Environmental Energy and Economic Research (2017) 1(1):125-140
DOI 10.22097/eeer.2017.46462

Energy and Economic Optimization of Distillation Sequencing

Reza Ahmadi Pouya[a,*], **Saeed Soltanali**[b]

[a] Shahid Hasheminejad Gas Refinery (Khangiran), Sarakhs, Iran
[b] Research Institute of Petroleum Industry (RIPI), Tehran, Iran

Received: 1 October 2016 /Accepted: 8 January 2017

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. As take a separation system with optimal performance is dependent on optimization of above mentioned effective parameters. 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. Likewise from money saving outlook our purpose to carry out of the design of one separation system that its design costs becomes minimum. In this paper, concentrate more on optimization of distillation sequencing problem with energy consumption and design costs for a multi-component mixture. Hence we studied the various alternative options to separate a multicomponent feed stream consist of C_3, i-C_4, n-C_4, i-C_5, n-C_5, C_6 and C_7.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. Finally with regard to the effects of operating conditions like operating pressure, temperature and reflux ratio, the optimum separating method has been suggested for this case study.

Keywords: Distillation column sequencing, Optimization of sequencing column, Energy saving, optimization

Introduction

Basically Distillation column used to separate one feed stream into two streams with more volatilizes (overhead product) and less volatilizes (bottom product). Almost all chemical processes require the separation of chemical species (components), to: purify a reactor feed, recover unreacted species for recycle to a reactor and separate and purify the products from a reactor. For a binary mixture, it may be possible to select a separation method that can accomplish the separation task in just one piece of equipment. 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

---

[*] Corresponding author E-mail: pooya14092@yahoo.com

divided as following (Coker, 2015; Smith, 2005; Caballero and Grossmann, 2015; Vargas and Fieg, 2012)

- Flash (based on pressure reduction or heat transfer)
- Ordinary distillation (based on heat transfer or shaft work)
- Gas absorption (based on liquid absorbent)
- Stripping (based on vapor stripping agent)
- Extractive distillation (based on liquid solvent and heat transfer)
- Azeotropic distillation (based on liquid entrainer and heat transfer)
- Liquid-liquid extraction (based on liquid solvent)
- Crystallization (based on heat transfer)
- Gas adsorption (based on solid adsorbent)
- Liquid adsorption (based on solid adsorbent)
- Membrane (based on membrane)
- Supercritical extraction (based on supercritical solvent)
- Leaching (based on liquid solvent)
- Drying (based on heat transfer)
- Desublimation (based on heat transfer)

The selection of separation methods depends on feed condition (partial condensation, cryogenic distillation, absorption, adsorption etc for vapor feed streams and partial vaporization, distillation, crystallization etc for liquid feed streams). 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:

$$\mathrm{SF} = \frac{\mathrm{C_1}^{\mathrm{I}}/\mathrm{C_2}^{\mathrm{I}}}{\mathrm{C_1}^{\mathrm{II}}/\mathrm{C_2}^{\mathrm{II}}} \tag{1}$$

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

SF is generally limited by thermodynamic equilibrium. For example, in the case of distillation, using mole fractions as the composition variable and letting 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) as:

$$\mathrm{SF} = \frac{y_1/x_1}{y_2/x_2} = \frac{K_1}{K_2} = \alpha_{1,2} \ \left(= \frac{P_1^s}{P_2^s}\right) \text{ for ideal L and V} \tag{2}$$

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. This separation system is called as distillation column sequencing system. 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 (Errico et al., 2014; Errico et al. 2014; Hasanzadeh Lashkajani et al., 2013; Cortez-Gonzalez et al., 2014; King, 2013).

Since several researches has been accomplished upon this issue. Different Column sequencing systems for separating one ternary mixture can be found (see fig.1). Conventional sequence includes two columns in series where first column’s product is as feed stream for second column (Jain et al., 2012). Here both of columns have one reboiler and one condenser. Thus the measure of energy consumption in subject to energy lost will be increased. Heat-integrated sequence due to notable reduction in energy consumption is one of the most effective sequence systems. In this system, the overhead stream of either of columns used to as a heating source for another column. In other words first column boils up the second or otherwise (Jain et al., 2012; Jana, 2010). In the thermo coupling sequence, heat demand for separation is provided through direct contact of the processes streams. Namely two main columns are connected with overhead and bottom product stream not interfering any reboiler and condenser. This matter cause to increase the thermodynamic efficiency of sequence and decrease design costs too (Caballero, 2009; Triantafyllou and Smith, 1992). 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 condenser. Further liquid and gas streams in the different columns must be same composition (Emtir, 2002).

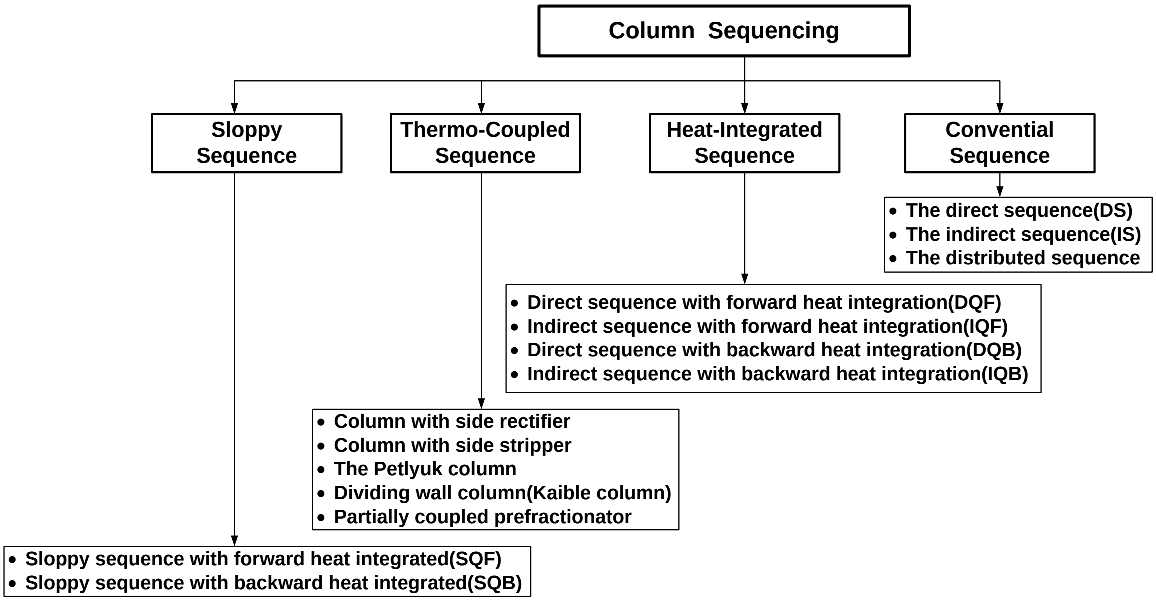


Figure 1. The possibilities of column sequencing for separating ternary mixture.

The separation of a multicomponent mixture is conventionally accomplished in a series of columns, each having a condenser and a reboiler. These conventional distillation columns require high energy input to the reboilers and lot of energy wasted in the condensers. 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.

In the table 1 is done a comparison between the aforementioned sequence columns (Emtir, 2002).

When we want to separate a n components mixture into n specific product, we need to (n-1) distillation columns with one feed stream and two product stream, (as an overhead & bottom product).Equation 1,gives a relation for estimating the number of column sequences to separate a n components into n component products (Setty, 2005).

$$S_n = \sum_{J=1}^{n-1} S_J \, S_{n-J} \tag{3}$$

where,

S_n : The number of column sequences.

S_J : The number of sequences by which the J overhead components from the first column can be separated in subsequent distillations.
S_{n-J} : The number of sequences by which the bottom components from first column can be separated in subsequent distillations.
n : The number of components.

In general, to separate a multi-component mixture can be used equation 2 (Setty, 2005).

$$S_n = [2(n-1)]!/[n!(n-1)!] \tag{4}$$

Table 2 based on equation (2) represents the number of required sequences to separate a multi-component (Setty, 2005).

Table 1. The specification of different column sequencing.

Column Sequencing	Specifications of Column sequencing
Conventional Sequence	1-Sharp separation: initially two components of adjacent relative volatility are separated and therefore difficulty separated. 2-Remixing of the middle component where result in dissipation of energy. 3-Two columns are connected with reboilers and condensers where result in addition of energy consumption.
Heat-Integrated Sequence	1-Sloppy separation: initially two components of extreme relative volatility are separated and therefore easily separated. 2-No remixing of the middle component where result in energy saving. 3-Replacing a heat exchanger instead of one reboiler and condenser where result in reduction of energy requirement for reboiler and energy losses in condenser.
Thermo-Coupled Sequence	1-Sloppy separation: initially two components of extreme relative volatility are separated and therefore easily separated. 2-No remixing of the middle component where result in energy saving. 3-Thermally coupler of main column and side unit (i.e. stripper, rectifier, prefractionator). 4-Directly connection of main columns without any reboiler or condenser.
Sloppy Sequence	1-Sloppy separation: initially two components of extreme relative volatility are separated and therefore easily separated. 2-No remixing of the middle component where result in energy saving. 3-Thermally coupler of main column and side unit. 4-Replacing a heat exchanger instead of one reboiler and condenser where result in reduction of energy requirement for reboiler and energy losses in condenser. 5-Energy requirement is provided through reboiler and condenser.

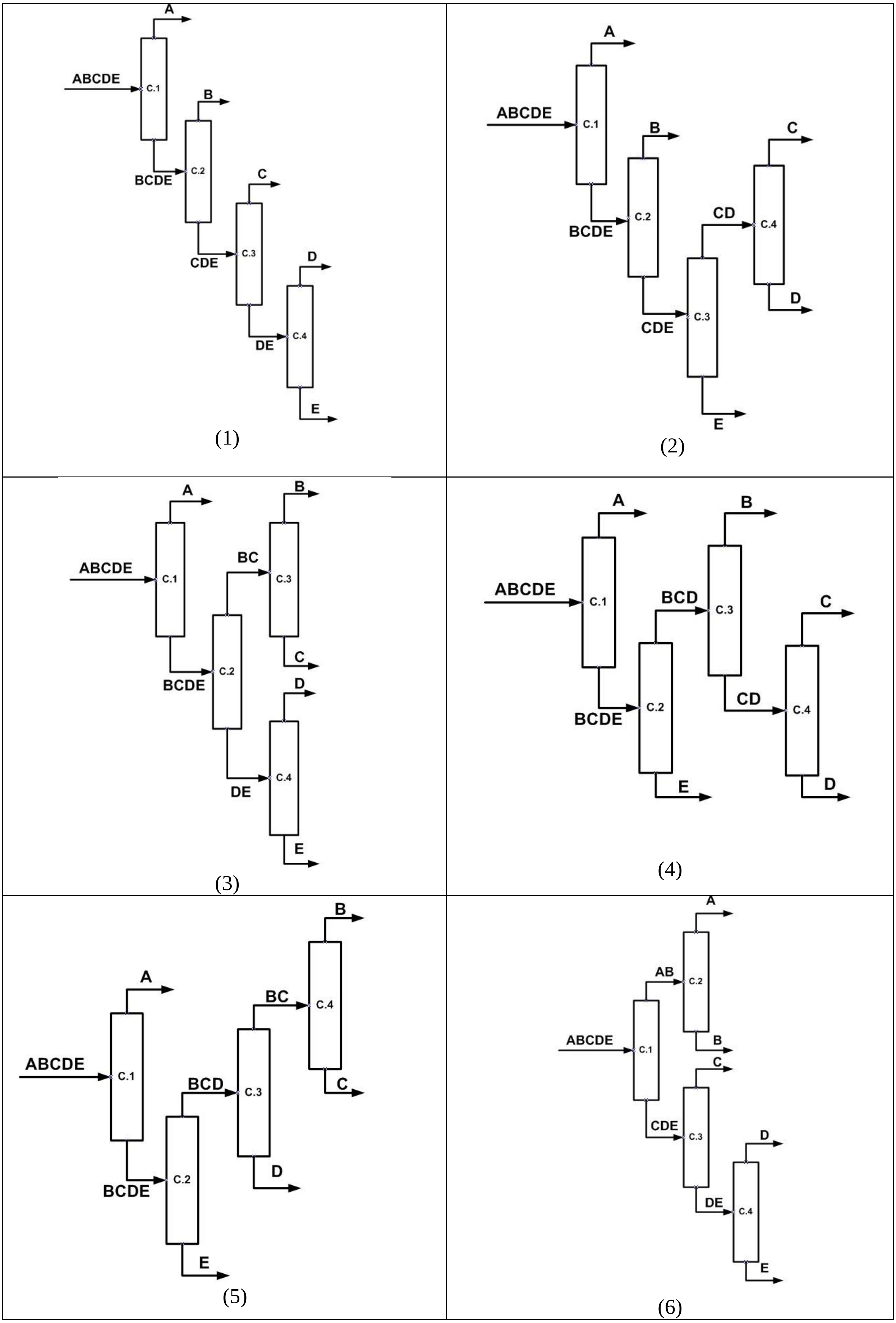
Table 2. Number or required sequences to separate a multi-component.

Number of Components	2	3	4	5	6	7	8	9	10
Number of Column Sequences	1	2	5	14	42	132	429	1430	4862

As a above-mentioned illustrations, there are 14 different column arrangements for separating of a mixture involved five components. These are shown in figure 2.

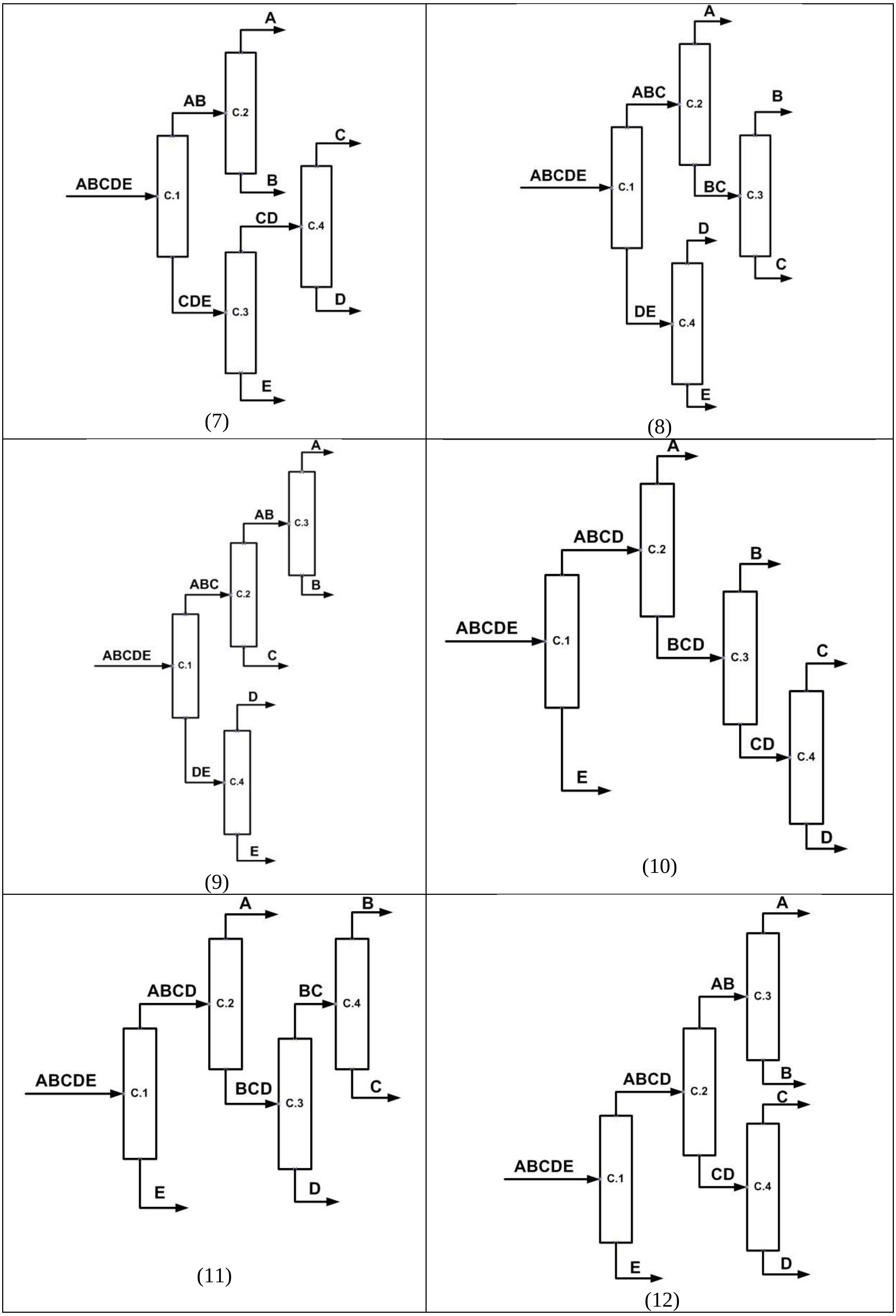
Material and Methods

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. The global steps of research can be realized from figure 3.



(1) (2) (3) (4) (5) (6)

Figure 2. different column sequences to separate a five-component mixture.

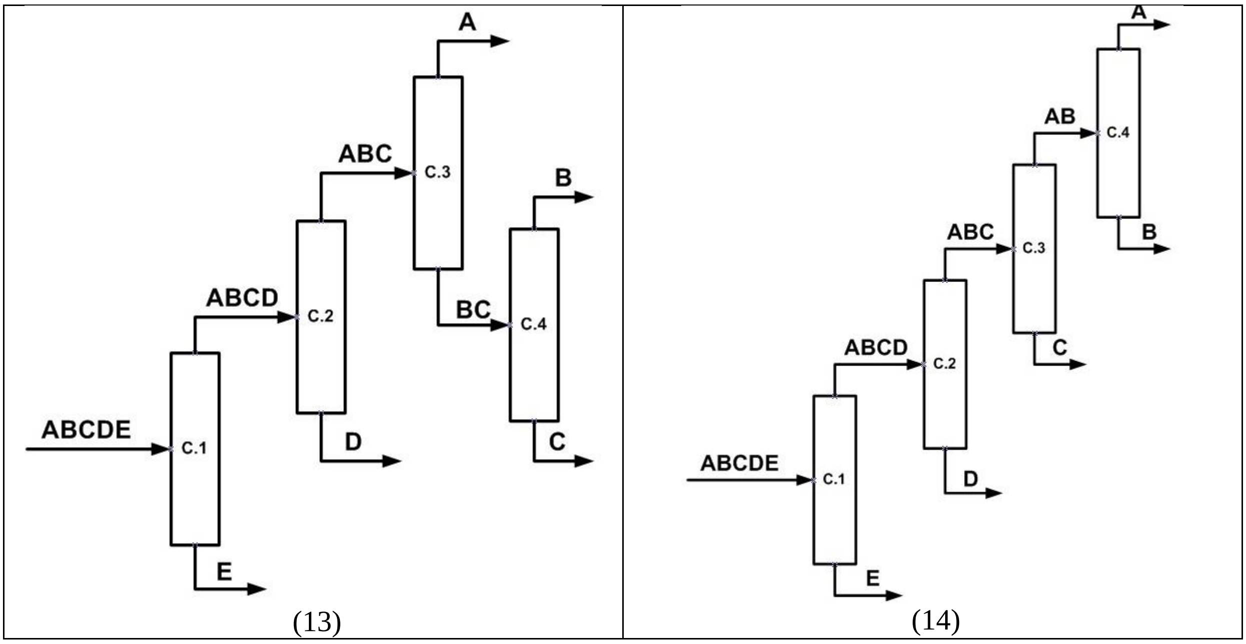


(7) (8)

(9) (10)

(11) (12)

Continued Figure 2. different column sequences to separate a five-component mixture.



Continued Figure 2. Different column sequences to separate a five-component mixture.

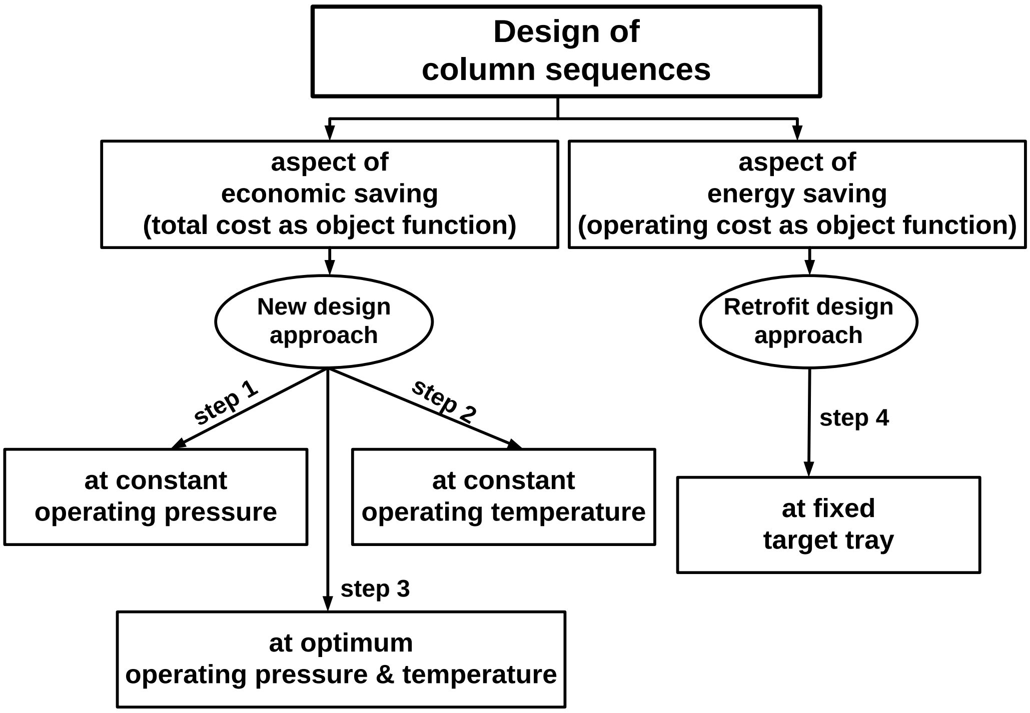


Figure 3. Global steps of research.

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 (Setty, 2005).

First law of thermodynamics :

$$\sum_{\text{out of system}} (\mathrm{nh} + \mathrm{Q} + \mathrm{W_S}) - \sum_{\text{in to system}} (\mathrm{nh} + \mathrm{Q} + \mathrm{W_S}) = 0 \tag{5}$$

Second low of thermodynamics :

$$\sum_{\text{out of system}} (\mathrm{ns} + \mathrm{Q}/\mathrm{T_S}) - \sum_{\text{in to system}} (\mathrm{ns} + \mathrm{Q}/\mathrm{T_S}) = \Delta\mathrm{S_{irr}} \tag{6}$$

Exergy balance :

$$\sum_{\text{in to system}} \left[\mathrm{nb} + \mathrm{Q}\left[1 - \frac{\mathrm{T_0}}{\mathrm{T_S}}\right] + \mathrm{W_S}\right] - \sum_{\text{out of system}} \left[\mathrm{nb} + \mathrm{Q}\left[1 - \frac{\mathrm{T_0}}{\mathrm{T_S}}\right] + \mathrm{W_S}\right] = \mathrm{LW} \tag{7}$$

Minimum work of separation :

$$\mathrm{W_{min}} = \sum_{\text{out of system}} \mathrm{nb} - \sum_{\text{in to system}} \mathrm{nb} \tag{8}$$

Second law efficiency :

$$\eta = \frac{\mathrm{W_{min}}}{\mathrm{LW} + \mathrm{W_{min}}} \tag{9}$$

where;
b= exergy function; b=h-T_0S
LW= lost work in the system; LW= T_0 (ΔS_{irr})
η= thermodynamic efficiency

For better explain about such systems, now we are modeling a conventional distillation column (figure3) (Jin Jang and Han Kim, 2015; Wakabayashi and Hasebe, 2015; Takase and Hasebe, 2015; Nakaiwa et al., 2003) in terms of the first and second-laws of thermodynamics. So that, following equations can be derived (Nakaiwa et al., 2003).

$$\mathrm{Q_{REB}} - \mathrm{Q_{COND}} + \mathrm{FH_F} - \mathrm{DH_D} - \mathrm{BH_B} = 0 \tag{10}$$

$$\Delta\mathrm{S} = \frac{\mathrm{Q_{COND}}}{\mathrm{T_{COND}}} - \frac{\mathrm{Q_{REB}}}{\mathrm{T_{REB}}} - \mathrm{FS_F} + \mathrm{DS_D} + \mathrm{BS_B} \geq 0 \tag{11}$$

$$\begin{aligned}\mathrm{W_{LOSS}} &= \mathrm{T_0}\,\Delta\mathrm{S} \\ &= \mathrm{Q_{REB}}(1 - \mathrm{T_0}/\mathrm{T_{REB}}) - \mathrm{Q_{COND}}(1 - \mathrm{T_0}/\mathrm{T_{COND}}) \\ &\quad - \mathrm{W_{min}}\end{aligned} \tag{12}$$

$$\begin{aligned}\mathrm{W_{min}} &= (\mathrm{DH_D} + \mathrm{BH_B} - \mathrm{FH_F}) - \mathrm{T_0}(\mathrm{DS_D} + \mathrm{BS_B} - \mathrm{FS_F}) \\ &= \Delta\mathrm{H} - \mathrm{T_0}\,\Delta\mathrm{S}\end{aligned} \tag{13}$$

$$\eta_{\mathrm{con}} = \mathrm{W_{min}}/(\mathrm{W_{Loss}} + \mathrm{W_{min}}) \leq \mathrm{W_{min}}/(\mathrm{Q_{REB}} - \mathrm{Q_{COND}}) \tag{14}$$

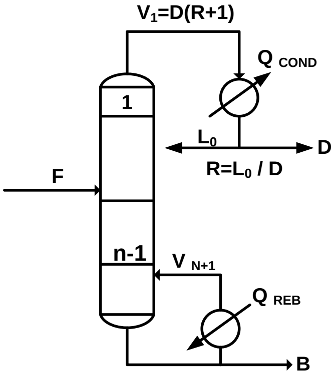


Figure 3. A conventional distillation column.

Case study

A multi-component mixture consist of C_3,i-C_4,n-C_4,i-C_5,n-C_5,C_6 and C_7 with given composition is available . General purpose is separating feed stream into five product streams through design an optimum separation system. The information of process stream exists in table 3.

Table 3. Information of feed and product streams.

Feed Stream Properties		
Component	**Composition (mole basis)**	
C3	0.05	
i-C4	0.15	
n-C4	0.25	
i-C5	0.2	
n-C5	0.2	
C6	0.1	
C7	0.05	
Temperature (℃)	**Pressure (bar)**	**Molar Flow Rate (kgmole/hr)**
67	5	100
Product Stream Properties		
Split Keys		
	Light key	**Heavy Key**
Split A/B	C3	i-C4
Split B/C	i-C4	n-C4
Split C/D	n-C4	i-C5
Split D/E	i-C5	n-C5

Results and discussion

In the present study, all of different possible sequence of distillation columns are 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).According to this, the synthesis of distillation sequences have done and the effects of different sequences splits have been surveyed. The results are presented at tables 4 and 5.

- 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 parameters. The results are presented at tables 6 and 7.
- 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. Then it has been solved sequencing and pressure optimization problems simultaneously. The results are presented at tables 8 and 9.
- 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 results are presented at tables 10, 11 and 12.

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.

Table 4. 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**	**Capital Cost** $(\$).\mathbf{10^6}$	**Operating Cost** $(\$/\mathbf{years}).\mathbf{10}$	**Total Cost** $(\$/\mathbf{years}).\mathbf{10^6}$	**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 5 Energy consumption at hot & cold utilities used to column sequences.

Design No.	**Sequence**	**Condenser Duty (MW)**	**Reboiler Duty (MW)**
1	A/BCDE, B/CDE, C/DE, D/E	2.9745	3.522
2	A/BCDE, B/CDE, CD/E, C/D	2.9016	3.419
3	A/BCDE, BC/DE, B/C, D/E	2.8902	3.308
4	A/BCDE, BCD/E, B/CD, C/D	2.8336	3.266
5	A/BCDE, BCD/E, BC/D, B/C	2.8454	3.243
6	AB/CDE, A/B, C/DE, D/E	2.7903	3.353
7	AB/CDE, A/B, CD/E, C/D	2.7208	3.250
8	ABC/DE, A/BC, B/C, D/E	2.8609	3.232
9	ABC/DE, AB/C, A/B, D/E	2.7376	3.170
10	ABCD/E, A/BCD, B/CD, C/D	2.8026	3.178
11	ABCD/E, A/BCD, BC/D, B/C	2.8144	3.154
12	ABCD/E, AB/CD, A/B, C/D	2.6502	3.072
13	ABCD/E, ABC/D, A/BC, B/C	2.8182	3.141
14	ABCD/E, ABC/D, AB/C, A/B	2.6949	3.080

Table 6. 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				Capital Cost $(\$).10^6$	Operating Cost $(\$/\text{years}).10^5$	Total Cost $(\$/\text{years}).10^6$	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 7. Energy consumption at hot and cold utilities used to column sequences.

Design Nu.	Sequence	Condenser Duty (MW)	Reboiler Duty (MW)
1	A/BCDE, B/CDE, C/DE, D/E	1.484	3.184
2	A/BCDE, B/CDE, CD/E, C/D	2.629	2.990
3	A/BCDE, BC/DE, B/C, D/E	2.723	3.139
4	A/BCDE, BCD/E, B/CD, C/D	2.597	2.904
5	A/BCDE, BCD/E, BC/D, B/C	2.740	3.124
6	AB/CDE, A/B, C/DE, D/E	2.658	3.082
7	AB/CDE, A/B, CD/E, C/D	2.737	3.067
8	ABC/DE, A/BC, B/C, D/E	2.613	3.035
9	ABC/DE, AB/C, A/B, D/E	2.720	3.082
10	ABCD/E, A/BCD, B/CD, C/D	2.748	3.231
11	ABCD/E, A/BCD, BC/D, B/C	2.740	3.051
12	ABCD/E, AB/CD, A/B, C/D	2.710	3.005
13	ABCD/E, ABC/D, A/BC, B/C	2.568	2.859
14	ABCD/E, ABC/D, AB/C, A/B	2.662	2.995

Table 8. 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.

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	3.635	3.385	1.131	2.655	2.063	7.121	1
		40	30	40	30				
2	A/BCDE, B/CDE, CD/E, C/D	10.13	3.635	2.580	1.131	2.668	2.057	7.141	2
		40	30	30	30				
3	A/BCDE, BC/DE, B/C, D/E	8.231	3.635	3.385	1.131	2.673	2.057	7.151	3
		30	30	40	30				
4	A/BCDE, BCD/E, B/CD, C/D	10.13	4.667	3.385	1.131	2.661	2..086	7.157	4
		40	40	40	30				
5	A/BCDE, BCD/E, BC/D, B/C	8.231	3.635	2.580	1.131	2.687	2.051	7.171	5
		30	30	30	30				
6	AB/CDE, A/B, C/DE, D/E	10.13	4.667	2.580	1.131	2.674	2.080	7.176	6
		40	40	30	30				
7	AB/CDE, A/B, CD/E, C/D	8.231	4.667	3.385	1.131	2.680	2.081	7.187	7
		40	40	40	30				
8	ABC/DE, A/BC, B/C, D/E	10.13	3.884	3.635	1.131	2.757	1.947	7.200	8
		40	40	30	30				
9	ABC/DE, AB/C, A/B, D/E	8.231	4.667	2.580	1.131	2.693	2.075	7.206	9
		30	40	30	30				
10	ABCD/E, A/BCD, B/CD, C/D	8.231	3.884	3.635	1.131	2.776	1.941	7.230	10
		30	40	30	30				
11	ABCD/E, A/BCD, BC/D, B/C	10.13	2.991	3.635	1.131	2.777	1.941	7.233	11
		40	30	30	30				
12	ABCD/E, AB/CD, A/B, C/D	8.231	2.991	3.635	1.131	2.796	1.936	7.263	12
		30	30	30	30				
13	ABCD/E, ABC/D, A/BC, B/C	10.13	3.884	4.667	1.131	2.786	1.960	7.268	13
		40	40	40	30				
14	ABCD/E, ABC/D, AB/C, A/B	4.662	8.231	3.635	1.131	2.830	1.889	7.281	14
		40	30	30	30				

Table 9. Energy consumption at hot & cold utilities used to column sequences.

Design No.	Sequence	Condenser Duty (MW)	Reboiler Duty (MW)
1	A/BCDE , B/CDE , C/DE , D/E	2.667	3.144
2	A/BCDE , B/CDE , C/DE , D/E	2.665	3.134
3	A/BCDE , B/CDE , C/DE , D/E	2.667	3.135
4	A/BCDE , B/CDE , C/DE , D/E	2.697	3.181
5	A/BCDE , B/CDE , C/DE , D/E	2.659	3.126
6	A/BCDE , B/CDE , C/DE , D/E	2.689	3.171
7	A/BCDE , B/CDE , C/DE , D/E	2.691	3.172
8	A/BCDE , BC/DE , B/C , D/E	2.601	2.958
9	A/BCDE , B/CDE , C/DE , D/E	2.683	3.162
10	A/BCDE , BC/DE , B/C , D/E	2.595	2.950
11	A/BCDE , BC/DE , B/C , D/E	2.595	2.950
12	A/BCDE , BC/DE , B/C , D/E	2.589	2.941
13	A/BCDE , BC/DE , B/C , D/E	2.619	2.978
14	ABC/DE , A/BC , B/C , D/E	2.564	2.866

Table 10. Retrofitting all of the feasible column sequences considering fixed target trays 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	5	5	5	5	3.791	2.330	0.9555	14
2	A/BCDE, B/CDE, CD/E, C/D	5	5	5	5	3.858	2.275	0.9627	13
3	A/BCDE, BC/DE, B/C, D/E	5	5	5	5	4.208	2.202	1.022	12
4	A/BCDE, BCD/E, B/CD, C/D	5	5	5	5	4.030	2.188	0.9867	11
5	A/BCDE, BCD/E, BC/D, B/C	5	5	5	5	4.248	2.172	1.027	10
6	AB/CDE, A/B, C/DE, D/E	5	5	5	5	4.176	2.141	1.010	8
7	AB/CDE, A/B, CD/E, C/D	5	5	5	5	4.243	2.085	1.017	4
8	ABC/DE, A/BC, B/C, D/E	5	5	5	5	4.158	2.151	1.007	9
9	ABC/DE, AB/C, A/B, D/E	5	5	5	5	4.438	2.069	1.053	3
10	ABCD/E, A/BCD, B/CD, C/D	5	5	5	5	4.092	2.111	0.9908	7
11	ABCD/E, A/BCD, BC/D, B/C	5	5	5	5	4.309	2.095	1.031	5
12	ABCD/E, AB/CD, A/B, C/D	5	5	5	5	4.444	1.982	1.095	1
13	ABCD/E, ABC/D, A/BC, B/C	5	5	5	5	4.238	2.098	1.017	6
14	ABCD/E, ABC/D, AB/C, A/B	5	5	5	5	4.518	2.016	1.062	2

Table 11. Energy consumption at hot & cold utilities used to column sequences.

Design No.	Sequence	Condenser Duty (MW)	Reboiler Duty (MW)
1	A/BCDE, B/CDE, C/DE, D/E	2.9778	3.520
2	A/BCDE, B/CDE, CD/E, C/D	2.9145	3.427
3	A/BCDE, BC/DE, B/C, D/E	2.9027	3.324
4	A/BCDE, BCD/E, B/CD, C/D	2.8528	3.291
5	A/BCDE, BCD/E, BC/D, B/C	2.8528	3.291
6	AB/CDE, A/B, C/DE, D/E	2.8768	3.357
7	AB/CDE, A/B, CD/E, C/D	2.8135	3.264
8	ABC/DE, A/BC, B/C, D/E	2.8762	3.252
9	ABC/DE, AB/C, A/B, D/E	2.8349	3.194
10	ABCD/E, A/BCD, B/CD, C/D	2.8215	3.201
11	ABCD/E, A/BCD, BC/D, B/C	2.8369	3.185
12	ABCD/E, AB/CD, A/B, C/D	2.7508	3.100
13	ABCD/E, ABC/D, A/BC, B/C	2.8411	3.172
14	ABCD/E, ABC/D, AB/C, A/B	2.7998	3.114

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. The performance of designed column sequences is affected by the changes of operating conditions. On the other hand, this problem should be solved around of a search domain and limited its through applying some restrictions. Thereby we can close to optimum design option subject to optimum operating conditions or object functions (usually total annual cost).

Table 12. Optimizing of reflux rations in all of the designed column sequences.

Design No.	**Sequence**	**Number of Trays**				**R / R_{min}**			
		column 1	**column 2**	**column 3**	**column 4**	**column 1**	**column 2**	**column 3**	**column 4**
1	A/BCDE, B/CDE, C/DE, D/E	20	65	30	75	1.076	1.025	1.020	1.167
2	A/BCDE, B/CDE, CD/E, C/D	20	65	75	30	1.076	1.025	1.173	1.020
3	A/BCDE, BC/DE, B/C, D/E	20	30	65	75	1.076	1.023	1.020	1.167
4	A/BCDE, BCD/E, B/CD, C/D	20	75	65	30	1.076	1.182	1.024	1.020
5	A/BCDE, BCD/E, BC/D, B/C	20	75	30	65	1.076	1.182	1.024	1.020
6	AB/CDE, A/B, C/DE, D/E	65	30	20	75	1.024	1.020	1.085	1.167
7	AB/CDE, A/B, CD/E, C/D	65	75	20	30	1.024	1.173	1.085	1.020
8	ABC/DE, A/BC, B/C, D/E	30	20	65	75	1.024	1.080	1.020	1.167
9	ABC/DE, AB/C, A/B, D/E	30	65	20	75	1.024	1.021	1.085	1.167
10	ABCD/E, A/BCD, B/CD, C/D	75	20	65	30	1.183	1.084	1.024	1.020
11	ABCD/E, A/BCD, BC/D, B/C	75	20	30	65	1.183	1.084	1.024	1.020
12	ABCD/E, AB/CD, A/B, C/D	75	65	20	30	1.183	1.024	1.085	1.020
13	ABCD/E, ABC/D, A/BC, B/C	75	30	20	65	1.183	1.024	1.080	1.020
14	ABCD/E, ABC/D, AB/C, A/B	75	30	65	20	1.183	1.024	1.021	1.085

Ultimately, the results obtained from previous steps are compared with specific object function (here total annual cost) and the optimum designed option are suggested.

Based on above-mentioned, the results of this problem have been checked with energy consumption and design costs consideration, can be observing at tables 13 and 14.

Table 13. Comparing the performance of designed column sequences with economic saving.

New Design Approach	**Object Function** TAC $(\$/\text{years}) \times \mathbf{10^5}$	**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 14. Comparing the performance of designed column sequences with energy saving.

Design	**Object Function** **Operating Cost** $(\$/\mathbf{years}) \times \mathbf{10^5}$	**Capital Cost** $(\$) \times \mathbf{10^6}$	**Saving (%)**	**Relative (%)**	**Rank**
Step 4	1.984	0	15.1	84.9	1
Strep 3	2.063	2.655	11.8	88.2	2
Step 2	2.089	2.736	10.7	89.3	3
Step 1	2.338	3.529	-	100	4

Reference

Caballero, J.A. (2009). Thermally-coupled Distillation, Computer Aided Chemical Engineering, 27, 59–64.

Caballero, J. A. and Grossmann, I. E. (2015). Optimal synthesis of thermally coupled distillation sequences using a novel MILP approach, Computers & Chemical Engineering, 61, 118–135.

Coker, A. K. (2015). Ludwig's Applied Process Design for Chemical and Petrochemical Plants. New York: Gulf Professional Publishing.

Cortez-Gonzalez, J. and Segovia-Hernández, J. G., Hernández, S., Gutiérrez-Antonio, C., Briones-Ramírez, A., Rong B. G. (2014). Chemical Engineering Research and Design, 90, 1425-1447.

Emtir, M. M. K. (2002). Economic and controllability Analysis of Energy-Integrated Distillation. Schemes. Department of chemical Engineering, Budapest University of Technology and Economics.

Errico, M., Pirellas, P., Rong, B.-G., Ortega, C. E. T. and Segovia-Hernandez, J. G. (2014). A combined method for the design and optimization of intensified distillation systems, Chemical Engineering and Processing: Process Intensification, 85, 69–76.

Errico, M., Pirellas, P., Rong, B.-G., Ortega, C. E. T. and Segovia-Hernandez, J. G. (2014). The importance of the sequential synthesis methodology in the optimal distillation sequences design, Computers & Chemical Engineering, 62, 1–9.

Hasanzadeh Lashkajani K., Ghorbani B., Salehi G. R. and Amidpour M. (2013). The Design and Optimization of Distillation Column with Heat and Power Integrated Systems, Gas Processing Journal, 1, 51-68.

Jain, S., Smith, R. and Kim, J.K. (2012). Synthesis of heat-integrated distillation sequence systems, Journal of the Taiwan Institute of Chemical Engineers, 43(4), 525–534.

Jana, K. (2010). Heat integrated distillation operation, Applied Energy, 87(5), 1477‑1494.

Jin Jang, D. and Han Kim, Y. (2015). A new horizontal distillation for energy saving with a diabatic rectangular column, Korean Journal of Chemical Engineering , 32, 2181-2186.

King, C.J. (2013). Separation Processes, 2nd Edition, New York: Dover Publications.

Setty, Y. P. (2005).Optimization of Distillation Sequences, Journal of Institution of Engineers, 85, 69-75.

Nakaiwa, M. Huang, K. Endo, T. Ohmori, T. Akiya T. and Takamatsu, T. (2003). Internally Heat- Integrated Distillation Columns: A Review, Chemical Engineering Research and Design, 81(1), 162–177.

Smith, R. (2005). Chemical Process Design and Integration. New York: John Wiley & Sons Ltd.

Takase, H. and Hasebe, S. (2015). Optimal structure synthesis of internally heat integrated distillation column, Journal of Chemical Engineering of Japan, 48, 222-229.

Triantafyllou, C. and Smith, R. (1992). The Design and Optimization of Fully Thermally-coupled Distillation Columns,Trans IChemE,70A, 118-132.

Vargas, M. A. and Fieg, G. (2012). Simulation study of alternatives for the efficient start-up of dividing-wall distillation column sequences, Computer Aided Chemical Engineering, 31, 750–754.

Wakabayashi, T. and Hasebe, S. (2015). Higher energy saving with new heat integration arrangement in heat-integrated distillation column, AIChE Journal, 61, 3479–3488.