

# Design Of Distillation Column Using Pseudo Binary System Method

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**Abstract:** This work is identified the distillation column design parameters, dimensions, behavior and hydrodynamics. These parameters later on shall be used as input data to develop a control system strategy. To achieve this goals, Pseudo binary system method is adopted and the feed is considered as a binary mixture.

**Keywords**—Distillation column parameters; binary system; light key; heavy key;

## I. INTRODUCTION

The distillation process is used widely in chemical or petrochemical industries to separate the liquid components based on the physical properties like boiling point temperature and relative volatility. The components with the highest relative volatility rise in a vapor phase to the top of the distillation column, while the lowest relative volatility components remain at bottom to form the lower product. Distillation is one of the most energy intensive operations in the petroleum refinery; it's used throughout the refinery to separate process products [1]. Distillation column is one of important equipment in oil refining process, which has different sizes, weights and boiling temperatures range. [2] In this study design calculation is made to figure out the dimensions and criteria like number of stages, column efficiency, column diameter and area of plates. To reach those results the feed to distillation column is treated as a binary mixture by using two components (light and heavy keys). During heating up, the liquid components with greater volatility (light key) rise up to the column top in a vapor phase, then by means of condensation the vapor will be condensed into distilled products. Some of the condensate product will return to distillation column as reflux to purify the vapor from heavy volatiles, see fig. 1. On the other hand, the low volatility components (heavy key) will be exit from the bottom of the distillation column in liquid phase and thermo circulated to re-boiler farther back to distillation column to insure all greater volatility components are transferred into vapor, see fig.1. In most cases, the distillation is operated at a continuous steady state, new feed is continuously fed to the distillation column and products are always being removed [3].

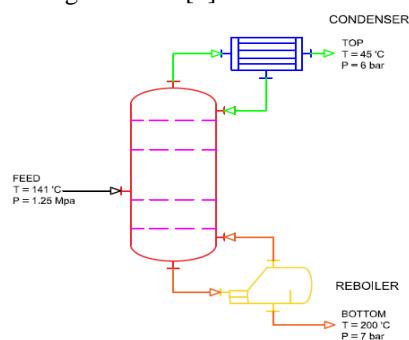


Fig. 1. Schematic Diagram Of Distillation column

## II. METHODOLOGY

To calculate the distillation column, the following steps are followed:

1. Distillation column material balance is done to identify the key components which are i-pentane (light key) and n-butane (heavy key).
2. Antonio equation is used to calculate the relative volatility of mixture.
3. Results from step 1 & 2 above are used to calculate the number of theoretical stages by McCabe Thiele method.
4. Distillation column efficiency is calculated by Bradford equation.
5. By identifying the column efficiency, both number of real stages and distillation column height are determined.
6. Distillation column diameter is calculated after flooding velocity and column total area are determined by using correlation of flood velocities for sieve trays chart refer to figure-2.
7. Area of plates is done based on the largest column diameter which is calculated on the step number 6 above.

## III. PROCESS DESIGN

1. Material balance for distillation column.  
Design is done based on Khartoum Refinery Naphtha hydro-treating. Initial input data were collected and material balance is calculated as follows:

Overall material balance equation

$$F = D + B \quad (1)$$

Where:

$F$   $\equiv$  feed rate

$D$   $\equiv$  distillate rate

$B$   $\equiv$  bottom rate

Partial material balance equation

$$F \cdot x_f = D \cdot x_d + B \cdot x_b \quad (2)$$

Where :

$x_f$   $\equiv$  mole fraction on feed

$x_d$   $\equiv$  mole fraction on column top

$x_b$   $\equiv$  mole fraction on column bottom

Mole rate for feed, top & bottom

$$M_f = F \cdot x_f \tag{3}$$

$$M_d = D \cdot x_d \tag{4}$$

$$M_b = B \cdot x_b \tag{5}$$

Where:

$M_f$  ≡ feed mole rate

$M_d$  ≡ column top mole rate

$M_b$  ≡ column bottom mole rate

From data sheet for I-BUTANE (i-C<sub>4</sub>):

$$D = 39 \text{ kmole / hr}$$

$$B = 456.62 \text{ kmole / hr}$$

$$x_f = 0.033$$

$$x_b = 0.00363$$

From “(1)”, the feed rate is:

$$F = 39 + 456.62$$

$$F = 495.62 \text{ kmole / hr}$$

Mole fraction on top can be calculated using “(2)”,

$$495.62 \cdot 0.033 = 39 \cdot x_d + B \cdot 456.62 \cdot 0.00363$$

$$x_d = 0.37687 = 37.687 \%$$

Accordingly, top mole rate obtained from “(4)”,

$$M_d = 39 \cdot 0.37687$$

$$M_d = 14.697 \text{ kmole / hr}$$

Same calculations are made for all feed components as shown in table -1.

**Table-1 DISTILLATION COLUMN MATERIAL BALANCE FOR KHARTOUM REFINERY NAPHTHA.**

component	Feed		Top		Bottom	
	Mole percent %	Mole rate kmole/hr	Mole percent %	Mole rate kmole/hr	Mole percent %	Mole rate kmole/hr
PROPANE	0.0013	0.66	1.41	0.55	0.00024	0.11
N-BUTANE	0.006	2.96	4.76	1.86	0.00242	1.1
I-BUTANE (i-C <sub>4</sub> )	0.033	16.29	37.5	14.64	0.00363	1.65
N-PENTANE(n-C <sub>5</sub> )	0.017	8.25	2.14	0.83	0.016	7.42
I-PENTANE	0.05	26.31	25.7	10.02	0.036	16.29
C <sub>6</sub> <sup>+</sup>	0.067	33.26	28.5	11.1	0.05	22.16
NHEXANE	0.06	29.7			0.07	29.7
METHYLCYCLOPENTANE	0.0045	2.20			0.0048	2.20
CYCLOHEXANE	0.03	13.58			0.03	13.58
BENZENE	0.0019	0.92			0.002	0.92
C7 PARAFFINS	0.135	66.46			0.146	66.46
C7 NAPHTENES	0.05	24.51			0.054	24.51
TOLUENE	0.01	4.91			0.01	4.91
C8 PARAFFINS	0.15	75.81			0.166	75.81
C8 NAPHTENES	0.06	31.19			0.07	31.19
C8 AROMATICS	0.02	9.43			0.02	9.43
C9 PARAFFINS	0.13	62.30			0.14	62.30
C9 NAPHTENES	0.04	22.15			0.05	22.15
C9 AROMATICS	0.02	9.36			0.02	9.36
C10+ PARAFFINS	0.08	41.64			0.1	41.64
C10+ NAPHTENES	0.02	8.09			0.018	8.09
C10+ AROMATICS	0.01	3.50			0.0077	3.50

The Light and Heavy Keys are retrieved from table-1 above and listed in Tabel-2

**Table-2 Light and heavy keys components**

component	Feed		Top		Bottom	
	Mole percent %	mole rate kmole/hr	Mole percent %	mole rate kmole/hr	Mole percent %	Mole rate kmole/hr
i-C4 (LK)	0.033	16.29	0.375	14.637	0.0036	1.65
n-C5 (HK)	0.017	8.25	0.0214	0.8346	0.0163	7.42

It is assumed that the feed to the distillation column is composed of the binaries listed in table-2 accordingly the total mole rate for feed and its component are recalculated and organized in table-3. Moreover, the mole fractions (feed, top & bottom) for light and heavy keys are determined from the table-3.

**Table-3 Key component**

component	Feed		Top		Bottom		Molecular weight
	Mole percent %	mole rate kmole /hr	Mole percent %	mole rate kmole /hr	Mole percent %	Mole rate kmole /hr	
i-C4 (LK)	0.6	16.2967	0.95	14.637	0.07	1.65	58.122
n-C5 (HK)	0.4	8.2546	0.5	0.8346	0.93	7.42	72.15
Total		24.55		15.47		9.1	

$$x_f = 60 \%$$

$$x_d = 95 \%$$

$$x_b = 07 \%$$

## 2. Application of Antoine Equation

This equation is used to calculate the partial pressure of the components

$$P_i = e^{\left( A - \left( \frac{B}{C+T} \right) \right)} \tag{6}$$

Where:

$P_i$  ≡ partial pressure

$A, B, C$  ≡ Antoine constant

$T$  ≡ given Feed Temperature

The relative volatility ( $\alpha_i$ ) is calculated using below equation

$$\alpha_{ij} = k_i / k_j \tag{7}$$

$$k_i = P_i / P_t \tag{8}$$

$$k_j = P_j / P_t \tag{9}$$

Where:

$P_t$  ≡ given total pressure

$k_i$  = light key distribution coefficient  
 $k_j$  = heavy key distribution coefficient

The partial pressure ( $P_i$ ) for i-C4 (LK) from “(6)”,

$$T = 141 \text{ }^\circ\text{C} = 414 \text{ K}$$

$$P_i = e^{\left(15.8 - \left(\frac{2150}{(-27.6) + 414}\right)\right)}$$

$$P_i = 27884.26 \text{ mmHg}$$

Using “(8)”, we can determine the light distribution coefficient ( $k_i$ ) for i-C4 (LK):

$$P_i = 1.25 \text{ mPa} = 9375.797 \text{ mmHg}$$

$$k_i = 27884.26 / 9375.797$$

$$k_i = 2.974$$

Same calculations are repeated for heavy component n-C5 (hk) and the partial pressure & distribution coefficient for light and heavy keys were calculated.

**Table-4** Calculated partial pressure & distribution coefficient

COMPONENT	A	B	C	Pi (mmHg)	K
i-C4 (LK)	15.8	2150	-27.6	27884.26	2.974
n-C5(HK)	16	2550	-36.3	10390.114	1.108

Relative volatility can be calculated using “(7)”,

$$\alpha_{ij} = 2.974 / 1.108$$

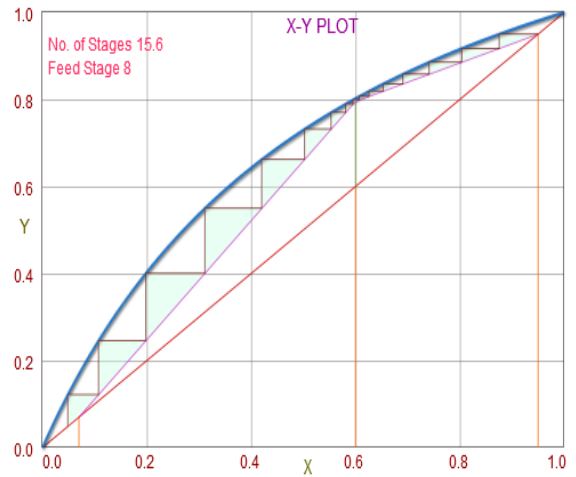
$$\alpha_{ij} = 2.7$$

### 3. Number of theoretical stages by McCabe Thiele

From steps 1 and 2 we will use all the results as input data to determine the number of theoretical stages by using McCabe Thiele method and fig. 2 illustrated the output diagram.

#### Input Data:

Relative volatility	$\alpha_{ij} = 2.7$
Feed mole fraction	$x_f = 60 \%$
Distillate mole fraction	$x_d = 95 \%$
Bottom mole fraction	$x_b = 07 \%$
Reflux ratio	$R = 0.79$
Quality of feed	$q = 1$



**Fig. 2.** McCabe Thiele diagram - [7]

Number of theoretical stages ( $N_{th}$ )  
 $N_{th} = 16$  Plates  
 Feed stage 8

### 4. Efficiency of the column by Bradford and Drickamer equation ( $E^o$ )

$$E^o = 0.17 - 0.616 \log (X_{if} - \mu_{il}) \quad (10)$$

Where:

$X_{if}$  = mole fraction of light key in feed

$\mu_{il}$  = light key viscosity in liquid phase.

$$E^o = 0.17 - 0.616 \log (0.6 - 0.1019)$$

$$E^o = 90 \%$$

### 5. Number of actual stages and distillation column Height.

Number of actual stages

$$N_{act} = N_{th} / E^o \quad (11)$$

Where:

$N_{act}$  = Number of actual stages

$N_{th}$  = Number of theoretical stages

$$N_{act} = 16 / 0.9 = 18 \text{ stages}$$

Height of the column ( $H_t$ )

$$H_t = (N_{act} - 1) * C + 0.05 H_t \quad (12)$$

Taking tray spacing  $C = 0.6$  (ref)

$$H_t = 11 \text{ m}$$

### 6. Column diameter calculations

Top Conditions

$L_n = 30$  kgmol/hr

$V_n = 70$  kgmol/hr

$T = 318$  K

Liquid density =  $\rho_L = 526 \text{ kg/m}^3$   
 Vapour density =  $\rho_v = 15.35 \text{ kg/m}^3$

**Bottom Conditions**

$L_m = 526.6 \text{ kgmol/hr}$   
 $V_m = 70 \text{ kgmol/hr}$   
 $T = 473 \text{ K}$   
 Liquid density =  $\rho_L = 574.5 \text{ kg/m}^3$   
 Vapour density =  $\rho_v = 10.85 \text{ kg/m}^3$

**Flow Parameter:**

**For Stripping Section**

$$F_{LV} = \left( \frac{L_n}{V_n} \right) \left( \frac{\rho_v}{\rho_L} \right)^{0.5} \quad (13)$$

$$F_{LV} = \left( \frac{30}{70} \right) \left( \frac{15.35}{526} \right)^{0.5}$$

$F_{LV} = \text{Liquid Vapor Factor} = 0.08$

**For rectifying section**

$$F_{LV} = \left( \frac{L_m}{V_m} \right) \left( \frac{\rho_v}{\rho_L} \right)^{0.5} \quad (14)$$

$$F_{LV} = \left( \frac{526.6}{70} \right) \left( \frac{11}{574.5} \right)^{0.5}$$

$F_{LV} = \text{Liquid Vapor Factor} = 1$

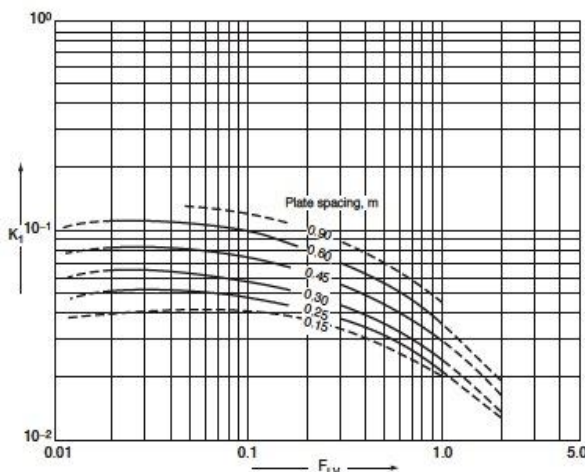


Fig. 3. Correlation of flooding velocities for sieve trays [9].

Flooding velocity equation

$$U_f = k * \sqrt{\frac{\rho_L - \rho_v}{\rho_v}} \quad (15)$$

Where:

k= Correlation of flooding velocities from fig. 3 the liquid vapor factors ( $F_{LV}$ ) were used to determine correlation (k) values.

$k_{top} = 0.1$   
 $k_{bottom} = 0.019$

$$U_{f_{top}} = 0.576 \text{ m/s}$$

$$U_{f_{bottom}} = 0.136 \text{ m/s}$$

**Operation at 85% flooding rate this will be allow to safety operation of flooding so the velocity:**

$$V_{top} = (0.576 * 0.85) = 0.489 \text{ m/s}$$

$$V_{bottom} = (0.136 * 0.85) = 0.1156 \text{ m/s}$$

**Maximum volumetric rate:**

$$q_{max} = \frac{m^3}{\rho} \quad (16)$$

$$q_{max_{top}} = \left( 45662 \frac{\text{kg}}{\text{hr}} \right) \div \left( 15.35 \frac{\text{kg}}{\text{m}^3} \right) \div 3600$$

$$= 0.826 \frac{\text{m}^3}{\text{hr}}$$

$$q_{max_{bottom}} = \left( 2545.66 \frac{\text{kg}}{\text{hr}} \right) \div \left( 11 \frac{\text{kg}}{\text{m}^3} \right) \div 3600$$

$$= 0.064 \frac{\text{m}^3}{\text{hr}}$$

**Total area required:**

$$A_{total} = q_{max} / v \quad (17)$$

$$A_{total_{top}} = \left( 0.826 \frac{\text{m}^3}{\text{s}} \right) \div \left( 0.489 \frac{\text{m}}{\text{s}} \right) = 1.7 \text{ m}^2$$

$$A_{total_{bottom}} = \left( 0.064 \frac{\text{m}^3}{\text{s}} \right) \div \left( 0.1156 \frac{\text{m}}{\text{s}} \right) = 0.68 \text{ m}^2$$

Will consider the distillation column top area as base and equivalent diameter is the required diameter

$$D_{top} = \sqrt{\frac{4 * A}{\pi}} = \sqrt{\frac{4 * 1.7}{\pi}} = 1.55 \text{ m}$$

$$D_{bottom} = \sqrt{\frac{4 * A}{\pi}} = \sqrt{\frac{4 * 0.68}{\pi}} = 1 \text{ m}$$

**7. Plate Areas:**

All areas plus the movement of vapor and liquid components are illustrated in fig. 4.

**Down comer area (12%  $A_{total}$ ):**

$$A_d = 0.12 * 1.7 = 0.204 \text{ m}^2$$

**Net area**

$$A_{net} = A_{total} - A_d \quad (18)$$

$$A_{net} = 1.7 - 0.204 = 1.5 \text{ m}^2$$

**Active area**

$$A_{active} = A_{total} - 2 * A_d \quad (19)$$

$$A_{active} = 1.7 - 2 * 0.204 = 1.3 \text{ m}^2$$

**Hole area**

$$A_{hole} = 10 \% * A_{active} = 0.13 \text{ m}^2$$

Accordingly, the hole diameter = 5 mm

Area of one hole =  $1.963 \times 10^{-5} \text{ m}^2$

Number of holes =  $0.13 / 1.963 \times 10^{-5} = 66225$  holes

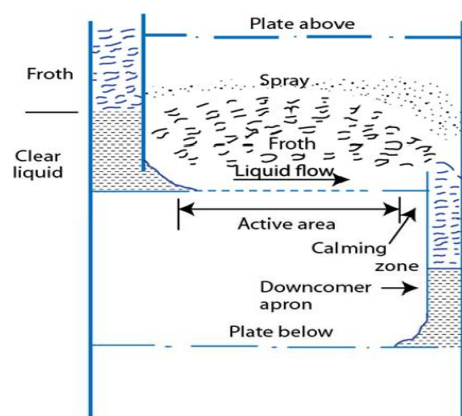


Fig. 4. Plate Areas [10]

**IV. DESIGN RESULTS AND DISCUSSION**

Table-5 Design Summary

DESCRIPTIO	ABBREVIATI ON	RESULT
LIGHT KEY COMPONENT		i-C4 (LK)
LIGHT KEY COMPONENT		n-C5 (HK)
MOLE FRACTION OF FEED	$x_f$	60 %
MOLE FRACTION ON TOP	$x_d$	95 %
MOLE FRACTION ON BOTTOM	$x_b$	07 %
PARTIAL PRESSURE OF LIGHT KEY	$P_i$	27884.26 mmHg
PARTIAL PRESSURE OF HEAVY KEY	$P_j$	10390.114 mmHg
FEED PRESSURE	$P_t$	9375.797 mmHg
FEED TEMPERATURE	$T$	414 K
DISTRIBUTION COEFFICIENT OF LIGHT KEY	$k_i$	2.974
DISTRIBUTION COEFFICIENT OF HEAVY KEY	$k_j$	1.108
RELATIVE VOLATILITY	$\alpha_{ij}$	2.7
REFLUX RATIO	$R$	0.79
NUMBER OF THEORETICAL STAGES	$N_{th}$	16 plates
Feed stage		8
COLUMN EFFECIENCY	$E^o$	90 %
NUMBER OF ACTUAL STAGES	$N_{act}$	18
COLUMN HEIGHT	$H_t$	11 m
FLOODING VELOCITY OF LIGHT KEY	$U_{f\ top}$	0.576 m/s

FLOODING VELOCITY OF HEAVY KEY	$U_{f\ bottom}$	0.136 m/s
FLOODING VELOCITY OF LIGHT KEY AT 85 %	$V_{top}$	0.489 m/s
FLOODING VELOCITY OF HEAVY KEY AT 85 %	$V_{bottom}$	0.1156 m/s
MAX VOLUMETRIC RATE OF LIGHT KEY	$q_{max\ top}$	0.826 m3/s
MAX VOLUMETRIC RATE OF HEAVY KEY	$q_{max\ bottom}$	0.064 m3/s
TOTAL AREA AT COLUMN TOP	$A_{total\ top}$	1.7 m2
TOTAL AREA AT COLUMN BOTTOM	$A_{total\ bottom}$	0.6 m2
COLUMN DIAMETER AT TOP	$D_{top}$	1.55 m
COLUMN DIAMETER AT BOTTOM	$D_{bottom}$	1 m
DOWN COMER AREA	$A_d$	0.204 m2
NET AREA	$A_{net}$	1.5 m2
ACTIVE AREA	$A_{active}$	1.3 m2
HOLE AREA	$A_{hole}$	0.13 m2
HOLE DIAMETER		5 mm
AREA OF ONE HOLE		$1.963 \times 10^{-5} \text{ m}^2$
NUMBER OF HOLES		66225 holes

The feed to the distillation column is assumed to consist from i-C4 as light key and n-C5 as heavy key, see table-3. Thus the feed total mole rate is the sum of both keys in molar rate of 24.55 kmole/hr from which mole fractions are calculated. In this design of the column, the number of theoretical trays, feed plate location and reflux ratio can be obtained from the plot manually or through the solution developed previously. Then parameters for the column hydrodynamics and dimensions were calculated by the normal conventional method pseudo. Both top and bottom column areas are calculated, but top area is considered as worst condition and top diameter is selected as distillation column diameter.

**V. CONCLUSION**

The number of theoretical stages and feed stage are determined using McCabe Thiele program fig.2. It is approved that McCabe-Thiele method can be applied for binary as well as multicomponent system. It is also concluded that under wood for multicomponent gives similar number of stages, but less reflux ratio which affect the overall material balance so the method of using Lk and hk in multi component system is recommended.

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