

Distillation Performance and Numerical Design Development: Procedure and Effectiveness

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ABSTRACT

In the past, distillation was used to cleanse liquids. A long-standing method for extracting scents from fruits and flowers. Distinguishing features of distillation processes, concepts, and equipment Design and operation of binary distillation columns are evaluated to enhance output rate. Column design (trays, tray hold up, reflux drum hold up) and performance (reflux ratio, start-up method) may enhance capacity greatly. Professional distillation engineers may find this equipment and column size development useful. Performance of batch and continuous distillation columns are studied.

Key words: Distillation, performances, procedures, equipment, effectiveness, design, development

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1. INTRODUCTION

Chemical process distillation is the most extensively used separation technology. Distillation is a process of equilibrating vapor and liquid mixes. Understanding VLE is crucial to distillation design process.

2. DISTILLATION RULES THAT ARE REASONABLE

a) Dissolving azeotropes: This kind of mixture necessitates the use of more complex techniques of separation. [1]

b) Solids: When the material to be separated is thick or contains tars or resins that might clog or foul a continuous unit, a batch separation temperature is necessary.

(i) A thicker column shell is needed since the distillation column pressure is greater than the ambient pressure.

(ii) A column pressure of less than 250 lb/in² should result in an average temperature driving force of 5–150C for overhead condensation with cooling water.

(iii) If the necessary column pressure is more than 250 pounds per square inch, use a refrigerant and decrease the column pressure for overhead condensation with cooling water.

c) Ideal pressure level:

(i) Use a vacuum for substances that are sensitive to heat or polymerizable materials. Vacuum is only used when absolutely essential [2,3] e.g. Variations in temperature are required for thermal breakdown to occur.

(ii) Distillation column pressure is higher, which necessitates the thickening of the column shell.

(iii) Condensers must have an average temperature driving force of 5-150C if the column pressure required for overhead condensation with cooling water is less than 250 lb/in².

(iv) There are many alternatives to utilizing cooling water as an overhead condensation technique. These include using a refrigerant and running the column at a lower pressure.

d) Temperatures in the reboiler and condenser should be at their optimal levels.

(i) Low reboiler temperatures avoid bottom fouling, therefore this should be the first rule of thumb.

As seen in Table 1, the most frequent temperature discrepancies between reboilers and condensers are shown here.

Table 1:Temperature variations for heat exchange [2,3]

	Temp, K
Condenser:	
Refrigeration	3-10
Cooling Water	6-20
Pressurized	10-20
Fluid	20-40
Boiling Water	20-50
Air	
Reboiler:	
Process Fluid	10-20
Steam	10-60
Hot Oil	20-60

3. ELEMENTS AND OUTCOME OF DISTILLATION

3.The Distillation Column

Each component of a distillation column is used to convey heat or material. Components of distillation include:

- A liquid separator shell.
- Component separation trays/plates and pickings assist separate components.
- A reboiler for vaporization.
- A condenser for the column's vapors.
- Reflux drum for recovering condensed vapour from column top.

The vertical shell houses the condenser and reboiler. One input and two product streams typical distillation machine

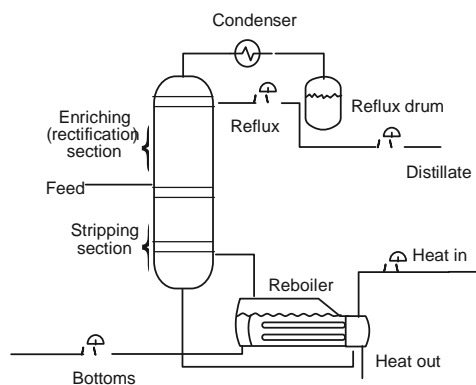


Fig. 1:Column of Distillation

3.2 Terminology and the Foundations of Knowledge

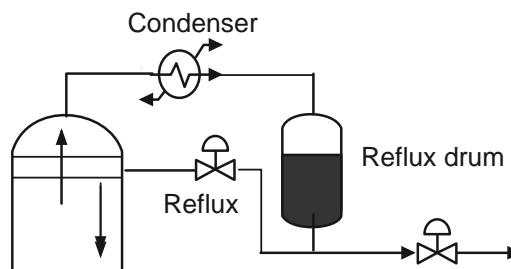


Fig. 2:Batch Distillation with a Rectifier 1

Into the column, the feed is carried to a tray known as the feed tray, where it is mixed with water. The enrichment and stripping regions of the column are separated by the feed tray. The feed is fed into the reboiler by way of a column.

Vapour is produced by heating the reboiler. Any appropriate fluid may be used as a heat source, however steam is the most common choice in chemical plants. refineries may heat up other columns by using their output streams. The vapour from the reboiler is recirculated via the column. Bottoms refers to the liquid that has been drained from the reboiler. The condenser at the top of the column cools the vapor as it rises. A reflux drum holds the condensed liquid. Some of the liquid rises back to the surface via a process known as reflux. The distillate [2] is the system's condensed liquid that has been removed.

3.3 Batch Distillation with a Rectifier

Batch distillation is done in an unstable batch still with a column that may be compared to numerous stages. Batch distillation with rectifying column. During distillation, the vapour ascend the column. Enriching overall column. At the column's apex, vapor turns to liquid. The liquid is distilled and then refluxed back into the column. Each run, nuts are added or withdrawn from the still. During distillation, MVC lowers.

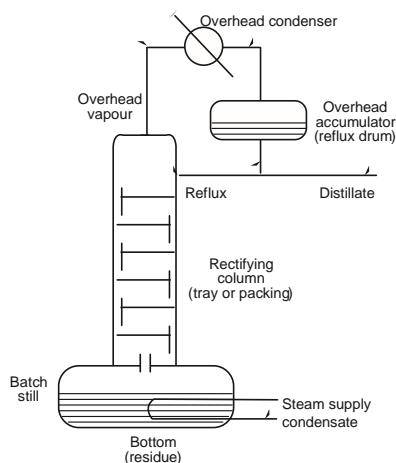


Fig. 3:Batch Distillation with a Rectifier 2

Fig. 4 shows an alternative configuration. The vessel is at the top. Inverted batch distillation or batch stripper.

Lesser ventricular cardiomyopathies (LVC) Less LVC, more MVC. [7]

A batch process uses less frequent steps. It produces batches of data instead of continuously. These steps are common in most batch procedures. Semi-continuous steps run continuously with pauses. [6]

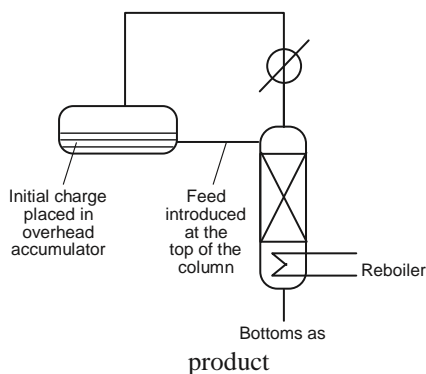


Fig. 4:Batch distillation using a Rectifying Column.

4. CONTINUOUS DISTILLATION PROCESSES

In this article, the following distillation methods are briefly discussed:

4.1 Steam Distillation

If you're looking for an efficient way to distill, steam distillation is the way to go. Most organic chemicals can't be dissolved in water, therefore these mixtures will boil at a lower temperature than either water or the other components. Useful for organic substances with high boiling points, which may dissolve if boiled too long. [10]. Steam distillation may be used for a variety of things, including these [12].

- a) In order to eliminate a little amount of volatile contaminant from a huge amount of product.
- b) The separation of vast quantities of heated materials.
- c) Remove impurities with higher boiling points from high-boiling substances.
- d) It is used in the distillation of materials that are either thermally unstable or react with other components when heated to boiling.
- e) Even at low pressure, high boiling temperatures make indirect distillation impossible.
- f) Because of fire safety issues, direct-fired heaters are not allowed.

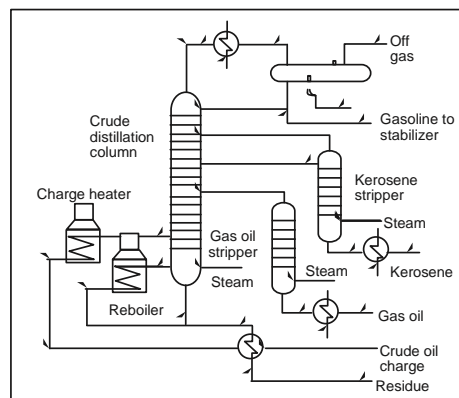


Fig.5:Crude Steam Stripper Distillation

Fig. 5 shows a crude distillation plant with steam strippers for kerosene and gas oil. This process is employed in petroleum refining in combination with vacuum distillation.

4.2 Vacuum Distillation

The pressure is quite low with this distillation method (near vacuum). This distillation method minimizes the boiling point of the mixture, reducing thermal damage. [3]

Vacuum distillation columns are frequently bigger in diameter and tray spacing to handle the higher vapor volume. 6. Crude distillation column flow sheet employing steam distillation.

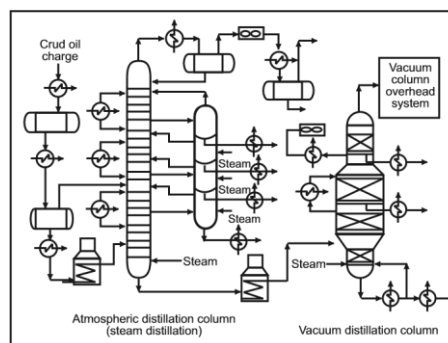


Fig. 6:Columns of Distillation with Vacuum

4.3 Extractive Distillation

This method and azeotropic distillation are quite similar. Extractive distillation is a kind of distillation that alters the relative volatilities of feed ingredients by heating a solvent to a high temperature. [5]

4.3.1 Azeotropic vs. Extractive Distillation

It is benzene that is used as an entrainer in the ethanol-water scenario. The bottoms product is ethanol, which is taken from the column. Because of its wide range of health risks, benzene is just not worth the risk.

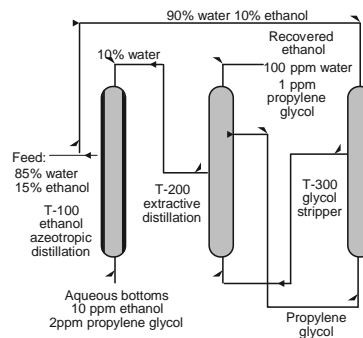


Fig. 7: The Process of Distillation in the Absence of Water Extractive distillation is an alternate method for ethanol recovery.

Propylene Glycol is the solvent utilized. When it comes to ethanol's boiling point, remember that it's at 89.4 mole percent (96 percent ethanol) when it's at its minimal boiling point with water. Figure 7 depicts a process flow diagram. All the criteria for an excellent extractive solvent are met by propylene glycol in this separation.

- As a rule of thumb, it can be dissolved in water at any concentration.
- It boils at a greater temperature than water (187 deg C at 1 atm).
- It does not combine with water to generate an azeotrope.
- A weak link occurs between the hydroxyl –OH group and the water molecule, giving it molecular attraction to water.
- It is a material that is generally considered to be safe for use in the workplace.

Ethanol-water azeotrope distillation is used in the first column, and virtually pure water is used as the bottoms in the second column. Propylene glycol is then introduced to the second column for extractive distillation. As the distillate rises to the top of the column, ethanol is created.

In a conceptual sense, there are three parts to this column. The rectification stage in the center removes water from the ethanol. Ethanol can be separated from water more easily because glycol bonds with water molecules, increasing the ethanol's relative volatility.

The propylene glycol content in the ethanol distillate is reduced to a minimal level by the top portion. Water is separated from ethanol in the bottom part. Glycol is recovered from the second column's bottoms using a glycol stripper in the third column. As a bottoms product, propylene glycol is returned to the extraction column as a solvent source. Fresh feed is blended with the overflow from the glycol stripper, which contains mostly water and a little amount of ethanol.

4.3.2 Selection of a Solvent

The solvent used decides which of the two components in the feed gets eliminated more during distillation. For example, using ethylene glycol (boiling point 197.350C) as the solvent, increases the volatility of ethanol while decreasing the volatility of water. So the extractive distillation column extracts ethanol, and the solvent recovery column separates water. [12]. Using conventional distillation to separate toluene (110.80 C) from isooctane (99.3 C) is problematic. Toluene-phenol mixtures leave the extractive distillation column as bottoms, whereas comparatively isooctane is recovered as overhead product. Second column (solvent recovery column) separates phenol-toluene mixture, with toluene appearing as distillate and phenol returning to first column. Flow chart for toluene and isooctane separation using phenol as solvent (Fig. 8).

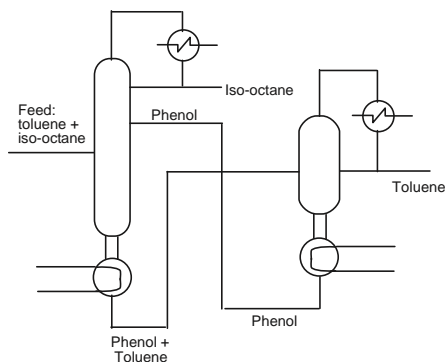


Fig. 8: Solvent separation of Toluene and Isooctane

4.4 Reactive (Catalytic) Distillation

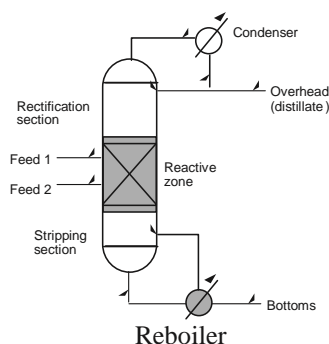


Fig. 9: Reactive Distillation Process

This method combines reaction and separation. Catalysts are packed within a distillation column. This approach employs distillation to remove products as they arise to change a reaction's chemical equilibrium towards 100% conversion (Fig. 9[4]).

RD uses one or more feeds, and the reactive zone may be anywhere in the column, depending on the product. Its uses include improving conversion, selectivity, energy consumption, lowering equipment costs, and separating difficult-to-separate mixes. [8, 4]

RD is now widely employed for etherification and esterification processes, as well as alkylation and nitration. Early uses used liquid phase processes and used a catalyst in solution. Solid catalysts were utilized recently. One example is the manufacture of MTBE, an octane enhancer for gasoline. Fig. 10 depicts the setup.

The pre-reactor delivers over 90% MTBE reaction equilibrium, and the RD adds additional 5-10% to almost complete the reaction. Bales of catalyst resin beads are placed in the reactive zone.[8]

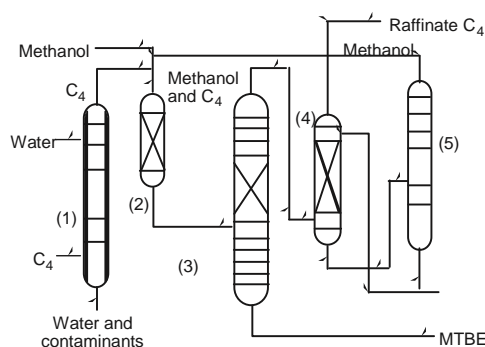


Fig.10: Production of MTBE by RD

As a result of not requiring sophisticated product recovery, separation, and recycling of unconverted reactants, reactive distillation saves on both equipment and energy expenditures, making it an attractive option.

4.5 Pressure-Swing Distillation

As previously indicated, when the system pressure is altered, certain binary azeotrope combinations lose their azeotropic properties. Separation may be accomplished without extra entrainment in this scenario. For example, an azeotrope does not develop below roughly 9.2 kPa in the case of an ethanol-water combination (azeotropic composition of 89.4 mole percent at 101.325 kPa). [2,12]

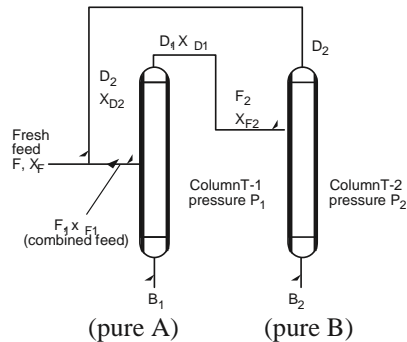


Fig. 11: Pressure-Swing Distillation Process

Two successively operated columns, each at a different pressure, are used in the pressure-swing distillation process to separate a pressure-sensitive azeotrope.

A lower proportion of A becomes azeotropic when pressure P_1 is approached (x_{P2} to x_{P1}). Figure 11 depicts the set-up for a pressure-swing distillation. x_F and x_{D2} are the mole fractions of new feed F_1 and recycled distillate D_2 for Column T1 operating at reduced pressure P_1 (close to azeotropic mole fraction x_{P2}). In terms of mole fraction, x_{F1} is greater than x_{P1} at pressure P_1 in terms of A content. Column T1's bottoms are almost all A. The mole fraction x_{D1} is present in the distillate D_1 that exits T1. Mole fraction x_{P2} has more A than the mole fraction of x_{P1} but less A than the mole fraction of x_{P1} azeotrope.

Column T2 receives feed F_2 from Distillate D_1 . Bottom of T2 yields almost pure B, and the distillate D_2 is recirculated to Column T1. Fig. 13 depicts the phase diagram after the modification.

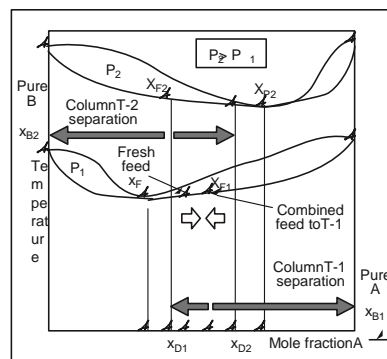


Fig.12:Diagram for Pressure-Swing Distillation Distillation Phase Changes

5. EQUIPMENT AND COLUMN SIZING

In order for a distillation column to work consistently, the flow of vapour and liquid must be controlled. [12] are the prerequisites.

- Vapor should only flow via the downcomer tray's open areas.
- Only the downcomers should be used for liquid flow.
- Tray holes should not allow liquid to seep through.
- Vapor should not be used to transport liquid up the column.
- The liquid should not carry the vapour down the column.
- The downcomers should not be filled with vapor.

5.1 Tray Constructions and Hydraulics

Bubble Cap Trays, Sieve Trays, and Valve Trays are the three most common kinds of trays. The liquid flow between trays is typically controlled by a weir on each tray. When the weir is long enough, and the tray's liquid level is high enough, flow may be determined.[11]

5.2 Tray Efficiency

Although it is ideal to assess the performance of real trays separating the materials of interest, this is frequently not feasible in the early stages of a design process. It is possible to derive estimates based on theory or on data that has been obtained in other columns.

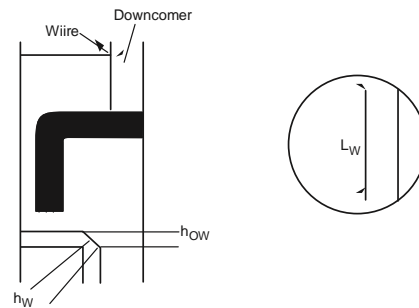


Fig. 13: Tray Efficiency for Distillation Column

Correlations based on real column data are used in the O'Connell correlation. For sieve and valve trays, it is based on bubble cap trays. [9] Column efficiency is correlated to a combination of feed viscosity and volatile component concentration in a mixture. The arithmetic mean of the top and bottom temperatures in the column should be used to calculate these attributes. The data has been analyzed and a fit has been found:

$$\eta_{oa} = 0.492(\mu_F \alpha_{HK})^{-0.245} \quad [1]$$

It's possible to acquire a rough approximation of efficiency figures using this or a comparable data set.

5.3 Column Diameter

Based on the flooding limitations, the column's diameter is computed. We need to know the vapor and liquid flow rates throughout the column before we can begin calculating the diameter. Once this is done, we determine how much heat is being added or removed from the system at various locations, such as the trays on top and bottom, and any other areas where we believe peak loads may be present, we do a diameter calculation. [9]

When the diameters are determined, we choose one to use for the column and then test it to see whether it works.

5.4 Flooding

When the downcomer area is too tiny, liquid backs up on a tray, resulting in downcomer flooding. The majority of the time, this is not an issue. Entrainment flooding, which occurs when the vapour stream carries too much liquid up the column, is much more worrisome.

Correlations and procedures exist that can determine the flood velocity; from this the active region of the column is estimated, so that the real velocity may be maintained to no more than 80% of flood; values as low as 60% are occasionally employed.

Droplets entrained in the vapour stream may be subjected to a force balance (which can lead to entrainment flooding). After doing the above calculations, the following formula is obtained: $C = (\text{vapor/liquid density} \times \text{velocity unit})$, where C is the capacity factor (in units of velocity).

$$V_{\text{flood}} = C \sqrt{\frac{\rho_L - \rho_V}{\rho_V}} \quad [2]$$

When it comes to determining the capacity factor, theoretical calculations may be used (droplet diameter and drag coefficient, for example), but the most common method is to use correlations based on distillation tray test results. In certain cases, C may incorporate the impacts of surface tension and foaming propensity, among other characteristics. For sieve trays, Fair presented a connection in the late 1950s and early 1960s, which can be

found in several places. Based on the liquid to vapour mass ratio, the capacity factor is plotted against the number of functional groups that make up the liquid to vapour mass ratio.

$$F_{LV} = \frac{L_{Mass}}{V_{Mass}} \sqrt{\frac{\rho_V}{\rho_L}} \quad [3]$$

This value is used to enter the plot from the bottom, and the capacity factor is read from the left. Non-foaming systems and trays that satisfy specified hole and weir size constraints have this capacity factor. Surface tension will have to be taken into account:

$$C = C_{Fair} \left(\frac{\sigma}{20} \right)^{0.2} \quad [4]$$

Where, σ the surface tension in dynes/cm.

5.6 Diameter

With these information, we can easily calculate the flooding velocity:

$$V_{Flood} = C_{Fair} \left(\frac{\sigma}{20} \right)^{0.2} \sqrt{\frac{\rho_L - \rho_V}{\rho_V}} \quad [5]$$

(The surface tension adjustment is included in this solution for the Fair correlation).

Vapour flow rate and desired flow velocity may be used to compute flow area, which we can then use to calculate flow area (a fraction of flood). To accommodate the downcomer area, which cannot be used for mass transfer, this space must be expanded. The calculated tray area may then be used to determine the column diameter. As a result of adding everything up, we arrive at:

$$D_T = \sqrt{\frac{4V_{Mass}}{V_{Flood} \cdot F_{Design} \cdot \pi \rho \left(1 - \frac{A_d}{A} \right)}} \quad [6]$$

We can't operate on columns less than roughly 1.5 feet in diameter, so trays definitely aren't a smart choice. Large-diameter columns need less packing (over about 5 ft in diameter).

5.7 Pressure Drop

Pressure drop per tray, which is around 0.10 psi, is a common unit of measurement for this gradient. There are detailed calculations that can be done, but the exact tray specs are so important that final values are normally acquired from professionals, although approximation approaches may be utilized to generate numbers to place in your design base

The pressure drop is made up of two primary components: the "dry tray" drop induced by the holes and slots in the trays and the head of the liquid through which the vapour must pass.

$$H_{tray} = h_d + h_l \quad [7]$$

5.8 Dry Tray Losses

Using an orifice flow equation, the dry tray head loss may be linked to

$$h_d = \left(\frac{0.186}{C_o^2} \right) \left(\frac{\rho_V}{\rho_L} \right) \cdot V_{hole}^2 \quad [8]$$

The dry tray drop, measured in inches of fluid, may be calculated using this equation. A sieve tray's units are taken care of by the constant 0.186. The orifice size coefficient C_o might range from 0.65 to 0.85 depending on the tray arrangement. Vapour flow rate may be calculated by dividing the tray's total hole area by the total hole flow rate.

5.9 Liquid Losses

Surface tension and foaming on the tray contribute to the decline in liquid head pressure. The height of the liquid on the tray and an aeration factor are often used to calculate it:

$$h' = \beta(h_w + h_{ow}) \quad [9]$$

Correlations for the aeration factor (β) are available; a value of 0.6 is suitable for a broad range of applications. The weir height and the liquid level over the weir are added together to get the liquid level in the tray. From the liquid volume on the tray and its active area, the total height may be determined. Another option is to take the height from a Francis Weir calculation and subtract it from it (which relates flow-off a tray to liquid height and weir length). Straight weir in inches and gallons per minute (gpm) is:

$$h_{ow} = 0.48 \left(\frac{L}{l_{weir}} \right)^{2/3} \quad [10]$$

These calculations are dependent on the weir's size and form.

5.10 Column Height:

When calculating the height of a trayed column, the number of (real) steps is multiplied by the number of tray separations. The best distance between trays may be calculated to save money, although this is not always the case. The most frequent tray spacing is 24 inches, which provides adequate room for personnel to operate on the trays if the column is large enough to need crawling within. Columns with diameters of less than 18 inches may be able to use 18-inch tray spacing. [1,2,10].

Additional height is required at the top and bottom of the column to accommodate the trays. Disengaging space normally requires an extra 5 to 10 feet of room at the top. There must be adequate space at the bottom of the tower to hold water.

6. DISTILLATION COLUMN PERFORMANCE FACTORS

A distillation column's performance is influenced by a variety of elements, including the following: [10]

- b) Feeding circumstances
- c) Feed quality.
- d) Feed composition.
- e) In liquid mixes, there are a number of trace components that may have a significant impact on VLE.
- f) The state of internal liquid and fluid flow.
- g) State of trays (packings).
- h) Temperatures and weather.

6.1 Feed Conditions

The working lines and, as a result, the number of separation stages necessitated depend on the condition and composition of the feed mixture. The position of the feed tray is also affected by this. Excessive departures from design parameters during performance may cause the column to lose its ability to accomplish the separation operation.

6.2 Reflux Conditions:

The gradient of the operating line for the rectification section increases as the reflux ratio increases. There are no distillate withdrawals under complete reflux conditions; hence, the minimum number of trays is needed. Because of the low operating expenses, most columns are built to run at 1.2 to 1.5 times the minimal reflux ratio (more reflux means higher reboiler duty).

6.3 Vapour Flow Conditions

Flooding and Foaming are two examples of adverse vapour flow situations.

6.4.1 Foaming

Because of the passage of gas or vapour, foaming occurs as liquids expand. Despite the fact that it offers high interfacial liquid-vapour contact, excessive foaming often leads to the accumulation of liquid on trays. Foaming may become so extreme that it mixes with the liquid in the tray above in certain circumstances.

6.4.2 Entrainment

When high vapour flow rates are present, entrainment occurs, which refers to liquid being taken up to the tray above. Lower volatile materials are transported to a plate containing a liquid of greater volatility, which is harmful to the tray's overall efficiency. A high-purity distillate might also be tainted by it. Flooding may result from excessive entrainment.

6.4.3 Weeping/Dumping

Low vapour flow is to blame for this phenomena. The liquid in the tray can't be held up by the vapour's pressure. As a result, holes begin to leak liquid. If you cry too much, you'll end up dumping. There is weeping when the column pressure drops rapidly and the separation efficiency decreases.

6.4.4 Flooding

Due to excessive vapour flow, liquid is carried up the column by the vapour, resulting in flooding. Excessive vapour also causes an increase in liquid hold-up on the plate above because of the increased pressure.

6.4 Column Diameter

Overly high or underly low vapour flow is to blame for most of the above-mentioned issues with column performance. [5,9,11] When it comes to vapor flow rate, the diameter of the column matters. Vapour flow requirements are determined by weeping, while the maximum capacity of the column is determined by flooding.

6.5 State of Trays and Packings

If packings are employed, the number of trays needed for a certain separation task is determined by the plate's efficiency and the number of trays needed. [11] As a result, the column's performance will be affected by anything that reduces tray efficiency. There are several factors that impact tray efficiency, including fouling, wear and tear, corrosion, and the rate at which these occur and the characteristics of the liquids that are processed.

6.6 Weather Conditions

The majority of distillation columns have their tops exposed to the environment. Changes in weather conditions may still impair the column performance, even if many of them are insulated. During cold and windy times, the reboiler must be sized suitably to create enough vapour, but it must also be able to be turned down enough during warmer seasons.

7. CONCLUSION

Distillation processes and operational concepts are explored in length in this study. Industrial case studies are used to demonstrate the distillation apparatus and its results. Design and performance of batch and continuous distillation columns are discussed. Engineers in the early stages of distillation column design may find the equipment and column size development given here interesting. There are several elements that may impact the performance of industrial-scale distillation.

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