THE USE OF DIRECTIONAL MOMENTUM DEVICES ON FRACTIONATION TRAYS

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INTRODUCTION

Since almost all industrial scale columns are round, the side downcomers present unique challenges for liquid distribution both to and from the downcomers. Liquid leaving these downcomers needs to spread outwardly, away from the flow path centerline, in order to evenly feed the diverging tray active area. Also, one of the characteristics of side downcomers is that they naturally tend to focus emerging liquid towards the center of the tray, opposite of what is desired. Even though a standard downcomer clearance takes a pressure drop that should help to equalize the liquid flow distribution onto the tray, testing has shown that a typical tray will have a disproportionate amount of liquid flow along the flow path centerline while the outer portions of the tray deck tend to stagnate because they are fed with below average amounts of liquid.

Various types of directional momentum devices have been used on fractionation trays over the years in an effort to better control fluid flows on the tray deck and subsequently enhance tray performance. Types of mechanical diverters can range from simple baffles to a combination of shaped downcomer clearances and outlet weirs. Vapor momentum can also be used to direct the liquid flows. Devices using this means can be individual directional vapor valves dispersed on the tray deck or groups of carefully organized directional push valves and froth promoters. This paper will review the fundamental aspects of these different devices, present new research data, and conclude with commercial operating results.

FUNDAMENTALS

When discussing directional flow devices on trays, there are a few fundamental questions that must be asked. The first one being, "What difference, if any, do these devices make to the tray performance?" This subject was studied in detail by Fractionation Research, Inc. (FRI) many years ago(1). These studies showed that conventional tray designs did have liquid maldistribution and that this maldistribution could be greatly reduced by altering the shape of the downcomer clearance and the outlet weir. This design method was patented by FRI and then further testing was conducted to evaluate its effectiveness. Unexpectedly, the testing showed, that, although the flow pattern on the tray decks was clearly improved, there was virtually no measurable difference in efficiency between the modified tray and a standard tray. Similar work was conducted during the same time period by Union Carbide(2). Their studies reached the same conclusion regarding maldistribution, especially on larger diameter trays but found definite improvements in tray performance. Union Carbide was granted several patents on the correction of liquid maldistribution with directional vapor valves on the tray deck and had commercial success with these designs.

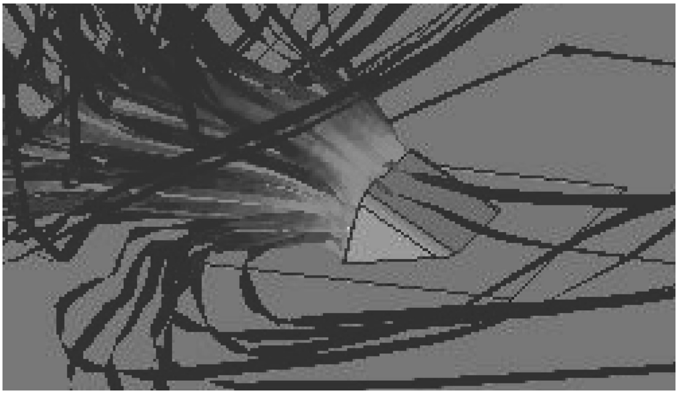
From a fundamental view, we know that a tray with a completely mixed liquid on the tray deck will achieve what is referred to as "point efficiency." We also know that trays with medium or longer flow paths can achieve efficiencies significantly higher than point efficiency due to a flow path length enhancement. Using this knowledge to evaluate the FRI results, we can say that there are a few possibilities to explain them. The first possibility is that the backmixing and deviation from the standard FRI test tray was not significant enough to adversely affect the efficiency of the tray. The test tray had a much smaller open area (8%) and larger downcomers (13%) compared with high performance trays recently tested at FRI. These features may limit the amount of detrimental maldistribution. If this were the case, any corrections made to alleviate maldistribution may show no effect. The second possibility is that the modifications did not completely correct the maldistribution problems on the tray. This is rather unlikely since FRI used a great deal of instrumentation to detect the resulting flow patterns on the tray. The final possibility is that the modifications made to the tray improved the maldistribution on the tray but also inhibited some of the interfacial mixing on the tray, thus compromising any efficiency gains that may have been obtained by the reduced maldistribution.

So, in answering the question regarding the effect of correcting flow maldistribution, we know the following. Union Carbide has claimed substantial benefits from their flow equalization techniques. Many of the FRI test trays have produced efficiencies of up to 120%, so there can be a significant benefit for a flow path length enhancement. We also know that the FRI test of their optimized device showed no efficiency benefit whatsoever. It is therefore conceivable to claim the benefit to be either of these extreme values but it is probably somewhere in between. Most likely, the benefit for moderate flow path length trays could be expected to be 5–10% while the benefit for larger flow path length trays would likely be 10–15%.

A second question is, regardless of efficiencies, "How effective are the various devices at properly equalizing liquid flow across the tray deck?" This is generally a matter of hydrodynamics and has to be answered individually for each type of device. Since the most common devices used are vapor directional momentum valves and mechanical baffles, we will examine these individually.

LIQUID FLOW CONTROL BY VAPOR DIRECTIONAL VALVES

A vapor directional valve is an opening or passage through a tray deck that preferentially directs vapor in a concentrated direction in an effort to influence the liquid flow on the tray deck. One of the advantages of using vapor to influence liquid flow is that trays need to take



some amount of vapor side pressure drop to maintain good vapor distribution across the tray deck and maintain enough resistance to prevent weeping of liquid through the tray orifices. Since this pressure drop is mandatory, it also provides a "free" source of energy to be used in a productive manner by moving liquid. If the valves are used correctly, energy that would otherwise generate liquid entrainment can be used to enhance the liquid side performance of the tray. A second advantage is mechanical simplicity. Most directional valves can be stamped directly from the tray deck itself, eliminating the need for an additional manufacturing step. The resulting valve is mechanically strong and inexpensive.

One of the important functions of vapor directional valves is the ability not only to influence the direction of the liquid it contacts but also to impart momentum. If liquid flows in streamlines along a well designed tray deck, then the streamlines located farther from the centerline parallel to the liquid flow path are longer and will require liquid to travel at a faster pace in order to maintain a uniform residence time on the tray deck. Directional vapor valves are ideal for this application.

Directional valves also have some disadvantages. First, since most vapor streams have a much lower density than liquid, a similar volumetric flow of vapor will have a much lower mass than a liquid stream. Less mass means less momentum. A question that immediately arises when dealing with vapor injection devices is whether or not vapor devices can provide enough momentum to significantly affect the liquid direction. To provide momentum, the vapor stream will need to have a higher velocity which generally comes from a lower open area on the tray deck. Mechanically, this is accomplished by using fewer and/or smaller deck openings. Fewer openings may lead to dead areas in the tray deck where mixing is limited. Smaller openings may be prone to fouling. Another issue is the physical placement of the directional valves on the tray deck. Most common directional valves will take the place of a standard valve but will have less open area. If the ability to obtain an adequate open area is a constraint, the addition of directional valves may not be feasible. With most applications, this can be overcome with careful design and layout(3).

In order to evaluate the effectiveness of vapor directional devices, we need to take a closer look at the hydrodynamics. Assuming that the tray is operating at total reflux, we can estimate some typical values for liquids flowing across the deck as well as the vapor streams flowing through the deck. We can then make some rather simplistic assumptions and calculate a local liquid momentum approaching a directional valve as well as a vapor momentum emitting from that valve. By adding the momentum vectors of the liquid and vapor streams, we can calculate a resultant vector to determine the directional effect of the vapor stream on the liquid stream. This, for certain, is not a hard scientific approach but should at least give us an indication of the effect we could expect from the pushing valves.

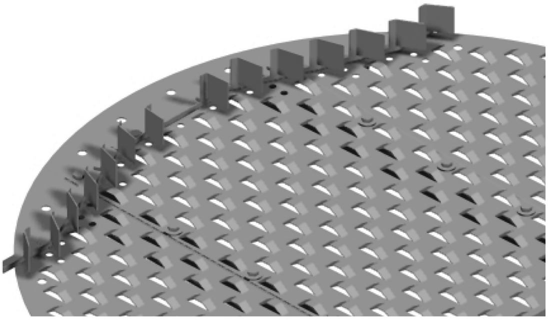
From the calculation, we find that a single pushing valve oriented 45° to the liquid flow will divert a local liquid stream by 1–2° depending upon what proportion of vapor stream actually acts upon the liquid stream. Since we typically wish to divert the liquid locally anywhere from 5–15°, it is clear that it will be necessary to use a group of directional valves to impart the required momentum on the liquid stream to have the desired effect on the liquid. With this analysis, it becomes apparent that unless used on a large scale, directional push valves can only perform fine adjustments of the liquid flow. It therefore becomes necessary to make sure that the liquid is delivered in a near uniform manner to the tray active area. This is typically accomplished with downcomer design and baffles.

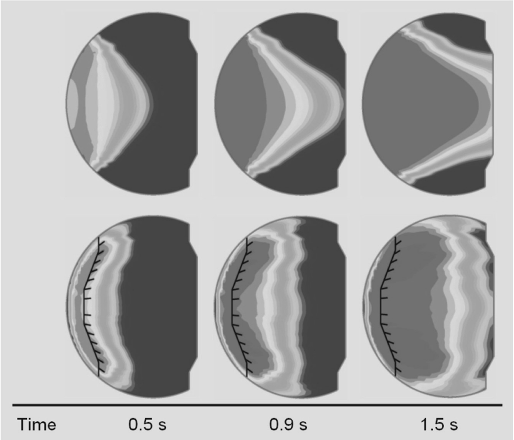
LIQUID FLOW CONTROL BY MECHANICAL MEANS

The most common form of mechanical flow control of liquid on tray decks is achieved with a baffle or series of baffles. The advantage of a baffle is the simple and effective function and design. A well designed baffle will equalize flow onto the tray deck.

Effective control of liquid flow does not just mean simple redirection but also often includes reduction of momentum. Excessive liquid momentum inhibits aeration on the inlet portion of a tray resulting in a loss of flow path length and bubbling area. It is important that the liquid momentum be disrupted to allow for vapor to flow as desired through all portions of the active area. An effective baffle design on the inlet side of the bubbling area will include some method to break the liquid momentum as well as proportion the liquid properly onto the tray. One example of such a device is a Sulzer Baffle Bar^{TM} (shown in the top picture). It uses a combination of a small vertical weir as well as baffles to decrease the liquid momentum from the downcomer and properly distribute liquid to the tray inlet (as seen in the liquid phase CFD study shown in the lower picture). Although a baffle itself will not aerate liquid or promote froth, a well designed baffle will allow the vapor valves or orifices at the inlet side of the tray to generate froth.

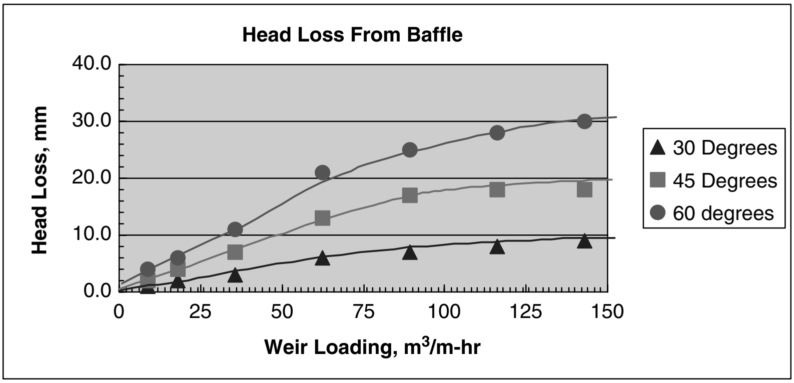
One disadvantage of baffles is that they are an extra piece of hardware that needs to be attached to the tray, adding some complexity and expense. Also, baffles cause resistance to flow and may cause an unwanted restriction if not designed properly. Some baffle designs may make the tray less fouling resistant while others can make a tray more fouling resistant by eliminating stagnant zones by the downcomer or on the tray deck.





The hydrodynamics for baffles is straightforward. Baffles will positively deflect liquid in the direction of the baffle. However some questions do exist on their performance. One question is the effect of liquid flow rate on baffle performance. Sulzer's in-house testing has shown that many baffle arrangements work quite well for a certain range of liquid flows but some lose their effectiveness as the liquid rates extend outside of these ranges. Various designs can be used to compensate for the difference in baffle flow as a function of liquid rate. Another issue with baffle flows can be communication. One of the advantages of trays is their ability to handle maldistributed feeds. If a very compartmentalized baffle system is used, it may have little or no ability for liquids to communicate between the flow paths on either side of the baffle. In this case, the ability of the tray to recover from initial maldistribution will be lessened.

One of the significant differences between the use of baffles and vapor directional valves is the influence on the liquid holdup on the tray deck. Baffles produce frictional losses that may lead to a higher liquid holdup on the deck while vapor devices generally push liquid across the tray deck. As mentioned earlier, some restriction/equalisation of liquid flow or momentum is usually desirable. So frictional losses are not necessarily a bad characteristic, but the amount of resistance needs to be considered in the tray design. To quantify frictional losses, Sulzer measured the influence of the baffle angle on the upstream liquid head. The test setup used a 100 mm baffle length and a height sufficient to prevent flow over the top of the baffle. The closed area of the baffle was similar to that used commercially with a Baffle Bar. The results, shown below, demonstrate that for baffle angles smaller 45°, the upstream backup increase is less than 20 mm of liquid head through the range of typical weir loading.



OTHER TRAY DESIGN CONSIDERATIONS

To assess which devices work best, it is important to understand how each of these devices works within the entire tray and what factors influence the fluid flows. These items are discussed below.

One of the fundamental factors influencing the liquid flow is the downcomer type. There are many types of downcomers but the most significant characteristic is whether the downcomer is a standard type or is truncated. A standard downcomer travels from one tray deck vertically downward to the tray deck below leaving only a clearance (typically 25–50 mm) to form the liquid exit. The other type would be a truncated, or hanging, downcomer. This type of downcomer is truncated vertically so that the bottom of the downcomer remains 100–200 mm above the tray deck. With a standard downcomer, the liquid is released horizontally onto the tray deck, while with a truncated downcomer; the liquid is released vertically downward through slots or holes.

STANDARD DOWNCOMERS

Theoretically, a standard downcomer with a sufficient frictional exit loss should release liquid evenly along the downcomer opening in a direction that is perpendicular to the wall forming the slot. The frictional loss for the downcomer exit is typically designed at approximately 25 mm of fluid. However, other factors can contribute significant amounts of uneven liquid flow that may offset the exit loss resistance and reduce the uniformity of the liquid release. A major factor is the feed into the downcomer. A slow gentle feed from a tray with a 450 mm tray spacing will cause liquid to exit a downcomer differently than a fast moving liquid falling into a downcomer with a 750 mm tray spacing. This is due to momentum effects and energy dissipation in the downcomer. Another important factor is whether the liquid entering the downcomer is impacting on the back wall of the downcomer and at what elevation. All of these factors change with various loading levels within the tower. Any effective device must properly handle the wide range of liquid flows and patterns on the trays over a large range of operating conditions.

Other issues such as downcomer backup, residence time, and vapor disengagement are important to the hydraulics of standard downcomers. All of these factors influence the control of liquid fed to the tray deck as well as the resultant distribution quality. For instance, a small downcomer backup means that there is less liquid mass in the downcomer to absorb and dissipate the energy from liquid entering the downcomer. Larger backups will tend to yield more uniform distribution leaving the downcomer as long as excessive velocities are not a problem. As for vapor disengagement, if it is poor, the liquid leaving the downcomer may not be clear liquid. This means lower density and higher volumetric flow rates. Baffles designed for a clear liquid flow rate may not be as effective at the higher flow rates seen from an aerated froth.

TRUNCATED DOWNCOMERS

As mentioned above, a truncated downcomer does not extend to the tray deck but has a perforated floor that is elevated some 100–200 mm above the tray deck. Whereas conventional trays release liquid along a chordal clearance at deck level, a truncated downcomer can be designed to release the liquid from any portion of the bottom of the downcomer floor. The most common release shape from a truncated side downcomer is an arcuate shape near the column wall. This design technique gives the tray the most effective flow path length but also tends to naturally focus liquid towards the centerline of the flow path. Some mechanical methods can be used in the downcomer design to lessen this bias but some sort of directional devices are typically required on the tray deck to further redistribute the liquid evenly along the inlet to the active area.

All the previously mentioned influences on the flow inside the downcomer and its influence on the discharge of the liquid are also valid for truncated downcomer designs. One unique issue for truncated downcomer is the result of its elevated release of liquid from the downcomer. The impingement of the falling liquid on the tray panel and the resulting liquid distribution and momentum/velocity distribution create a different flow pattern with higher velocity gradients. The equalization and guidance of this flow can be very challenging and the proper device selection is critical.

COMMERCIAL/INDUSTRIAL SCALE APPLICATIONS

Listed below are three examples of commercial applications where directional flow devices were used successfully on difficult tray applications. The cases are examples where vapor directional devices only were used, mechanical baffles only were used, and combinations of both types of technology were used. These examples emphasize that these technologies can be used successfully and that the device must be appropriate for that service.

EXAMPLE 1 – DIRECTIONAL FLOW VALVES ONLY(4)

The application was for a Beer Mash Tower, which separates "beer" into overhead vapor consisting of ethanol and water and a bottoms "stillage" consisting of the majority of the water and fermentation solids. The existing equipment in this tower was exhibiting very poor performance, causing the bottoms stillage stream to have a very high alcohol content. Sulzer proposed using the SVG™ V-Grid™ tray deck along with integrated directional vapor valves into the bubbling area as well. After a successful installation, the unit was restarted and all performance expectations were met and exceeded. There was a 27% increase in tray efficiency observed with the use of this technology. In addition, a significant improvement in run length time, due to fouling resistance characteristics, was also observed. Another example of the exclusive use of directional flow valves is presented in the references(3). Based on these observations it is safe to say that the application of vapor directional devices on V-Grid trays not only improve tray performance but also work well in severe fouling service.

EXAMPLE 2 – TRAY BAFFLES ONLY (5)

The Sulzer Chemtech VGPlus tray was tested at Fractionation Research Inc. under the Category 1 test program. This is a particularly interesting example because it links modern high performance technology with the same test column that showed essentially no efficiency benefit for trays modified to reduce maldistribution. In this test program, the VGPlus tray was designed specifically for the 7 bar butane system and was tested at pressures of 7 and 11 bar. These systems have higher liquid rates than those seen in the previous FRI maldistribution studies.

The goal of this tray design was to maximize capacity while maintaining a typical efficiency as seen in this service. The tray had sloped and truncated downcomers in order to maximize bubbling area as well as liquid handling capacity. The downcomer sloping produced a relatively small downcomer bottom area (about half that of the FRI tray used in the maldistribution testing) so it was important to control the liquid entering the tray to promote bubbling as well as redirect the liquid evenly onto the tray. A Sulzer Baffle Bar was used to accomplish this.

The net result was that the VGPlus tray had the highest useful capacity of any tray ever tested in this system at FRI. The experimental results of the VGPlus test tray were compared to those of the standard FRI Type 2 valve tray. For both pressures, the test tray showed substantially higher capacity (20%–30%) than the Type 2 valve tray. The efficiency of the MVGT tray was about 3 to 4 percent higher than the Type 2 valve tray at low to medium vapor rates, but substantially higher at high vapor rates due to the higher capacity.

EXAMPLE 3 – COMBINATION OF BAFFLES AND DIRECTIONAL VAPOR VALVES (6)

A refinery hydrofluoric acid alkylation unit was revamped to achieve a 20% increase in capacity. A central portion of the revamp was the debottlenecking of the depropanizer with high performance VGPlus trays.

The alky depropanizer service is a high pressure distillation with the separation of propane, isobutane, and normal butane at a pressure of roughly 19 bar (275 psia). The high liquid volumetric flow rates combined with the high vapor density make downcomer design critical. To achieve the required performance, the downcomers were highly sloped and the tray decks used a Sulzer Baffle Bar in combination with directional vapor valves. The Baffle Bar was used to perform the primary redirection of the liquid entering the tray. The directional vapor valves were used to keep the liquid moving do the final redirection of liquid and also minimize any flow gradient on the tray deck.

Upon startup, the unit was actually able to achieve a 25% increase in capacity. The column is running smoothly making on spec products while achieving a throughput of 7% in excess of the revamp design conditions.

RECOMMENDATIONS

Research and experience clearly shows that benefits in tray performance can be gained by the use of directional flow devices on tray decks. The main devices reviewed were directional vapor valves and baffles. Both types of devices have advantages and disadvantages but can both be successfully employed in the appropriate applications.

Directional vapor valves are effective when subtle changes in liquid flow are required. They are especially useful in situations where tray deck top fouling or excessive hydraulic gradient on the tray deck is a concern. In these cases, the propulsion from the valves serves to remedy both situations when applied properly.

In services where large amounts of liquid redistribution is required or where tray deck open area is a critical criteria, directional vapor valves alone are generally not the ideal solution.

Mechanical baffles are also well proven and provide clear advantages in services where larger amounts of liquid redistribution are required. When used along with some form of momentum breaker such as an inlet weir, mechanical baffles provide excellent results with respect to both efficiency and capacity.

Care should be taken when using mechanical baffles in a fouling service. If the baffles present a significant restriction, the baffles may reduce fouling resistance. However if they serve to prevent stagnant zones on the tray deck, baffles may actually improve fouling resistance.

In some cases the combination of both devices is the best solution.

In conclusion, both types of devices, when applied properly, can provide significant improvement to a great many tray applications.

BIBLIOGRAPHY

1. Fractionation Research, Inc., Topical Report No. 61, "Effects of Liquid Mixing on Commercial Scale Sieve Tray Efficiency," Yanagi, T. and Scott, B.D., Oct. 20, 1972
2. Weiler, D.W. and Catani, S.J., "Performance of Linde Slotted Sieve Trays in the CCB Styrene Process," 74th AIChE National Meeting, Nov. 10, 1981
3. Summers, D.R., "Push Valve Experience on Distillation Trays," AIChE Spring Meeting, Distillation Symposium – Session 4, April 12, 2005
4. Summers, D.R. and Ehmann, D., "Enhanced V-Grid Trays Increase Column Performance," AIChE Annual Meeting, Distillation Honors Session, Nov. 4, 2002
5. Pilling, M, "Testing of the MVGT Tray at FRI," AIChE Annual Meeting Distillation Symposium, November 2003
6. Pilling, M. and Szymanski, A., "Alkylation Unit Depropanizer Revamp with High Performance Internals," World Refining, Sept. 2003, p. 40–46