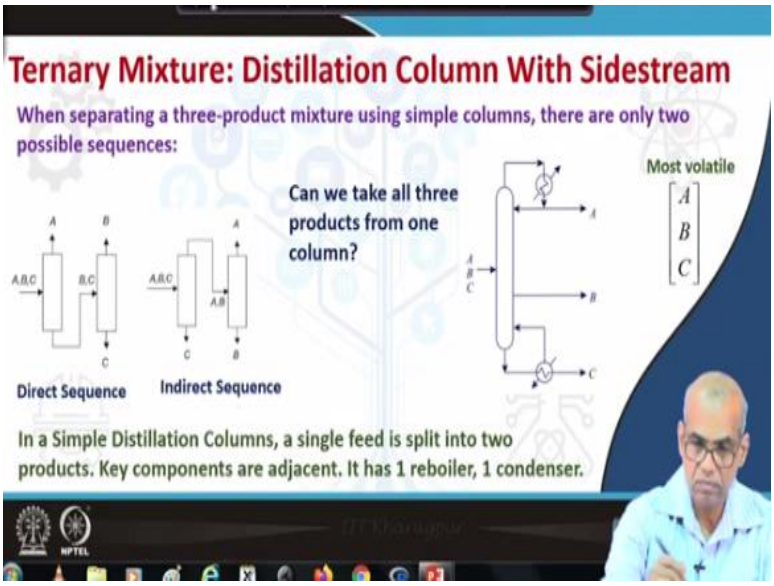

Now let us move on to distillation column which sidestream, when separating a three product mixture using simple columns, there are only two possible sequences; one direct sequence another is indirect sequence. In a simple distillation column, remember a single feed is split into two products. The key components are adjacent components and simple displacement column has one reboiler and one condenser.

So this is our definition of simple distillation columns, so we see that to separate a three product mixture to separate us three component mixtures, we need two distillation column and these two possible sequences are possible. So the question I ask is, can I take all the three products ABC? From one distillation column as shown in the figure A as top of the top product C as bottom product and B as sidestream.B as product withdrawn from the sidestream.

Note that A B C are arranged according to their volatility. So where? A is most prototype, so if we can do that we will of course say a significant amount of fixed capital.

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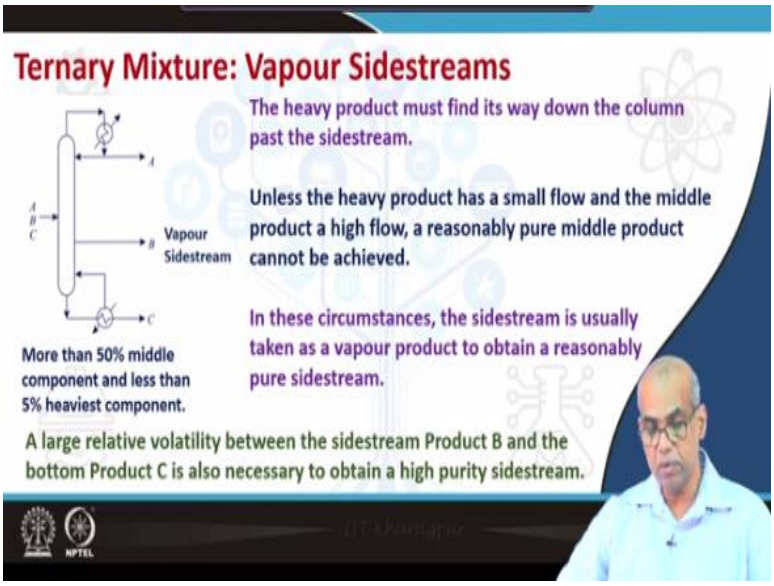

A sidestream distillation column can be used to separate any non-azeotropic multi component mixture into three products. Therefore it can often substitute for a sequence of two columns. However purity of the sidestream product is restricted by thermodynamics and the nature of the distillation process. So you consider the vapour liquid equilibria at each tray in the distillation column, so that thermodynamics will restrict the purity of the sidestream product.

Such distillation columns with sidestreams are appropriate either as pre fractionators where the sidestream is paid to another column for further separation or to generate recycle streams, when there is no strict requirement of the recycle composition, also the distillation column with sidestreams is broadly used in the petroleum industry, the reason is obvious in petroleum industries generally the products are blends of various hydrocarbons.

So often times we are not interested in pure products, but we are interested in blends, so the sidestream is heavily used in petroleum industries where fractionation is a very very important separation process, such as side steam design is both feasible and cost effective when I compare. A distillation column with sidestream on a stand alone basis for certain ranges of conditions with the two ordinary distillation column sequence.

And the comparison is made on stand alone basis for example, the reboilers and the condensers are being operated on by the utilities, no heat integration has been implemented. If the feed is

dominated by the middle product typically more than 50% of the feed. And the heaviest product is present in small quantities typically less than 5% then the arrangement as shown in the figure which correspond to a vapour sidestream arrangement can be an attractive option.

So a vapour sidestream, which is taken in the section below the entry of the field, so an arrangement with vapour sidestream may be attractive when the feed is predominantly middle product, and the bottom the heaviest component is present only in small quantities typically less than 5%, then we can withdraw a vapour sidestream. The heavy product must find its way down the column past the sidestream.

And this is possible only when the heavy product has a small flow and the middle product a very large flow and unless this happens reasonably pure middle product cannot be obtained, in such circumstances, the system is usually taken as a vapour product to obtain a reasonably pure site stem also a large relative volatility between the sidestream product B and the bottom product C is also necessary to obtain a high purity sidestream.

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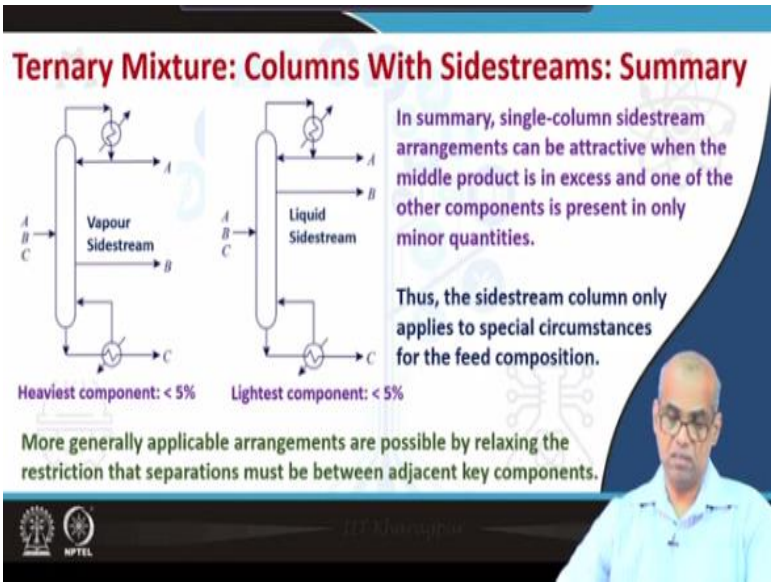

Now when you take out the vapour sidestream there are practical problems it is straightforward to split a liquid flow in a column, but it is not so straight forward to split a vapour flow. The reasons are as follows, the flow of vapour of the column must have enough pressure to overcome the pressure drop in the piping and the equipment associated with the sidestream flow. It may be

necessary to implement tight flow rate control for sidestream.

We must take care that carry over of liquid droplets does not take place, so carry about of the liquid droplet into the sidestream should be prevented by introducing, separation drum with missed eliminator. Similar to vapour sidestream, we can also have an arrangement with liquid sidestream and the liquid sidestream is withdrawn from the upper part of the distillation column above the feed entry point.

Similar to vapour sidestream arrangement this liquid sidestream arrangement may also be an attractive option when your feed is predominantly middle product typically more than 50% and the light component that is lightest component is present in only small quantity typically less than 5%. Here the light product must find its way up the column pass the sidestream, unless the light product is a small flow.

And the middle product is a high flow originally pure middle product cannot be obtained. We also require large relative volatility between the side stem product B and the overhead product A, so that high purity sidestream product can be obtained. So in summary, a single column sidestream arrangement can be attractive, when the middle product is in excess and one of the other components either heavy or the light is present only in small quantity.

So both; vapour sidestream or liquid sidestream may be attractive option, but only in specialized conditions what is that? Feed is predominantly middle product and the other one of the other components is present only in small quantity, but remember with vapour side steam arrangement there are some practical difficulties. So, sidestream column applies only to special circumstances for the feed composition that it is predominantly middle product.

And one of the other components is present only in minor quantities more generally applicable arrangements are possible by relaxing the restriction the separation must be between adjacent key components. So we have been now talking about that the separation is taking place between adjacent components adjacent key components. Now if we relax this that means, if we think of the sloppy distribution that means the separation is not between adjacent keys, Then other

arrangements are possible.

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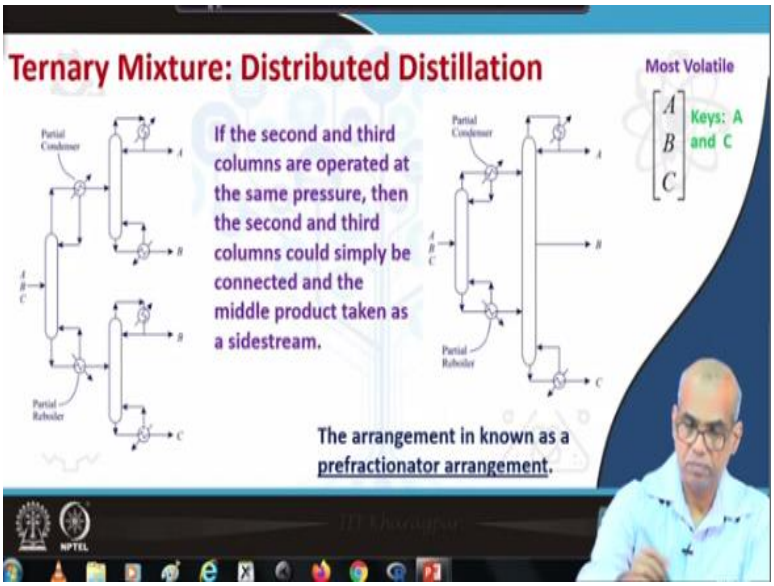

Let us talk about such an arrangement distributed distillation. So again we are thinking of ternary mixture, let us consider ternary mixture consisting of A B and C where a is most volatile, then B and c is less volatile, and now we consider non adjacent key components, so key components are now A and C this requires three columns instead of two. So separation of such a mixture, so separation of a ternary mixture with such non adjacent keys will require two columns as shown in the figure.

So what you do in the first column the top, is essentially a mixture of A and B which goes as fit to the column number 2, which separates into overhead A and bottom B. The bottom stream from the column number 1 which is predominantly B and C goes to column number 3 as V Which splits this mixture of B and C into over at A and bottoms C. Now at the first instance we can think that such arrangement is not efficient because we are requiring three columns instead of two.

However, there are certain advantages, these three columns can be operated at different pressures. So by utilizing different pressures in different columns, you can influence the vapour liquid equilibrium and you can influence the separation. The distribution of the middle product B between the second column and the third column is an additional degree of freedom that a

designer can use to his or her advantage.

Finally, we can use these particular degrees of freedom of distribution of middle product B between second and third column as well as the fact that all three columns can be operated at different pressures both the degrees of freedom can be used to make the reboilers and condensers more cost effective. Now if the second and third columns are operated at the same pressure. Then the second and third column can simply be connected and the middle product can be taken as a sidestream product.

So if this column number 2 and column number 3 are operating at the same pressure we can actually merge them, so you can connect them and can take out A and C as usual and be as a sidestream product. So this arrangement is known as prefractionator arrangement. Note that we are using partial condensers here because the vapour stream is going to another displacement column has feed we do not have to condense all the vapours.

Similarly we are using partial reboiler here and use of such partial condenser and partial the boiler can reduce the energy requirement, so this particular arrangement is known as prefractionater arrangement. So the first column is basically supplying feed at two points to the second distillation column. And from the second distillation column, we take all A B and C as stock product sidestream product and bottom product.

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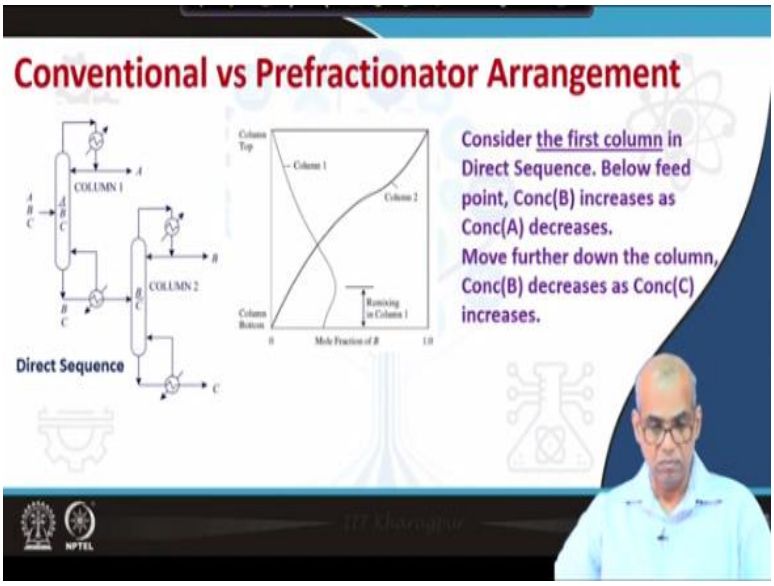

Now what you see is all the arrangements that we have talked about so far conventional arrangement direct sequence in indirect sequence. Distributed distillation line and the prefraction at a arrangement. The distributed and reflection are arrangement typically required twenty to thirty percent less energy than conventional arrangements for the same separation duty, their thermodynamically more efficient.

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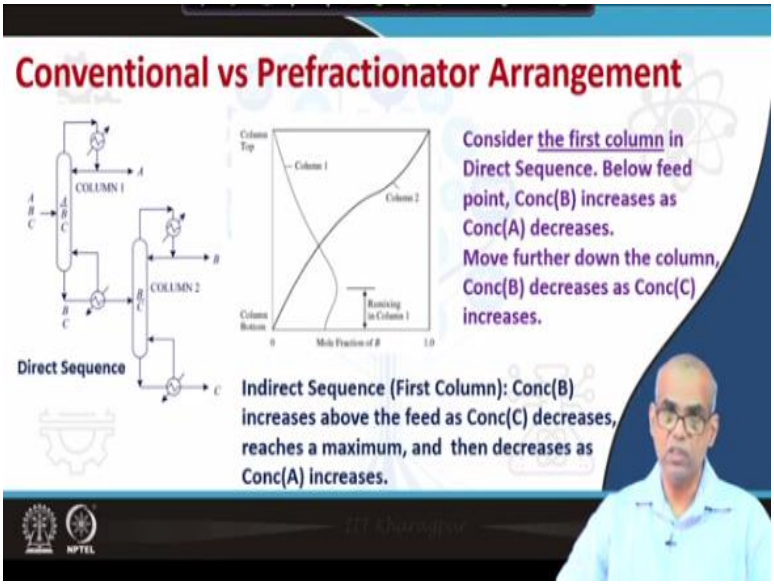

Why they are dynamically more efficient? Let us try to understand. Consider this direct sequence consider the first column in the direct sequence focus your attention on the feed point, below the feed point the concentration of B increases as concentration A decreases because concentration A increases towards the top of the column. Now, if you move further down the column

concentration of B will start decreasing because concentration of C, which is the bottom product starts increasing.

So the concentration of B increases and then decreases due to mixing, the same thing happens in case of indirect sequence. If you look at if you consider the first column of indirect sequence the concentration of B will increase above the feed point as concentration C decreases there concentration, B will leach a maximum and then decreases as concentration A increases there, so concentration of B increases and then decrease.

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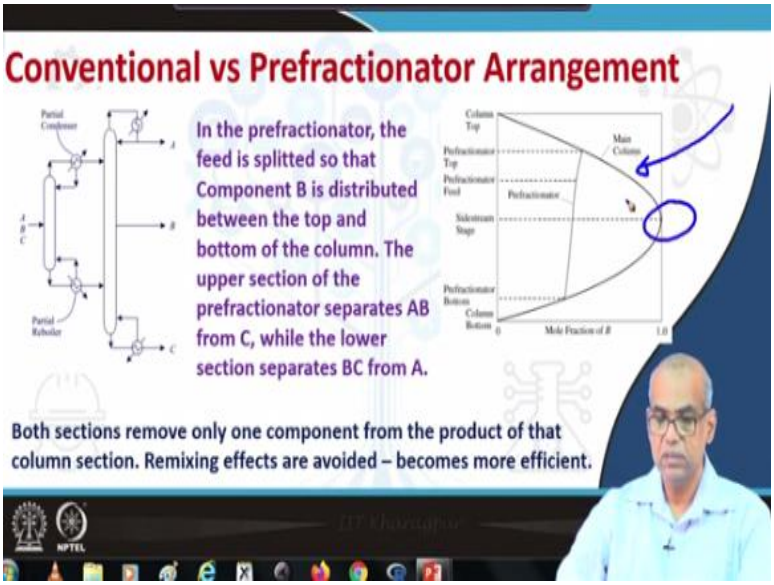

In case of prefractionator arrangement the feed is splitted so that component B is distributed between the top and the bottom of the column, the upper section of the prefractionator separates AB from C and well the lower section separates BC from A, so both sections remove only one component from the product of that column section. So the inefficient mixing that happen in case of direct sequence or indirect sequence is absent in case of prefractionated arrangement.

And remixing effects are completely avoided so this becomes more efficient, you can see from the changes in concentration of B along the height of the distillation column. As the number of stages changes how the concentration of B changes, so look at this indices maximum around the sidestream stage.

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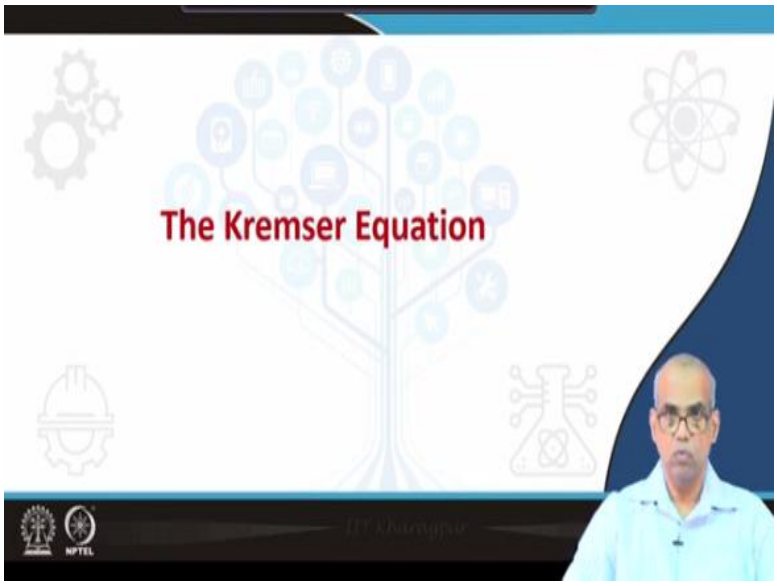

Now finally will briefly talk about the Kremser equation, which can be used to determine the. Number of theoretical trays required for equilibrium stage operations under certain circumstances where we consider the operating line and the equilibrium relationship both the straight line.

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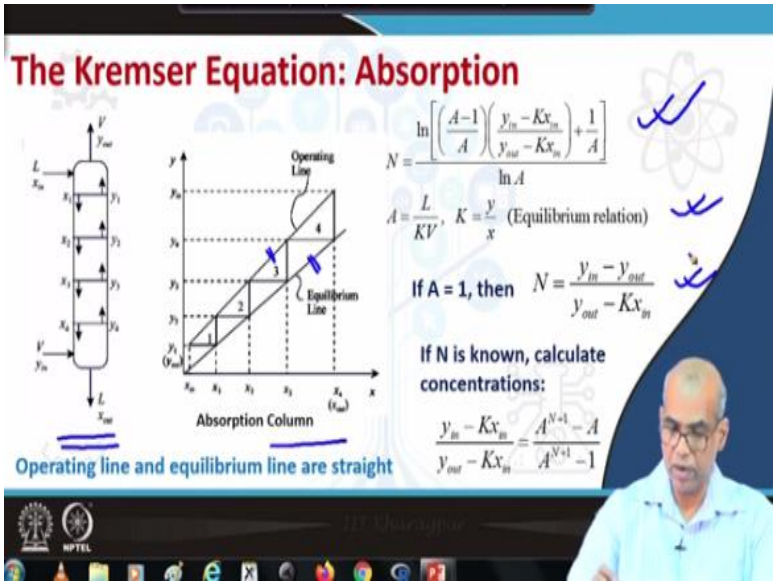

So consider an absorption operation, you can draw the usual staircase construction to determine the number of the trays, between the equilibrium line and the operating line both operating line and equilibrium liners straight the operating conditions are shown in the diagram. Now under such condition when operating line and equilibrium lines are straight. This graphical construction of number of trays can be replaced by analytical solutions of number of trays using this Kremser

equation.

Note that A is defined as l by k into v where k is represents the equilibrium relation, when A equal to 1, the number of theoretical trays expression becomes simplified and if you know the number of theoretical trays you can also find out the concentrations. Kremser equation, you can also write for the stripping column.

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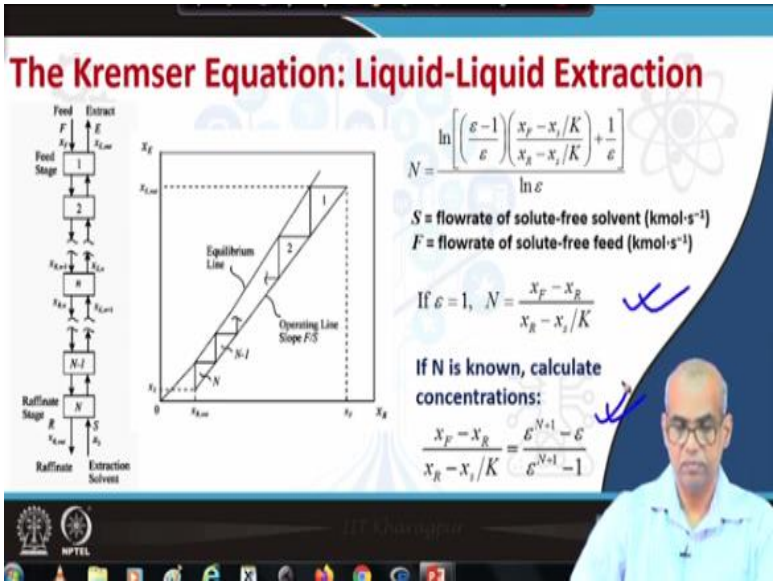

And you can also write for liquid-liquid extraction operation. Note here we have used epsilon as separation extraction factor KS by F, the nomenclatures given here. Here also when the extraction factor is 1, the expression of number of stages is simplified and also N is known we can calculate the concentrations. So with this we stop today's discussion here.