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| <b>KLM Technology Group</b><br><br>Practical Engineering Guidelines for Processing Plant Solutions             | <br><br><b>Engineering Solutions</b><br><br><a href="http://www.klmtechgroup.com">www.klmtechgroup.com</a> | Page : 1 of 61                    |
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| KLM Technology Group<br>#03-12 Block Aronia,<br>Jalan Sri Perkasa 2<br>Taman Tampoi Utama<br>81200 Johor Bahru | <b>Kolmetz Handbook<br/>         of Process Equipment Design</b><br><br><b>PROPYLENE C3 SPLITTER<br/>         (ENGINEERING DESIGN GUIDELINE)</b>   | Co Author:<br>Rev 01 Aprilia Jaya |
|  |  | Editor /Author<br>Karl Kolmetz    |

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## **INTRODUCTION**

### **Scope**

This design guideline reviews the basic elements of propylene splitter fractionators in sufficient detail to allow an operations personnel or engineer to review the design a propylene splitter. This Guideline covers the sizing of tower diameter, tray spacing, reflux ratio, down comer sizing, and number of stages. These parameters may affect the tower performance, capacity and efficiency.

The design of propylene splitters depends on density, and rate of vapor / liquid through the column. Ideally, the vapor and liquid leaving the stage are in equilibrium. Equilibrium is a function of the rate operations of mass and heat transfer between liquid and vapor in distillation and will determine the efficiency of tray. The design of propylene splitter may be influenced by factors, including process requirements, economics and safety.

Traditionally, the separation is performed in distillation columns containing about 125 plates, making it a high equipment cost and energy intensive separation process; thus, consideration is needed before designing and installing a propylene splitter. In this guideline the process simulation of propylene splitter distillation column is reviewed to help understanding its basic concepts.

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## General Design Consideration

Propylene is second in importance to ethylene as an olefin raw material for petrochemical manufacture. Propane needs to be separated from propylene to get the desired product. This separation process is not easy since propane and propylene are close-boiling point components. Traditionally, the separation is performed in distillation columns containing about 125 plates, making it the cost and energy intensive separation process. Thus, a good consideration is needed before installing a propylene splitter.

Some of the topics that will be covered in this design guideline are:

1. Process simulation of a propylene splitter – proper simulation techniques
2. From the simulation to the field – tray efficiencies
3. Utilizing a process simulation to develop column hydraulics
4. The types of internals that have been used in propylene splitter columns
5. Design considerations that need to be addressed when considering a revamp.

Initial design of a distillation tower involves specifying the separation of a feed of known composition and temperature. Constraints require a minimum acceptable purity of the overhead and the bottoms products. The desired separation can be achieved with relatively low energy requirements by using a large number of trays, thus incurring larger capital costs with the reflux ratio at its minimum value. On the other hand, by increasing the reflux ratio, the overhead composition specification can be met by a fewer number of trays but with higher energy costs.

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There's some initial information to design a distillation column such as:

1. Feed flow rate
2. Composition of feed
3. Temperature and pressure of feed
4. Heat losses from the column, usually assumed to be negligible for an initial design.
5. Type of condenser, either total or partial.
6. Desired key recoveries, i.e. a desired composition of a single component in either the bottoms or distillate.

The procedure for designing the column is as follows:

1. Specify the operating pressure.
2. Determine the degrees of freedom of the column and the independent variables required for the design.
3. Determine the number of trays and reflux ratio. Use McCabe - Thiele, simulator, or other method.
4. Determine the feed location. Usually add at tray with identical composition.
5. Determine heat duties for reboiler and condenser, using an energy balance on the column.
6. Determine column width. Use 3 ft/sec at average temperature and pressure of column for estimation purposes, or a more detailed method.

Determining the design of a Propylene Splitter requires an understanding of the simulation model used to generate the internal loads and physical properties, vapor and liquid equilibrium data utilized, tray hydraulics, and how the selection of the internals will affect the actual efficiency of the installed equipment in the field.

Simulation of a propylene splitter seems very simple and can be done quickly by 3rd year engineering students. There are a small number of components and the equipment layout is not complex. The challenge of a propylene splitter is that, unless engineer use the correct vapor and liquid equilibrium data, the simulation can have greater than 15% inaccuracies as compared to actual field data.

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Physical properties are critical to the success of a simulation model and are also very important to the accuracy of the model. Poor physical property data may prevent your simulation model from converging. The most typical problem is missing parameters in the thermodynamic package utilized. This is not unusual in most commercial simulation packages. Physical property parameters for most compounds are not known for every thermodynamic model at every pressure and temperature range. Below is some physical property that should be considered in designing propylene splitter

### 1. Pressure consideration

Propylene splitter is high pressure distillation column. There are many factors to be considered when designing at high operating pressures. As the pressure of a column is raised:

1. Separation becomes more difficult since the relative volatility decreases - more plates and reflux are required to achieve the separation.
2. The latent heat of vaporization decreases, reducing the duties of the reboiler and condenser.
3. The vapor density increases, resulting in a smaller column diameter.
4. The reboiler temperature increases. This is usually limited by the decomposition temperature of the material being vaporized.
5. Condenser temperature increases.

As the distillation pressure is increased, the vapor density increases. When the critical pressure is approached, the compressibility factor of a saturated vapor usually has a value less than 0.75. Thus the vapor density of the gas phase is quite high at pressures greater than 40% of critical. As the operating pressure is increased for the same Cs (Capacity Factor) value, the vapor mass flow rate will be much greater than at atmospheric operating pressure because of the high vapor density.

While at the same time the liquid mass flow rate will be greater at high operating pressure than at atmospheric operating pressure. Therefore, liquid flow rates per unit of column cross-sectional area will be higher as operating pressure increases. The

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capacity of the fractionating device at high pressure may be dependent on its ability to handle these high liquid flow rates.

As the pressure is lowered, these effects are reversed. A lower pressure limit is usually encountered by a desire to avoid vacuum operation and / or refrigeration in the condenser.

For an initial design, it is adequate to set the distillation pressure to as low a pressure above ambient as allowed by cooling water or air cooling in the condenser. An initial starting value might be selected so that the bubble point of the overhead product is 10°C above the summer cooling water temperature.

## 2. Reflux ratio considerations

If the optimal reflux ratio is less than 1.1 times the minimum reflux, select 1.1 times the minimum reflux since a small error in design data or operating conditions might lead to a column that does not work. As the reflux ratio is increased:

1. The purity of the product is increased.
2. The capital costs decrease since the number of trays is decreased.
3. The energy costs increase as more reboiling and condensing are required.

## 3. Feed considerations

The feed consideration is more of an afterthought rather than a critical design parameter. The question is whether the feed is at the bubble point, subcooled, partial vapor, or all vapor. In general, a subcooled feed:

1. Decreases the number of tray in the rectifying section but increases the trays in the stripping section.
2. Increases the size of the reboiler but decreases the size of the condenser.

There are two general typical design of a propylene splitter: high-pressure system and heat pumped system.

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## High Pressure System

A high-pressure system is designed to utilize cooling water as the source to cool the overhead vapor, and a high pressure is needed to condense the propylene vapor at ambient temperatures of about 40°C.

In distillation, both saturated liquid and vapor are involved. Therefore, each pressure corresponds to a certain bubble and/or dew point temperature, and with increasing pressure the temperature increases accordingly. The choice of the operating pressure, more precisely the pressure profile, depends on the system considerations; since distillation is a typical economy of scale technology, it is a natural tendency to strive for the most cost-effective designs.

A distillation column designer must be aware of the effects of the pressure on all relevant physical properties of both phases, to be able to understand what happens or could occur in the system under consideration. Table 4 summarizes the influence of increasing pressure on all relevant properties and design and operating parameters. This information can be used for the first estimations; however, rigorous calculations need to be performed in each case to quantify the sensitivity of the variable change caused by operating pressure variations

Table 1: Trends in physical properties of saturated liquid and vapors with increasing pressure

| Property                 | Trend    |
|--------------------------|----------|
| Temperature              | Increase |
| Liquid density           | Decrease |
| Liquid viscosity         | Decrease |
| Liquid diffusivity       | Increase |
| Surface tension          | Decrease |
| Vapor density            | Increase |
| Vapor viscosity          | Increase |
| Vapor diffusivity        | Decrease |
| Enthalpy of vaporization | Decrease |

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High pressure distillations normally use a top column pressure of 6 bar or greater. It usually occurs in thermally integrated processes or when the normal boiling point of the vapor product is lower than the temperature of the cooling water required condensing. These high pressures produce a greater vapor density that might represent a significant percentage of the liquid density. The accompanying increase in boiling temperature not only lowers the liquid density, but also reduces the surface tension and the viscosity of the liquid phase.

The relative volatility, in general, will reduce as the pressure is increased. Since separation becomes more difficult with reduced volatility, the number of theoretical stages required is greater for the same operation at higher pressure. Even through the capacity of a column increases at higher pressure, owing to the greater vapor density, the number of theoretical stages or reflux ratio required will also be greater. High Pressure Propylene is usually distilled at a pressure of at least 16 bar, so that condenser can be cooled with water to reduce refrigeration system cost.

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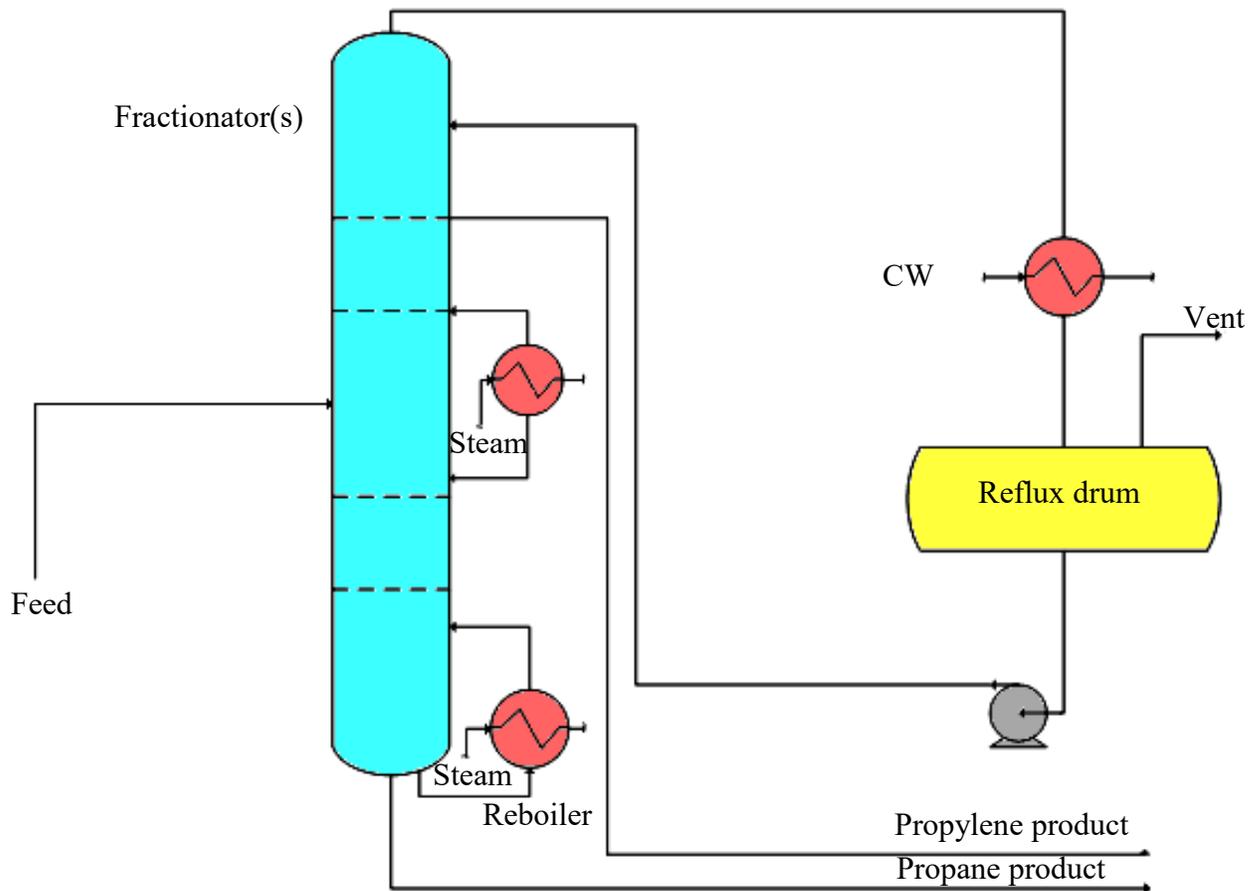


Figure 1 High Pressure Systems

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## Heat Pump System

A heat pump system, utilizes a compressor to reduce the tower pressure to allow the distillation column to be smaller. In most distillation applications relative volatilities can be improved by lowering the column pressure. This results in lower number of required theoretical stages and reflux flow. These savings are offset by the required energy cost of the compressor.

A heat pump is a device for raising low grade heat to a temperature at which the heat can be utilized. It pumps the heat from a low temperature source to the higher temperature sink, using a small amount of energy relative to the heat energy recovered. Heat pumps are increasingly finding applications in the processes industries. A typical application is the use of low grade heat from the condenser of a distillation column to provide heat for the reboiler.

Heat pump distillation is promising in the case where the recovering energy is very large and the temperature difference between the top and the bottom is not distinct, often below 20°C. It is reported that if a heat pump of open type with adiabatic flash and compression can improve thermodynamic efficiency from 20% to 70%.

The working fluid, usually a commercial refrigerant, is fed to the reboiler as a vapor at high pressure and condenses, giving up heat to vaporize the process fluid. The liquid refrigerant from reboiler is then expanded over a throttle valve and the resulting wet vapor fed to the column condenser. In the condenser the wet refrigerant is dried, taking heat from the condensing process vapor. The refrigerant vapor is then compressed and recycled to the reboiler, completing the working cycle.

If the conditions are suitable the process fluid can be used as the working fluid for the heat pump. The hot process liquid at high pressure is expanded over the throttle value and fed to the condenser, to provide cooling to condense the vapor from the column.

A good rule of thumb is that if the propylene system is associated with an ethylene plant, in which there is typically an abundance of quench water that can be used to heat the C3 Splitter reboiler a non heat pump system may be the best choice. If no source of sufficient low-grade heat is available for example in a refinery FCC unit or propane dehydrogenation unit, then the use of a Heat Pump is typically the economical choice.

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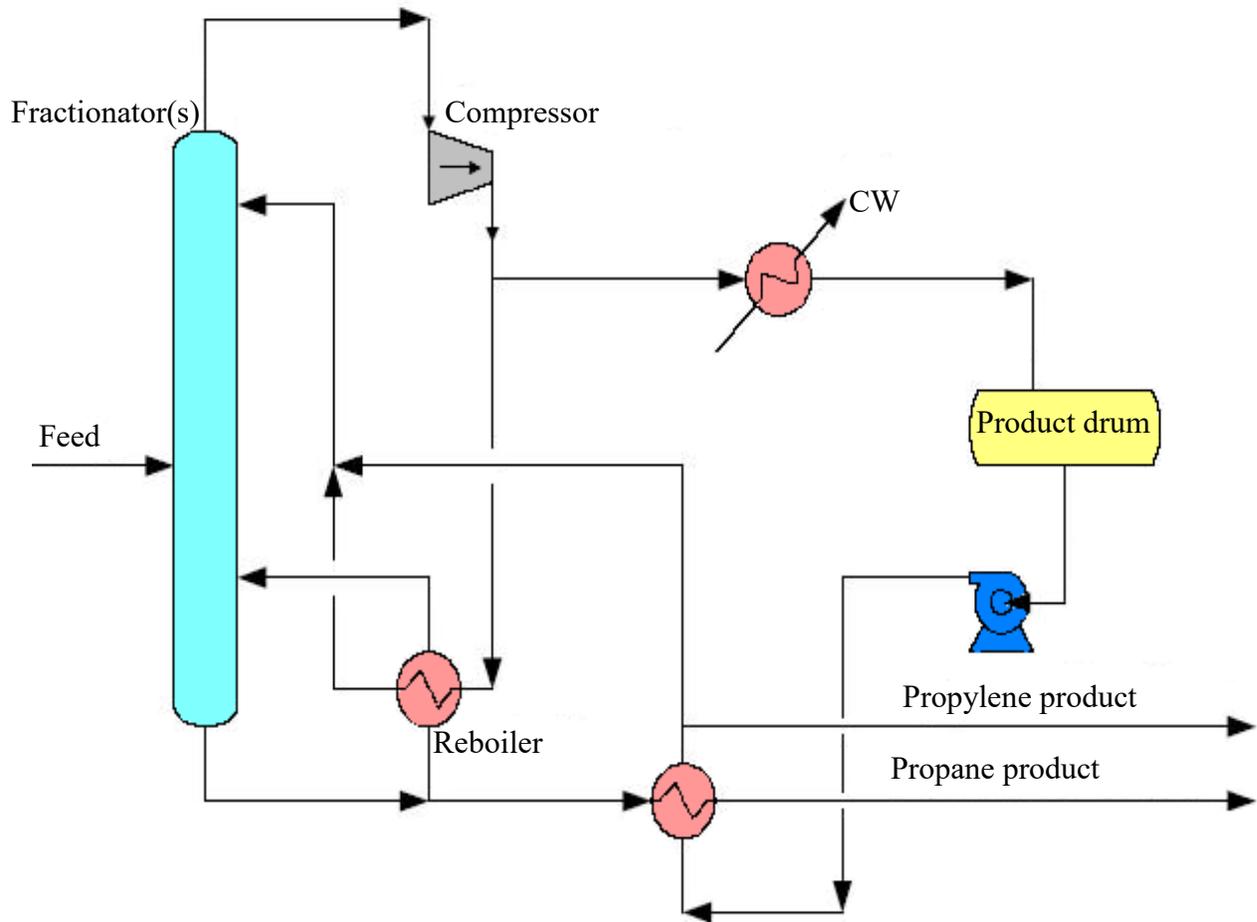


Figure 2 Heat Pumped Systems

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Most simulation packages have tower-sizing routine. These routines are fairly easy to use and yield quick results. However, these results should be verified by calculation. Column sizing is done on a trial and error basis. The first step is to set design limits. The design limits are as follows:

1. Maximum Design rates – Vapor/Liquid Traffic is needed at Maximum Operating rates.
2. Design rates - Vapor/Liquid Traffic is needed at Design Operating Conditions.
3. Minimum Design rates - Vapor/Liquid Traffic is needed at Minimum Operating rates.

Sizing calculations need to be performed in areas of the column where the vapor/liquid traffic is expected to be highest and lowest for each section. For example,

1. The top tray and bottom tray in the column.
2. The feed tray.
3. Any product draw-off tray or heat addition/removal tray.
4. Trays where the vapor liquid loading peaks.

Once the preliminary tower diameter has been set the internals can be chosen. The task of choosing the type of tower internal to use is very important. The type of column internals used dictates a column's efficiency and capacity. All of the modeling and careful design work will mean nothing if the wrong type of column internals is chosen. For propylene fractionation trays are the only type of internal that should be considered.

The types of internals that have been used in propylene splitter columns are:

1. Conventional Multi pass Trays

Conventional Multi pass trays are typically used when a column is initially designed. Four pass or six pass trays are usually used because of their ability to handle high liquid loads like seen in propylene fractionation. The downside to using multi pass trays is the reduction in separation efficiency that is experienced due to the reduction in active area. Great care must be taken when sizing down comers in high-pressure distillation applications. The difference between vapor and liquid densities becomes smaller and separation of vapor from liquid in a down comer becomes more difficult.

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This can result in increased aeration back-up and possible premature downcomer flooding.

## 2. Multi-Down comer Trays

Multi-Down comer trays are used for large liquid loads, particularly when the volumetric ratio between vapor and liquid rates is low. These situations occur in medium to high-pressure distillation, in absorption and stripping, and in direct contact heat transfer applications.

Multi-Down comer trays can be used at close tray spacing. This will allow a reduction in both height and diameter of a new column compared to a column fitted with conventional multi-pass trays. Vessel shell costs can be significantly reduced with the use of Multi-Down comer trays. When retrofitting an existing column with Multi-Down comer trays, a significantly greater number can be installed, providing increased product purities and recoveries, as well as reduced reflux ratio for reduced energy consumption and/or increased column capacity.

The use of Multi-Down comer trays has often reduced the number of columns needed in difficult separations, such as the fractionation of propylene-propane.

## 3. Structured and Random Packing

Structured packing typically consist of thin corrugated metal plates or gauzes arranged in a way that they force fluids to take complicated paths through the column, thereby creating a large surface area for contact between different phases. Structured packing offer excellent capacity and low pressure drop per theoretical stage. Structured Random Packing should be limited to low pressure application of less than 10 Bar.

## 4. High Capacity Trays

High-capacity trays can greatly increase distillation tower capacity. In a high-capacity tray, the clearance needed to allow vapor to escape from under the down comer creates a large down comer opening. The large down comer opening does not impose sufficient back pressure to hold a liquid level in the down comer. A restriction in the down comer creates sufficient pressure drop on the liquid that a head builds up and vapor cannot bypass.

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Direction and momentum can also help to prevent vapor bypassing up the down comer. In some designs the vapor rising through the active area under the down comer is sent through slots angled across the tray instead of through conventional slots.

In a propylene fractionator column, the tower cross sectional area is the sum of the trays active area plus the total down comer area. The amount of required active area (Vapor-Liquid Bubbling Area) is determined by vapor flow rate. The down comers handle a mixture of clear liquid, froth, and aerated liquid. The down comer area required to handle the high liquid flow not only increases with the liquid flow rate, but also with the difficulty in achieving separation between the liquid and vapor phases.

The volume required for the down comer increases at a lower surface and a smaller density difference between the liquid and vapor. Because of the large down comer area required to handle the high liquid flow rates the area may be 40% to 80% greater than the calculated tray active area for the vapor flow rates for propylene fractionator distillation. The down comer area becomes a significant factor in the determination of the tower diameter.

Downcomer assist the froth generation improve efficiency. The downcomer top needs to be large enough for vapor-liquid disengagement. The liquid at the bottom downcomer is almost clear that the downcomer bottom can be much smaller without great effect in downcomer performance. The longer exit length and fully opened downcomer bottom help liquid easily flow out of the downcomer, lowering downcomer head loss and reduce the clear liquid in the downcomer. If the downcomer cannot handle the liquid loading, downcomer flooding can be achieved that can reduce efficiency. There is several type of down comer.

- a. Straight downcomer is the type most commonly used. Utilities column area for downflow and is cheaper and much more simple.
- b. Sloped downcomer have a larger top width than bottom width. By sloping the downcomer, the cross-sectional area of the downcomer is reduces towards the bottom. This tends to equalize the downward velocity throughout the length of the downcomer and helps to control the frictional losses. Sloped downcomer is used to increase the active area and improve downcomer separation without wasting the active area on the tray below to increase the tray capacity. Typically the wall vertical of the downcomer is 100-150 mm

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- c. Truncated downcomer. A bottom plate is mounted in order to achieve dynamic sealing and ends above the clear liquid height of the tray deck. The truncated downcomer allows all the area under the downcomer except for the liquid downpour area to be used as active area.

In order to determine the accuracy of a simulation it is always desirable to construct a McCabe-Thiele diagram from the data generated from the simulation. The data from the simulation can be easily transferred to a software package where the graph can be constructed. This graph is used more as a tool to identify possible problems that won't be discovered until the column fails. The following is a list of the areas where a McCabe-Thiele diagram can be used as a powerful analysis tool.

1. Pinched regions - Pinching is readily seen on an x-y diagram.
2. Miss-located feed points - The feed point should be where the q-line intersects the equilibrium curve. This is generally the rule in binary distillation. However, it is not always true in multicomponent distillation. A key ratio plot is often developed in the design phase. This type of plot is far superior to an x-y diagram for identifying miss-located feeds, especially with large multicomponent systems.
3. Determining if the column is being over refluxed or reboiled - This can be recognized by too wide of a gap between the component balance line and the equilibrium curve throughout the column.
4. Identify cases where feed or intermediate heat exchangers are needed.

Most commercial simulation programs will provide the information required to generate these plots. Here the design simulation that should be considered in process simulators.

1. Pressure Profile
  - a. The pressure in the column can be defined either by the overall column or by the individual trays.
  - b. Overall requires: top tray pressure and overall pressure drop (per tray or whole column)
  - c. Individual trays: allows user to specify the pressure on individual trays

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## 2. Feeds and Products

- a. Vapor and liquid might be on feed tray or flashed. If the feed is flashed the liquid portion of the feed stream will go to the feed tray, while the vapor will go to the tray above the feed tray.
- b. Estimation of one of the two product stream (overhead and bottoms) flow rates is needed. Setting both streams can lead to over specification of the system.

## 3. Performance specifications

- a. It is possible to define a distillation column just using column parameters or stream parameters.
- b. The other parameters that can be set are the variables that will be modified in fitting the column. The condenser and reboiler duties are the default variable, but these can be changed.
- c. Number of specification and variables should be the same.
- d. Performance specifications are based on adjustment of heating and cooling loads in the column to obtain the target concentrations.
- e. This effectively adjusts the reflux ratio.
- f. The top concentration is controlled using the condenser cooling load
- g. The bottom concentration is controlled using the reboiler heating load.

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## DEFINITIONS

**Acentric factor** – a measure of the non-sphericity (centricity) of molecules.

**Bottoms** – The stream of liquid product collected from the reboiler at the bottom of a distillation tower.

**Bubble point** – The temperature at constant pressure (or the pressure at constant temperature) at which the first vapor bubble forms when a liquid is heated (or decompressed).

**Bubble Area** - the deck area of the tray which may either be perforated or fitted with valves or bubble caps and is the area available for vapor/liquid contacting

**Critical point (critical state)** – specifies the conditions (temperature, pressure, and sometimes composition) at which a phase boundary ceases to exist.

**Dew point** – The temperature at constant pressure (or the pressure at constant temperature) at which the first liquid droplet forms when a gas (vapor) is cooled (or compressed).

**Distillate** – The vapor from the top of a distillation column is usually condensed by a total or partial condenser. Part of the condensed fluid is recycled into the column (reflux) while the remaining fluid collected for further separation or as final product is known as distillate or overhead product

**Downcomer** - a vertical channel that connects a tray with the next tray below which carries froth and creates residence time which helps the vapor disengage from the froth.

**Downcomer Area** - is the area available for the transport of liquid from one tray to the next tray below.

**Downcomer Back-up Flood** - occurs when the head of liquid in the downcomer backs up onto the tray deck. The head of clear liquid in the downcomer is a balance of the pressure drop across the tray plus the head loss through the downcomer clearance. However an aeration factor must be applied to estimate the actual height of aerated liquid in the downcomer

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**Downcomer clear liquid** - the measure of the amount of liquid in the downcomer.

**Downcomer velocity** - the maximum clear liquid velocity into the top of the downcomer.

**Equation of state** – A relation between the pressure, volume and temperature of a system, from which other thermodynamic properties may be derived. The relation employs any number of ‘constants’ specific to the system. For example, for a pure component, the constants may be generalized functions of critical temperature, critical pressure and acentric factor, while for a mixture, mixing rules (which may be dependent on composition or density), are also used.

**Entrainment** – liquid carried by vapor up to tray above and caused by high vapor flow rates

**Foaming** – expansion of liquid due to passage of vapor or gas.

**Flooding** – brought about by excessive vapor flow, causing liquid to be entrained in the vapor up the column.

**Head of clear liquid** - a function of weir height and weir length (as well as liquid and vapor rates and physical properties) and so pressure drop may be reduced by increasing the number of flow paths in high liquid rate services.

**Light key** – The lighter (more volatile) of the two key components. Light key is collected at the distillate. All non-key components lighter than the light key are known as the light components.

**Open Area (or Hole Area)** - is the aggregate area available for vapor passage through the tray deck via perforations or valve and bubble cap slots. This is a critical factor in the tray operating range since high vapor velocity through the open area (hole velocity) will induce heavy liquid entrainment (as well as high pressure drop), but low hole velocity may allow liquid to "weep" or even "dump" through the tray deck to the tray below. The influence of open area on pressure drop also impacts on the liquid back-up in the downcomer

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**Reboiler** –Is a heat exchanger typically used to provide heat to the bottom of industrial distillation columns. They boil the liquid from the bottom of a distillation column to generate vapors which are returned to the column to drive the distillation separation.

**Reflux ratio** – The ratio of the reflux stream to the distillate. The operating reflux ratio could affect the number of theoretical stages and the duties of reboiler and condenser.

**Relative volatility** –Defined as the ratio of the concentration of one component in the vapor over the concentration of that component in the liquid divided by the ratio of the concentration of a second component in the vapor over the concentration of that second component in the liquid. For an ideal system, relative volatility is the ratio of vapor pressures i.e.  $\alpha = P_2/P_1$

**Tray Pressure Drop** - may also be a limiting criterion particularly in low pressure services. The operating tray pressure drop is the sum of the dry pressure drop caused by the resistance to vapor flow through the tray open area and the head of clear liquid on the tray deck.

**Tray Spacing** - is the vertical distance between adjacent tray decks. This effects both the height of spray that may be generated on the tray deck before liquid carryover and also the allowable head of liquid in the downcomers.

**Turndown ratio** - the ratio of the highest to the lowest flow rates

**Vapor-liquid equilibrium (VLE)** – a condition where a liquid and its vapor (gas phase) are in equilibrium with each other; a condition or state where the rate of evaporation equals the rate of condensation on a molecular level, thus there is no net (overall) vapor-liquid interconversion.

**Weeping/dumping** – caused by low vapor flow. The pressure exerted by vapor is insufficient to hold up liquid on the tray. Liquid starts to leak through perforations. Excessive weeping lead to dumping; where liquid on all trays will crash (dump) through the base of column.

**Weep point** - the lower limit of the operating range occurs when liquid leakage through the plate holes becomes excessive.

**Weir loading** – a measure of the amount of liquid going over the outlet weir.

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## NOMENCLATURES

|            |  |
|------------|--|
| $A_N$      | Bubbling area, ft <sup>2</sup>                             |
| $A_D$      | Downcomer area, ft <sup>2</sup>                            |
| $A_T$      | Total tower area, ft <sup>2</sup>                          |
| $B$        | Bottom flow rate, lb/hr                                    |
| $CFS$      | Vapor flow rate, ft <sup>3</sup> /s                        |
| $CSB$      | C-Factor at flood, ft/s                                    |
| $D_T$      | Tower diameter, ft   |
| $D$        | Distillate flow rate, lb/hr                                |
| $d_H$      | Hole diameter, in  |
| $d_T$      | Tower diameter design, ft                                  |
| $E_{OC}$   | Overall column efficiency, %                               |
| $F$        | Feed flow rate, lb/hr                                      |
| $GPM$      | Tray liquid loading, gpm                                   |
| $H_D$      | Enthalpy of overhead product, btu/lb                       |
| $H_B$      | Enthalpy of bottoms product, btu/lb                        |
| $H_F$      | Feed enthalpy, btu/lb                                      |
| $h_{ct}$   | Clear liquid height, in.liq                                |
| $L$        | The liquid flows, lb/h                                     |
| $L_w$      | Weir length, in  |
| $N$        | Number of theoretical stages,                              |
| $N_m$      | Minimum stages   |
| $N_{act}$  | Actual stages  |
| $Q_L$      | weir load, gpm/in  |
| $Q_R$      | Reboiler heat requirement, btu/hr                          |
| $Q_C$      | Condenser heat load requirement, btu/hr                    |
| $R$        | Reflux ratio   |
| $R_m$      | Minimum reflux ratio                                       |
| $S$        | Tray spacing, in   |
| $U_N$      | Flooding vapor velocity, ft/s                              |
| $V$        | Vapor flows, lb/hr   |
| $VD_{dsg}$ | Velocity of clear liquid at downcomer, GPM/ft <sup>2</sup> |
| $X_D$      | Mole fraction overhead light key                           |
| $X_F$      | Mole fraction feed light key                               |
| $X_B$      | Mole fraction bottom light key                             |

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## Greek Letters

|           |                                    |
|-----------|------------------------------------|
| $\alpha$  | Relative volatility,               |
| $\eta$    | Plate efficiency, %                |
| $\sigma$  | Surface tension, dyne/cm           |
| $\rho_L$  | Liquid density, lb/ft <sup>3</sup> |
| $\rho_V$  | Vapor density, lb/ft <sup>3</sup>  |
| $\lambda$ | Latent heat, btu/lb                |
| $\mu_L$   | Liquid viscosity, Cp               |

## Superscript

|     |                                     |
|-----|-------------------------------------|
| B   | Bottom flow rate, lb/hr             |
| CFS | Vapor flow rate, ft <sup>3</sup> /s |
| CSB | C-Factor at flood, ft/s             |
| D   | Distillate flow rate, lb/hr         |
| F   | Feed flow rate, lb/hr               |
| GPM | Tray liquid loading, gpm            |
| L   | The liquid flows, lb/h              |
| N   | Number of theoretical stages        |
| R   | Reflux ratio                        |
| V   | Vapor flows, lb/hr                  |

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