Putting
the
focus

on
tray
efficiency

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describe the different factors that can
affect tray efficiency and hydraulics.

A common misconception widely repeated by academia and textbooks is the notion that a tray is a platform carrying liquid smoothly from the inlet downcomer on one side, to the outlet downcomer on the other. In this idealised arrangement, the vapour or gas is evenly sparged into the liquid through perforations in the tray. The narrative continues with the gas rising through the liquid as a swarm of well-defined bubbles which eventually pass through an interface at the top of the biphase. Figure 1 is a sketch of this idealisation. The reality, however, is a different story. The biphase shows extremely turbulent, violent interaction between the vapour and liquid to the extent that it often makes it hard to discern gas from liquid, and even to identify the upper surface of the biphase to the extent that photographing the biphase provides only very blurred, poorly-defined images. Idealisation and reality bear little resemblance to one another. However, hydraulic calculations (pressure drop, liquid depth on the tray, effective density of the biphase) can be quite reliably and usefully done on the idealised basis.

The hydraulic behaviour of trays is not their only important characteristic. Although hydraulics determines the ultimate vapour and liquid-handling capacity of trays (i.e., plant throughput), the separation one achieves is determined by the tray's mass transfer characteristics, commonly referred to as tray efficiency, and theoretical stages in what are (unjustifiably) called, state-of-the-art models. In the following, it is posited that except for designs with quite poor vapour-liquid contact in the first place (for example dual-flow and disc-and-doughnut trays), most trays have efficiencies ranging from 92 – 108% depending on the tray design and tray type. This applies to standard hydrocarbon test systems, e.g., C_6-C_7 and iC_4-nC_4 mixtures.

Traditionally, tray development has focused primarily on pressure drop and column capacity, and somewhat less on efficiency. With hydrocarbons, efficiencies tend to lie in a relatively narrow range. In reactive systems (common in absorption, especially in gas treating) and in many chemical separations (especially those with highly nonideal phase equilibrium thermodynamics), however, the separation is controlled primarily by mass transfer rate limitations. Mass transfer rates depend on diffusion coefficients of the transferring species, on the interfacial areas for mass (and heat) transfer. In systems of chemicals, these species often interact with each other so that diffusion rates become collaborative even to the extent that a species can diffuse against its own concentration gradient.

This article offers a written and pictorial description of the kind of motion observed on most crossflow trays operating at normal vapour and liquid rates. It describes the effect of pressure on the appearance of the biphase, how the kind of deck perforation visually affects the flows and influences pressure drop, hydraulic capacity, and how hydraulics affects mass transfer.

Chaotic violence

At the design point in a well-designed column, most of the space between trays is filled with the vapour-liquid mixture, also called

the biphase. At low L/V ratios and very low pressure (vacuum), liquid tends to be dispersed and vapour continuous (Figure 2), turning the biphase into a concentrated spray of droplets (spray regime). Entrainment occurs when liquid droplets are carried by the vapour onto the tray deck above by being carried by the vapour through the holes in the deck. At high L/V ratios and at high pressure, the biphase tends to appear as a churning mass of geysers, violently interacting to the extent that frequently some of the geysers will pass through the tray above as entrainment – under such conditions, entrainment may not
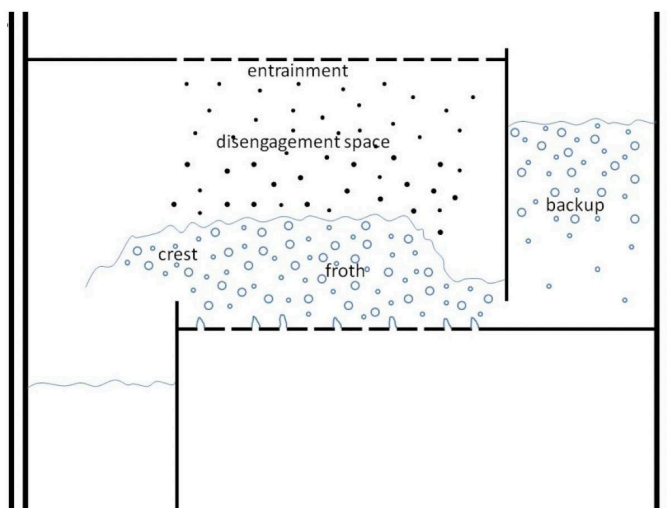

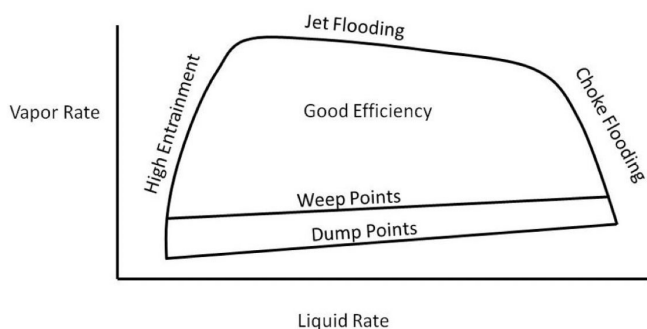**Figure 1.** Idealised tray hydraulics.
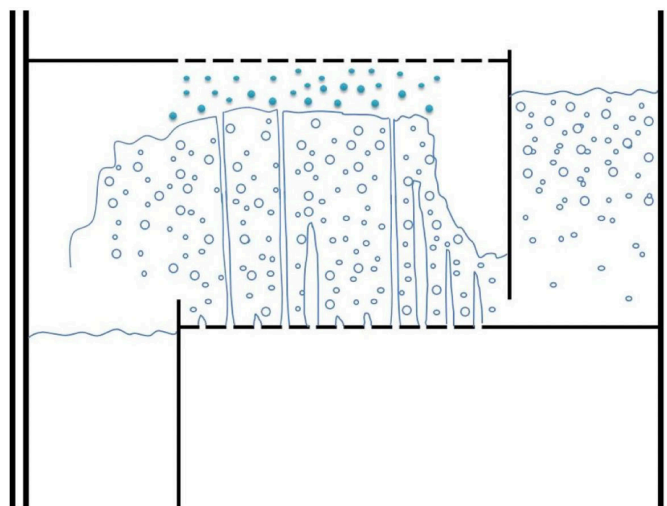

Figure 2. Tray hydraulic regimes.

Figure 3. Sieve trays and vapour bypassing.

be the most descriptive term. At intermediate L/V ratios and moderate pressure, the biphase has the appearance of an ill-defined mass of vapour and liquid where neither phase is clearly dominant or even clearly identifiable. Often even the place of transition from biphase to vapour is not clearly defined.

Except under vacuum and at quite low vapour flows, the vapour is considered to be dispersed and the liquid continuous, but the vapour rarely adopts the idealised form of bubble warms. Further, it consists of violently interacting jets and large gas and liquid volumes being torn apart by energetically intense interactions. Comparing the biphase to the activity in a washing machine does not adequately describe the turbulence of the interaction if only because of the comparatively much higher vapour volume, which a washing machine can neither produce nor sustain. To drive the phases towards a state of compositional equilibrium, however, intense interaction between phases is exactly what is wanted.

In gas treating operations, typified by carbon dioxide (CO_2) removal from the gas feeding an LNG facility, L/V ratios tend to be high and the tray will be operating close to downcomer choke flood. A downcomer is choke flooded when the total froth flow is unable to get into the downcomer mouth. It is backup flooded when all the liquid is unable to get out of the downcomer bottom, even with the downcomer full of liquid.

Sieves, valves, and other treatments

Vapour flow through sieve holes is vertically directed and no attempt is made through mechanical construction to force or even encourage interaction between adjacent jets except insofar as the sieve holes are close together. With interaction, mixing would be intensified, and better mixing implies better phase contact and better efficiency of mass transfer. Figure 3 is a graphical representation of the jets emanating from sieve holes coalescing into larger jets in which the vapour content largely bypasses the liquid and most of the biphase. Contacting is poor quality, entrainment occurs early, and tray efficiencies tend to be at the low end of the range.

Vapour distribution within the biphase and turbulence intensity can be improved when caps or valves are placed over larger holes (Figure 4). Vapour enters the biphase horizontally through the curtain between the valve cap and the tray deck, then interacts with the vapour from adjacent valves by intense mixing and turbulence generation. The use of valve caps opens a whole vista of new capabilities that can result from using fixed vs moving valves,[1] trapezoidal-shaped valves which offer a slight push to the liquid, canted valves to induce greater push, mini valves (fixed or moving) to convert coarse, highly nonuniform froths into finer dispersions with lower entrainment and more interfacial area for better efficiency, and multipass trays which reduce hydraulic gradients and lead to better dispersions. Some types of treatment are intended to mitigate against the deposition of solids (fouling) on the trays. For example, fixed valves perform better in fouling service because moving valves have a tendency to stick open or closed. There are many additional types of crossflow trays, too numerous even to mention here and limited only by the imagination of tray developers.

Almost all crossflow trays rely on gravity to separate the biphase into the upflowing vapour and downflowing liquid before they pass to the trays above and below. In recent years, trays have been developed that generate a centrifugal flow which greatly improves the ability to separate the phases. Examples are the ULTRA-FRAC® tray (Koch-Glitsch), and Shell's ConSep™ tray (Sulzer). Trays based on centrifugal flow offer greatly increased capacity, but at the expense of somewhat lower efficiency than more conventional crossflow trays.

Every factor in a tray design has the potential to affect hydraulic performance, pressure drop, and efficiency to greater or lesser extents. Such factors include tray type, valve weight(s), valve type (standard vs mini vs push), moving vs fixed. Even deck thickness affects pressure drop. But, perhaps the most important factor in tray selection is cost. Tray selection and try design are specialties of tray suppliers who are generally very well-placed to make recommendations, and who usually back up their detailed designs with performance guarantees.

Pressure drop

Pressure drop is one of the most important factors determining tray performance. This is increasingly the case as the column operating pressure decreases – in a high-pressure tower, the pressure drop is unlikely to be a critical factor because pressure drop is such a small fraction of the tower pressure. In a vacuum tower, the maximum available pressure drop is the tower pressure itself.

The total pressure drop across an operating tray is the sum of the dry tray pressure drop and hydrostatic head of biphase on the tray. Dry tray pressure drop is determined by the geometry, construction, and number density of the tray deck perforations (and the weight of moving valves), as well as on the density and velocity of the flowing vapour. Obviously, dry tray pressure drop is unaffected by liquid properties.

Wet tray pressure drop is the pressure drop experienced by the vapour as it goes from the biphase on the tray deck to the vapour space above the tray. This is a function of the biphase density, the depth of vapour-liquid mixture on the tray, and possibly surface tension insofar as this might affect the release of vapour from attachment to the metal surrounding the tray perforations.

Wet and dry pressure drops are mutually independent but linearly additive because once the vapour has passed through the tray perforations, it carries no memory of how it got into the biphase.

Wet tray pressure drop requires that the biphase not try to expand beyond the confines of the physical volume between trays. There are numerous reasons this requirement may be violated. Most common amongst them are:

- One or other phase flow rate exceeds the capacity of the equipment: vapour jet flooding, downcomer backup flooding, downcomer choke flooding.

- Foaming.

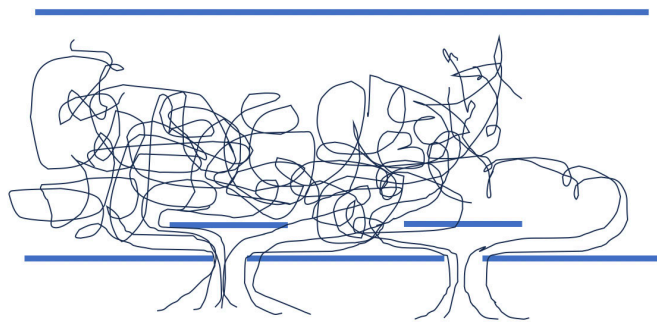- Perforations plugged or valves stuck closed by fouling.

Figure 4. Vapour flow through valves on a tray. Flows through curtain areas experience directly opposing flows from adjacent valves.

Tower capacity

A perfectly-designed tray will have adequate space between trays to permit entry of an average size human being for maintenance and inspection, and it will operate close to 85% jet, downcomer backup and downcomer choke flood. This provides a tray with maximum capacity and enough operating cushion to handle modest process upsets reliably and gracefully.

Tray suppliers each have their own design procedures based on years of experience and extensive pilot and large scale hydraulic data, mostly using air-water simulators several feet in diameter, although some have hydrocarbon towers of sufficient diameter to confirm tray performance under real-world conditions. FRI, a consortium of 75 companies, have 1.22 m and 2.44 m dia. hydrocarbon towers in which they generate capacity and efficiency data on packing and trays. Final designs should always be done by the tray supplier who will also provide a performance guarantee for the particular application.

Mass transfer and tray efficiency

Crossflow trays are widely used in distillation and gas absorption. In distillation, tray efficiencies are typically 80+% at low pressure and low liquid rates, and 90 – 110% at high pressure and high liquid rates, the spread being a function of valve design and layout. Efficiencies in distillation are controlled mostly by resistance to mass transfer in the vapour phase. In gas absorption, efficiencies are more typically in the range 5 – 60%, with low values being more common than high. The reason for low efficiencies is the low solubility of most noncondensable gases (e.g. CO_2) which tends to make their absorption rates liquid-phase controlled, and the fact that gas absorption is often accompanied by chemical reaction which provides very high solvent capacity for gas in its reacted form but leaves the solubility of the molecular unreacted gas very low. This pairs high capacity with a small driving force[2] for absorption. It takes a long time to saturate a high-capacity solvent if the gas absorbs only slowly.

Mass transfer rates depend on liquid and vapour-phase film coefficients for mass transfer (k_G and k_L) and on the effective vapour-liquid interfacial area (a). In distillation, the liquid-film coefficient is not of great importance except in the case of very high purity separations, e.g., in demethanisers where the distillate contains only a trace of any components with boiling point above methane or in the bottom product with only a trace of hydrogen and methane. In such cases, the low boilers

can have significant liquid-side diffusion control and the trays in those sections will have low efficiency for those components.

Applications involving gas absorption are dominated by CO_2 and hydrogen sulfide (H_2S) removal from gas streams. Other impurities to be removed include mercaptans, carbonyl sulfide (COS), and other trace sulfur-bearing species. Solvents are aqueous solutions of one or more amines with which the acid gases react. In fact, H_2S reacts instantaneously, and this often throws its dominant resistance to absorption into the gas phase. CO_2, though, reacts much more slowly, and its absorption remains liquid-side controlled. When this situation ensues, there is the potential for preferentially absorbing one of the two components at the expense of the other (which is in effect rejected into the gas). This implies that chemical reaction rates can have a very significant influence over absorption, a fact that is accounted for by the so-called enhancement factor.[3] Vapour vs liquid-side control of mass transfer is responsible for the ability of tertiary and hindered amines to preferentially remove and recycle residual H_2S from the tail gas produced by sulfur plants, allowing very low sulfur emissions to be met.

Conclusion

Mass transfer requires the presence of both phases so it occurs only in the biphase, after the vapour has passed through the tray deck perforations and is contacting the liquid. The actual device on the tray can be expected to play a role in the mass transfer process only to the extent that it influences the turbulence and interfacial area in the biphase. Mini-valves produce a somewhat finer dispersion than conventional valves and large-hole sieves produce a somewhat coarser dispersion than small ones. However, the differences are most evident

closest to the tray deck and gradually weaken as one moves away from the tray and higher up into the biphase. What this says in effect is that the type of tray device itself has somewhat muted effect on mass transfer, i.e., on tray efficiency because the effect of the perforation details is felt mostly close to the tray deck and falls away as the vapour rises through the biphase. This is borne out to some extent by much of the efficiency data collected for hydrocarbon systems (iC_4 + n-C_4 and C_6 + C_7 are common test systems) in large scale test equipment, efficiencies in such systems being generally in the range 80 – 110% in any case The effects are more pronounced in gas absorption However, the biphase loses its memory of how it was created shortly after it is formed so, as one might expect, valve shapes for example do not play a dominant role in determining mass transfer performance. Valve layout probably does, but such factors do not appear ever to have been studied. **LNG**

Notes

1. Moving valves allow a tray to operate at greater turndown because at low vapour flow, some of the valves shut and reduce the open area for throughflow of vapour.

2. The gas has to dissolve into the liquid before it can react. Reactive absorption is a two-step process – dissolution followed by reaction. The capacity of the solvent is how much gas it can react with at saturation but the driving force for absorption is the physical solubility of the gas (not its chemical solubility).

3. Enhancement factor is the ratio of absorption rates with and without chemical reaction, found by solving the relevant reaction-diffusion equations for the kinetics involved.