# Energy and Economic Optimization of Distillation Sequencing

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*Abstract*— Effective parameters that can effect on the performance of the separation system consist of operating pressure, operating temperature, reflux ratio, and kind of produce desirable products and different sequences of splits. In generally, there are two criteria (as object function) for estimating of the performance of the separation systems. These criteria included of measure of energy consumption and design costs (i.e. capital cost, energy cost and total annual cost). From energy saving outlook our purpose is the design of one separation system that operates at minimum rate of energy consumption. In this paper, concentrate more on optimization of distillation sequencing problem with energy consumption and design costs for a multicomponent mixture. Hence we studied the various alternative options to separate a multicomponent feed stream consist of C3, i-C4, n-C4, i-C5 and n-C5,. Afer that all of options are compared with each other and ranked based on minimum (or optimum) energy consumption (heating/cooling duties) and design costs.

***Key words:*** Energy Optimization, Cost Estimation, Distillation Sequencing

## I. INTRODUCTION

Basically Distillation column used to separate one feed stream into two streams with more volatilizes (overhead product) and less volatilizes (bottom product).Around all chemical processes need the separation of chemical species to purify a reactor feed, recover unreacted species for recycle to a reactor and separate and purify the products from a reactor. However, more commonly, the feed mixture involves more than two components, involving more complex separation systems. According to separating agent(s), the common industrial separation methods can be divided as flash, Ordinary distillation , Gas absorption , Stripping , Extractive distillation , Azeotropic distillation , LLE, Gas adsorption , Membrane separation.

The selection of separation methods depends on feed condition. The separation factor (SF), defines the degree of separation achievable between two key components of the feed. This factor, for the separation of component 1 from component 2 between phases I and II, for a single stage of contacting, is defined as:

$$SF = \frac{C_1{}^{I}/C_2{}^{I}}{C_1{}^{II}/C_2{}^{II}}$$

Where:
C: composition variable
I, II: phases rich in components 1 and 2

SF is generally limited by thermodynamic equilibrium. For example, in case of distillation, using mole fractions as the composition variable and let phase I be the vapor and phase II be the liquid, the limiting value of SF is given in terms of vapor-liquid equilibrium ratios (K-values).

If feed input stream to column consist of more than two components then to perform separation, we require to the set of distillation column that configure in sequential form. Whereas in all of the existing Industrial plants deals with multi-components mixture therefore optimum design one of the distillation column sequencing system is as paramount challenge.

Since several researches has been accomplished upon this issue. Different Column sequencing systems for separating one ternary mixture can be found. Conventional sequence includes two columns in series where first column's product is as feed stream for second column. Here both of columns have one reboiler and one condenser. In other word first column boils up the second or otherwise. In the thermo coupling sequence, heat demand for separation is provided through direct contact of the processes streams. This matter cause to increase the thermodynamic efficiency of sequence and decrease design costs too. Sloppy sequence is one of the more efficient sequence columns. However, this sequence has much similarity to thermo-coupling sequence but Here heat demand for separation is provided with reboiler and condense.

$$SF = \frac{y_1 \;\; x_1}{y_2/x_2} = \frac{K_1}{K_2} = \alpha_{1,2} \quad = \frac{P_1}{P_2^s} \quad \text{for ideal L and V}$$

Column Sequencing for seperation of ternary mixture –

1) Sloppy sequence
2) Thermocouple sequence
3) Conventional sequence
4) Heat integrated sequence

The separation of a multicomponent mixture is conventionally accomplished in a series of columns, each having a condenser and a reboiler. This results in high energy and low thermal efficiency. But in the column sequences systems require only one condenser and one reboiler. This results in low energy and high thermal efficiency.

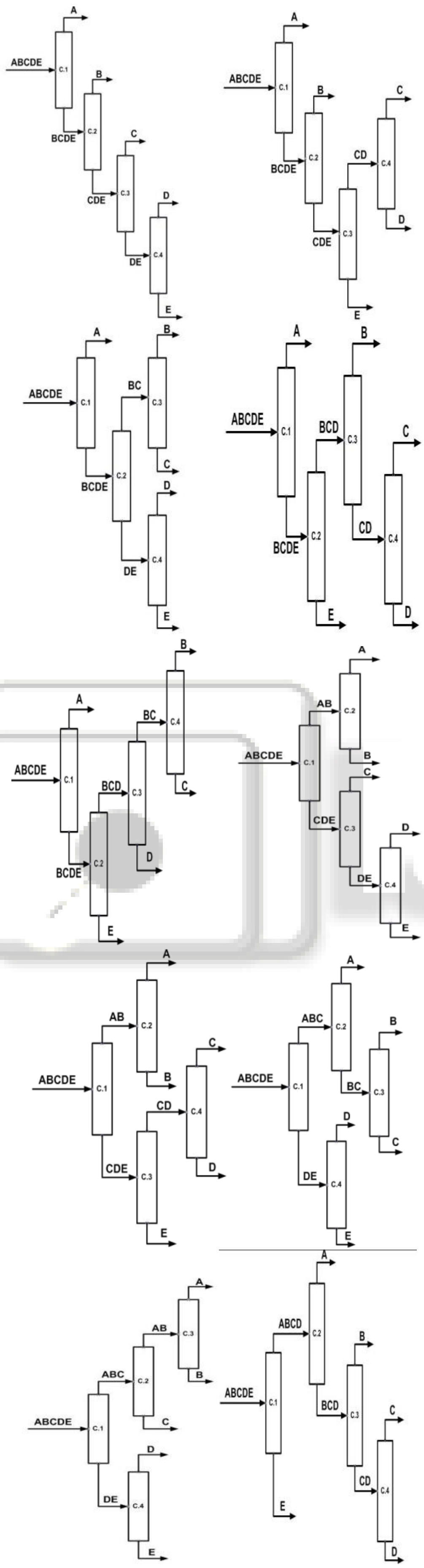
When we want to separate a n components mixture into a specific product, we need to (n-1) distillation columns with one feed stream and two product stream. Equation 1, gives a relation for estimating the number of column sequences to separate an components into n component products .

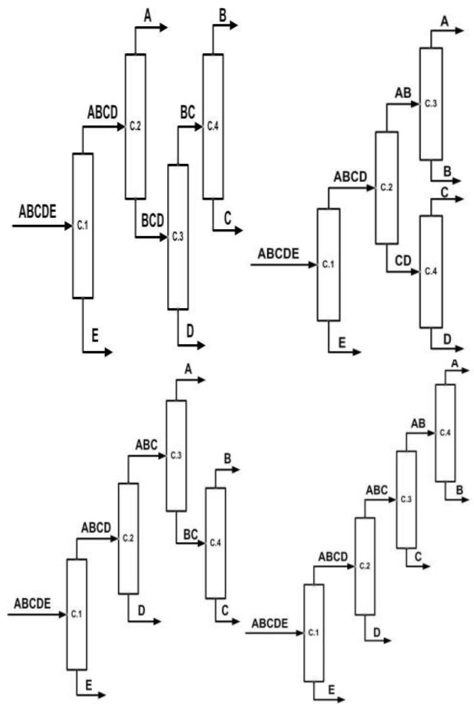
$$S_n = [2(n-1)]! \,/\, [n!\,(n-1)!] \qquad (1)$$

## II. MATERIAL & METHODS

For the evaluation of influences of parameters like operating pressure, temperature, split of product streams, arrangement of sequence and reflux ratio on the performance of column sequences with design costs and energy consumptions deal with the designing and then optimizing of column sequences system..

Different column sequence is:-




As above mentioned, so the determining of key parameters like energy efficiency, amount of energy consumption and other effective factors are related to column sequencing process, is depended upon thermodynamic analysis performing. For this purpose, we used the following equations for column sequencing system.

First law of thermodynamics :

$$\sum_{\text{out of system}} (nh + Q + W_S) - \sum_{\text{in to system}} (nh + Q + W_S) = 0$$

Second low of thermodynamics :

$$\sum_{\text{out of system}} (ns + Q/T_S) - \sum_{\text{in to system}} (ns + Q/T_S) = \Delta S_{irr}$$

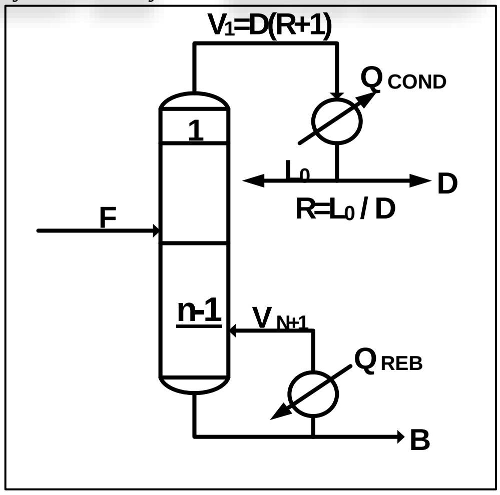



Fig. 3: A conventional distillation column.

*A. Case study -*

1) A multi-component mixture consist of composition (mole basis) $C_3$(0.05) ,i-$C_4$(0.15), n-$C_4$(0.25), i-$C_5$(0.2), n-$C_5$(0.2), $C_6$(0.1) and $C_7$(0.05) is available.
2) Light key and heavy key sequence : $C_3$ < i-$C_4$ < n-$C_4$ < i-$C_5$ < n-$C_5$ (light key < heavy key)

## III. RESULTS & DISCUSSION

In the present study, all of different possible sequence of distillation columns is simulated within four steps.

- At the first step, we looks at the classical column sequencing problem where all the tasks (i.e. all potential columns of sequence), operate at a fixed pressure (P=5 bar).
- At the second step, we are investigated to the reach of optimum column sequences by adjusting the search domain of operating pressure as a variable and operating temperature as a constant parameter.
- At the third step, we are expanded the search domain by allocating instances of tasks that perform identical separation but operate at different pressure and temperature. The results are presented at tables 3.
- At the last step, we are limited design option by imposes some constraints on the search space domain to utilize the available assets more effectively and finding the most promising and retrofitting column sequences due to fixed target trays.

The first three steps assume a grass-roots situation, while the fourth step addresses retrofitting the real industrial plant. In general, the performance of the optimum design changes as the search domain is expanded.

| Design No. | Sequence | Capital Cost ($). $10^6$ | Operating Cost ($/years). $10^5$ | Total Cost ($/years). $10^6$ | Rank |
|---|---|---|---|---|---|
| 1 | A/BCDE, B/CDE, C/DE, D/E | 3.529 | 2.338 | 9.062 | 1 |
| 2 | A/BCDE, B/CDE, CD/E, C/D | 3.573 | 2.277 | 9.085 | 2 |
| 3 | A/BCDE, BC/DE, B/C, D/E | 3.702 | 2.198 | 9.252 | 7 |
| 4 | A/BCDE, BCD/E, B/CD, C/D | 3.638 | 2.179 | 9.111 | 3 |
| 5 | A/BCDE, BCD/E, BC/D, B/C | 3.748 | 2.159 | 9.301 | 8 |
| 6 | AB/CDE, A/B, C/DE, D/E | 3.772 | 2.143 | 9.331 | 10 |
| 7 | AB/CDE, A/B, CD/E, C/D | 3.817 | 2.081 | 9.354 | 11 |
| 8 | ABC/DE, A/BC, B/C, D/E | 3.658 | 2.145 | 9.116 | 4 |
| 9 | ABC/DE, AB/C, A/B, D/E | 3.811 | 2.059 | 9.321 | 9 |
| 10 | ABCD/E, A/BCD, B/CD, C/D | 3.711 | 2.102 | 9.173 | 5 |
| 11 | ABCD/E, A/BCD, BC/D, B/C | 3.821 | 2.082 | 9.363 | 12 |
| 12 | ABCD/E, AB/CD, A/B, C/D | 3.981 | 1.969 | 9.555 | 14 |
| 13 | ABCD/E, ABC/D, A/BC, B/C | 3.758 | 2.085 | 9.245 | 6 |
| 14 | ABCD/E, ABC/D, AB/C, A/B | 3.910 | 2.000 | 9.451 | 13 |

Table 1: Designing all of the feasible column sequences at 5 bar and have been ranked based on Total Annual Cost (TAC) as an object function

| Design No. | Sequence | Operating Pressure | | | | Capital Cost ($). $10^6$ | Operating Cost ($/years). $10^5$ | Total Cost ($/years). $10^6$ | Rank |
|---|---|---|---|---|---|---|---|---|---|
| | | column 1 | column 2 | column 3 | column 4 | | | | |
| 1 | A/BCDE, B/CDE, C/DE, D/E | 9.153 | 4.130 | 2.963 | 1.324 | 3.529 | 2.089 | 7.303 | 1 |
| 2 | A/BCDE, B/CDE, CD/E, C/D | 9.153 | 4.130 | 2.220 | 2.963 | 3.711 | 2.120 | 7.801 | 5 |
| 3 | A/BCDE, BC/DE, B/C, D/E | 9.153 | 3.418 | 4.130 | 1.324 | 3.573 | 1.968 | 7.328 | 2 |
| 4 | A/BCDE, BCD/E, B/CD, C/D | 9.153 | 2.707 | 4.130 | 2.963 | 3.702 | 2.063 | 8.138 | 7 |
| 5 | A/BCDE, BCD/E, BC/D, B/C | 9.153 | 2.707 | 3.418 | 4.130 | 3.748 | 2.055 | 8.173 | 8 |
| 6 | AB/CDE, A/B, C/DE, D/E | 5.486 | 2.963 | 9.153 | 1.324 | 3.658 | 1.994 | 7.784 | 4 |
| 7 | AB/CDE, A/B, CD/E, C/D | 5.486 | 2.220 | 9.153 | 2.963 | 3.772 | 2.029 | 8.283 | 10 |
| 8 | ABC/DE, A/BC, B/C, D/E | 4.132 | 9.153 | 4.130 | 1.324 | 3.638 | 1.914 | 7.396 | 3 |
| 9 | ABC/DE, AB/C, A/B, D/E | 4.132 | 5.486 | 9.153 | 1.324 | 3.758 | 1.885 | 7.886 | 6 |
| 10 | ABCD/E, A/BCD, B/CD, C/D | 3.262 | 9.153 | 4.130 | 2.963 | 3.811 | 2.059 | 8.268 | 9 |
| 11 | ABCD/E, A/BCD, BC/D, B/C | 3.262 | 9.153 | 3.418 | 4.130 | 3.817 | 2.025 | 8.307 | 11 |
| 12 | ABCD/E, AB/CD, A/B, C/D | 3.262 | 5.486 | 9.153 | 2.963 | 3.910 | 2.012 | 8.702 | 13 |
| 13 | ABCD/E, ABC/D, A/BC, B/C | 3.262 | 5.486 | 9.153 | 2.963 | 3.910 | 2.012 | 8.702 | 12 |
| 14 | ABCD/E, ABC/D, AB/C, A/B | 3.262 | 4.132 | 5.486 | 9.153 | 3.981 | 1.982 | 8.728 | 14 |

Table 2: Designing all of the feasible column sequences at 35 ℃ and have been ranked based on Total Annual Cost (TAC) as an object function.

| Design No. | Sequence | Operating Pressure (bar) / Operating Temperature (℃) | | | | Capital Cost ($). $10^6$ | Operating Cost ($/years). $10^5$ | Total Cost ($/years). $10^6$ | Rank |
|---|---|---|---|---|---|---|---|---|---|
| | | column 1 | column 2 | column 3 | column 4 | | | | |
| 1 | A/BCDE, B/CDE, C/DE, D/E | 10.13 / 40 | 3.635 / 30 | 3.385 / 40 | 1.131 / 30 | 2.655 | 2.063 | 7.121 | 1 |
| 2 | A/BCDE, B/CDE, CD/E, C/D | 10.13 / 40 | 3.635 / 30 | 2.580 / 30 | 1.131 / 30 | 2.668 | 2.057 | 7.141 | 2 |
| 3 | A/BCDE, BC/DE, B/C, D/E | 8.231 / 30 | 3.635 / 30 | 3.385 / 40 | 1.131 / 30 | 2.673 | 2.057 | 7.151 | 3 |
| 4 | A/BCDE, BCD/E, B/CD, C/D | 10.13 / 40 | 4.667 / 40 | 3.385 / 40 | 1.131 / 30 | 2.661 | 2..086 | 7.157 | 4 |
| 5 | A/BCDE, BCD/E, BC/D, B/C | 8.231 / 30 | 3.635 / 30 | 2.580 / 30 | 1.131 / 30 | 2.687 | 2.051 | 7.171 | 5 |
| 6 | AB/CDE, A/B, C/DE, D/E | 10.13 / 40 | 4.667 / 40 | 2.580 / 30 | 1.131 / 30 | 2.674 | 2.080 | 7.176 | 6 |
| 7 | AB/CDE, A/B, CD/E, C/D | 8.231 / 40 | 4.667 / 40 | 3.385 / 40 | 1.131 / 30 | 2.680 | 2.081 | 7.187 | 7 |
| 8 | ABC/DE, A/BC, B/C, D/E | 10.13 / 40 | 3.884 / 40 | 3.635 / 30 | 1.131 / 30 | 2.757 | 1.947 | 7.200 | 8 |
| 9 | ABC/DE, AB/C, A/B, D/E | 8.231 / 30 | 4.667 / 40 | 2.580 / 30 | 1.131 / 30 | 2.693 | 2.075 | 7.206 | 9 |
| 10 | ABCD/E, A/BCD, B/CD, C/D | 8.231 / 30 | 3.884 / 40 | 3.635 / 30 | 1.131 / 30 | 2.776 | 1.941 | 7.230 | 10 |
| 11 | ABCD/E, A/BCD, BC/D, B/C | 10.13 / 40 | 2.991 / 30 | 3.635 / 30 | 1.131 / 30 | 2.777 | 1.941 | 7.233 | 11 |
| 12 | ABCD/E, AB/CD, A/B, C/D | 8.231 / 30 | 2.991 / 30 | 3.635 / 30 | 1.131 / 30 | 2.796 | 1.936 | 7.263 | 12 |
| 13 | ABCD/E, ABC/D, A/BC, B/C | 10.13 / 40 | 3.884 / 40 | 4.667 / 40 | 1.131 / 30 | 2.786 | 1.960 | 7.268 | 13 |
| 14 | ABCD/E, ABC/D, AB/C, A/B | 4.662 / 40 | 8.231 / 30 | 3.635 / 30 | 1.131 / 30 | 2.830 | 1.889 | 7.281 | 14 |

Table 3: Designing all of the feasible column sequences with variable temperature & pressure and have been ranked based on Total Annual Cost (TAC) as an object function

## IV. CONCLUSION

Generally, the achievement of an optimum sequence of different possible sequence of distillation columns for a multicomponent mixture is relevant to many parameters as operating pressure, operating temperature, and reflux ratio, the sort of desirable products and different sequences of splits. On the other hand, this problem should be solved around of a search domain and limited its through applying some restrictions. Different sequencing require different operating cost. So we can do case study and choose optimum one.

| New Design Approach | Object Function TAC (\$/years)×$10^5$ | Saving (%) | Relative (%) | Rank |
|---|---|---|---|---|
| Step 3 | 7.121 | 21.4 | 78.6 | 1 |
| Step 2 | 7.303 | 19.4 | 80.6 | 2 |
| Step 1 | 9.062 | - | 100 | 3 |

Table 4: Comparing the performance of designed column sequences with economic saving

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