UNDERSTANDING MALDISTRIBUTION IN 3-PASS TRAYS

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Abstract
Understanding 3-pass trays is the key to design of 6-pass trays, such as those in the large towers expected in carbon-capture services. This paper presents a hydraulic distribution model for 3-pass trays with no liquid or vapor equalization. The model is verified by comparison with FRI's test data and with one operating tower. Our paper predicts good distribution for the 3-pass trays tested at FRI, and shows that the poor efficiencies in some of the tests were due to losing the downcomer seals and not tray maldistribution. The model predicts good distribution at maximum rates in the operating tower, but finds that at lower rates, where valves open and close, there is an extreme sensitivity of vapor distribution to small pressure drop variations. This sensitivity precludes reliable modeling of distribution in this region and may define an unstable region in the operation of 3-pass trays.

Keywords: Multipass trays, Trays, Distribution, Maldistribution, Hydraulics

1. Background
Three- and 6-pass trays are highly prone to maldistribution due to their non-symmetry. Most designers avoid 3-pass trays, jumping from two to four passes.1-5. Recently, economics in many processes, including carbon capture schemes, has favored large (>20-30 ft ID) towers, often requiring six tray passes. The key to successful design and operation of both 3- and 6-pass trays is understanding and reliable modeling of 3-pass maldistribution. Much of the 3-pass phobia stems from, or at least has been fueled by, tests performed by FRI6 in 1962. The FRI report concluded “Extreme caution should be used in the design of any 3-pass tray. Three commercial 3-pass trays were tested. Two of them had low efficiencies which could not be adequately explained. The low efficiencies...may be due, at least in part, to an unbalanced vapor distribution as was observed in the FRI column”. So for successful 3-pass and 6-pass tray design, it is important to understand what went wrong in the FRI tests and incorporate the lessons learnt.

Maldistribution varies the liquid to vapor (L/V) ratio from pass to pass. Pinching, and therefore poor separation, occurs in the low L/V regions, while the high L/V ratios in other regions only slightly offset the separation loss. The regions where maldistribution increases the vapor or liquid loads are pushed closer to flooding, while other regions where the loads are reduced have surplus capacity. Overall, observed efficiencies and capacities diminish, sometimes grossly. Bolles’ defined the distribution ratio Φ as the ratio of the maximum pass L/V to the minimum pass L/V, and recommended keeping this distribution ratio below 1.2 for good tray efficiency. Summers tightened Bolles’ criterion to 1.1. Reliable models for multi-pass tray maldistribution are scarce. Past models by Bolles7 and Jaguste and Kelkar8 have not addressed the effect of the hydraulic equations and tray type on the L/V split, and both were tested only against design cases. Our experience has been that tray type and hydraulic equations make a major difference. Comparing predictions with a design case is inadequate for validating a multi-pass model. The adequate test compares the model with field data. Proprietary software programs are available, but they rate the proximity to floods based entirely on L/V ratios from their own distribution models, models often untested against field data. Many of these models yield incorrect L/V ratios, as is illustrated in case studies in our recent paper4. If a model yields an incorrect L/V ratio (common), the capacity rating is incorrect, and so is the tray design.

Recently, we developed a model4 to reliably quantify maldistribution and pass L/V ratios in 4-pass trays, and validated it by maldistribution gamma scans in two towers for which other models failed. This paper extends our model to 3-pass trays, a basic step towards extension to 6-passes. Extension to 3-passes permits testing the model against measured data, presently unavailable for 6-pass trays.

2. 3-Pass Maldistribution Model
Balancing and optimization of multi-pass trays was the subject of excellent papers by Pilling3, Summers2,5, and Jaguste and Kelkar8. There are two balancing strategies: equal bubbling areas, and equal flow path lengths. Many designs provide vapor and liquid equalization across the off-center
downcomers; others do not. Addressing all these cases is too bulky to include here. We therefore focus on the most popular design of equal flow path length with no equalization. This is the design tested by FR6. The vapor and liquid splits on 3-pass trays are governed by the following relationships:

Mass balance on the liquid and vapor (kg/h) gives for each tray N (Figure 1)

\[
\begin{align*}
L_{A,N} + L_{B,N} + L_{C,N} &= L \\
V_{A,N} + V_{B,N} + V_{C,N} &= V
\end{align*}
\]

The liquid that enters Panel C on tray N consists of all the liquid \(L_{A,N+1}\) that descends from Panel A on the tray above via the side downcomer,

\[
L_{C,N} = L_{A,N+1}
\]

Similarly, the vapor that enters Panel C consists of all the vapor \(V_A\) from Panel A on the tray below,

\[
V_{C,N+1} = V_{A,N}
\]

The following pressure balance (\(\Delta P\)'s in mm of clear liquid) always applies to 3-pass trays:

\[
\Delta P_{A,N} + \Delta P_{C,N+1} = \Delta P_{B,N} + \Delta P_{B,N+1}
\]

This relationship simply states that the pressure is equalized in the vapor space above each off-center downcomer. On trays \(N\) and \(N+1\), the vapor path through the inside Panels B has the same pressure drop as the vapor path through the outside Panels A and C. The second force balance is

\[
h_{dc,OC,C} = h_{dc,OC,B}
\]

The above are six equations with six unknowns: \(L_{A,N}\), \(L_{B,N}\), \(L_{C,N}\), \(V_{A,N}\), \(V_{B,N}\), \(V_{C,N}\). The equations include vapor and liquid flows from the tray above, \(N+1\), but these will keep moving up (or down) the tower, with each tray having the six equations showing dependence on the adjacent trays. The end conditions force balances are slightly different than the others. The pressure drop across panel C of the bottom tray equals that across panel B, i.e.,

\[
\Delta P_{C,1} = \Delta P_{B,1}
\]

For the top tray, a relationship that expresses the liquid distribution to the panels is required. Often, a splitting device meters a third of the liquid to a false side downcomer, i.e.,

\[
L_{C,top} = L/3
\]

Equation 8 can be replaced by any other relationship that adequately describes the quantity of liquid entering from the side downcomer on the top tray. The balance of the liquid feed to the top tray is usually fed to a false downcomer, for which equation 6 above applies, but since it is the top tray, the pressure drop of the non-existent tray above is not included in the downcomer backup equation.

3. 3-pass Maldistribution Model Hydraulics

The hydraulic relationships in equations 5-7 can make or break the maldistribution calculation, as demonstrated in our recent paper for 4-pass trays. Our previous paper contains a detailed discussion of the relationships successfully used. Below is a summary. Recent editions of Perry’s Handbook contains the classic downcomer equation, and this is the equation we exclusively used, i.e.,

\[
h_{dc} = \Delta P + h_w + h_{bw} + h_{ud} + h_{hg}
\]

Where \(h_w\) is the outlet weir height, mm; \(h_{bw}\) is the liquid head over the weir; \(h_{ud}\) is the liquid head loss under the downcomer apron; \(h_{hg}\) is the tray hydraulic gradient. All heads are in mm clear liquid. Our experience is that alternative approaches for downcomer backup calculation led to multi-pass maldistribution results that did not fit plant measurements. An alternative useful format of equation 9 is
Understanding maldistribution in 3-pass trays

\[ h_{dc} = \Delta P + h_t + h_{ud} + 0.5 h_{hg} \]  \hspace{1cm} (10)

The liquid head \( h_c \) on the tray can be calculated from a correlation (e.g., Colwell’s correlation\(^{10}\) has been popular and often recommended\(^1\) for sieve trays in the froth regime) or it can be evaluated from the classic relationship

\[ h_c = h_W + h_{ow} + 0.5 h_{hg} \]  \hspace{1cm} (11)

The pressure drop \( \Delta P \) is the sum of the dry pressure drop, i.e., the pressure drop across the tray dispersion unit (sieve holes, valves), and the pressure drop through the aerated liquid on the tray\(^1\)

\[ \Delta P = h_d + h_L \]  \hspace{1cm} (12)

The pressure drop across the aerated liquid is given by (\( \beta \) is the tray aeration factor)

\[ h_L = \beta h_c \]  \hspace{1cm} (13)

Our experience is that the clear liquid head term needs to be applied consistently in multi-pass maldistribution calculations. Calculating clear liquid height in the pressure drop equation by a different method than in equation 10 may lead to results which do not fit plant measurements.

For the head loss under the downcomer and for the hydraulic gradient, we applied the relationship in the 8th edition of Perry’s Handbook\(^1\). Pressure drop equations vary from one tray type to another. Perry’s Handbook\(^1\) has methods for sieve and valve trays, and we had success with these. We have also had success with the Glitsch\(^{11}\) and the Klein\(^{12}\) pressure drop methods for valve trays. We have had success with some proprietary pressure drop calculation methods, as long as we used the downcomer backup equation 9 or 10. We found it important to apply the pressure drop method intended for a given tray, and have seen problems with using sieve tray pressure drop methods for characterizing maldistribution in multi-pass valve trays.

4. Model Application to FRI's Tests

Fractionation Research Inc. (FRI) tested two 3-pass sieve tray designs in their 8-ft ID tower\(^6\). One is discussed here; the second design has little practical application, and was omitted per referee’s comments due to space limits. The five test trays had equal flow paths, no vapor or liquid equalization, and were at 610 mm spacing. Test systems were isobutane - normal butane (iC\(_4\)-nC\(_4\)) at 11.4 bara and cyclohexane -n-heptane (C\(_6\)-C\(_7\)) at 1.65 and 0.34 bara. Outlet weirs as well as downcomer clearances were 50 mm tall. Details are in FRI’s report\(^6\).

Tray efficiencies measured for the iC\(_4\)-nC\(_4\) system were 100 to 110 percent, similar to those measured for the same test system in FRI's tests with one and two pass trays. Throughput was limited by the tower auxiliaries, so no capacity measurement was made. FRI’s report states that visually this system showed only a small amount of maldistribution. In contrast, tray efficiencies for the C\(_6\)-C\(_7\) system were well below those measured with one and two pass trays, in many runs (especially at higher throughput) less than half. FRI visually observed severe vapor maldistribution on the trays, with the spray height on the center panel consistently higher than on the sides. Close to flood blowing was observed on the center panel. These effects became more severe with the vacuum tests. Flooding was premature, and for the 1.65 bara test occurred at about 70 percent of the flood point measured with the same system on one-pass trays.

Table 1 shows the results of our model calculations for key FRI tests. For the iC\(_4\)-nC\(_4\) system, we used the FRI run at “90% of the (auxiliaries) limit”. Two alternative methods were used for pressure drop calculations, FRI’s and Perry’s. Table 1 shows that both methods gave similar results. Both confirm good distribution, with most distribution ratios around 1.1 and none significantly exceeding 1.2. This is in excellent agreement with the high efficiency measured by FRI for this run (108%). For C\(_6\)-C\(_7\) at 1.65 bara, Table 1 shows a slightly worse distribution than for iC\(_4\)-nC\(_4\). Most distribution ratios were in the 1.0 to 1.2 range. On tray 3, above which the observation window was located, the distribution ratios were less than 1.13, and the middle panel B appeared to receive an even share of the vapor and of the liquid. There is nothing in this calculation that can explain the poor efficiency (37%) measured for this run (compared to an efficiency of around 80% measured for this system at the same vapor loads with 2-pass trays). Nor can the calculation explain the high spray height in the middle panel B seen through the observation window during the test. There is also nothing in this calculation to explain the proximity to flood (81% of the measured flood point), compared to 58% of the measured flood point of an equivalent 1-pass tray.
5. Cause of Low Capacity and Efficiency in FRI’s C₆-C₇ Tests

An efficiency of 74% was measured for the C₆-C₇ system at one of the turndown runs. Our distribution model did not identify any major shortcomings in the 3-pass tray liquid and vapor distribution to explain the measured poor efficiencies and premature flood. Table 1 reveals that the tray liquid loads in the FRI Design were very low, ranging from 6 to 10 m³/h m of outlet weir length. Usually, the switch to a higher number of passes is made when the liquid load exceeds 90 to 135 m³/h m. So the liquid loads in this test were an order of magnitude lower than those typical of 3-pass trays. At 6-10 m³/h m, one would expect to find very little liquid on the trays, and the trays to operate in the spray regime. The Pinczewski and Fell froth to spray transition correlation marks the transition from partial spray to the fully developed spray. This correlation confirmed that the C₆-C₇ operation at 1.65 bara was indeed in fully developed spray.

In the fully developed spray, vapor is the continuous phase. There is not much liquid on the tray floor. Most of the liquid is dispersed as drops in the inter-tray space. This means that vapor is present right near the downcomer liquid outlet, i.e., the outlet weir does not provide a positive liquid seal to the downcomer. The FRI movie for this test confirmed that a significant portion of the downcomer outlet was not liquid-covered. There was nothing to prevent the vapor from ascending through the downcomer, so it split between the tray and the downcomer. To keep the downcomers liquid-sealed, high resistance (pressure drop) is needed at the downcomer liquid exit. In contrast, the downcomer clearances, which provide the exit pressure drops, were 50 mm, extremely large for the spray regime. Applying the standard head under the downcomer calculation gives liquid heads of 0.15 to 0.5 mm at the downcomer exit, which is insignificant resistance to vapor upflow. So the vapor has free access to the downcomer, and partially bypasses the tray, which explains the poor observed efficiency.

If the vapor flow up the downcomer is too high, it interferes with the liquid descent. The downcomer behaves like a wetted-wall column, which floods at high vapor rates. Kister’s downcomer sealing model can calculate the vapor split between the tray active areas and downcomers and at what rates flooding occurs. For C₆-C₇ at 1.65 bara, our sealing calculation showed that 75% of the vapor rising above the off-center downcomer ascends into the tray active areas above. The balance splits fairly evenly between the side and off-center downcomers. For vapor above the side downcomer, 74% rises into the active area above, while 26% rises into the off-center downcomer. At these loads, the off-center downcomer operated at a calculated 75% of flood, which compares closely with FRI’s determination that this run operated at 81% of measured flood. We repeated the calculation for the run at which FRI observed flood with this system. For this run, our sealing model predicted operation at 92% of flood. This verifies that the premature flood observed is a sealing-loss flood, caused by excessive vapor velocities up the off-center downcomers due to lack of liquid seal.

The liquid loads for the C₆-C₇ system at 0.34 bars were about half of those for the same system at the higher pressure, so the downcomer unsealing and bypassing issue would have been much worse. We therefore did not analyze this system in details. It would have been a miracle had good efficiencies
been obtained in tests with this system with this design. In fact, in most of the runs with this system the efficiency was about 25-33% of those measured at the same vapor loads with 2-pass trays. Premature flooding was experienced with this system too.

6. Insight into Vapor and Liquid Behavior on 3-Pass Trays

We have test data for a commercial C3-C4 Splitter containing thirty 3-pass standard V-1 valve trays in the stripping section which achieved a good separation at 20 bara pressure. Later, the trays were replaced with 3-pass trays in which near-perfect distribution was ascertained. Replacing the initial trays by those with near-perfect distribution did not improve separation, nor increase capacity. This does not necessarily mean that the old trays were efficient. The stripping section was overtrayed and the separation was pinched, so that a loss of efficiency may have remained hidden. All we can say with confidence is that the old 3-pass trays were not grossly inefficient.

Table 2 gives the tray geometry and test operating conditions. The test was conducted at low hydraulic loads, about 53% of jet flood. The downcomer liquid load was also low, and the tower was not near a limit. The test conditions will be discussed, but first we address the maximum load operation which was not practiced due to limitations elsewhere in the plant.

Table 2 – TRAY & OPERATING DATA FOR C3-C4 SPLITTER

<table>
<thead>
<tr>
<th>tray geometry</th>
<th>test operating conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower Diameter, mm</td>
<td>2,243</td>
</tr>
<tr>
<td>Tray Spacing, mm</td>
<td>610</td>
</tr>
<tr>
<td>weir height, mm</td>
<td>50</td>
</tr>
<tr>
<td>downcomer clearance, mm</td>
<td>38</td>
</tr>
<tr>
<td>downcomer top &amp; bottom</td>
<td>Surface tension, dyn/cm</td>
</tr>
<tr>
<td>Area side/off-center, m²</td>
<td>0.40 / 0.93</td>
</tr>
<tr>
<td>Width side/off-center, mm</td>
<td>330 / 356</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Panel</th>
<th>Flow path length, mm</th>
<th>Number of valves</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>457</td>
<td>113</td>
</tr>
<tr>
<td>B</td>
<td>457</td>
<td>157</td>
</tr>
<tr>
<td>C</td>
<td>457</td>
<td>113</td>
</tr>
</tbody>
</table>

Table 2

Figures 2a and 2b show the distribution ratios in the stripping section using the Klein and the Glitsch pressure drop correlations, respectively. The results are similar. Panel B receives more liquid and more vapor, as could be expected in an equal flow path length tray. Within a few trays from the top or bottom, the vapor and liquid loads settle into a uniform and steady distribution profile. Once this profile is established, panels A and C appear to have the same vapor loads and the same liquid loads.

Figure 3 shows the corresponding distribution ratios. Regardless of the pressure drop correlation used, the steady profile distribution ratios between A and C panels are 1.0. The steady profile distribution ratio between A and B is the same as that between C and B. The steady profile distribution ratio between A and B was 1.21 based on the Klein pressure drop correlation and 1.28 based on the Glitsch pressure drop correlation, which is in very good agreement.

Figure 3
Figure 4 is similar to Figure 3, but for the actual lower throughput test case. The trends in Figure 4 are the same as in Figure 3. The steady profile distribution ratio between A and B and between B and C were 1.14 based on the Klein pressure drop correlation, which was slightly lower than that calculated for the maximum case with this correlation (1.21). However, the corresponding distribution ratio calculated based on the Glitsch correlation was huge, 1.60, much larger than any others.

In the test, the trays operated in the region where some valves were open, others closed. Per the downcomer backup equation, differences in tray liquid heads and losses under the aprons on panels A and B need to be balanced by the pressure drops of panels B and C on the tray above. For both the Glitsch and Klein methods, the balancing pressure drop needed to be 3 mm of liquid higher on panel B than on panel C. The parameter used to balance the difference is the vapor rate. In that region the pressure drop is very insensitive to vapor rate, so a large variation in vapor flow is required to offset a small difference in pressure drop. With the Glitsch method, it took big jump in vapor rate to raise the panel B pressure drop by 3 mm of liquid. The Klein correlation has the opposite influence, and here lower vapor rate gives higher pressure drop, as it raises the aeration factor.

In either case, in the region in which valves open and close, small pressure drop variations can cause huge differences in vapor loads from panel to panel. We made a somewhat similar observation when investigating the turndown of 4-pass valve trays. This is a region in which the ultrasensitivity of vapor distribution to small pressure drop variations renders calculation and modeling of maldistribution in 3-pass trays unreliable. That ultrasensitivity may be a manifestation of an actual physical phenomenon, and caution is required when designing or operating 3-pass moving valve trays in that region.

7. Conclusions

This paper presents a hydraulic distribution model for 3-pass trays with no liquid or vapor equalization. The model predictions compared well to FRI’s test data for the iC4-nC4 system and to one case of an operating tower. The model predicts good distribution for the FRI tests, and the paper shows that the poor efficiencies in some of the tests were due to spray regime operation and loss of the downcomer seals and not due to tray maldistribution. We found that the distribution calculation for the maximum rates in an operating valve tray tower was robust, but at lower rates, where valves open and close, there is an extreme sensitivity of vapor distribution to small pressure drop variations, which precludes reliable distribution prediction.

References
6. Fractionation Research Inc., Research Progress Reports for November (1962). Obtainable upon request from Oklahoma State University archives, Stillwater, OK.