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Kolmetz Handbook Of Process Equipment Design

Distillation Column Tray Hydraulics Selection, Sizing and Troubleshooting

(ENGINEERING DESIGN GUIDELINES)

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INTRODUCTION

Scope

This design guideline covers the basic elements of tray hydraulics in sufficient detail to allow an engineer to design a trayed tower with the suitable size of tray spacing, weir height, holes, down-comer, and open area. These factors will influential flooding and weeping, and will effect the tray performance, capacity and efficiency.

The design of trays depends on the density, the rate of vapor and liquid through the tray. Each tray in a distillation column is designed to promote contact between the vapor and liquid on the stage, so there is mass and heat transfer. Ideally, the vapor and liquid leaving the stage are in equilibrium. Equilibrium is a function of the rate of mass and heat transfer between liquid and vapor in distillation and it has an effect on the efficiency of tray.

To increase efficiency and capacity of tray, a system is needed which will cover the whole spectrum of tray applications. One of the keys to make good quality products and high purities is tray hydraulics. Parameters of tray hydraulics beside the geometry of the tray as it mention in first paragraph, are vapor-liquid loading, the allowable pressure drop on the tray and in the downcomer, flooding, turndown and weir loading.

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

Generally, path flow liquid on tray is divided into single pass, two pass, three pass, and four pass. In this guideline, these differences will be discussed in detail for the proper engineering design for vapor-liquid loading and down comer design.

The theories used in this guideline are commonly used in industries such as Bennet, Van Winkle, Fair and Eduljee. Their application to tray hydraulic theory with examples will help the engineer understand tray hydraulics and be ready to perform the actual design of the trayed tower.

Included in this guideline is an example data sheet which is generally used in the industry and a calculation spreadsheet for the engineering design.

Types of Tray Distillation Column

Distillation is the most widely used separation process in the chemical industries. It is normally used to separate a mixture of materials to obtain one or more desired products which is achieved by selection of conditions of temperature and pressure so that at least a vapor and a liquid phase coexist and a difference in relative concentration of the materials to be separated in the two phases is attained.

Trays are the most commonly selected type of distillation column. Trayed Columns utilize a pressure and temperature differential to separate the products. For most tray columns, the weir holds a liquid level of each tray. The vapor must overcome this liquid head to move up the column. On the tray the vapor and liquid are contacted and then above the tray they are separated. Trayed column perform well in high liquid and vapor loading. At low flow parameters the capacity and efficiency of trays can be reduced. Tray have higher pressure drop than packing, and it may also have higher resistance to corrosion. Some other items are to consider when to use trays in a tower.

1. Usually trays have downcomer capacity problems in heavy foaming service.
2. Trays have higher pressure drop than structured packing column
3. Trays have a high resistance to corrosion
4. Entrainment is an issue with trays. Trays usually have more entrainment than packing. Excessive entrainment can lead to efficiency loss
5. Excessive vapor and liquid maldistribution can lead to a loss of efficiency in a tray tower.

There are five major types of tray column; bubble cap tray, sieve deck tray, dual flow tray, valve tray and baffle tray. Bellow is discussed each type.

A. Bubble Cap Tray

The oldest widely used equilibrium-stage plate is the bubble cap tray. A bubble cap tray is perforated flat plate which has a riser (chimney) over the holes covered with a cap. They are usually equipped with slots to allow the passage of vapor to be mixed with the liquid flowing across the tray forming bubble where the mass transfer takes place. Each tray is provided with one or more downcomers which the liquid flowing across the tray is conducted to the tray below. A liquid head is maintained on the tray by a dam placed on outlet side of the tray near the downcomer, it called the outlet weir. Bubble cap tray is able to operate at low vapor and liquid rates (less than 2 gpm per foot of average of flow width) because liquid and foam is trapped on the tray to a depth at least equal to the weir height.

Bubble cap trays work well in high turndown applications because the orifices in the bubble caps are in the form of risers whose top opening is elevated significantly above the tray deck. The size of the cap tends to create hydraulic gradient across the deck and a high vapor side pressure drop. The cost of bubble cap tray is by far the highest.

B. Sieve Tray

Sieve tray is perforated plate with holes punched into the plate and usually has holes 3/16 in to 1 in diameter. The standard size is 0.5 inch with the perforation punched downward. Vapor comes out from the holes to give a multi orifice effect. The vapor velocity keeps the liquid from flowing down through the holes (weeping). Vapor flow through the tray deck to contact the liquid is controlled by the number and size of the perforations.

The punching direction affects the dry pressure drop, a smaller hole diameter result in lower pressure drop for the same open area. This due to the ratio of hole diameter to the tray thickness. The number and hole size are based on vapor flow up the tower. The liquid flow is transported down the tower by down-comers, a dam and overflow device on the side on the plate. A sieve tray has higher entrainment than valve tray at the same vapor velocity. This is due to the spray of liquid directed upwards to the next tray. For efficient operation, the hole velocity must be sufficient to balance the head of liquid on the tray deck and thus prevent liquid from passing through the perforations to the tray below

Sieve trays can be used in almost all services. Sieve deck tray has a minimum capacity approximately 70%. Their capacity and efficiency are at least as high as that of other standard trays used commercially. Sieve trays may be used in moderately fouling services, provided that large holes (3/4 to 1 in. [19 to 25 mm]) are used. Sieve trays are simple and easy to fabricate and therefore relatively inexpensive.

C. Dual flow tray

Dual flow tray is a sieve tray without a downcomer. Vapors move up to the tray above through the hole, while the liquid traveles down in the same hole that can result in mal-distribution and low efficiency. Dual flow trays are designed with enough open area on the tray deck to eliminate stagnation and promote back missing that makes it suited to handle highly fouling services, slurries, and corrosive services. Dual flow trays are well suited also for the fractionation of polymerizable compounds and give more bubbling area, therefore have a greater capacity than other tray types. Dual flow tray is also the least expensive to make and easiest to install and maintain. Dual flow tray performs best in the operating region of 60 to 85 % of flood and increases the efficiency with vapor rate.

The challenge of dual flow tray is mal-distribution in larger diameter towers. The top of a column will move in a typical storm as much as six inches. This movement will cause the hydraulic load to migrate in the column. If hydraulic flow instability is developed it propagates down the column. Improper feed, reflux or vapor distribution can also create mal-distribution problems,

Dual flow tray have poor turndown ratio resulting from the rapid fall off in efficiency as the vapor loading decreases. Therefore the operating vapor and liquid rate ranges must be kept small. Two types of dual flow trays are available; standard deck and rippled deck. The standard deck has a flat plate, and the rippled deck has sinusoidal waves

D. Valve Tray

Valve Tray uses valve (moveable disc) which almost closes off completely at low vapor rate, thus minimize tray open area. When lifted, as vapor rate increases, the open area increases for vapor flow between the valve disc and the tray deck.

Valves can be round or rectangular, with or without caging structured. Most types of valves, the opening may be varied by the vapor flow, so that the trays can operate over a wide range of flow rates with high separation efficiency and large flexibility. Because of their flexibility and price (slightly more expensive than sieve tray), valve trays are tending to replace bubble-cap trays.

Valve tray has minimum capacity of approximately 60%. The dry pressure drop of valve tray is lower than bubble cap, because the valve does not need a chimney for the vapor and it depends on weight of valve.

The valve tray can used in condition where vapor rate change unpredictability over a given section of tower, a tower utilized in blocked operation at varying rate and feed compositions, a fluctuations in feed rate, and servicing of auxiliary equipment operating the entire unit at low rate.

E. Baffle Tray

Baffle trays contain tower internals designed to cause the liquid to cascade down the tower in a series of curtains through which the vapor must pass as it rises through the tower. Baffle tray are generally used in the desuperheating zone FCCU and Coker primary fractionators, Coker scrubbers and in other severely fouling services such as slurry strippers. Baffle tray has three type's tray, there are Shed Decks, Side to Side Trays, Disk and Donuts Tray.

a. Shed Decks

Shed Deck trays are angle irons beam of various size from two to ten inches that are placed in rows across the column. The trays are rotated 90° from tray to tray to distributed vapor-liquid. It has 50% open area and makes the efficiency very low. The fouling potential of the decks is almost zero because there are no stagnate zones and low residence time. The efficiency of the tray almost matches the fouling potential, particularly if wide shed decks are utilized. Shed decks work well in fouling applications where their application is essentially for heat-transfer purposes.

b. Side to Side Trays

Side to side tray is trays that allow the liquid to splash from side to side. The decks can be sloped. The Vapor flowing upward through the curtain of liquid leaving the tray above. Liquid fouling potential is low as with efficiency.

c. Disk and Donuts Trays

Disk and donut trays are slightly sloped trays that allow the liquid to splash from inner circle ring to outer circle ring. Fouling potential of this tray is low along with the efficiency.

Standard Cross Flowing Trays

Standard cross flow trays operate with the liquid flowing downwards through a column in a serpentine pattern while contacting the vapors that are flowing upward through the column. Larger diameter trays may be fitted with multiple downcomer to reduce the liquid load across each active area section. This reduces the weir load and liquid head on the tray deck resulting in higher vapor capacity, lower pressure drop and improved operating turndown range. Once the liquid resistance becomes substantial, the liquid is normally split mechanically into multiple streams or passes. The number of passes to be used is specified through the hydraulic design of the tray. Tray fluid passes can be divided into single pass, two pass, three pass, and four pass.

1. Single pass

In single pass, the liquid flow across the tray from the inlet to the outlet. The direction of the liquid on the trays one on the top of the other countercurrent.

2. Two pass

   Two pass trays are quite common and generally don't pose significant design challenges since the flow paths and tray designs are symmetric. Two pass trays have got two different geometries. One tray is provided with side downcomers (panel A) and the other with a central downcomer (panel B). Both have got flow paths perfectly symmetrical to the central axis.

3. Three pass

   Three pass trays are quite rare because of their inherent asymmetric design and difficulty to balance. This tray is not symmetrical. Three pass trays need to be balanced to make sure that the Liquid over Vapor (L/V) ratio is constant for each pass. Three pass trays are discouraged and should be avoided whenever possible. They are very difficult to balance and introduce a feed or reflux but it has only one single design.

4. Four pass

   Four pass trays are much more common. Four pass trays has four different flow paths, two for the even and two for the odd trays, there is a need to balance the two different flow paths of the same trays.

General Design Consideration

A tray hydraulic design is normally divided into two main steps, a process design followed by a mechanical design. The purpose of the process design is to calculate the jet flood, entrainment limits, pressure drop, downcomer backup, downcomer inlet velocity, weir loadings, downcomer residence time, weeping and efficiency. On the other hand, the mechanical design focuses on the tray design.

In designing tray there are many factor have to be considered for the suitability of the hydraulic such as the safety, environmental requirements, tray performance, economics of the design and other parameters, which may constrain the work.

Tray towers may be used for many vapor liquid contacting operations. A process engineer can use the following guideline in making preliminary selection on whether use tray column for particular application.

1. The operation involves liquid that contains dispersed solids. Tray are more accessible and convenient for cleaning
2. Trays have a high resistance to corrosion
3. Tray can be designed to handle wide range of liquid rates without flooding.
4. Interstage cooling can be installed on the trays to remove heats of reaction or solution.
5. Trays are preferred if side streams are to be produced like refinery crude distillation column.
6. When large temperature changes are involved, as in distillation operations.
7. There is a lack of experience in the service
8. Vessel wall needs periodic inspection
9. There are multiple liquid phases
10. There are many internal transitions

There are five types of trays that have each advantages and disadvantages. The principal for selection type of tray which used consider to their cost, capacity, operating range, efficiency and pressure drop. Here the principal when select type of tray.

1. Cost: Sieve tray and dual flow tray are relatively inexpensive, valve trays are slightly more expensive than sieve tray, and bubble cap is the most expensive. The relative cost depend on the material construction used, for the mild steel the ratios of bubble cap, valve and sieve are 3 : 1.5 : 1.

2. Capacity: The diameter of the column required for a given flow rates either the capacity. The highest capacity is the sieve follow with dual flow, valve and bubble cap.

3. Operating range: Bubble cap have a positive liquid seal therefore can operate efficiently at very low vapor rates. Sieve tray relies on the flow of vapor through the holes to hold the liquid on the tray and cannot operate at very low vapor rates. But, with good design, sieve tray can be designed to give a satisfactory operating range, typically, from 50 to 120% of design capacity. Valve tray is intended to give greater flexibility than sieve tray.

4. Efficiency: The Murphree efficiency of all types of trays are almost the same when operating over their design flow range.

5. Pressure drop: Pressure drop depend on the detail design of the tray. Generally, sieve trays give the lowest pressure drop followed by valves and the highest is bubble cap.

The service conditions should be consideration as well because the tray hydraulic is designed to accommodate all combinations of loading situations such as heat and mass transfer, density and rate of vapor and liquid, equilibrium phase, pressure, temperature and other moments that may occur simultaneously and they are used to result the efficiency of tray.

The first step to tray distillation column is determining the rate of vapor and liquid from density of vapor and fluid, it will influence to tray spacing, weir height, open area, and pressure drop. In general, the steps to tray hydraulic designed are summarized into the follows.

1. Calculate the maximum and minimum vapor and liquid flow rates for the turndown ratio required.
2. Select a trial plate spacing
3. Estimate the column diameter
4. Decide the liquid flow arrangement
5. Make a trial plate lay out: downcomer area, active area, hole area, hole size, weir height
6. Check the weeping rate
7. Check the plate pressure drop
8. Check downcomer backup
9. Recalculate the percentage flooding based on chosen column diameter.
10. Check entrainment
11. Predicting the efficiency: point efficiency, Murphree efficiency and overall efficiency.
12. Optimize design to find smallest diameter and plate spacing acceptable (lowest cost).

The theoretical explanation and sample calculations of each step above are discussed in detail in later sections.

Tray Hydraulic Parameter

The plate structure must be designed to support the hydraulic loads on the plate during operation and the loads imposed during construction and maintenance. The basic requirements of a tray are that should:

1. Provide good vapor-liquid contact
2. provide sufficient liquid holdup for good mass transfer (high efficiency)
3. have sufficient area and spacing to keep the entrainment and pressure drop within acceptable limits
4. have sufficient downcomer area for the liquid to flow freely from tray to tray

The range of operation of the installed trays governs the maximum and minimum vapor and liquid loads. The maximum possible loading of vapor and liquid is important to determine diameter column and tray hydraulic parameter such as pressure drop. Figure 7 is a typical operating region for tray. When the vapor loading is raise at constant liquid loading, the entrainment (jet flooding) is reached.

The liquid content in the column is increases as well as the pressure drop over the total height of the column. Otherwise, when the liquid loading is raise at constant vapor load the downcomer flooding can be achieved. The downcomer is not able to handle the high loading and therefore the liquid content and the pressure drop of the column increase.

For both the vapor and liquid loading, lower and upper limits exist. Hydraulic mechanism should be control these limits. The operating area of a column should be chosen by carefully considering these limitations. The operation area is located under the jet flood line. In this area a wide surface area of the phases is present for the mass transfer and the best mixing of the phases exist.

For both the vapor and liquid loading, lower and upper limits exist. Hydraulic mechanism should control these limits.

DEFINITIONS

Active Area (or 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

Blowing Flood - occurs at low liquid rates at which the tray operates in the spray regime resulting in massive entrainment of liquid to the tray above to the extent that the tray deck is essentially blown dry.

Calming zones - unperforated strips of plate at the inlet and outlet sides of the plate

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

Downcomer Clearance - is the space below the downcomer apron allowing liquid to flow from the downcomer to the tray deck below. This must be sized to provide a balance between the minimum head loss required for good liquid distribution across the tray deck and avoiding excessive downcomer back-up.

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

Downcomer Flood- occurs at high liquid loads when the downcomers are too small to allow effective vapor disengagement (either because the downward velocity or "inlet velocity" of the liquid is too high or else insufficient residence time) causing vapor entrainment to the tray below. The resulting increased aeration of the liquid in the downcomer may also cause premature downcomer back-up flood.

Downcomer froth backup - the amount of froth in the downcomer which is a function of the pressure drop across the tray deck the froth level on the tray itself and any frictional losses in the downcomer and its clearance.

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

Entrainment Limit - is reached when the velocity of vapor through the tray open area is high enough to project liquid droplets to the tray above.

Flow Path Length - is the span of tray deck between the downcomer inlet and the outlet weir and is the shortest path that the liquid takes in crossing the active area from one downcomer to the next. This has a big influence on tray efficiency, particularly in small columns as well as trays with large or multiple downcomers.

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.

Jet Flood - is the criteria used to predict the point at which massive liquid carryover will occur due to the height of spray on the tray deck exceeding the available tray space. It is normal practice to limit tray design to a maximum of 80% of jet flood to allow a safety margin on tower control, possible discrepancies of VLE data and also the limitations of the flooding correlation used.

Number of Flow Paths - Larger diameter trays may be fitted with multiple downcomers to reduce the liquid load across each active area section. This reduces the weir load and liquid head on the tray deck resulting in higher vapor capacity, lower pressure drop and improved operating turndown range.

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

Operating area - the range of vapor and liquid rates over which the plate will operate satisfactorily (the stable operating range).

Outlet Weir Height - The outlet weir is used to maintain a head of liquid on the tray deck as well as to ensure a positive vapor seal to the bottom of the downcomer.

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

System limit (ultimate capacity) - the maximum available capacity for vapor flow in a given column diameter with a known liquid rate and physical properties. The ratio of design vapor load to the vapor load for ultimate capacity.

Vapor handling capacity of a tray - proportional to the active area (i.e. inversely proportional to the approach to Jet Flood)

Weeping - occurs when the velocity of the vapor through the tray open area is too low to prevent liquid from leaking through the open area thus by-passing contact area to the tray below. Most valve and sieve trays will weep in normal operation. Weeping is considered excessive when it is sufficient to cause loss of efficiency - usually 10 to 20%.

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.

NOMENCLATURE

a	Interfacial area, m^2
A_a	Active area, m^2
A_{ap}	The clearance area under downcomer, m^2
A_c	Column Area, m^2
A_d	Downcomer area, m^2
A_h	Hole area, m^2
C_o	Orifice coefficient
d_h	Hole diameter, mm
E_{MV}	Murphree efficiency
E_O	Overall efficiency
E_{OG}	Point efficiency
H_v	Valve thickness (mm)
h_{ap}	The clearance area under the downcomer, m^2
h_c	Clear liquid head, mm
h_{bc}	Downcomer backup , mm
h_d	Dry drop, mm
h_{dc}	Downcomer headloss, mm
h_f	Froth height, mm
h_{ow}	Height of liquid crest over weir, mm
h_r	Residual head drop, mm
h_t	Total pressure drop, mm
h_w	Weir height, mm
K_G	Vapor phase mass transfer coefficient , mm/s
K_L	Liquid phase mass transfer coefficient, mm/s
L_m	Liquid rate, kmole/s
L_w	Liquid flow rate, kg/s
L_{wd}	Liquid flow rate in downcomer, kg/s
M	Molecular weight, kg/kmol
N_G	Vapor phase mass transfer
N_L	Liquid phase mass transfer
P	Absolute pressure, N/m^2 or Pa
Q_L	Liquid rate, m^3/s
R	Universal gas constant, $JK^{-1}mol^{-1}$
R_{vw}	Ratio of valve weight with legs to valve weight without legs

T	Absolute temperature, K
t_G	Vapor residence time, s
t_L	Liquid residence time, s
t_r	Downcomer residence time, s
u_a	Vapor velocity through active area
u_d	Downcomer velocity, m/s
u_h	Vapor velocity through hole area, m/s
u_f	Flooding velocity, m/s
$u_{vh\ OBP}$	Vapor hole velocity in opened balance point, m/s
$u_{vh\ CBP}$	Vapor hole velocity in closed balance point, m/s
V_m	Vapor rate, kmole/s
V_w	Vapor flow rate, kg/s

Greek Letters

Ψ	Entrainment fractionating
σ	Surface tension, dyne/cm
ρ	Density, kg/m^3
μ	Viscosity, cP
Φ	Froth density

Superscript

L	liquid phase
V	vapor phase