Plant Design and Economics
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Lecture No -43
Distillation Sequencing using Thermal Coupling

Welcome to lecture 43 of plant design and economics. In today's lecture we will talk about distillation sequencing using thermal coupling. Distillation is an energy intensive process it requires lot of energy, so saving energy through energy integration will greatly improve the process economics.

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Separation System Synthesis

Today's Topic:

- Distillation Sequencing using Thermal Coupling
- Guidelines on Distillation Sequencing for Complex Columns

So we will first talk about distillation sequencing using thermal coupling and then we will talk about certain rules or guidelines that can be used for distillation sequencing for complex distillation columns. So we will discuss what we mean by complex columns as we go ahead.

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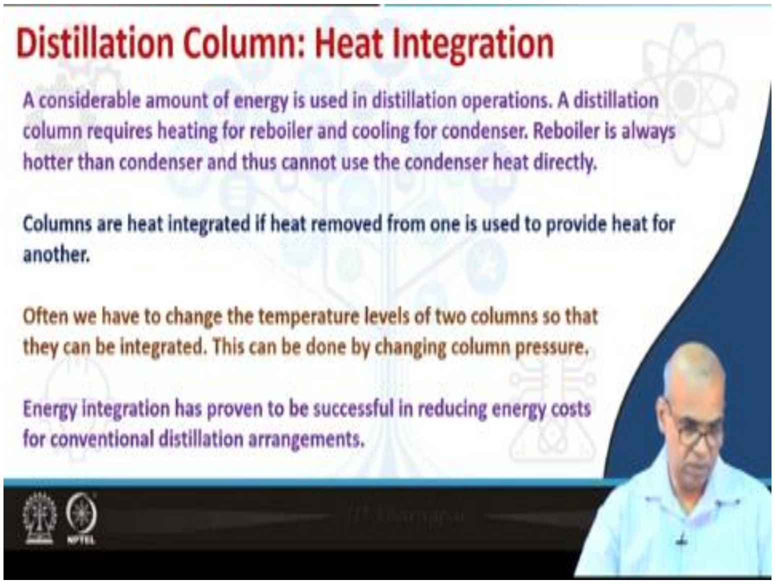

Distillation Column: Heat Integration

A considerable amount of energy is used in distillation operations. A distillation column requires heating for reboiler and cooling for condenser. Reboiler is always hotter than condenser and thus cannot use the condenser heat directly.

Columns are heat integrated if heat removed from one is used to provide heat for another.

Often we have to change the temperature levels of two columns so that they can be integrated. This can be done by changing column pressure.

Energy integration has proven to be successful in reducing energy costs for conventional distillation arrangements.

A considerable amount of energy is used in distillation operations. A distillation column requires heating for reboiler and cooling for condenser. Reboiler is always hotter than condenser and thus cannot use the condenser heat directly. Distillation columns are heat integrated in case heat recovered from one column is used to provide heat for the other column. Often we have to change the level of the temperatures of the two columns so that heat integration between the two columns is possible.

Now the changes in temperature can be affected by changing the column pressure. Energy integration has proven to be successful in reducing energy cost for conventional distillation arrangement.

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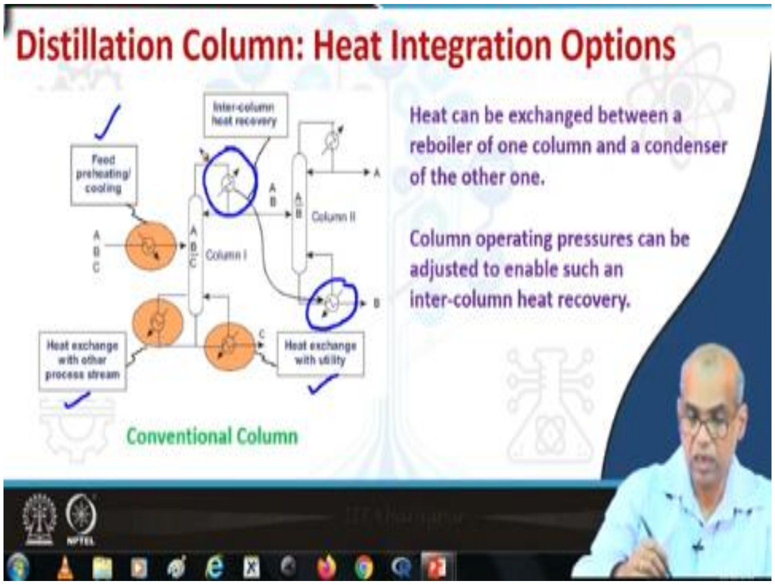

Distillation Column: Heat Integration Options

Heat can be exchanged between a reboiler of one column and a condenser of the other one.

Column operating pressures can be adjusted to enable such an inter-column heat recovery.

For example, if you look at the figure the figure shows heat integration options for a conventional column. This particular conventional column is basically an indirect sequence. Note that; if C is the least volatile component that is being taken out as bottom product. So, the heat integrations options are shown feed preheating or cooling. Heat exchange with utility, heat exchange with other process stream.

And also we can have inter column heat recovery, that means heat recovery between column 1 and 2. Heat can be exchanged between the reboiler of one column and the condenser of another column. Column operating pressures must be adjusted to enable such inter column heat recovery.

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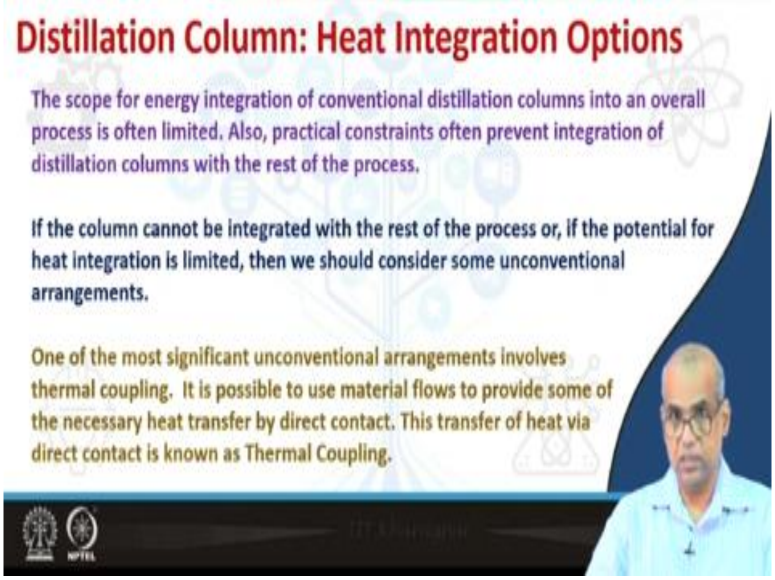

Distillation Column: Heat Integration Options

The scope for energy integration of conventional distillation columns into an overall process is often limited. Also, practical constraints often prevent integration of distillation columns with the rest of the process.

If the column cannot be integrated with the rest of the process or, if the potential for heat integration is limited, then we should consider some unconventional arrangements.

One of the most significant unconventional arrangements involves thermal coupling. It is possible to use material flows to provide some of the necessary heat transfer by direct contact. This transfer of heat via direct contact is known as Thermal Coupling.

However the scope for energy integration for conventional distillation into an overall process is often limited. Also there are practical constants which often prevent integration of distillation columns with the rest of the process. If the column cannot be integrated with the rest of the process or if the potential for the heat integration is limited, then we should consider some unconventional arrangement other than conventional distillation sequences.

One of the most significant unconventional arrangements involved thermal coupling. It is possible to use material flows to provide some of the necessary heat transfer by direct contact. This transfer of heat via direct contact is known as thermal coupling. So in this lecture we will look at some of this unconventional arrangement for thermal coupling which is affected by heat transfer through direct contact by material flows.

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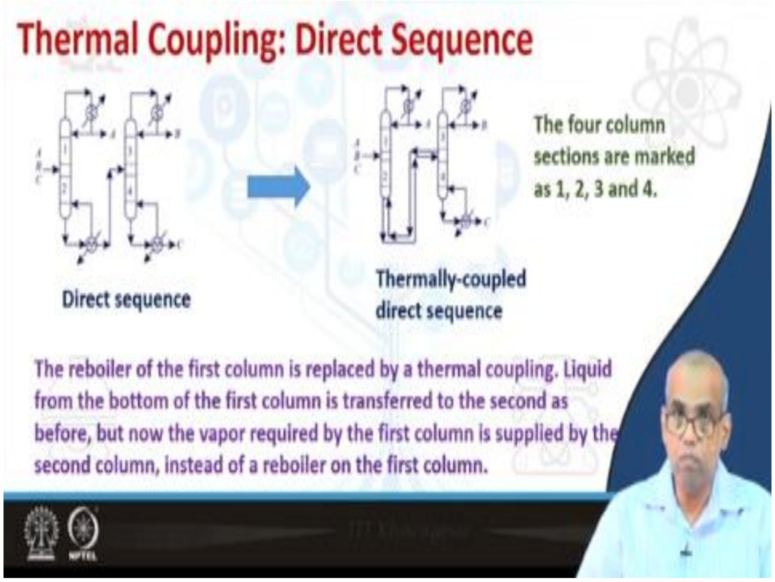

Thermal Coupling: Direct Sequence

Direct sequence

Thermally-coupled direct sequence

The four column sections are marked as 1, 2, 3 and 4.

The reboiler of the first column is replaced by a thermal coupling. Liquid from the bottom of the first column is transferred to the second as before, but now the vapor required by the first column is supplied by the second column, instead of a reboiler on the first column.

First let us consider thermal coupling of a direct sequence, we are considering separation of a ternary mixture A, B and C. So what you see is a sequence of two distillation columns where the light product A is taken out a stop product from column 1 and from the column 2, we take out B a stop product and C as bottoms, so this is a direct sequence. Now a thermal coupling is possible between these two columns, how?

We can have a thermally coupled direct sequence by replacing the reboiler of the first column by a thermal coupling between the first column and the second column. Note in the original direct sequence the liquid from the bottom of the first column goes as feed to the second column. In case of thermally coupled direct sequence, we have the same flow of bottom liquid from column 1 to column 2.

But in column 1, there is no reboiler. So the vapour required by the first column is supplied by the second column and that replaces the requirement of the reboiler in the first column. So a thermally coupled direct sequence is possible by replacing the reboiler in the first column by thermal coupling. So there is a coupling of material flows between the two columns. So whenever we replace the reboiler in the first column the vapour requirement of the first column is being supplied by column number 2.

Note we have marked sections 1, 2, 3 and 4 on both direct sequences as well as thermally coupled direct sequence. So, let us have this four marked sections 1, 2, 3 and 4.

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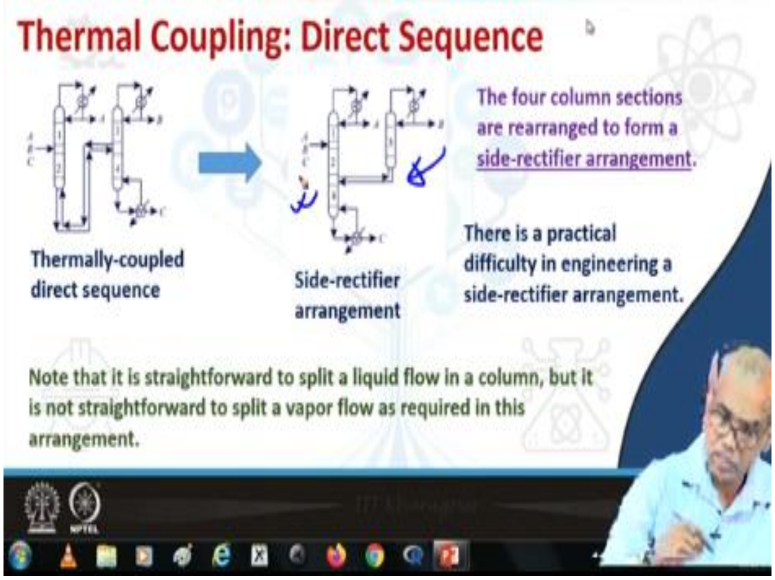

Thermal Coupling: Direct Sequence

Thermally-coupled direct sequence

Side-rectifier arrangement

The four column sections are rearranged to form a side-rectifier arrangement.

There is a practical difficulty in engineering a side-rectifier arrangement.

Note that it is straightforward to split a liquid flow in a column, but it is not straightforward to split a vapor flow as required in this arrangement.

Now these four sections can be rearranged to form a side rectifier arrangement as shown in the figure. So the four sections of thermally coupled direct sequence can be rearranged to form a side rectifier rearrangement. However, as we discussed before that there is a practical difficulty in engineering a side rectifier rearrangement, which comes due to the fact that it is not straight forward to split a vapour flow which is required in this particular arrangement.

Note in this side rectifier arrangement, the side rectifier is receiving a vapour flow from the first column. And as we have discussed previously that it may be straightforward to split a liquid flow in a column but it is not straight forward to split vapor flow in a column. So there is some practical engineering difficulty in this side rectifier arrangement.

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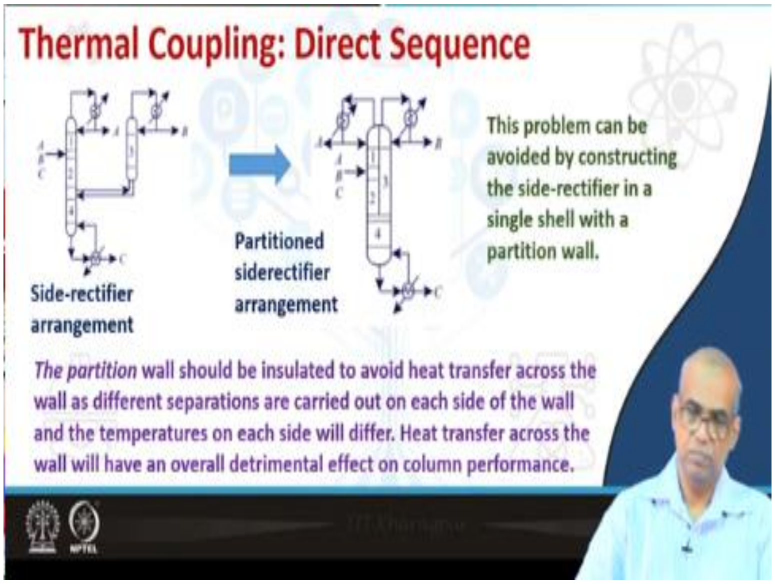

Thermal Coupling: Direct Sequence

Side-rectifier arrangement

Partitioned siderectifier arrangement

This problem can be avoided by constructing the side-rectifier in a single shell with a partition wall.

The partition wall should be insulated to avoid heat transfer across the wall as different separations are carried out on each side of the wall and the temperatures on each side will differ. Heat transfer across the wall will have an overall detrimental effect on column performance.

So; how to bypass this problem? This problem can be avoided by constructing the side rectifier in a single cell. So we can place the rectifier in the first cell itself with help of a partition wall. So the side rectifier, which is represented by section 3 is now incorporated in the first cell itself and what you need to do is you have to place a partition wall. Note now all the force excess are present in the single cell itself.

This is being made possible by placing this partition wall we can call this partition side rectifier arrangement. Now when you place the partition wall in the single cell and place the rectifier section within it, we have to take care of certain things. The partition wall should be insulated to avoid heat transfer across the wall, why so? Because different separations are being carried out on each side of the wall.

Note each side of the partition wall represents different sections, so different separations are being carried out on different sections. So, different separations are being carried out on each side of the wall. So temperatures or each side of the wall will differ. Heat transfer across the wall will have an overall harmful effect on the performance of the column.

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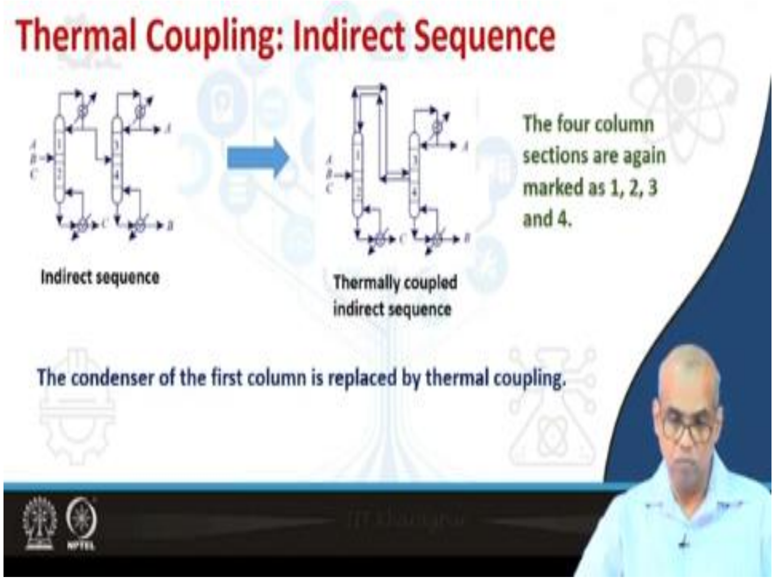

Thermal Coupling: Indirect Sequence

Indirect sequence

Thermally coupled indirect sequence

The four column sections are again marked as 1, 2, 3 and 4.

The condenser of the first column is replaced by thermal coupling.

Now, let us consider the case of indirect sequence. So again, we are considering indirect sequence for separation of a ternary mixture A, B and C. Note now C is being withdrawn as bottom product from the first column and A and B are being withdrawn as top product and bottom product from the second column. Now this indirect sequence can be converted to thermally coupled indirect sequence by making a coupling of material flows between these two columns.

We are replacing the condenser on the column 1 and the liquid required for the column 1 is being supplied by the column 2. So in case of thermally coupled indirect sequence the condenser of the first column is replaced by thermal coupling between these two columns. Again, notice the four sections marked as 1, 2, 3 and 4.

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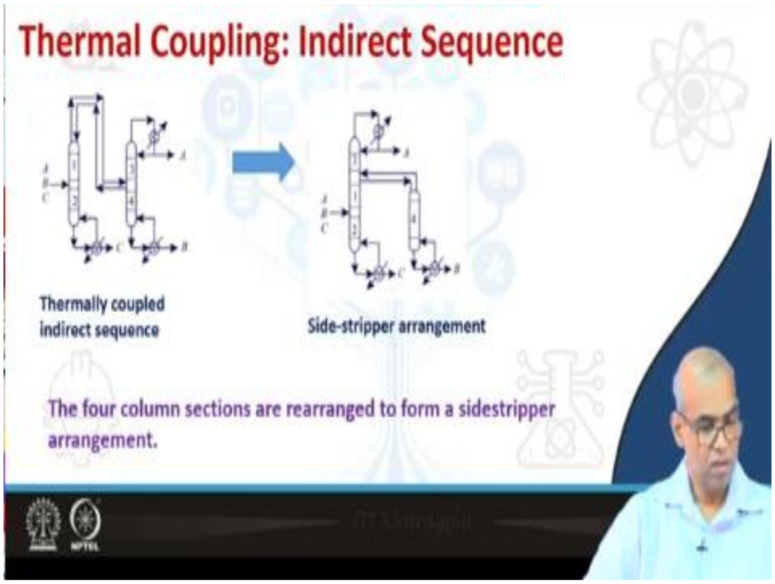

Thermal Coupling: Indirect Sequence

Thermally coupled indirect sequence

Side-stripper arrangement

The four column sections are rearranged to form a sidestripper arrangement.

We can again rearrange these four sections to form a side-stripper arrangement. Note the side-stripper arrangement, we are taking a liquid side stream from first column and being fed to the side-stripper. Now there is engineering difficulty associated with the side stripper arrangement because we are taking a liquid side stream. Note that the side-stripper represents the fourth section.

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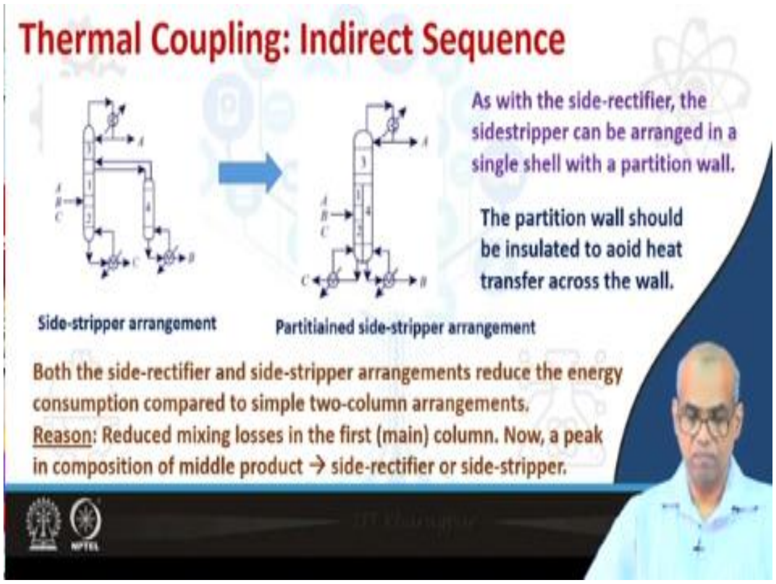

Thermal Coupling: Indirect Sequence

As with the side-rectifier, the sidestripper can be arranged in a single shell with a partition wall.

The partition wall should be insulated to aoid heat transfer across the wall.

Side-stripper arrangement

Partitiained side-stripper arrangement

Both the side-rectifier and side-stripper arrangements reduce the energy consumption compared to simple two-column arrangements.

Reason: Reduced mixing losses in the first (main) column. Now, a peak in composition of middle product → side-rectifier or side-stripper.

Now as in the case with the side rectifier the side-stripper can also be arranged in the single cell with help of a partition wall. So again, we can put a partition wall in the cell and can have all four sections together in the single cell. Note now that this section four which represents the side-stripper has now been put in the single cell itself and the partition wall separates this side stripper sections from the other sections.

Again as with the case of side rectifier here also the partition wall must be insulated to avoid the heat transfer across this one, because of the same reason that different separations are being carried out on each side of the partition wall and it transfer across the world will have a detrimental effect on the performance of the column. Both the side rectifier and side-stripper arrangements reduce the energy consumption compared to simple two column arrangements.

Again, the reason is the reduced mixing loss in the first column. Note that when you talked about indirect sequence and direct sequence there was inefficient mixing. There was mixing effect in the first column which resulted in inefficient separation and that was eliminated with alpha free fraction at an arrangement. Here also the reduced mixing losses in the first column discuss now a peak in composition of the middle product is transferred to the side rectifier or the side steeper as the case may be.

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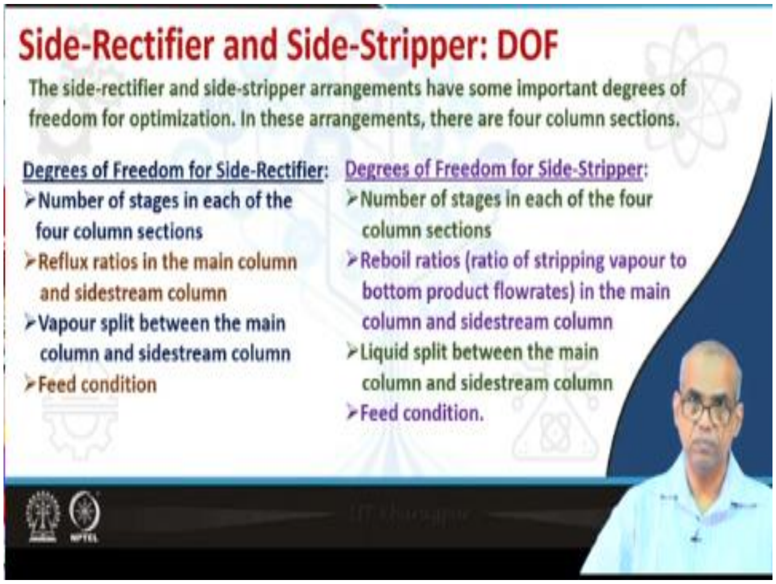

Side-Rectifier and Side-Stripper: DOF

The side-rectifier and side-stripper arrangements have some important degrees of freedom for optimization. In these arrangements, there are four column sections.

Degrees of Freedom for Side-Rectifier:

- Number of stages in each of the four column sections
- Reflux ratios in the main column and sidestream column
- Vapour split between the main column and sidestream column
- Feed condition

Degrees of Freedom for Side-Stripper:

- Number of stages in each of the four column sections
- Reboil ratios (ratio of stripping vapour to bottom product flowrates) in the main column and sidestream column
- Liquid split between the main column and sidestream column
- Feed condition.

Side rectifier and side stripper offers some important degrees of freedom for optimization, what are these degrees of freedom? Note that we have four sections. Number of stages in each of the four column sections is degrees of freedom. Let us first consider side rectifier, so number of stages in each of the four column sections, refluxes in the main column and sidestream column is another degree of freedom.

Vapour speed between the main column and sidestream column is another degree of freedom, the feed condition is also another degree flow of freedom. So, degrees of freedom for side rectifiers are number of stages in each of the four column sections, reflux ratios in the main column and sidestream column vapour speed between the main column and side stream column as well as feed condition.

Similarly the degrees of freedom for side-stripper are number of stages in each of the four column sections reboil ratios, what is reboil ratios? Is the ratio of the stripping vapor to the bottom product flow rates. So reboil ratios in the main column as well as side stream column, liquid split between the main column and sidestream column and also feed conditions. So both sidestream and side-stripper offers this degrees of freedom which can be used to our advantage for the purpose of optimization of the column performance.

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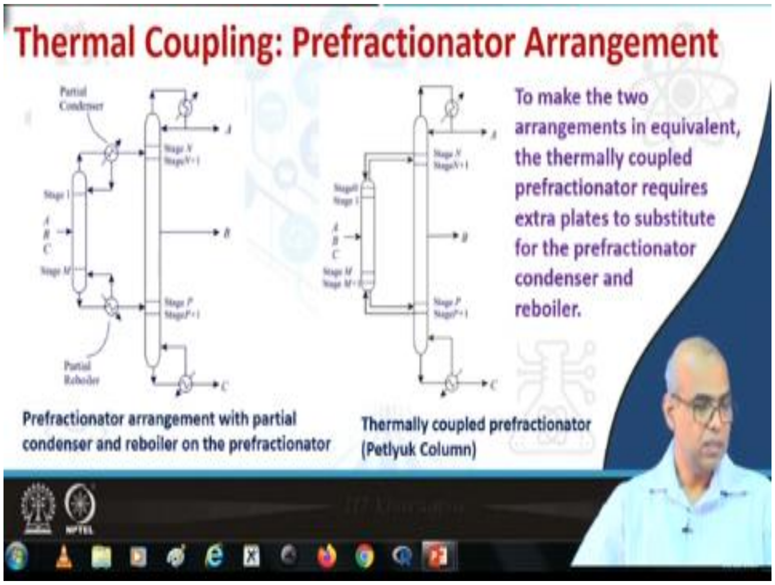

Thermal Coupling: Prefractionator Arrangement

To make the two arrangements in equivalent, the thermally coupled prefractionator requires extra plates to substitute for the prefractionator condenser and reboiler.

Prefractionator arrangement with partial condenser and reboiler on the prefractionator

Thermally coupled prefractionator (Petlyuk Column)

Now, let us look at thermal coupling of the prefractionator arrangement. So we have a partial condenser and a partial reboiler in this pre fractionator. Now these both of this partial condenser and the partial reboiler can be replaced by making a thermal coupling between the prefractionator and the main column as shown here. So this thermally coupled prefractionator arrangement is known as Petlyuk arrangement or Petlyuk column.

To make the two arrangements equivalent, the thermally coupled prefractionator requires extra place to substitute for the prefractionator condenser and prefractionator reboiler. So thermal coupling between this prefractionator column and the main column is possible and we can replace the partial condenser and the partial reboiler by thermal coupling. So, material flows between these two columns will provide the heat requirement and the cooling requirement in case of in the first column.

So the liquid requirement and the vapour requirement will both be supplied by the second column.

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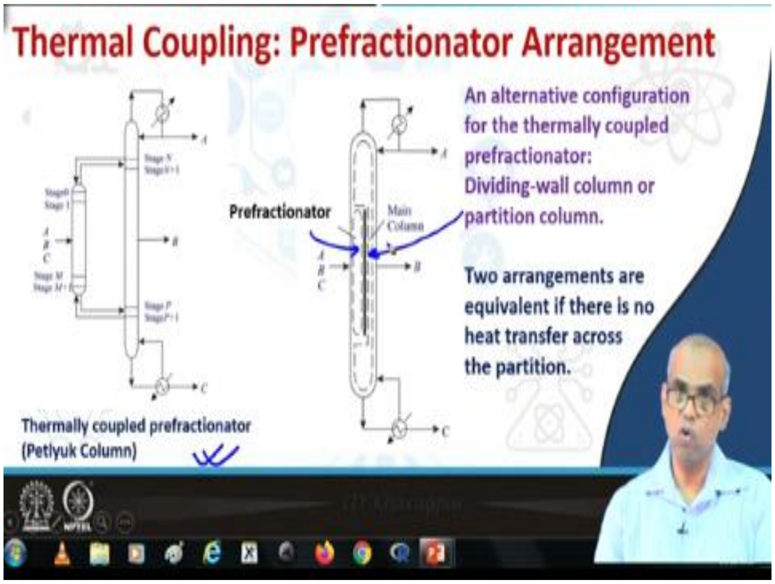

Thermal Coupling: Prefractionator Arrangement

An alternative configuration for the thermally coupled prefractionator: Dividing-wall column or partition column.

Two arrangements are equivalent if there is no heat transfer across the partition.

Thermally coupled prefractionator (Petlyuk Column)

We can also think of an alternative configuration for the thermal coupling or the thermally coupled prefractionator. As we have seen that by putting a partition wall we can put both the sidestepper and side rectifier in the single cell, we can also here put a partition wall which will call a dividing wall column or partition column and can have the prefractionator in all the same cell. So these thermally coupled pre fractionator which is known as Petlyuk arrangement can be converted to an alternate arrangement by having or dividing wall column.

Where see one side of the dividing column represents the prefractionator and the other side represents the main column. These two arrangements are equivalent if there is no heat transfer across the partition.

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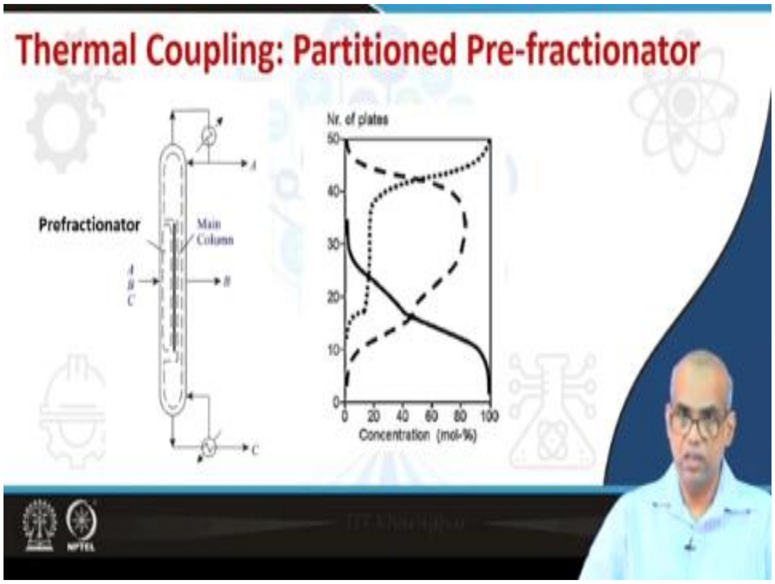

Thermal Coupling: Partitioned Pre-fractionator

Now if you look at the concentration profiles of say A, B and C components you can see clearly that at the top of the distillation column the one component picks up this is the light component A. At the bottom the component C has picked up the concentration, the concentration of C is maximum here. And the concentration of the middle product B is maximum where the side stream is located.

Here the number of plates is going up this way, so this represents my bottom and this represents my top. So this way the dividing wall column clearly separates the components A, B and C using a single distillation column.

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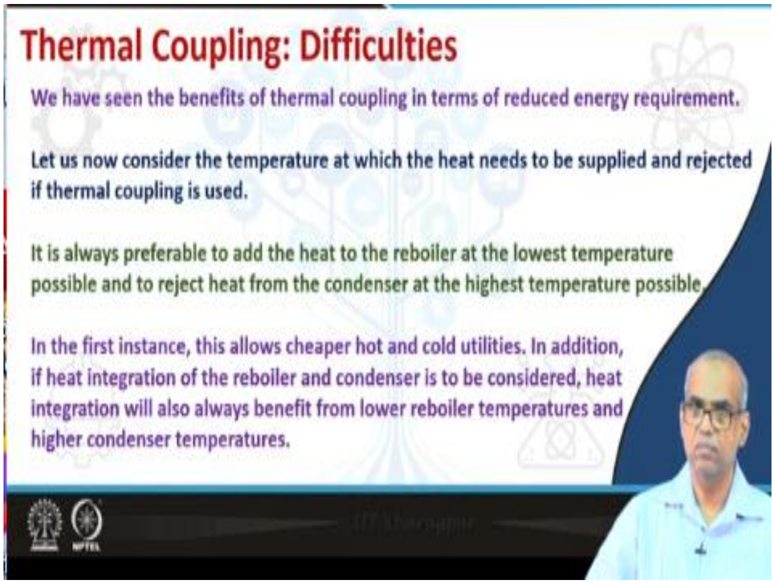

Thermal Coupling: Difficulties

We have seen the benefits of thermal coupling in terms of reduced energy requirement.

Let us now consider the temperature at which the heat needs to be supplied and rejected if thermal coupling is used.

It is always preferable to add the heat to the reboiler at the lowest temperature possible and to reject heat from the condenser at the highest temperature possible.

In the first instance, this allows cheaper hot and cold utilities. In addition, if heat integration of the reboiler and condenser is to be considered, heat integration will also always benefit from lower reboiler temperatures and higher condenser temperatures.

Now let us talk some difficulties associated with the thermal coupling, we have seen the benefits of thermal coupling in terms of reduced energy requirement. Thermal coupling reduces the energy requirement. Now, let us consider the temperature at which the heat needs to be supplied and rejected if thermal coupling is used. It is always preferable to add the heat to the reboiler at the lowest temperature possible and to reject heat from the condenser at the highest temperature possible.

In the first instance this will allow cheaper hot and cold utilities. In addition, if heat integration of the reboiler and condenser is to be considered, heat integration will also benefit from lower reboiler temperature and higher condenser temperature.

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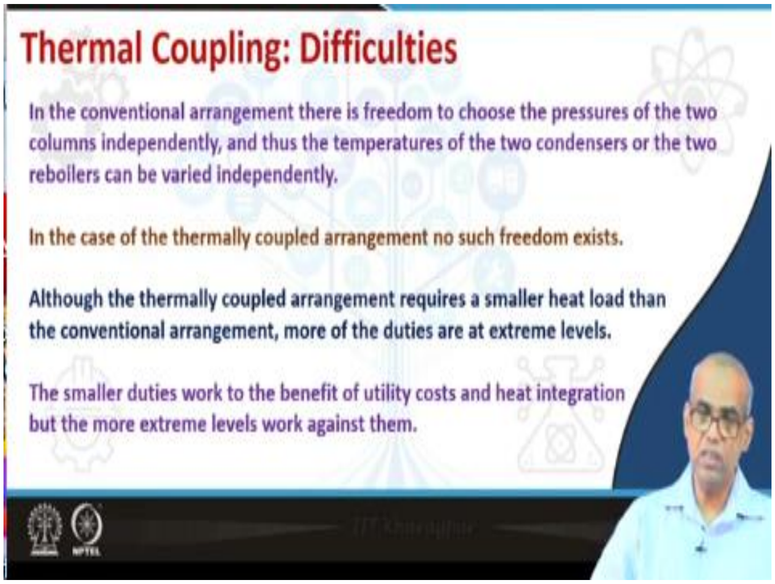

Thermal Coupling: Difficulties

In the conventional arrangement there is freedom to choose the pressures of the two columns independently, and thus the temperatures of the two condensers or the two reboilers can be varied independently.

In the case of the thermally coupled arrangement no such freedom exists.

Although the thermally coupled arrangement requires a smaller heat load than the conventional arrangement, more of the duties are at extreme levels.

The smaller duties work to the benefit of utility costs and heat integration but the more extreme levels work against them.

In the conventional arrangement we are free to choose the pressure of the two columns independently and thus the temperatures of the two condensers or the two revolvers can be varied independently. However, in case of thermally coupled distillation columns, we do not have any such freedom. So although the thermally coupled arrangement requires a smaller heat load then the conventional arrangement more of the duties are at extreme levels.

The smaller duties work to the benefit of utility cost because you will require less utility, you will require less energy. So the smaller duties work to the benefit of utility cost and heat integration, but the more extreme levels work against them. So these are certain difficulties associated with the thermal coupling, that the duties are at extreme level the duty is reduced, but the duties are at extreme levels.

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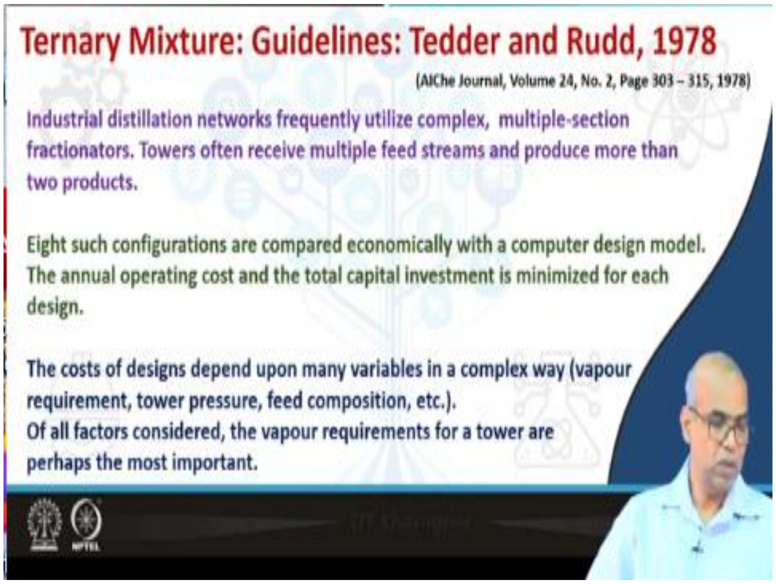

Ternary Mixture: Guidelines: Tedder and Rudd, 1978

(AIChe Journal, Volume 24, No. 2, Page 303 – 315, 1978)

Industrial distillation networks frequently utilize complex, multiple-section fractionators. Towers often receive multiple feed streams and produce more than two products.

Eight such configurations are compared economically with a computer design model. The annual operating cost and the total capital investment is minimized for each design.

The costs of designs depend upon many variables in a complex way (vapour requirement, tower pressure, feed composition, etc.).
Of all factors considered, the vapour requirements for a tower are perhaps the most important.

Now, let us look at certain guidelines as proposed by Tedder and Rudd for sequencing of complex distillation columns. So, complex distillation columns are capable of giving you more than two products from one column. Complex distillation columns may have multiple sections, such as fractionators, side rectifiers side-stripper etcetera. So industrial distillation; network frequently utilized complex, multiple-section, fractionators.

Towers often receive multiple feed streams and produce more than two products. We will consider eight such configurations. Eight such configurations are compared economically with a computer design model. The annual operating cost and the total capital investment is minimized for each design. The cost of designs depend upon many variables in a complex way vapour requirement, tower pressures, feed compositions, all contributes towards cost of designs.

However, among all these factors consider the vapour requirement for a tower at the perhaps the most important factor to be considered.

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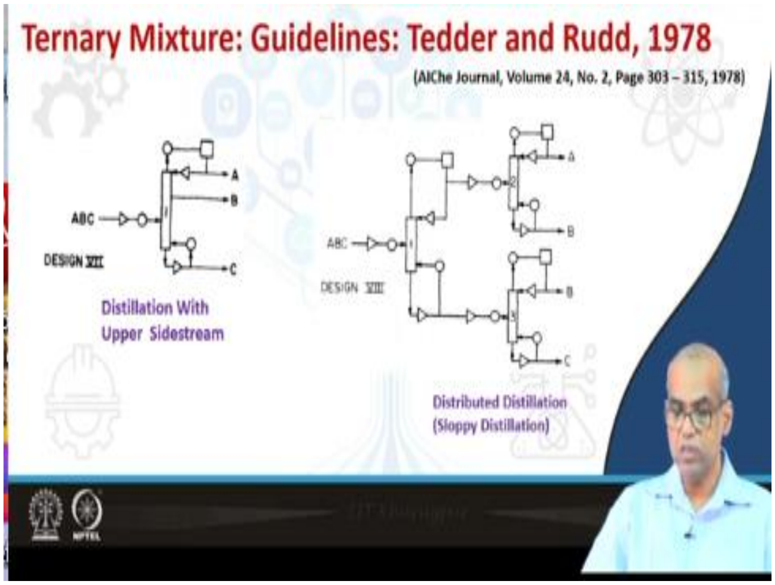

Ternary Mixture: Guidelines: Tedder and Rudd, 1978

(AIChe Journal, Volume 24, No. 2, Page 303 – 315, 1978)

Distillation With Upper Sidestream

Distributed Distillation (Sloppy Distillation)

So, as Tedder and Rudd proposed eight designs are being considered here, two conventional designs and six complex designs. So what are those designs, first direct sequence, indirect sequence, vapour sidestream rectifier, liquid sidestream stripper, prefractionator with distillation arrangement, distillation with lower sidestream, distillation with upper sidestream and distributed distillation or sloppy distribution, so these eight arrangement or eight designs will consider.

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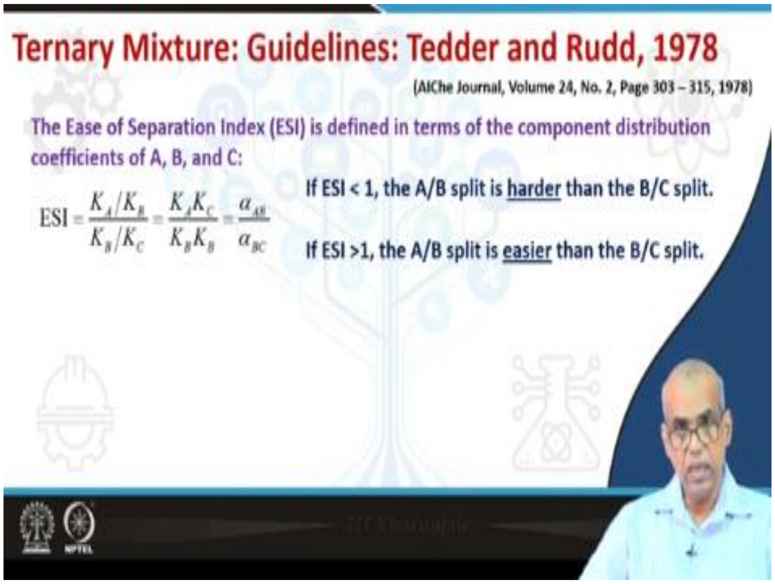

Ternary Mixture: Guidelines: Tedder and Rudd, 1978

(AIChe Journal, Volume 24, No. 2, Page 303 – 315, 1978)

The Ease of Separation Index (ESI) is defined in terms of the component distribution coefficients of A, B, and C:

$$\mathrm{ESI} = \frac{K_A/K_B}{K_B/K_C} = \frac{K_A K_C}{K_B K_B} = \frac{\alpha_{AB}}{\alpha_{BC}}$$

If ESI < 1, the A/B split is harder than the B/C split.

If ESI >1, the A/B split is easier than the B/C split.

Now Tedder and Rudd define an index known as ease of separation index, ease of separation index is defined in terms of the component distribution coefficients of A, B and C. So this is if we have ternary mixtures of A, B and C, the ease of separation index is the relative volatility between AB divided by relative volatility between BC. So if ease of separation index is less than

1, it means that the relative volatility between AB is less than the relative volatility between B and C.

So the AB split is more difficult compared to BC split. Similarly if ease of separation index is greater than 1 then the relative volatility between AB is greater than the relative volatility between BC. So the split between AB is easier compared to BC split.

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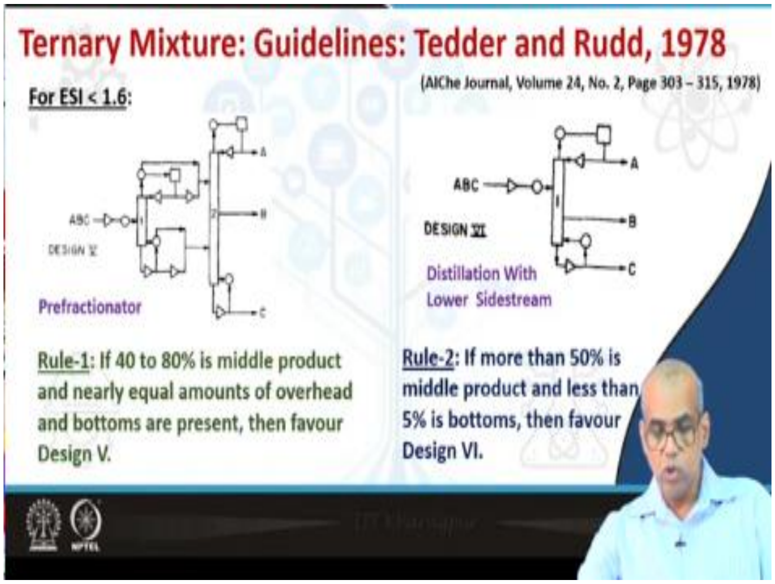

Ternary Mixture: Guidelines: Tedder and Rudd, 1978

(AIChe Journal, Volume 24, No. 2, Page 303 – 315, 1978)

For ESI < 1.6:

Prefractionator

Distillation With Lower Sidestream

Rule-1: If 40 to 80% is middle product and nearly equal amounts of overhead and bottoms are present, then favour Design V.

Rule-2: If more than 50% is middle product and less than 5% is bottoms, then favour Design VI.

Now so based on the ease of separation index value where it is less than 1.6 or greater than equal to 1.6 Tedder and Rudd has given certain guidelines, so let us look at those guidelines. Rule 1, if 40 to 80% is middle product and nearly equal amounts of overhead and bottom are present then we favor the design 5 which is prefractionator. All these rules we are talking about now correspond to ease of separation index less than 1.6.

If more than 50% is middle product and less than 5% is bottom product then we favor design 6, which is distillation with lower side stream.

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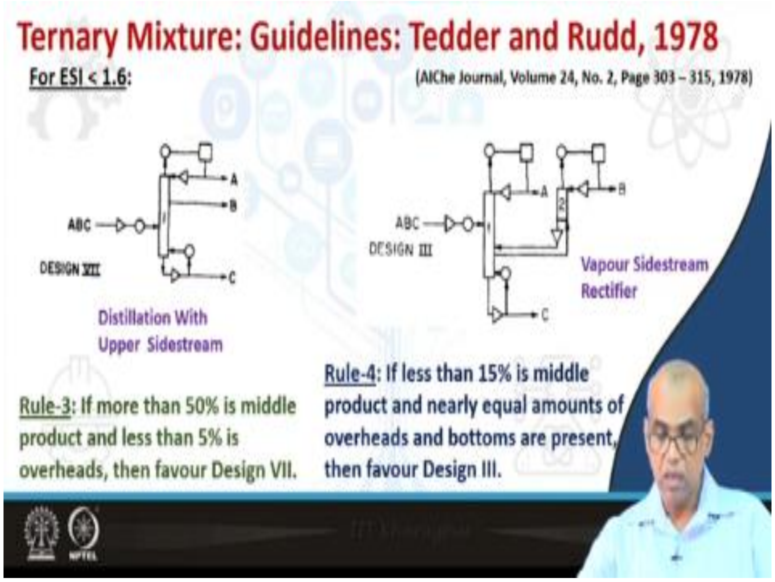

Ternary Mixture: Guidelines: Tedder and Rudd, 1978

For ESI < 1.6:

(AIChe Journal, Volume 24, No. 2, Page 303 – 315, 1978)

Distillation With Upper Sidestream

Vapour Sidestream Rectifier

Rule-3: If more than 50% is middle product and less than 5% is overheads, then favour Design VII.

Rule-4: If less than 15% is middle product and nearly equal amounts of overheads and bottoms are present, then favour Design III.

Rule 3, more than 50% is middle product and less than 5% is overheads, then favor design 7 which is distillation with upper side stream. Rule 4, if less than 15% is middle product and nearly equal amounts of overheads and bottoms are present then we favor design 3, which is vapour side stream rectifier.

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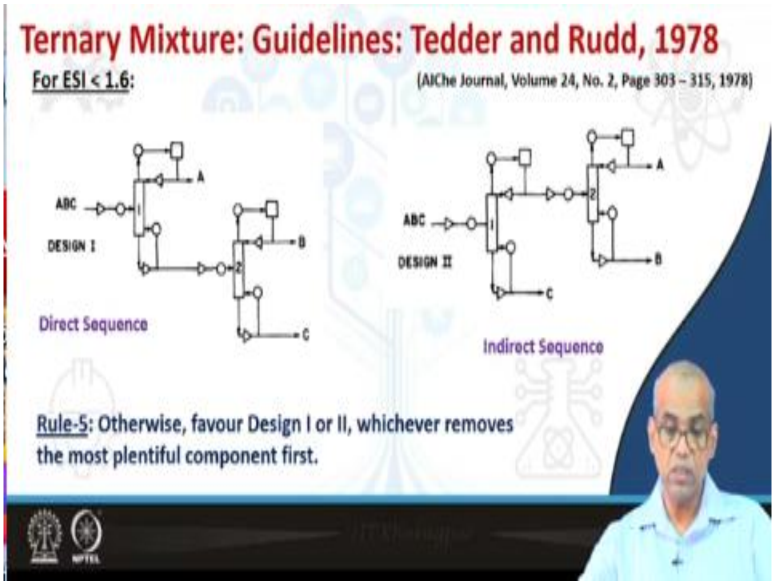

Ternary Mixture: Guidelines: Tedder and Rudd, 1978

For ESI < 1.6:

(AIChe Journal, Volume 24, No. 2, Page 303 – 315, 1978)

Direct Sequence

Indirect Sequence

Rule-5: Otherwise, favour Design I or II, whichever removes the most plentiful component first.

Rule 5, otherwise we will favor design 1 or design 2 that means either direct sequence or indirect sequence, whichever removes the most plentiful component first. So these are about ease of separation index less than 1.6.

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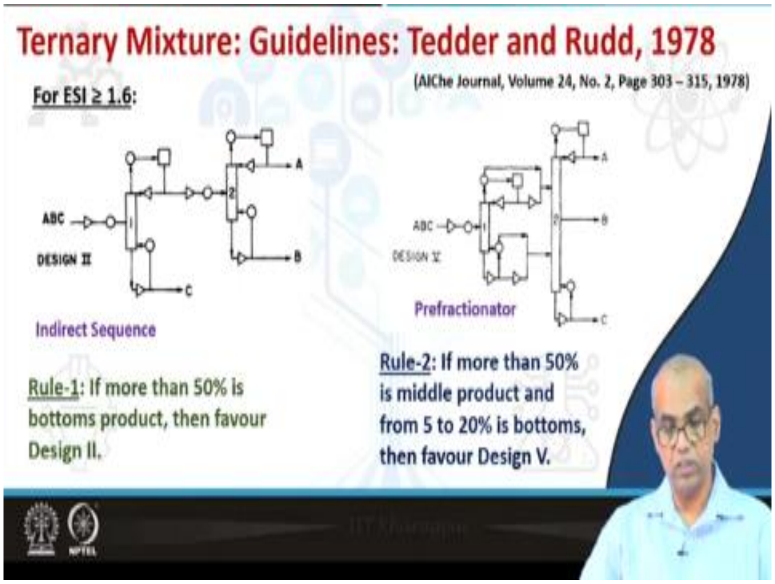

Ternary Mixture: Guidelines: Tedder and Rudd, 1978

(AIChe Journal, Volume 24, No. 2, Page 303 – 315, 1978)

For ESI ≥ 1.6:

Indirect Sequence

Prefractionator

Rule-1: If more than 50% is bottoms product, then favour Design II.

Rule-2: If more than 50% is middle product and from 5 to 20% is bottoms, then favour Design V.

Now let us talk about rules for ease of separation index greater or equal to 1.6. Rule 1, more than 50% is bottom product then we favor design 2, which is indirect sequence. Rule 2 if more than 50% is middle product and from 5 to 20% is bottoms, then you favor design 5, which is prefractionator.

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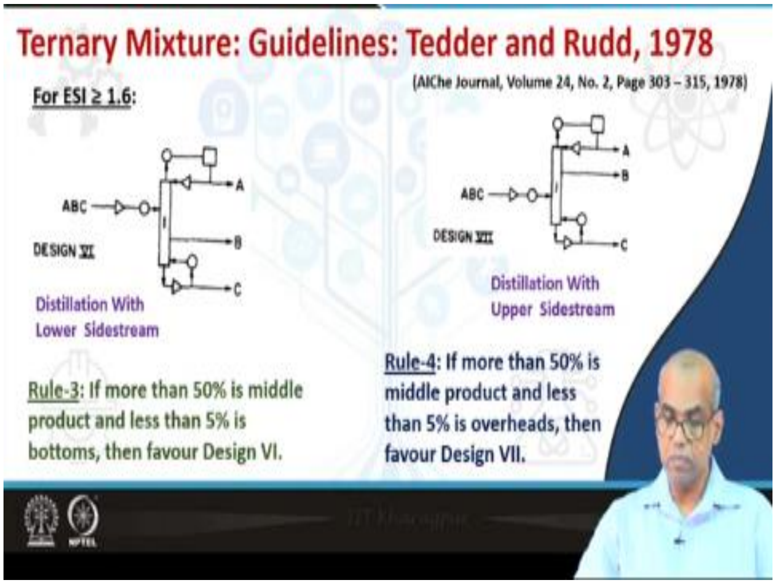

Ternary Mixture: Guidelines: Tedder and Rudd, 1978

(AIChe Journal, Volume 24, No. 2, Page 303 – 315, 1978)

For ESI ≥ 1.6:

Distillation With Lower Sidestream

Distillation With Upper Sidestream

Rule-3: If more than 50% is middle product and less than 5% is bottoms, then favour Design VI.

Rule-4: If more than 50% is middle product and less than 5% is overheads, then favour Design VII.

Rule 3 more than 50% is middle product and less than 5% is bottoms then favor design 6, which is distillation with lower side stream. Rule 4, if more than 50% is middle product and less than 5% is overheads then we favor design 7, which is distillation with upper side stream.

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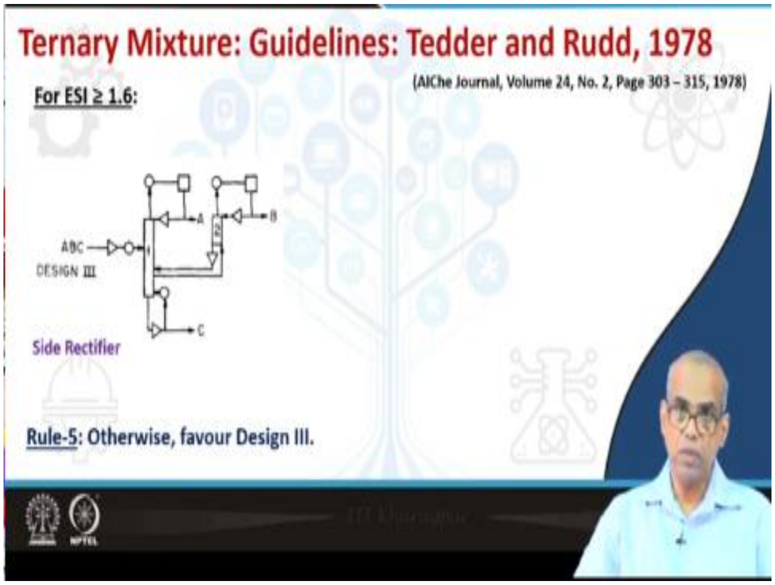

Ternary Mixture: Guidelines: Tedder and Rudd, 1978

(AIChe Journal, Volume 24, No. 2, Page 303 – 315, 1978)

For ESI ≥ 1.6:

Side Rectifier

Rule-5: Otherwise, favour Design III.

Finally rule 5 otherwise we favor design 3, which is side rectifier, so these rules or the guidelines can be used based on value of ease of separation index.

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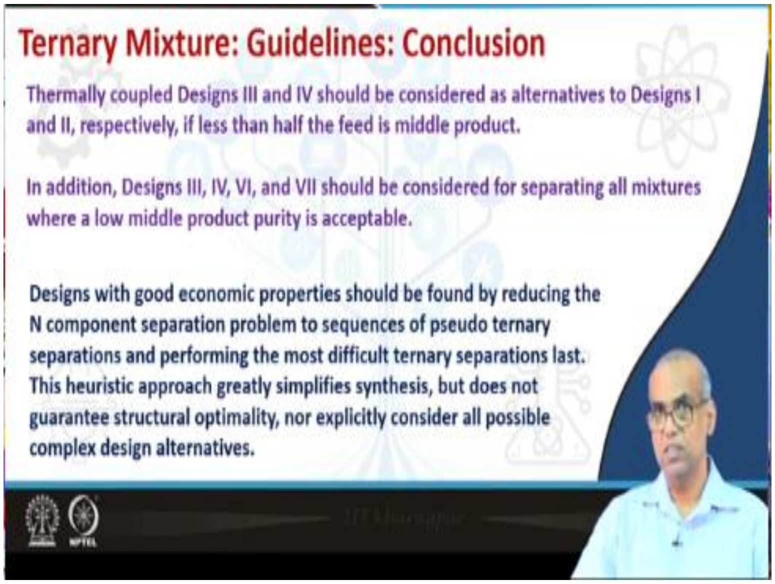

Ternary Mixture: Guidelines: Conclusion

Thermally coupled Designs III and IV should be considered as alternatives to Designs I and II, respectively, if less than half the feed is middle product.

In addition, Designs III, IV, VI, and VII should be considered for separating all mixtures where a low middle product purity is acceptable.

Designs with good economic properties should be found by reducing the N component separation problem to sequences of pseudo ternary separations and performing the most difficult ternary separations last. This heuristic approach greatly simplifies synthesis, but does not guarantee structural optimality, nor explicitly consider all possible complex design alternatives.

Thermally coupled designs 3 and 4 should be considered as alternative to design 1 and 2 respectively, if less than half the feed is middle product. In addition design 3, 4, 6 and 7 should be considered for separating all mixtures where a low middle product purity is acceptable. Finally designs with good economic properties should be found by reducing the N component separation problem to a sequence of pseudo ternary separations and performing the most difficult ternary separation last.

This heuristic approach greatly simplifies synthesis but does not guarantee structure of optimality nor explicitly consider all possible complex design alternatives. However, this heuristics can always be used to our advantage as a starting design step. With this we stop our discussion here.