

<b>KLM Technology Group</b>  Practical Engineering Guidelines for Processing Plant Solutions	  <a href="http://www.klmtechgroup.com">www.klmtechgroup.com</a>	Page : 1 of 66
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		September 2012
KLM Technology Group #03-12 Block Aronia, Jalan Sri Perkasa 2 Taman Tampoi Utama 81200 Johor Bahru	<b>ETHYLENE SPLITTER          (ENGINEERING DESIGN GUIDELINE)</b>	Rev 01 Aprilia Jaya
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## **INTRODUCTION**

### **Scope**

This guideline covers the basic elements of ethylene splitter design in sufficient detail to allow an engineer to design an ethylene splitter with the suitable size of tower diameter tower height, feed point location, tray spacing, reflux ratio, and number of stages. These will effect in tower performance, capacity and efficiency.

The C2 splitter is commonly operated at high-pressure, utilizing closed-cycle propylene, ethylene or mixed refrigeration, some design at low and medium pressure. The revamp required significant modifications to the C2 splitter system. The economics of the expansion required the use of the existing column and exchanger shells.

The design of ethylene splitter may be influenced by factors, including process requirements, economics and safety. In this guideline there are tables that assist in making these factored calculations from the various reference sources

Traditionally, the separation is performed in distillation columns containing about 100 - 130 plates, making it the high cost- and high energy-intensive separation process. Thus, a good engineering review is needed before installing an ethylene splitter. In this guideline, the process simulation of ethylene splitter distillation column is explained to help engineers understanding the basic concept. Some theories are also described in this design guideline to help the engineers as well.

The theories used in this guideline are commonly used in industrial such as Kister, Van Redlich Kwong, SRK, and Van Der Waals. The application of the ethylene splitter theory with the example and simulation by Process Simulator will assist the engineer to study for the ethylene splitter and be ready to perform the actual design of the tower.

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## General Design Consideration

Ethylene is one of the most versatile and widely used petrochemicals in the world today. Its main use is for the manufacture of polyethylene. With a worldwide capacity of more than 130 million metric tons per year the economic importance of the ethylene business is evident. The trend has been to build larger and larger units, and consequently the ethylene splitter (C2 splitter) have increased size up to 20 ft in diameter.

In the olefin business reducing energy consumption is a significant driver. Modifying the trays in the C2 splitter can have an impact on the capacity and energy consumption of the plant. Several revamps for increased capacity have been reported.

Longer flow path lengths and plug flow of the froth across the tray deck are needed to achieve high tray efficiency. To increase tray efficiency these features might be include

1. Inlet weirs and bubble promoters to generate good froth quality
2. Use vapor tunnel and truncated down comers to maximize bubbling area
3. Down comer shapes that meter liquid to all zones of the tray
4. Mechanical features to reduce complexity, increase mechanical strength, reduce fouling, and simplify installation.
5. Trays with a large number of down comer, and short path lengths, 28% more trays would have been needed to do the same separation.
6. Having more trays also has a negative impact on the overall pressure drop
7. Having trays on a lower tray spacing also reduces the capacity of trays
8. Using a higher reflux ratio to compensate for reduces efficiency is generally not desirable since it increases energy consumption, could necessitate de-bottlenecking more equipment, and further reduces the tray capacity.

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

1. Process simulation of a ethylene 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 ethylene 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. 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. Total is the usual case.
6. Desired key recoveries, i.e. a desired composition of a single component in either the bottoms or distillate.

Advanced distillation control should be considered because without it olefin recovery might be lower. To minimize recycling of olefins, the operator would try to keep the plant as steady as possible, and maximize throughput.

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Column feed as well as each of the products, could contain several components. There are two manipulated variables: product draw and reboiler heat duty. There may be on-stream analyzers for measuring product compositions continuously or the laboratory may take measurements periodically.

The distillation control application must find a way to set reboiler heat duty and top product draw such that product compositions are steady at targets. This is a difficult control problem for a number reason:

1. Interaction between the top and bottom purities.
2. Slow dynamics of the columns, measurable in hours.
3. Nonlinear dynamic behavior, which changes with plant conditions.
4. Changing feed composition and flow makes distillation control a moving target.

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. At a high temperature most of hydrocarbon materials tend to degrade. To prevent thermal degradation of distilled material, the operating pressure has to be accommodated to allow most economical operation.

Determining of the operating pressure (profile) is the first step in the design of a new column. This implies first establishing the column top pressure, and then the pressure drop of the column, which determines the bottom pressure and temperature. In case of redesign (revamping, retrofitting) of existing columns, the new reduced pressure drop is aimed for, which depends on the type of the internals and the operating conditions.

A typical operating pressure for a C2 splitter might be 16 bar. There are three general typical design of an ethylene splitter: high-pressure, low pressure, and medium pressure.

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## Low Pressure System

The low pressure distillation a compressor is utilized in the overhead vapor. The low pressure distillation column internals must provide good vapor-liquid contacting while, at the same time, maintaining a very low pressure increases from the top of the column top to the bottom. Therefore, the low pressure column uses distillation trays only where withdrawing products from the side of the column. Most of the column uses packing material for the vapor-liquid contacting because such packing has a lower pressure drop than distillation trays. Packing has been utilized in C2 Splitter below 10 Bar.

The lowest pressure and consequently the lowest temperature in a distillation column system is established in the reflux accumulator. This pressure, enlarged by the pressure drop of the condenser and the vapor transport line connecting the top of the column and the condenser, makes the column top pressure. The pressure at the bottom of the column results from the addition of the pressure drop of the column internals to the column top pressure. This is usually taken as the highest pressure point which however is in the reboiler placed nearby.

Below is some design that should be considered when using low pressure system

1. The column pressure drop of 0.25 bar, can be considered as rather small however, regarding the absolute value it is nearly four times larger than the column top absolute pressure.
2. New columns equipped with structured packing experience a rather low-pressure drop ( $< 0.1$  bar) and, consequently, all are designed as one diameter column.
3. In the revamps of low pressure tray columns the stripping section diameter was the limiting factor.
4. In low pressure columns the weir heights  $< 3$  cm are preferred. Owing to a rather low liquid load, the trays employed in low pressure distillation are usually single-pass trays
5. If diameters  $>5$  m are required in a low pressure application two pass trays are considered.
6. Low pressure distillation deals with heavy components having a large viscosity. Therefore, low pressure distillation is generally associated with a low flow rate of a high-viscosity liquid.

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The advantages of low-pressure distillation process over Atmospheric pressure distillation are as under:

1. Use of lower process temperatures.
2. Shorter time of thermal exposure of the distillate.
3. Increase in relative volatility. Materials become more volatile and therefore more evaporation takes place, resulting in higher production rates.
4. Fractional distillation leads to easier separation of components of a mixture.
5. Reduction of energy consumption.
6. Oxidation losses of the feed stock are reduced.

### Medium Pressure System

Medium pressure system using heat pump as compressor to reduce the tower pressure and allow the distillation column to be smaller. A heat pump is a device that upgrades heat from a lower temperature source to a higher temperature. Originally heat pumps were only used for refrigeration as heating was done by burning cheap fossil fuels.

The objective of a heat pump in distillation is to use the heat of condensation released at the condenser for evaporation in the reboiler. As the temperature at the reboiler is higher a heat pump is required.

For a heat pump to be effective there are a number issues to be considered:

1. The pinch temperature and the flexibility of the plant
2. The thermodynamic cycle and the heat pump efficiency
3. The temperature lift required
4. The enthalpy balance
5. The selection and constraints of heat pump equipment
6. The configuration of the system
7. The available utilities
8. The economy or the annualized capital cost versus the utility cost

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In the heat pump system the working fluid is the vapor leaving at the top of the column, which is compressed, condensed in the reboiler and partially refluxed to the top of the column after pressure reduction over a valve. A small trim condenser is needed to balance the heat input, mainly generated by the compressor. An interesting alternative for the heat pump is the bottom flash column (BFC). The advantage of the heat pump is the condenser in a heat pump is smaller and that the temperature lift is about 5 K lower because heat is exchanged only once. This results in a higher thermodynamic efficiency. Because of these advantages heat pump system has become the standard technology.

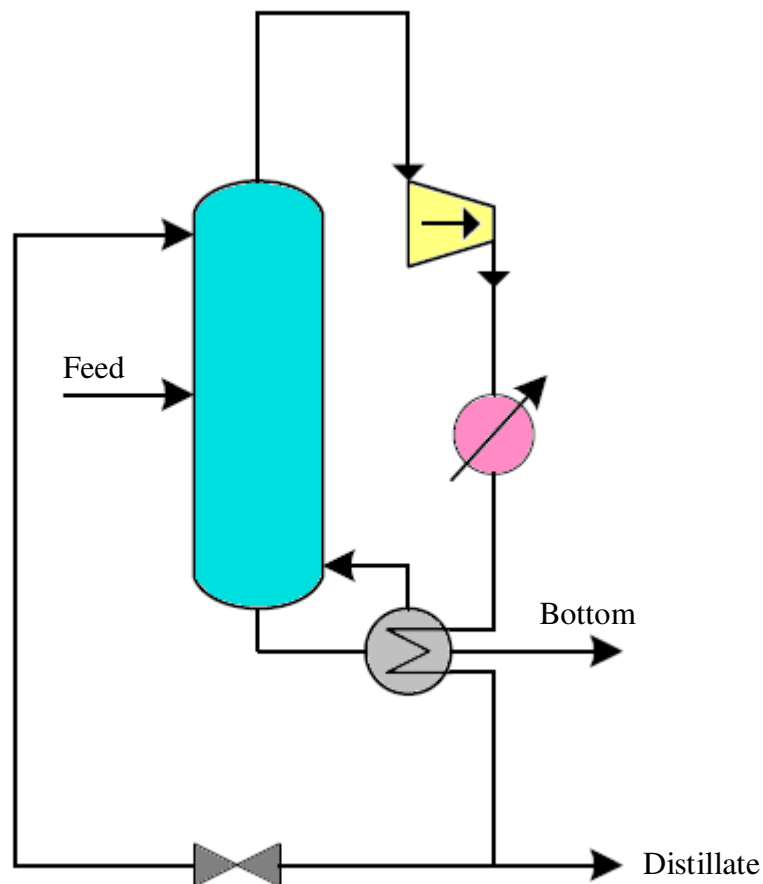


Figure1: Medium pressure/heat pumped system

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## High pressure system

To reduce the pressure drop these columns had to have much larger diameter, with the resulting vapor load equivalent to 50% instead of 80% of the flooding limit.

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. A distillation column designer must be aware of the effects of the pressure on all relevant physical properties of both phases Table 1 summarizes the influence of increasing pressure on all relevant properties and design and operating parameters.

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

In high-pressure columns even those with very high absolute but relatively small (<10%) pressure drop the pressure drop is usually not a concern from fluid dynamics point of view, but, if underestimated, it could be highly detrimental to thermodynamics A pressure drop of around 1 bar is not affecting significantly the vapor flow. Namely, a rather small change in the relative volatility <1.2 (close boiling systems) influences strongly both the stage and reflux requirements. As pressure is raised:

1. Separation becomes more difficult (relative volatility decreases), that is, more stages or reflux are required;

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2. Latent heat of vaporization decreases, that is, reboiler and condenser duties become lower;
3. Vapor density increases, giving a smaller column diameter;
4. Reboiler temperature increases with a limit often set by thermal decomposition of the material being vaporized, causing excessive fouling;
5. Condenser temperature increases.

Below is some design that should be considered when using high pressure system

1. A pressure drop of around 1 bar is not affecting significantly the vapor flow.
2. Since column diameter depends strongly on vapor density, the increasing operating pressure results for the same internal mass flow in a smaller column diameter accompanied by a correspondingly increased specific liquid load.
3. Expressed as superficial liquid velocity per hour, the specific liquid load of distillation columns varies generally from 1m/h in low vacuum to 70m/h in high pressure applications.
4. At high flow parameter end, which is characteristic of high-pressure distillation, down comer and/ or system flood is a limiting factor
5. The capacity of an existing column can be increased by increasing the operating pressure.
6. The evaporation enthalpy and consequently required reboiler duty decreases with increasing pressure.
7. Under vacuum conditions trays operate mainly in spray (drop) regime, around the atmospheric pressure mixed-froth regime prevails, and high-pressure operation is usually associated with the emulsion regime.
8. If bubbles which are created are so small (high pressure in conjunction with rather low surface tension) that they cannot escape from the liquid then a significant amount of vapor entrainment occurs, this is accompanied by a reduction in tray efficiency.
9. At high pressures, i.e., high liquid loads and heights on trays, the relatively much larger liquid cross-flow velocities contribute to the breakage of larger bubbles into smaller bubbles.

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10. The pressure drop of both packed and tray columns increases with increasing pressure owing to an increase in the specific liquid load.
11. High-pressure tray columns have a larger downcomers and weir height, which implies a higher clear liquid layer and consequently higher pressure drop for the given vapor load
12. The wall thickness of column shell increases with increasing pressure. The diameter decreases but a taller column may be necessary.
13. In high pressure applications, weir heights from 5 to 10 cm are common. Skirt clearance (inlet downcomer opening) is slightly lower than the weir height and also increases with increasing liquid load.
14. In general, with increasing operating pressure, at a certain point the liquid load becomes so large that it cannot be handled properly by a single-pass tray and this tendency becomes more pronounced with increasing column diameter.
15. If the exit weir load exceeds 60 m<sup>3</sup>/h per meter weir length, two or more passes are required to handle the liquid appropriately. multi-downcomer trays are generally less efficient than common cross-flow single-pass trays.
16. the hydrocarbons distilled at high pressure are the lightest ones and therefore the absolute values of the viscosity are rather small
17. Vapor viscosity increases slowly with the increasing pressure while vapor density increases proportionally to the pressure.

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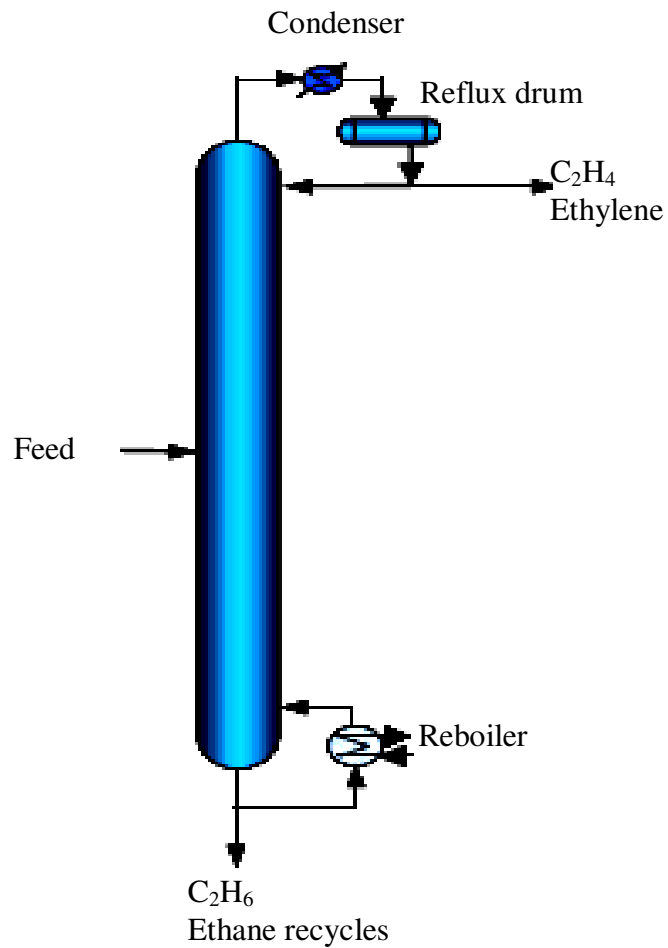


Figure 2: High pressure C2 splitter

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It is well understood that distillation is a critical aspect of any ethylene plant design. Moreover, the optimization techniques and the selection process for tower internals requires yet greater knowledge and individual experience to achieve the best solution most especially within a major ethylene plant expansion.

It is well recognized that heat transfer within an ethylene plant is best represented by the Prefractionation System comprised of major column(s) for Oil and/or Water Quench Tower Service specific to the feedstock(s) of choice. Both the industry and other technology suppliers to the industry have utilized a variety of commercial tray and/or packing types for the Prefractionation System; namely, conventional valve and sieve or stepped-down sieve trays, "disk-and donut" trays, baffle-deck, angle iron, dual-flow trays and many other random/structured packing types.

Continued efforts by technology suppliers of high capacity tower internals have resulted in improvements in all current tray technologies to increase capacity and retain, if not improve, efficiency performance.

Cross-flow tray technology improvements and innovations have resulted in the following directional design alterations:

1. Lengthening downcomer weirs
2. Altering downcomer geometry by reducing the size at the bottom of the downcomer relative to the top of downcomer
3. Removing the outlet weir
4. Shaping the downcomer outlet lip
5. Improving active area performance
6. Enhancing vapor space performance
7. Boosting downcomer performance
8. Designing dynamic seals with hanging downcomers

Both trayed and packed columns shall continue to have significant roles to play in distillation. Understanding the factors involved in optimizing each contact device provides a basis for choosing between either trays or packing. In general, for both showcase projects, packing was not considered for existing tray installations where the

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application had either a relatively large diameter and/or significant height thus requiring regular re-distribution, or had the potential for fouling.

For expansion projects usually applying packing, the mandatory liquid (and often vapor) distribution (and re-distribution), requirements cannot increase the “net” number of theoretical stages due to the finite volume of the (existing) column. The types of internals that can be used in ethylene splitter columns are:

### High Capacity Tray Technology

Commercially available high capacity contact devices are well-known by industry members using distillation-intensive unit operations. Their applications within ethylene plant expansions have become a highly acceptable (near mandatory) solution, due to the positive economics from proven performance.

There are fundamentally three types of industry-accepted high capacity tray technologies; namely, (1) countercurrent contact, (2) multiple downcomer, and (3) cross-flow with elevated downcomer.

#### 1. Counter-Current Contact

This tray utilizes corrugated and perforated tray decks to promote vapor and liquid contact. Corrugation geometry provides a significantly increased area for higher hydraulic tray capacity. The has no downcomers, thereby enabling the entire cross-sectional area of a tower to be used for vapor and liquid contact. A high degree of liquid and vapor mixing also occurs on the tray itself.

The effective corrugation geometry, plus the elimination of the receiving pans, often provides upwards of 40 -50% (or more) additional capacity as compared to conventional valve and/or sieve trays. For highly liquid-loaded applications, when a large portion of the tower cross-sectional area for conventional cross-flow trays must be reserved for downcomer receiving pans, the Ripple Tray™ offers significant capacity increases. Additionally, the highly turbulent operating regime and absence of dead zones make this tray the pre-eminent tray for fouling services, but should not be utilized in C2 Splitters.

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## 2. Multiple Downcomer

These trays generally used for large liquid loads and particularly when the volumetric ratio between vapor and liquid rates is low. Multiple downcomers provide large total weir length and large downcomer area to provide high liquid handling capability.

Multiple downcomers can be used at close tray spacing thus providing an effective solution to significant capacity increases. The tray spacing for multiple downcomers is usually determined by the backup of froth in the downcomer itself. These trays use an elevated downcomer thus effectively using the area under the downcomer as “active”. The ability of a multiple downcomer to handle greater volumetric liquid rates at relatively extreme reductions in tray spacing as compared to a conventional cross-flow tray (i.e., valve or sieve) is countered by its loss in efficiency.

However, there is a resultant net positive gain in performance using a multiple downcomer. This net positive gain by virtue of its ability to increase capacity from a fixed number of stages (despite lower efficiency) within a given column height for a typical retrofit expansion has been successfully incorporated within many applications but most prominently within superfractionation. It should be noted because of the low path flow lengths these trays have 8 to 10% less efficiency than Cross Flowing Trays.

## 3. Cross-Flow Trays with Elevated Downcomers

The use of an elevated downcomer provides the opportunity to convert the area under the downcomer into “true” active area for fractionation. The alternates to affect this area under the downcomer are either perforated holes or “directional” valves. The various design techniques which must be superimposed upon this new active area to ensure passage of liquid from the downcomer to the tray below are often referred to as dynamic seals.

There are essentially four (4) criteria to review during the design/selection process:

1. Distance between tray active area and downcomer
2. Downcomer liquid head
3. Relative directional movement between liquid from the downcomer and vapor rising under the downcomer
4. Superficial vapor velocities to the tray and volumetric liquid rates from the downcomer

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The design techniques for proper performance to overcome the criteria stated above ensure that:

1. The distance between the bottom of the elevated downcomer and the tray deck is properly calculated so that the vapor escaping sideways or through the outlet downcomer area is sufficient to prevent flooding and the downcomer volume is acceptable to provide the necessary residence time to disengage the froth to its vapor and liquid phases respectively.
2. The liquid head exerts a pressure equal to (or greater than) the height of liquid in the downcomer multiplied by its density.
3. The proper direction and momentum are given to prevent vapor bypassing up the downcomer.
4. A suitable dynamic seal is provided to reduce the tray pressure drop thus increasing capacity in part.

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. Mis-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 multi-component 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 mis-located feeds, especially with large multi-component 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.

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Most commercial simulation programs will provide the information required to generate these plots. Here are some design simulation guidelines that should be considered.

### 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

### 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

**Derating Factor** - A multiplier used to reduce the current carrying capacity of conductors in more adverse environment

**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 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

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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.

**Operating reflux** - An amount in excess of the minimum that ultimately should be established by an economic balance between operating and capital costs for the operation.

**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.  $\alpha = P_2/P_1$

**Splitter** - A name applied to fractionators, particularly those separating isomers

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**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.

**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.

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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
$F_j, V_j, L_j$	Fed, vapor and liquid molar flow rates for Stage j
$GPM$	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
$H$	The column height, ft
$H_F$	Molar enthalpy of the feed
$H_j^V, H_j^L$	Vapor and liquid molar enthalpies for Stage j
$K_{i,j}$	Vapor–liquid equilibrium constant between $x_i$ and $y_i$ for Stage j
$L$	The liquid flows, lb/h
$L_w$	Weir length, in
$N$	Number of theoretical stages,
$N_m$	Minimum stages
$N_{act}$	Actual stages
$NC$	Number of components
$N_r$	Number of stages above the feed, including any partial condenser;
$N_s$	Number of stages below the feed, including the reboiler;
$Q_L$	weir load, gpm/in
$Q_R$	Reboiler heat requirement, btu/hr
$Q_C$	Condenser heat load requirement, btu/hr
$Q_j$	Heat transfer from Stage j (negative for heat transfer to the stage)
$R$	Reflux ratio
$R_m$	Minimum reflux ratio
$S$	Tray spacing, in

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$U_N$	Flooding vapor velocity, ft/s
$V$	Vapor flows, lb/hr
$VD_{dsg}$	Velocity of clear liquid at downcomer, GPM/ft <sup>2</sup>
$W_j, U_j$	Vapor and liquid side streams for Stage j
$X_D$	Mole fraction overhead light key
$X_F$	Mole fraction feed light key
$X_B$	Mole fraction bottom light key
$X_{F,HK}$	Concentration of the heavy key in the feed;
$X_{F,LK}$	Concentration of the light key in the feed;
$X_{D,HK}$	Concentration of the heavy key in the top product;
$X_{B,LK}$	Concentration of the light key if in the bottom product
$Z_{i,j}, Y_{i,j}, X_{i,j}$	Feed, vapor and liquid mole fractions for Stage j

### 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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