

# MULTIOBJECT APPROACH FOR TOTAL SEPARATION NETWORK

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## Abstract

A multiobject approach for synthesis the sharp separation network is developed in this paper .This approach consists of two parts, first part for the selection of the best sequence of separation network (without heat integration) and second part synthesis of separation network (with heat integration). The synthesis algorithm is based on application of three expert rules qualification of the estimated mass load, difference in boiling point and relative volatility. Two fuzzy analogical gates are employed (symmetric and asymmetric). The symmetric gate (AND gate) inputs are the normalized estimated mass load with the normalized relative volatility. The asymmetric gate (INVOKE gate) inputs are the output of AND gate and the normalized boiling point difference. The proposed approach is simple to implement and can be done by manual computation. Several illustrative examples using existing fuzzy analogical gate are given to demonstrate the effectiveness of the proposed method.

**Keywords:** distillation sequence synthesis, heat integration , fuzzy analogical gate

## Introduction

Distillation is a well-known commercial procedure for multicomponent separation that uses a lot of energy. Synthesis of energy efficient distillation systems leads not only to improved economic benefits but also to reduced pollution levels By consuming fewer carbon-containing fuels, decreased energy consumption reduces co2 emissions, promoting cleaner production and environmental protection, and hence remains a subject of growing interest of chemical process optimization.

Among the most important topics in the field of process systems engineering is the synthesis of multi - component separation processes. In the petroleum refining industry, multi - component separation methods are used frequently. Multi - component separation sequencing, which is concerned with the choice of the appropriate method and sequence for the separation, is a significant process design challenge.[1]

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One of the most researched difficulties in the synthesis of chemical units is the construction of sharp separation sequences. It can be explained as follows: based on single multicomponent feed mixture with defined circumstances (i.e. flowrate, composition, temperature, and pressure), synthesize a process that can separate the desired products from the feed with a limited annual cost (comprising the sum of the plant's investment cost and annual operating cost). [2]

All such methods of synthesis can be divided into three categories: (a) heuristic methods based on engineering experience, (b) evolutionary strategies that determine the optimal sequence by improving the initially chosen sequence, and (c) algorithmic methods that use optimization techniques in the field of mathematical programming. [3]

Separation is a relatively energy-intensive process in the chemical process industries, with distillation which is the most used method for fluid separation. Considering greater energy awareness and increasing environmental concerns, industry must reduce its energy use. To achieve separation, distillation devices use a lot of energy. Given the increasing cost of energy, it is critical to create distillation systems that use less energy. [4]

The net energy requirements of these systems often vary greatly because to changes in the splitting of the feed into different sub-mixtures. Unfortunately, the numerous design options make it difficult to find the most energy-efficient and operable configurations, especially because configurations that use some of these design characteristics are more difficult to analyze and manage than others.

In general, there are two subtasks in the synthesis of a heat-integrated distillation system. One is to identify the levels or values of design/operating parameters (pressure, flowrate, etc.) of each column in the flow sheet. The other determines the best flow sheet structure, which includes a separation sequence and a heat integration diagram in order to arrive at the overall minimum cost for the process. [5]

Column pressures are chosen to raise the temperature of specific columns so that the heat generated by their condensers could be used to heat the re-boilers of all other columns. [6]

The search for possible heat matches among all the simple columns' condensers and re-boilers is the task of designing a heat-integrated simple column configuration. This is usually accomplished by increasing the pressure of a simple column so that its condenser can serve as a heat source for another column's re-boiler. Although a heat-integrated simple column configuration typically saves energy, its capital cost is frequently higher than its traditional simple column sequence equivalents. [7]

To achieve the global optimum, distillation sequences and heat integration networks should be modified simultaneously. Through superstructure representation and mathematical formulation, mathematical programming methods, which seem to be the most popular methods to synthesize HIDiSs, can accomplish simultaneous optimization of these two sub-problems. [8]

In this work multi-object function of sharp separation is presented that used to select the optimum separation sequence. This approach is consists of two parts, first using the fuzzy analogical gate to select the largest separation weight and the second part is the heat integration to reduce the energy and total annual cost for separation process.

## Problem statement

The problem to be addressed in the paper can be stated as follows: a single multicomponent feed stream with known conditions of flowrate, composition, temperature and pressure, which is to be separated into pure components, and synthesize a heat integrated distillation sequence to satisfy the criterion of minimum total annual cost. Fuzzy analogical gates strategy is employed in the present work to select the optimal separation sequence with heat integration which accordingly leads to minimum total annual cost.

To simplify the synthesis problem, it is assumed that:

- 1) Each distillation column performs a simple split (i.e. one feed and two products):
- 2) Energy matches occur only between boiling and condensing streams.
- 3) The energy match is considered between the re-boiling stream (energy sink) and the condensing stream (energy source). Minimum approach temperature ( $\Delta T_{\min}$ ) is held constant at 2.5K.
- 4) Each column operates at high recovery.
- 5) The volatility order does not change with changes in pressure.
- 6) The cost of changing the temperature and pressure of streams as they pass between columns is negligible compared to column capital and energy costs.
- 7) No matches occur with streams outside of the distillation system.
- 8) No vapor recompression is used

## Synthesis methodology

The synthesis strategy comprises the following seven sequential steps.

- Step1. Determine the three main multiobject functions (the estimated mass load, the difference in boiling point, and the relative volatility).

Table 1 Estimated mass load for N number of components

Number of components (N)	EML Coefficients
1	0
2	$x_A + x_B = 1$
3	$3/2x_A + 2x_B + 3/2x_C$
4	$11/6x_A + 5/2x_B + 5/2x_C + 11/6x_D$
5	$25/12x_A + 17/6x_B + 3x_C + 17/6x_D + 25/12x_E$

N	$\sum_{i=1}^N a_{n,i} \text{ with } a_{1,1} = 0$ $a_{1,i} = \sum_{k=1}^{i-1} \frac{1}{k} \text{ if } i > 1$ $a_{i,j} = \sum_{k=1}^{i-j} \frac{1}{k} + a_{i,j} \text{ if } k < i$
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- Step2. Normalized the three functions including maximum of boiling point temperature difference , minimum of estimated mass load , and maximum of relative volatility using the following equations :

$$\text{Normalized temperature difference} = \frac{\Delta T - \Delta T_{\min}}{\Delta t_{\max} - \Delta t_{\min}} \tag{1}$$

$$\text{Normalized estimated mass load} = \frac{EML_{\max} - EML}{EML_{\max} - EML_{\min}} \tag{2}$$

$$\text{Normalized relative volatility} = \frac{\alpha - \alpha_{\min}}{\alpha_{\max} - \alpha_{\min}} \tag{3}$$

Step3. use the fuzzy analogical gate network as shown in (Fig1) to calculate the separation weight of each possible sequence and then select the best sequence as the largest separation weight value.

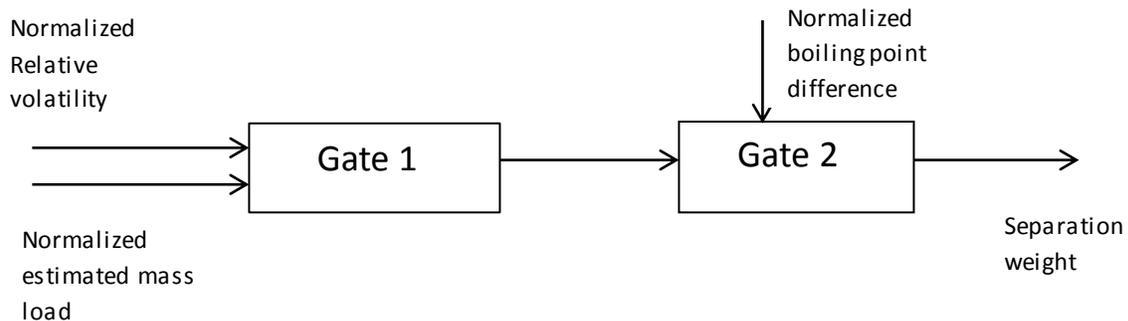


Fig1 fuzzy analogical gate network

Step4. Create a Heat- integrated matrix with the best unconnected sequence, The column temperature difference and column heat load have a significant impact on profitability that select the best heat integration which reduce energy and total cost.

Step5. use heuristic rules to reject infeasible matches

- Rule (1): It is not economical to heat match a column on both ends.
- Rule (2): Select potential matches where the source column's heat load is lower than the sink column's.
- Rule (3): Avoid matching between the columns that have the largest temperature differences

Step6. use the (heat load and temperature difference) to specified the possible splits then normalized the main three parameters ( $Q$ ,  $\Delta T$ ,  $Q \cdot \Delta T$ ) as an input to fuzzy analogical gate

Step7. use the normalized heat load ( $Q$ ), normalized boiling point temperature difference ( $\Delta T$ ) to be the input for the first gate (Gate1) and use the output from (Gate1) with the normalized of ( $Q \cdot \Delta T$ ) value to be the input for second gate (Gate2), then use the separation weight which is the output from (Gate2) to choose the best sequence in the possible matches.

The following figure (Fig2) is summarized the previous steps of fuzzy analogical gate strategy which show how we select the optimum separation sequence with heat integration from the possible splits.

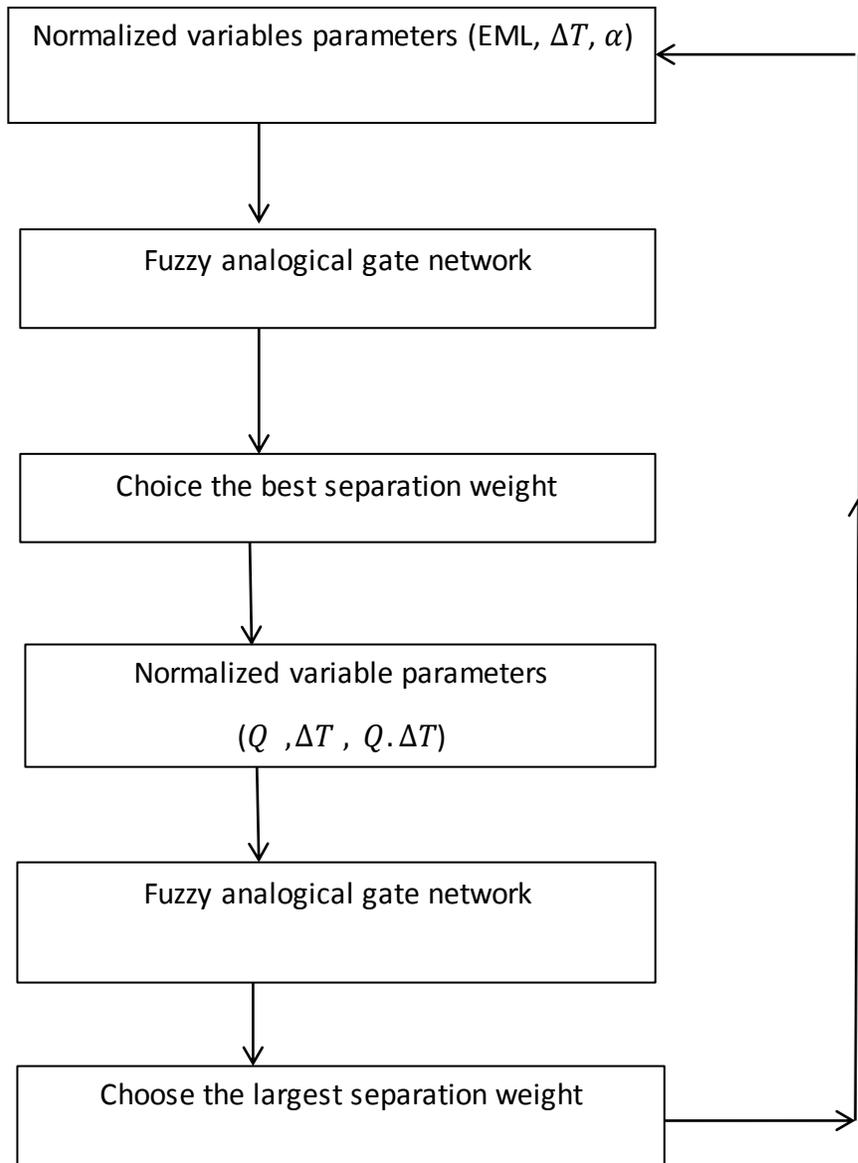


Fig2: fuzzy analogical gate strategy for the separation sequence with heat integration

Step8. determine the temperature elevation and the pressure of the source column then calculate the total cost.

the temperature elevation in the source column

$$\Delta T_i = T_j - T_i + \Delta T_{min} \quad (4)$$

Where i,j is the citation number of source and sink columns, respectively, and  $\Delta T_{min}$  is the minimum approach temperature.

the operating pressure for source column

$$\ln(P_2) = 10.6 \left[ 1 - \frac{T_{co1}}{T_{co2}} \right] + \left[ \frac{T_{co1}}{T_{co2}} \right] \ln(P_1) \quad (5)$$

Where  $T_{co}$  is the condenser temperature in degrees kelvin and  $P$  is the pressure atmospheres

## Fuzzy analogical gate

Fuzzy analogical gates are a novel method of describing multi-valued logical statements. It is a more comprehensive scheme which makes use of the more widespread variation of system variables and their associated values. This method widens the scope of operation of binary logic-based systems to true multi-valued logic-based systems. Furthermore, the design and implementation of these gates for practical physical systems have proven to be efficient and simple. Two fuzzy analogical gates are employed (symmetric and asymmetric) :

### Symmetric Gates

In the fuzzy analogical-AND gate as shown in Fig. 3, the output grows fastest when both inputs simultaneously grow. Also no output is produced if either input is zero. The parameters  $a$  and  $b$  can be obtained by using the boundary conditions and zero derivative on the main axis.

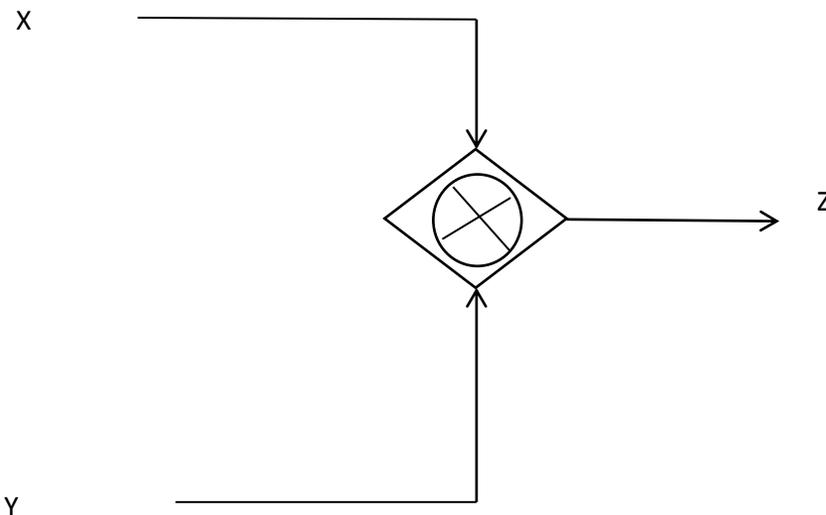


Fig3: Symbols for the analogical (AND) gate

$$Z=X[1 - \varepsilon(X,Y)] + Y[1 - \varepsilon(X,Y)] \quad (\text{equation 7})$$

$$\varepsilon(Y, X) = \exp\left[\frac{-ay^2+byx}{y^2+x^2}\right] \quad \text{and } x, y \in R \quad (\text{equation 8})$$

$$\varepsilon(X, Y) = \exp\left[\frac{-aX^2+bxY}{y^2+x^2}\right] \quad \text{and } x, y \in R \quad (\text{equation 9})$$

The parameters a and b can be obtained by using the boundary conditions and zero derivative on the main axis. In this work the determined values of the coefficients of the exponential function a and b are 2.28466 and -0.89817, respectively.

### Asymmetric Gates

The invoke gate is characterized such that as the x-input grows, the share of the y-input to the output increases. The absence of the x-input inhibits the output. In the absence of the y-input, the x-input is linearly passed to the output as shown in Fig.4 . In prevail gate the x-port is assigned an exceptional prevalence over the y-port. The latter is put-through directly to the output as long as the former is absent. However, once the input is at the prevalent part it strongly dominates the output .

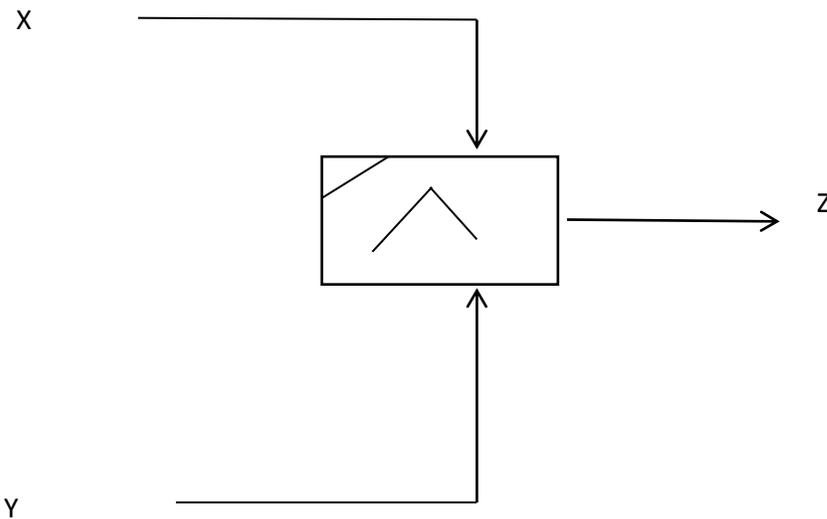


Fig4: Symbols for the analogical (invoke) gate

$$Z = X[1 - \varepsilon_1(X, Y)] + Y[1 - \varepsilon_2(X, Y)] \quad (\text{equation 10})$$

$$\varepsilon(Y, X) = \exp\left[\frac{-a_1 y^2 + b_1 yx}{y^2 + x^2}\right] \quad \text{and } x, y \in R \quad (\text{equation 11})$$

$$\varepsilon(X, Y) = \exp\left[\frac{-a_2 X^2 + b_2 xy}{y^2 + x^2}\right] \quad \text{and } x, y \in R \quad (\text{equation 12})$$

The coefficients of the exponential functions can be obtained by using the boundary conditions and zero derivative on the main axis. The determined values of the constants are as follows:

$$a_1 = 1.4749267, \quad b_1 = 0.92870491$$

$$a_2 = 2.6317713, \quad b_2 = 0.2287955$$

## Examples

Three examples are solved to show the effectiveness of the proposed method. The first example to separate a feed consists of four light hydrocarbons mixture, the second example separating five light hydrocarbons mixture and the third example separate six light hydrocarbons mixture to compare the efficiency of our technique with other methods proposed in the literature.

### Example 1:

The first example consisting of four components that separated in four products by sharp separation. This example given by P. FLOQUET and etc.(1994). The feed stream flow rate is 861.8 kmol/hr with mole fractions as showed in table 2.

Table 2 feed stream characteristics for example 1

component	Mole fraction	Boiling point difference ( $\Delta T$ )	Relative volatility
A: I butane	0.158	11.3	1.49
B: n butane	0.263	28.3	2.72
C: I Pentane	0.210	8.20	1.35
D: N pentane	0.369		

The possibilities split of components (ABCD) and their properties (boiling point temperature difference, estimated mass load and relative volatility) are shown in the following table

Table 3 possible splits and their properties of example1

split	Boiling point Temperature difference ( $^{\circ}\text{K}$ )	Estimated mass load	Relative volatility
A/BCD	11.3	1.368	1.49
AB/CD	28.3	1.000	2.72
ABC/D	8.20	1.078	1.35

The following table show the normalized of the three functions (boiling point temperature difference, estimated mass load and relative volatility) that used as input for fuzzy analogical gate to calculate the separation weight of each spilt to choose the optimum separation sequence.

Table 4 the normalized of the properties for example1

split	Normalized boiling point temperature difference	Normalized Estimated mass load	Normalized relative volatility	Separation weight
A/BCD	0.154	0.000	0.102	0.000
AB/CD	1.000	1.000	1.000	1.000
ABC/D	0.000	0.788	0.000	0.000

AB/CD is the best choice because it has the largest separation weight value (1.000) where AB top product and CD bottom product then we use two column for both AB and CD.

In the next table we represent all possibilities of separation sequence for four components (ABCD) and correspond the total cost for each spilt

Table 5 the cost of all possible splits for example1

NO.	SEPARATION	COST $\times 10^6$
1	AB/CD, A/B, C/D	1.548
2	ABC/D, AB/C,A/B	1.792
3	A/BCD, B/CD,C/D	1.879
4	A/BCD, BC/D,B/C	1.903
5	ABC/D, A/BC,B/C	1.931

SO, the best sequence without heat integration is (AB/CD – A/B - C/D) as shown in table 5 which is the lowest cost compare with other sequences

The optimum separation sequence in pervious section is used to be a data for the next step which is the selection for the best heat integration sequence to minimize the energy and cost of separation processes

Table 6 the characteristics of separation splits for example1

Column	Top temperature (°K)	Bottom temperature (°K)	Pressure (Atm)	Condenser duty	Re-boiler duty
AB/CD	326.9	385.8	5.99	5,257,820	5,367,352
A/B	323.9	340.8	7.08	5,069,522	5,124,112
C/D	325.3	334.8	2.18	1.246E+07	1.286E+07

Table 7 the splits with their heat load for example1

split	Heat load (10 <sup>6</sup> )	Temperature difference (°K)
AB/CD	5.370	58.9
A/B	5.120	16.9
C/D	12.86	9.50

Table 8 the heat integration of separation sequence for example1

source \ sink	AB/CD	A/B	C/D
AB/CD	R1	R2	
A/B	R3	R1	
C/D	R2	R2	R1

The possible schemes for heat integration

- 1) [C/D-AB/CD], A/B
- 2) [C/D-A/B], AB/CD

Table 9 the value of the three functions for the possible matches for example1

Separation scheme	Heat load $Q \times 10^6$ (kcal/hr)	Boiling point temperature difference $\Delta T$	$Q \cdot \Delta T \times 10^6$ (kcal/hr)
Scheme1	5.37	68.4	438
Scheme2	5.12	26.4	208

The following table show the normalized of the three functions (heat load  $Q$ , boiling point temperature difference  $\Delta T$  and the value of  $Q \cdot \Delta T$ ) that used as input for fuzzy analogical gate to calculate the separation weight of each split to choose the best match that yields the optimum heat integration separation sequence.

Table 10 the normalized of the three functions for example1

Separation scheme	Normalized heat load ( $\mu_1$ )	Normalized boiling point difference ( $\mu_2$ )	Normalized (Q. $\Delta T$ ) value ( $\mu_3$ )	Separation weight
Scheme1	1.000	1.000	1.000	1.000
Scheme2	0.953	0.386	0.475	0.363

We chose scheme1 because it yields the largest separation weight [C/D-AB/CD], A/B

The next step is Calculating the temperature elevation in the source column AB/CD from (equation 4)  $\Delta T_i = 334.8 - 326.9 + 2.5 = 10.4$  So the temperature for AB/CD is raised from 326.9 to 337.3 ( $^{\circ}\text{K}$ )

Then Calculating the operating pressure for source column AB/CD from (equation 5) So The operating pressure for AB/CD is raised from 5.99 to 7.86 atm

The final flow sheet for the separation sequence of four components (ABCD) is shown in the following figure (Fig5)

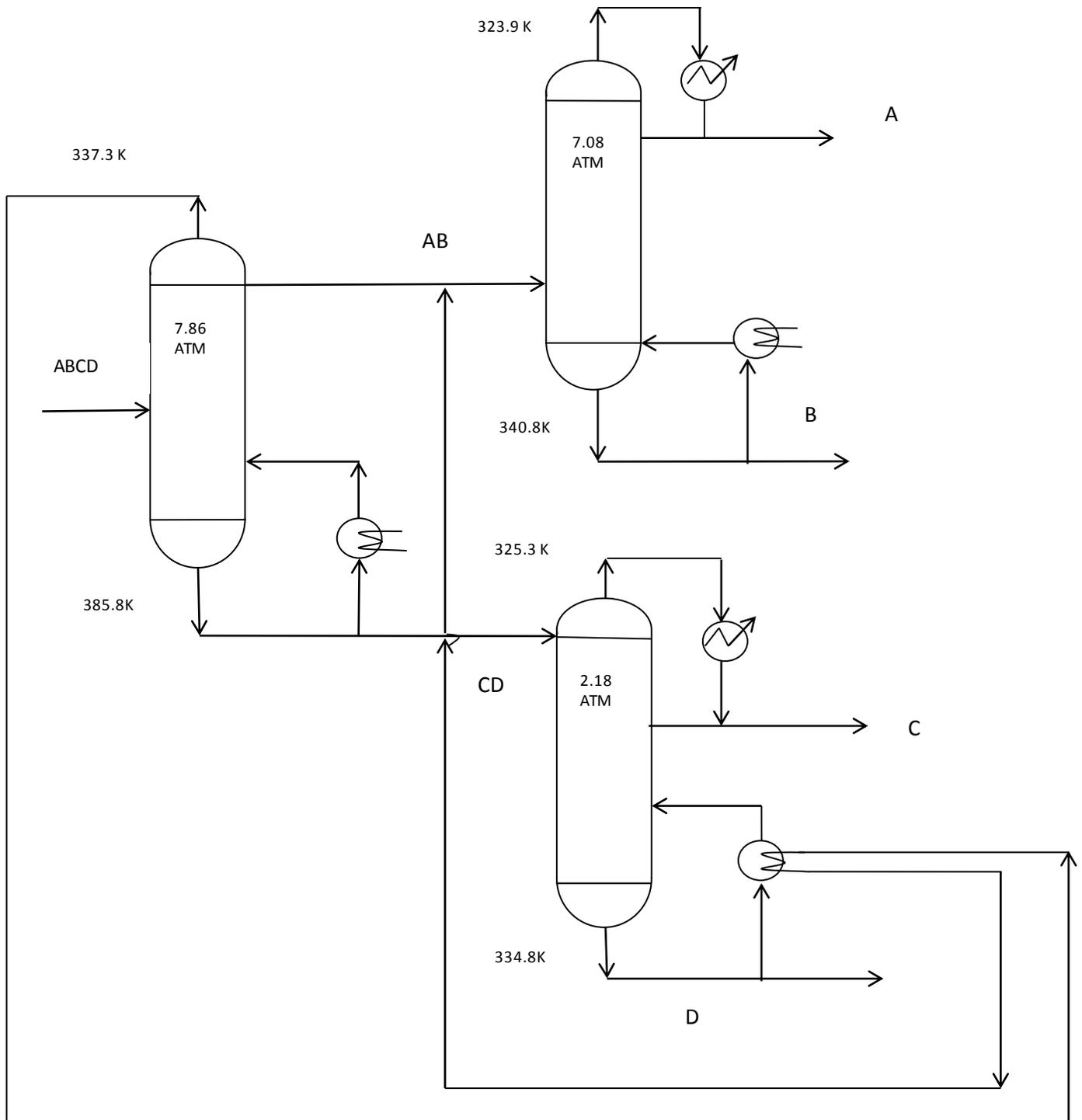


Fig5 flow sheet with heat integration of separation sequence for example 1

**Example2:**

The second example is consisting of five components that separated in five products by sharp separation. This example given by P. FLOQUET and etc. (1994) It is desired to find the optimal sequence for the following feed . The feed stream is 980 kmol/hr with mole fraction as showed in table11

Table 11 the feed stream characteristics for example2

component	Mole fraction	Boiling point difference ( $\Delta T$ )	Relative volatility
A: propylene	0.16	5.70	1.25
B: propane	0.36	30.3	3.36
C: I-Butane	0.21	11.3	1.25
D: n-butane	0.16	36.5	4.21
E: n pentane	0.11		

The possibilities split of components (ABCDE) and their properties (boiling point temperature difference, estimated mass load and relative volatility) are shown in the following table

Table 12 possible splits and their properties of example2

split	Boiling point Temperature difference ( $^{\circ}K$ )	Estimated mass load	Relative volatility
A/BCDE	5.70	1.79	1.25
AB/CDE	30.3	1.32	3.36
ABC/DE	11.3	1.55	1.52
ABCD/E	36.5	2.01	4.21

The following table show the normalized of the three functions (boiling point temperature difference, estimated mass load and relative volatility) that used as input for fuzzy analogical gate to calculate the separation weight of each spilt to choose the optimum separation sequence.

Table 13 the normalized of the properties for example2

split	Normalized temperature difference	Normalized estimated mass load	Normalized relative volatility	Separation weight
A/BCDE	0.000	0.319	0.000	0.000
AB/CDE	0.799	1.000	0.713	0.819
ABC/DE	0.182	0.667	0.091	0.019
ABCD/E	1.000	0.000	1.000	0.000

AB/CDE is the best choice because it has the largest separation weight value (0.819) where AB top product and CDE will separated in the bottom as shown in next paragraph

For separating CDE

The possibilities split of components (CDE) and their properties (boiling point temperature difference, estimated mass load and relative volatility) are shown in the following table

Table 14 possible splits and their properties of example2

split	Boiling point Temperature difference( $^{\circ}k$ )	Estimated mass load	Relative volatility
C/DE	11.3	0.562	3.70
CD/E	36.5	0.771	1.51

The following table show the normalized of the three functions (boiling point temperature difference, estimated mass load and relative volatility) that used as input for fuzzy analogical gate to calculate the separation weight of each split to choose the optimum separation sequence.

Table 15 the normalized of the properties for example2

split	Normalized boiling point temperature difference	Normalized estimated mass load	Normalized relative volatility	Separation weight
C/DE	0.309	0.729	1.000	0.748
CD/E	1.00	1.000	0.408	0.359

The best choice is C/DE because its yield the largest separation weight (0.748) and the total sequence is (AB/CDE – C/DE – A/B – D/E)

In the next table we represent all possibilities of separation sequence for five components (ABCDE) and correspond the total cost for each split

Table 16 the total cost for all possible splits for example2

NO.	SEPARATION	COST $\times 10^6$
1	AB/CDE, A/B, C/DE, D/E	1.19
2	AB/CDE, A/B, CD/E, C/D	1.26
3	A/BCDE, B/CDE, C/DE, D/E	1.30
4	ABC/DE, D/E, A/BC, B/C	1.35
5	ABC/DE, D/E, AB/C, A/B	1.36
6	A/BCDE, B/CDE, CD/E, C/D	1.38
7	A/BCDE, BC/DE, B/C, D/E	1.51
8	ABCD/E, A/BCD, B/CD, C/D	1.58
9	A/BCDE, BCD/E, B/CD, C/D	1.58
10	ABCD/E, AB/CD, A/B, C/D	1.63
11	ABCD/E, ABC/D, A/BC, B/C	1.65
12	ABCD/E, ABC/D, AB/C, A/B	1.66
13	ABCD/E, A/BCD, BC/D, B/C	1.98
14	A/BCDE, BCD/E, BC/D, B/C	1.98

SO, the best sequence is (AB/CDE – C/DE – A/B – D/E) which is the lowest cost compare with other sequences.

The optimum separation sequence in pervious section is used to be a data for the next step which is the selection for the best heat integration sequence to minimize the energy and cost of separation processes

Table 17 the characteristics of separation splits for example2

Column	Top temperature ( $^{\circ}\text{K}$ )	Bottom temperature ( $^{\circ}\text{K}$ )	Pressure (atm)	Condenser duty	Reboiler duty
AB/CDE	346.0	440.3	19.0	4,401,279	5,764,112
C/DE	336.2	369.4	7.20	5,897,697	6,553,032
A/B	323.1	363.2	20.7	1.1E+07	1.14E+07
D/E	335.1	389.3	5.20	1,568,992	1,855,121

Table 18 the splits with their heat load for example2

split	Heat load ( $10^6$ )	Temperature difference
AB/CDE	5.76	94.3
C/DE	6.55	33.2
D/E	1.86	54.2
A/B	11.4	40.1

Table 19 the heat integration of separation sequence for example2

source \ sink	AB/CDE	C/DE	D/E	A/B
AB/CDE	R1		R2	
C/DE	R2	R1	R2	
D/E	R3		R1	
A/B	R2	R2	R2	R1

The possible schemes for heat integration

- 1) [A/B-AB/CDE] [C/DE-D/E]
- 2) [A/B-D/E] [C/DE-AB/CDE]
- 3) [A/B-C/DE], ABC/DE, D/E

Table 20 the value of the three functions for the possible matches for example1

Separation scheme	Heat load $Q \times 10^6$ (kcal/hr)	Boiling point temperature difference $\Delta T$	$Q \cdot \Delta T \times 10^6$ (kcal/hr)
Scheme1	7.62	(134.4,87.4)	(1000,318.3)
Scheme2	7.62	(94.3,127.5)	(558,760.6)
Scheme3	6.55	(73.3)	(675)

The following table show the normalized of the three functions (heat load  $Q$ , boiling point temperature difference  $\Delta T$  and the value of  $Q \cdot \Delta T$ ) that used as input for fuzzy analogical gate to calculate the separation weight of each split to choose the best match that yields the optimum heat integration separation sequence.

Table 21 the normalized of the three functions for example1

Separation scheme	Normalized heat load ( $\mu_1$ )	Normalized boiling point difference ( $\mu_2$ )	Normalized ( $Q \cdot \Delta T$ ) value ( $\mu_3$ )	Separation weight
Scheme1	1.000	1.000	0.471	0.956
Scheme2	1.000	0.949	0.827	0.997
Scheme3	0.859	0.545	1.000	0.655

We chose scheme2 because it yields the largest separation weight [A/B-D/E] [C/DE-AB/CDE]

The next step is Calculating the temperature elevation in the source column (ABC/DE) and (D/E) from (equation 4) For (ABC/DE)  $\Delta T_i = 369.4 - 346 + 2.5 = 25.9 \text{ } ^\circ k$  so the temperature of ABC/DE is raised from 346 to 371.9  $^\circ k$  And For (D/E)  $\Delta T_i = 363.2 - 335.1 + 2.5 = 30.6 \text{ } ^\circ k$  so the temperature of D/E is raised from 335.1 to 365.7  $^\circ k$

Then Calculating the operating pressure for source column (ABC/DE) and (D/E) from (equation5) The operating pressure for ABC/DE is raised from 19 to 32.4 atm  
The operating pressure for D/E is raised from 5.2 to 10.99 atm

The final flow sheet for the separation sequence of four components (ABCDE) is shown in the following figure (Fig6)

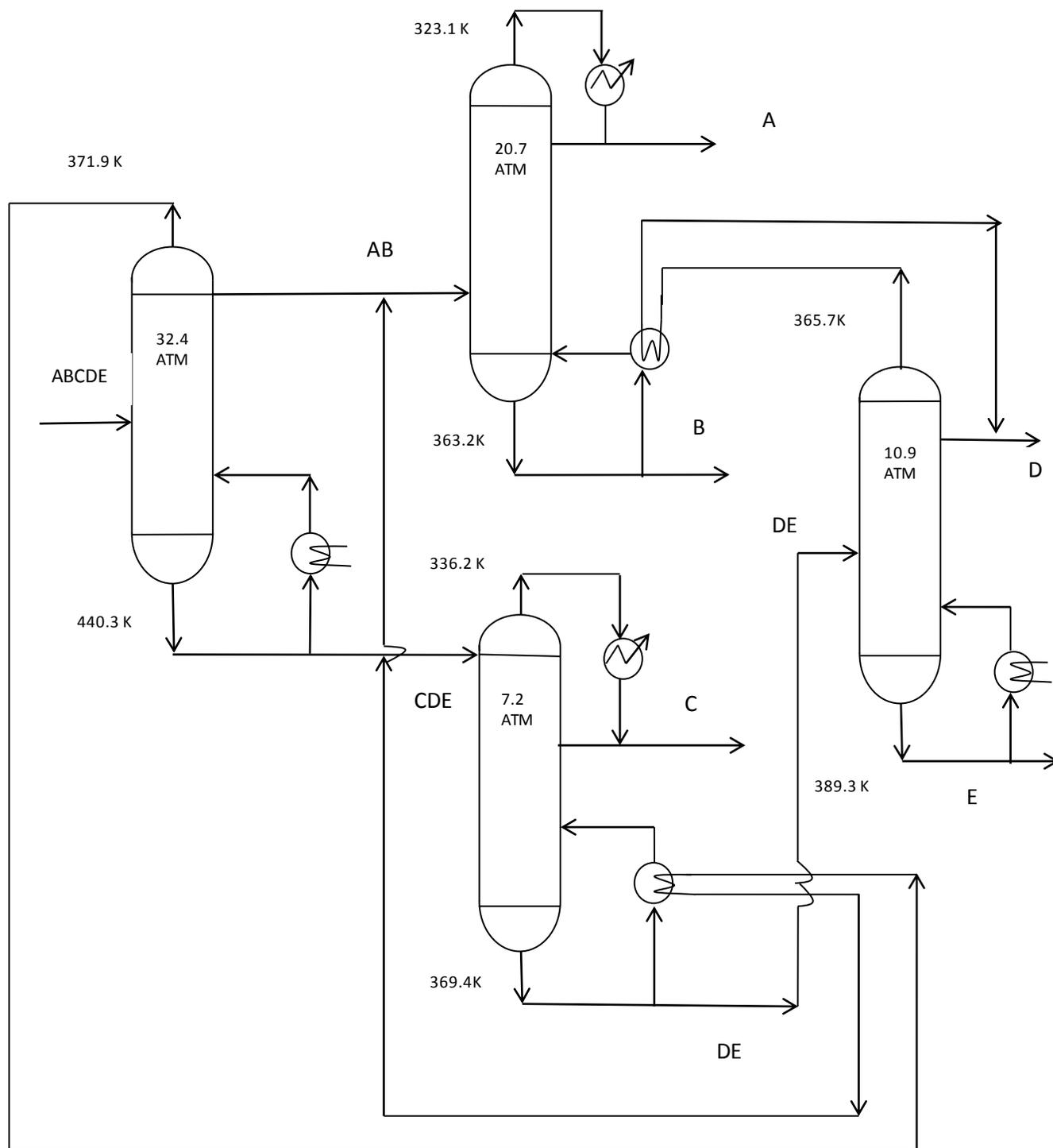


Fig 6 the flow sheet with heat integration of separation sequence for example2

**Example 3:**

The third example is consisting of six components that separated in six products by sharp separation. This example given by R.w Thompson and etc. (1972) and S.aly in (1997) ) It is desired to find the optimal sequence for the following feed ,the feed stream is 800 kmol/hr with mole fraction as showed in table 22

Table 22 Feed stream characteristics for example3

component	Mole fraction	Boiling point difference ( $\Delta T$ )	Relative volatility
A: Ethane	0.20	40.9	5.21
B: propylene	0.15	5.70	1.27
C: propane	0.20	35.8	4.31
D: I butene	0.15	5.80	1.25
E: n-butane	0.15	36.5	4.65
F: n pentane	0.15		

The possibilities split of components (ABCDEF) and their properties (boiling point temperature difference, estimated mass load and relative volatility) are shown in the following table

Table 23 possible splits and their properties of example3

split	Boiling point Temperature difference ( $^{\circ}\text{K}$ )	Estimated mass load	Relative volatility
A/BCDEF	40.9	2.07	5.21
AB/CDEF	5.70	1.74	1.27
ABC/DEF	35.8	1.65	4.31
ABCD/EF	5.80	1.82	1.25
ABCDE/F	36.5	2.18	4.65

The following table show the normalized of the three functions (boiling point temperature difference, estimated mass load and relative volatility) that used as input for fuzzy analogical gate to calculate the separation weight of each split to choose the optimum separation sequence.

Table 24 the normalized of the properties for example3

split	Normalized temperature difference	Normalized estimated mass load	Normalized relative volatility	Separation weight
A/BCDEF	1.000	0.208	1.000	0.062
AB/CDEF	0.000	0.830	0.005	0.005
ABC/DEF	0.855	1.000	0.773	0.887
ABCD/EF	0.003	0.679	0.000	0.000
ABCDE/F	0.875	0.000	0.859	0.000

ABC/DEF is the best choice because it has the largest separation weight value (0.887) where ABC will separated in the top and DEF will separated in the bottom as shown in next paragraph

For separating ABC

The possibilities split of components (ABC) and their properties (boiling point temperature difference, estimated mass load and relative volatility) are shown in the following table

Table 25 possible splits and their properties of example3

split	Boiling point Temperature difference( $^{\circ}k$ )	Estimated mass load	Relative volatility
A/BC	40.9	0.636	6.92
AB/C	5.70	0.636	1.28

The following table show the normalized of the three functions (boiling point temperature difference, estimated mass load and relative volatility) that used as input for fuzzy analogical gate to calculate the separation weight of each split to choose the optimum separation sequence.

Table 26 the normalized of the properties for example3

split	Normalized boiling point temperature difference	Normalized estimated mass load	Normalized relative volatility	Separation weight
A/BC	1.000	1.000	1.000	1.000
AB/C	0.139	1.000	0.185	0.082

For separating DEF

The possibilities split of components (DEF) and their properties (boiling point temperature difference, estimated mass load and relative volatility) are shown in the following table

Table 27 possible splits and their properties of example3

split	Boiling point Temperature difference( $^{\circ}k$ )	Estimated mass load	Relative volatility
D/EF	5.80	0.666	1.24
DE/F	36.5	0.666	3.69

The following table show the normalized of the three functions (boiling point temperature difference, estimated mass load and relative volatility) that used as input for fuzzy analogical gate to calculate the separation weight of each split to choose the optimum separation sequence.

Table 28 the normalized of the properties for example3

split	Normalized boiling point temperature difference	Normalized estimated mass load	Normalized relative volatility	Separation weight
D/EF	0.159	1.000	0.336	0.235
DE/F	1.000	1.000	1.000	1.000

So, the best sequence is (ABC/DEF – A/BC - DE/F – B/C - D/E)

The optimum separation sequence in pervious section is used to be a data for the next step which is the selection for the best heat integration sequence to minimize the energy and cost of separation processes

Table 29 the characteristics of separation splits for example3

Column	Top temperature (k)	Bottom temperature (k)	Pressure (atm)	Condenser duty	Reboiler duty
ABC/DEF	269.3	543.9	3.50	4,858,335	5,471,896
A/BC	310.0	436.2	3.68	5,971,482	6,397,339
DE/F	340.0	402.5	5.14	2,114,962	2,565,052
B/C	353.4	364.8	2.40	7,215,913	8,459,995
D/E	338.6	347.0	1.57	10,120,003	10,326,764

Table 30 the splits with their heat load for example3

split	Heat load ( $10^6$ )	Temperature difference
ABC/DEF	5.471	274.6
A/BC	6.397	126.2
DE/F	2.565	62.50
B/C	8.459	11.40
D/E	10.326	8.400

Table 31 the heat integration of separation sequence for example3

source \ sink	ABC/DEF	A/BC	DE/F	B/C	D/E
ABC/DEF	R1	R3	R2		
A/BC	R2	R1	R2		
DE/F			R1		
B/C	R2	R2	R2	R1	
D/E	R2	R2	R2	R2	R1

The possible matches for heat integration separation sequence :

1. [D/E-ABC/DEF] [B/C-A/BC], DE/F
2. [D/E-ABC/DEF] [B/C-DE/F], A/BC
3. [D/E-ABC/DEF] [A/BC-DE/F], B/C
4. [D/E-A/BC] [B/C-ABC/DEF], DE/F
5. [D/E-A/BC] [B/C-DE/F], ABC/DEF
6. [D/E-A/BC] [ABC/DEF-DE/F], B/C
7. [D/E-DE/F] [B/C-ABC/DEF], A/BC
8. [D/E-DE/F] [B/C-A/BC], ABC/DEF
9. [B/C-ABC/DEF] [A/BC-DE/F], D/E
10. [B/C-A/BC] [ABC/DEF-DE/F], D/E

Table 32 the value of the three functions for the possible matches for example3

Separation scheme	Heat load $Q \times 10^6$ (kcal/hr)	Boiling point temperature difference $\Delta T$	$Q \cdot \Delta T \times 10^6$ (kcal/hr)
Scheme1	11.868	(283,137.6)	(1589,903.7)
Scheme2	8.0310	(283,73.9)	(1589,256.4)
Scheme3	8.0310	(283,188.7)	(1589,967.3)
Scheme4	11.868	(134.6,286)	(894,1598.8)
Scheme5	8.9570	(134.6,73.9)	(894,256.4)
Scheme6	8.9570	(134.6,337.1)	(894,1662.3)
Scheme7	8.0310	(70.9,286)	(246.7,1598.8)
Scheme8	8.9570	(70.9,137.6)	(246.7,903.7)
Scheme9	8.0310	(286,188.7)	(1598.8,967.3)
Scheme10	8.9570	(137.6,286)	(903.7,1662.3)

The following table show the normalized of the three functions (heat load  $Q$ , boiling point temperature difference  $\Delta T$  and the value of  $Q \cdot \Delta T$ ) that used as input for fuzzy analogical gate to calculate the separation weight of each split to choose the best match that yields the optimum heat integration separation sequence.

Table 21 the normalized of the three functions for example1

Separation scheme	Normalized heat load ( $\mu_1$ )	Normalized boiling point difference ( $\mu_2$ )	Normalized ( $Q \cdot \Delta T$ ) value ( $\mu_3$ )	Separation weight
Scheme1	1.000	0.729	0.956	0.865
Scheme2	0.677	0.392	0.956	0.447
Scheme3	0.677	1.000	0.956	0.808
Scheme4	1.000	0.713	0.962	0.849
Scheme5	0.755	0.392	0.538	0.431
Scheme6	0.755	0.713	1.000	0.826
Scheme7	0.677	0.376	0.962	0.414
Scheme8	0.755	0.376	0.544	0.401
Scheme9	0.677	1.000	0.962	0.809
Scheme10	0.755	0.729	1.000	0.831

We chose scheme1 because it yields the largest separation weight [D/E-ABC/DEF] [B/C-A/BC], DE/F

The next step is Calculating the temperature elevation in the source column (ABC/DEF) and (A/BC) from (equation 4) For ABC/DEF  $\Delta T_i = 347 - 269.3 + 2.5 = 80.2 \text{ }^\circ\text{k}$  So ABC/DEF is raised from 269.3 to 349.5 K For A/BC  $\Delta T_i = 364.8 - 310 + 2.5 = 57.3 \text{ }^\circ\text{k}$  A/BC is raised from 310 to 367.3  $^\circ\text{k}$

Then Calculating the operating pressure for source column (ABC/DEF) and (A/BC) from (equation5) The operating pressure for ABC/DEF is raised from 3.5 to 29.9 atm  
The operating pressure for A/BC is raised from 3.68 to 15.69 atm

The final flow sheet for the separation sequence of four components (ABCDEF) is shown in the following figure (Fig7)



## CONCLUSION

A fuzzy analogical gate approach has been proposed for synthesizing multicomponent separation sequences. This approach consists of two parts, first part for the selection of the best sequence of separation network (without heat integration) and second part synthesis of separation network (with heat integration). The synthesis algorithm is based on application of three expert rules qualification of the estimated mass load, difference in boiling point and relative volatility. three examples are solved (four components, five components and six components) to show the power of the proposed method. It is evident that the performance of the Fuzzy analogical gates is quite encouraging, characterized by its simplicity and can be implemented by hand calculations. a fuzzy analogical gate technique has been presented as a first step in selecting the optimum sequence for sharp separation and using three heuristic rules for detecting the possible matches within condenser and re-boiler to minimize the total cost by heat integration matrix, that shows all potential matches that could occur in the system and select the best sequence.

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