Effect of Maldistribution on TGTU Absorber Performance

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Traditional wisdom is to be wary of *liquid* maldistribution in packed towers because of its deleterious effects on column performance, yet it is hard to find quantitative information about just how negative its effect can really be. Imbalanced liquid distribution is less problematic in trayed columns so is rarely mentioned in that context[1]. However, uneven *vapor* distribution can drastically decrease the performance of both types of columns. A mechanical device[2] is sometimes used to help achieve more uniform vapor distribution in large-diameter columns where vapor maldistribution is prone to occur. Nevertheless, maldistribution caused by poorly introduced vapor has the same potential to cause serious performance loss as liquid maldistribution, caused, for example, by an out-of-level or damaged distributor. Although the initiating event may be associated with one phase or the other, liquid and vapor imbalance are tightly connected and always occur together—maldistributed vapor causes the liquid to maldistribute and *vice versa*—so one must consider both phases in any deliberations. As discussed later, well distributed countercurrent vapor and liquid flows in a packed column tend to be unstable in that nonuniformities, once initiated, usually grow, persist, and expand over the entire depth of the packed bed.

This article describes a quantitative study of the effect of liquid and vapor maldistribution on the separation performance of a packed column used in a Tail Gas Treating Unit (TGTU). The study was done with the aid of a proprietary simulation tool[3] applied to a hydraulic representation of the ill-performing physical column using two parallel simulated columns[4]. It reveals that a surprisingly small degree of unevenness in the distribution of either phase will cause a highly significant rise in the H_2S leak from the TGTU without displaying common, telltale symptoms of column issues, for example, measurably affecting the pressure drop across the column.

It is not possible to predict the extent of maldistribution—this is a complex hydraulics problem needing detailed information on such things as distributor out-of-levelness and the results of a computational fluid mechanics study of the flows in the tower sump and vapor entry. However, if maldistribution is suspected, thermal imaging of the column from several positions around its periphery can provide an estimate of where liquid flow is excessive and, by inference, where vapor flow is abnormally high. This kind of information, combined with accurate simulation of a rough hydraulic representation of the tower with maldistribution in mind, can be useful in troubleshooting this challenging situation.

Maldistribution hydraulics

Almost all the literature dealing with maldistribution of countercurrent gas and liquid flows in packed columns deals primarily with hydraulic modeling of the flow patterns within the packing given the initial distribution of liquid (see Sun et al., 2000, for one of the more recent studies). However, there appear to be no plausible methods for predicting the extent of liquid and/or vapor maldistribution. The practitioner must be prepared to make assumptions and propose estimates as to what fraction of the column cross-section carries excess liquid (or vapor) and what the excess in liquid (or vapor) flow is. The maldistribution is modeled by segregating the two cross sections into two separate parallel columns connected at top and bottom according to the assumed cross-sectional areas. Once the

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[1] Note, however, that most trays under severely turned down conditions, and dual flow trays under almost all conditions (Weiland, 2001), will show severely nonuniform liquid passage through the tray perforations. Weeping and nonuniformity are both responsible for low efficiency.

[2] An example is the Schoepentoeter™, a proprietary Shell vane type inlet device used to introduce gas into a vessel or column.

[3] ProTreat® is the mass transfer rate-based simulator used in this study.

[4] This follows the approach suggested by Kooijman et al. (2022).

specifications of area and excess flow are made, the rest of the parameters are fixed by enforcing the requirement of equal pressure drop across the two columns (which must behave as one, when merged).

Maldistribution can be mitigated, but it cannot be prevented because uniform countercurrent two-phase flow through packed beds is inherently unstable. The preferred flow pattern is segregated. Evidence for this is abundant. If liquid is introduced at only one point at the top of a packed bed, it will tend to remain well segregated from the vapor as it flows down the column. It naturally takes (or even creates) the flow path of least resistance. Likewise, the path of least resistance for the vapor is where there is little or no confronting liquid counterflow. As liquid and vapor flow through the column, they tend to segregate even after great pains have been taken to ensure these phases were introduced with very uniform distribution. This is why liquid redistributors can be such a critical part of a packed column (see Schultes, 2000, for a detailed discussion).

There are numerous causes of maldistributed flows. These include (i) introducing vapor at high velocity through a single feed pipe at the base of a large diameter column (causing maldistributed vapor), (ii) careless dumping of random packing into the column leading to large voids, (iii) using packing that is too large for the diameter of the column causing preferential flows through the high voidage areas adjacent to the column walls[5], (iv) wrong distributor type for the liquid flowrate, (v) poorly designed liquid distribution (see Schultes, 2000), (vi) out-of-level distributor, (vii) lack of liquid redistributors (dumped packings) or wall wipers (structured packings), (viii) packed bed too deep (single beds should not exceed L/D = 15–20 without liquid redistribution), (ix) failure to rotate alternate structured packing sections, (x) tower is out-of-round.

Case Study

The TGTU absorber that forms the basis for this study contains 15 feet of IMTP-40 random packing and uses 45 wt.% MDEA solvent. Other data are shown in Table 1. This packing depth maximizes CO_2 slip at almost 93% while removing H_2S to 85 ppmv. Although a depth of 40 feet will remove H_2S to 31 ppmv, it will lower CO_2 slip to only 82%. However, whether 15 or 40 feet of packing are used, the conclusions reached in this study are qualitatively unaffected. To handle the flows, the column needs to be about 5.3-ft diameter (65% flood). With the bed depth (15 ft) being less than three times the column diameter, no redistributor is needed.

Table 1 - Gas and Solvent Conditions for Case Study

	Tail Gas	**Solvent**
Flow	10 MMSFCD	150 USgpm
Pressure (psig)	1.0	1.0
Temperature (°F)	100	110
MDEA (wt%)	—	45
CO_2	5 mol%	0.005 Loading
H_2S	1.5 mol%	0.001 Loading
N_2	93.5 mol%	—
H_2O	Saturated	Remainder

Two scenarios are considered: in the first, varying but specific degrees of excess gas flowrate are assumed to pass through part of the cross-sectional area of the absorber and a deficit through the remainder. Here, two cases of gas maldistribution are considered: one in which half the column area carries the excess, and other where ¼ of the area carries the excess. The extent of liquid maldistribution required to produce equal pressure drops across the two parallel columns is then calculated. In the second scenario, varying degrees of liquid maldistribution are considered,

[5] The conventional guideline that D/d > 8 gives the maximum packing size (d) relative to the column diameter (D) to ensure negligible wall flow is, in our experience, optimistic — a value of 12–15 is minimal for surety. There has been a tendency in experimental data collection to use columns that are of too small diameter to yield results that reliably reflect commercial equipment. This particularly the case for work emanating from academic institutions.

and the corresponding gas maldistribution is calculated the same way. Figure 1 shows a typical parallel-column simulation model when 27.5% vs. 25% of the total gas flow is to ¼ of the absorber cross-section. Note that this seemingly small amount of gas maldistribution pushes almost all the liquid from that part of the column so that only 3.7% vs. 25% of the liquid contacts this gas. Figure 2 shows another simulation in which the liquid flow to ¼ of the absorber cross-section is purposely raised from 25% to 30% of the total liquid flow (45 vs. 37.5 USgpm). In this case,

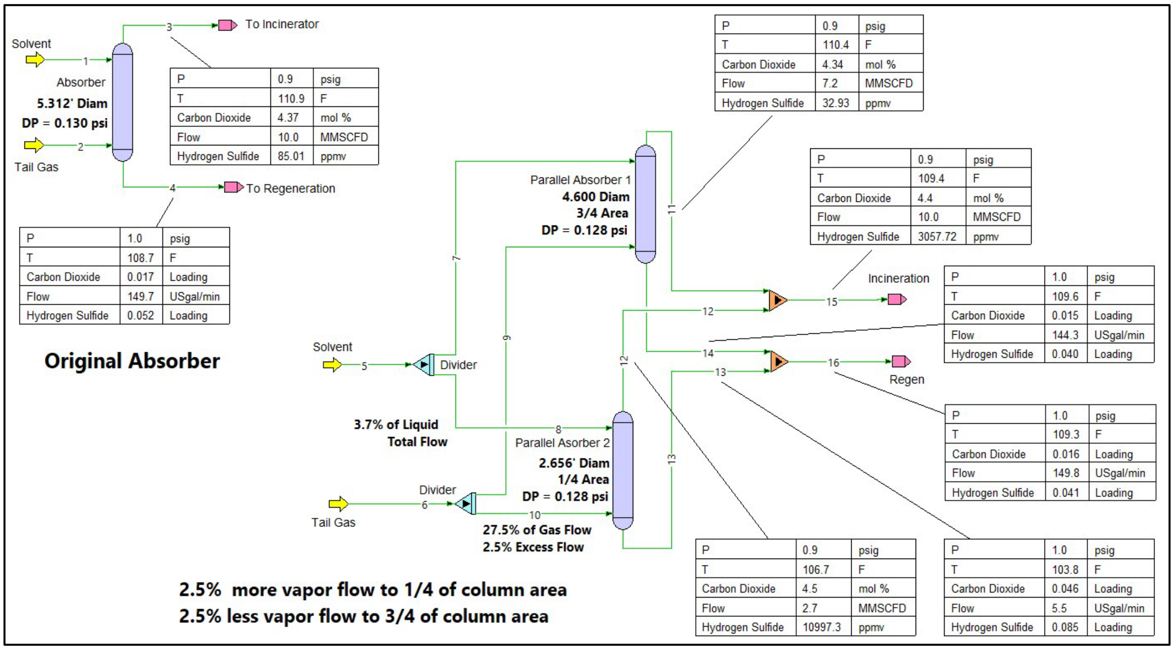

Figure 1. Parallel Column Model for Simulation with 2.5% Excess **Gas** Flow to ¼ of Absorber Area

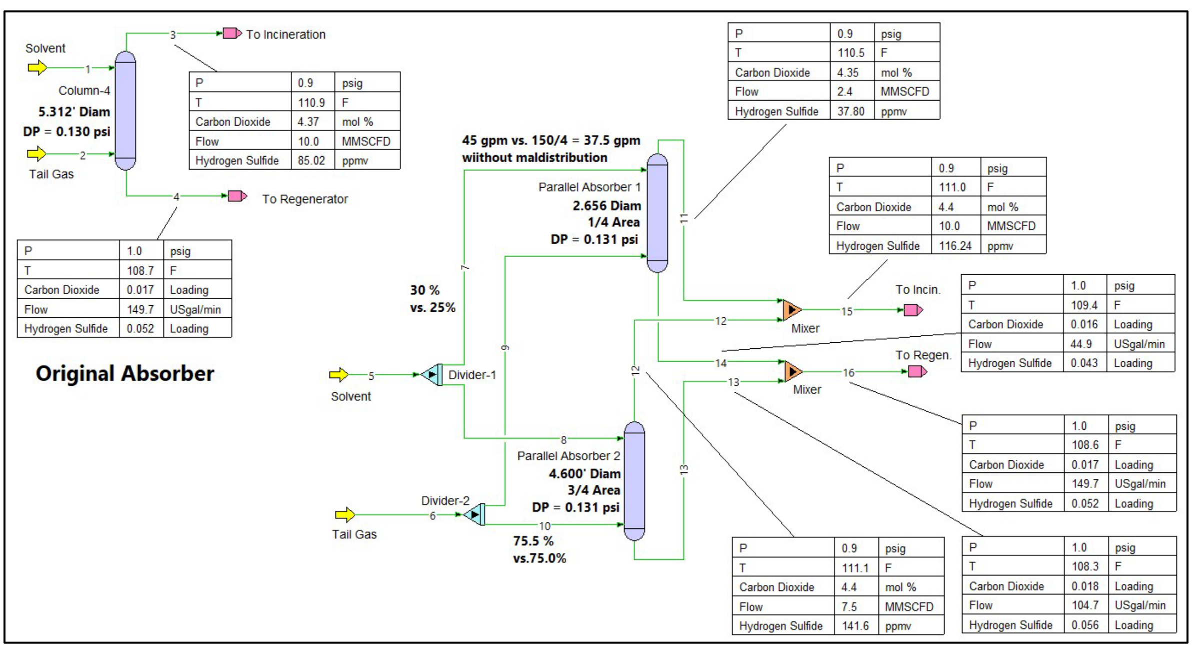

Figure 2 Parallel Column Model for Simulation with 5% Excess **Solvent** Flow to ¼ of Absorber Area

the increased solvent flow forces only quite a small corresponding reduction in gas flow to maintain balanced pressure drop, and the effect on H_2S treating is not nearly as significant. It is, perhaps, worth noting that maldistributed gas seems to have a more severe impact on performance than a similar amount of liquid maldistribution does. This makes sense when one realizes that pressure drop is a lot more responsive to gas flow than to liquid rate. Liquid films on packing surfaces somewhat narrow the size of passages available for gas flow; however, it is the gas flow that directly causes pressure drop.

Balancing Gas and Solvent Flows

The balanced hydraulic distribution of gas and solvent plays an important role in setting TGTU absorber performance. Because the gas flow splits into two parts at the base of the actual absorber, the split streams in the model pass through two parallel columns, and then recombine at the top of the absorber (solvent flow splits similarly). The pressure drop across these two columns must be identical, otherwise the flows will redistribute. Figure 3 shows how the gas and solvent flow rates are related[6] in the ¼-area column under the overall conditions of Table 1.

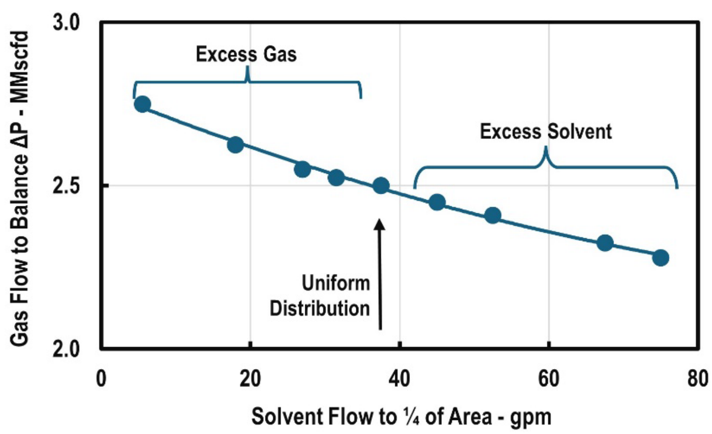

Figure 3 How the Flowrate of One Phase Responds to Flowrate Changes in the Other Phase when Absorber is Split into ¼- and ¾-Area Parallel Columns

It is useful to appreciate from Figure 3 that when, for example, a poorly constructed or maintained distributor discharges too high a solvent flow into one part of the column, the gas flow there sees more resistance, and it will respond by reducing its local flowrate and divert the excess to some another part of the column. The net result is that higher solvent rate combines with lower gas rate so the L/G ratio there becomes even more elevated; thus, one might expect somewhat better treatment (lower residual H_2S). However, the L/G ratio decreases in the other part of the column, and this can be expected to result in poorer treatment (increased H_2S leak). The question then is, what is the net effect on the recombined gas, i.e., on the real absorber's performance, from these competing effects?

Effect of Maldistribution on Mass Transfer Performance

One set of simulations was done at several solvent rates deviating positively from the uniform distribution value (37.5 gpm flow to ¼ of the area of the actual absorber) with the gas rate to that quarter adjusted to give equal pressure drop across the ¼- and ¾-area sections. A second set of simulations was done with gas rates deviating

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[6] Similar calculations have been done for flows that maldistribute to each **half** the absorber area. The results are substantially the same, so they are omitted here for the sake of brevity. The effect on mass transfer performance is qualitatively the same, too.

positively from the uniform distribution value of 2.5 MMscfd. Here, equal pressure drops across the parallel columns required the solvent rate to be reduced. The results of all simulations were consolidated into the combined plots in Figures 4 and 5. Figure 4 shows the H_2S content of the treated gas from the ¼- and ¾-area columns and the treated

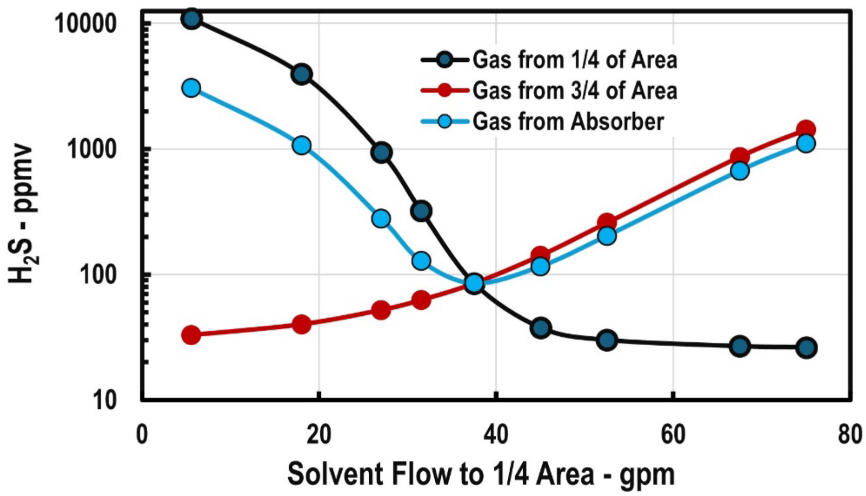

Figure 4 How Solvent Maldistribution in Terms of Actual Flowrate (gpm) to the ¼-area Column Affects H_2S Content of the Treated Gas from the ¼- and ¾-Area Parallel Columns and from these Columns when Combined into the Real Absorber

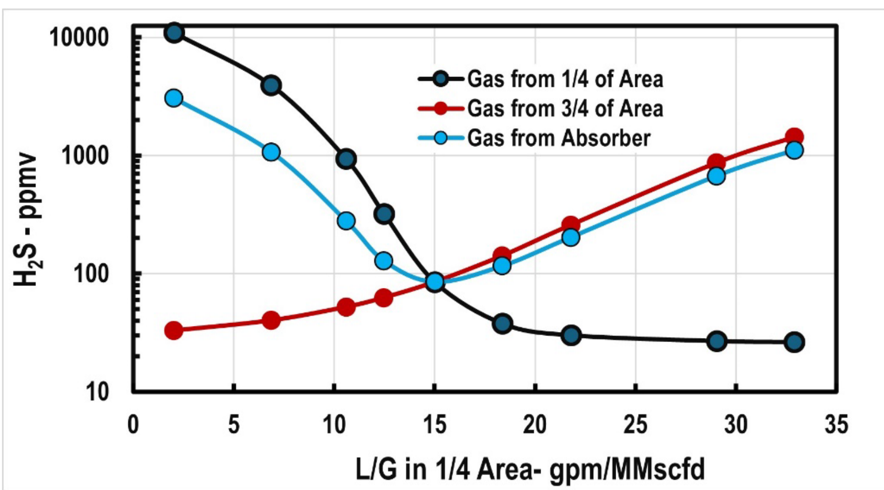

Figure 5 How Solvent and Gas Maldistribution Expressed as L/G ratio (gpm/MMscfd) in the ¼-area Column Affects H_2S Content of the Treated Gas from the ¼- and ¾-Area Parallel Columns and from these Columns when Combined into the Real Absorber

gas from the combined columns, i.e., from the real absorber, as a function of the actual solvent flow to the ¼-area column. Figure 5 combines liquid and gas maldistribution into the L/G ratio which explicitly contains the effect of liquid maldistribution *and* the concomitant gas maldistribution.

As expected, optimal absorber performance is realized when both phases are perfectly distributed over the tower's entire cross-section. However, a deviant solvent flow to ¼ of the absorber (with the remaining ¾'s) affects the two sections to an unequal extent. H_2S treating is not a linear function of compositions and flowrates. As Figure 5 shows, H_2S treatment from the ¼-area section is much more negatively affected by reduced L/G ratio (note the logarithmic scale on the y-axis of these plots). However, Figure 6 shows that when one of the phases is maldistributed in fully one-half of the absorber cross-section, the two columns in the parallel column model (and the two sections of the real column) become indistinguishable. Perfect phase distribution is optimum, although performance loss is more severe when either phase is maldistributed over *half* the absorber cross-section. In either case, though, in this example only a relatively small degree of maldistribution pushes treating to exceed 100 ppmv H_2S. In other words, treating performance is quite sensitive to phase maldistribution.

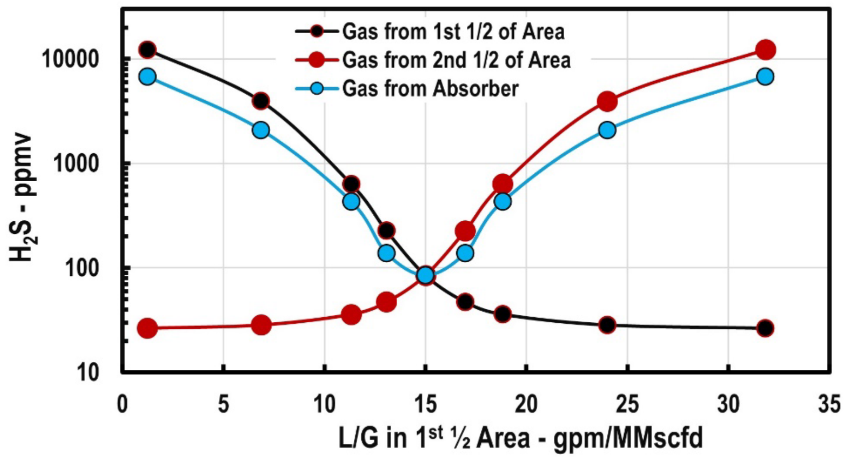

Figure 6 How Solvent and Gas Maldistribution Expressed as L/G ratio (gpm/MMscfd) in the ½-area Column Affects H_2S Content of the Treated Gas from Each Parallel Columns and from these Columns when Combined into the Real Absorber

Qualitatively, the foregoing offers the possibility of some guidance as to what effect maldistribution might have on TGTU performance, but quantitatively it is predicated on being able to assess actual flowrates to various areas across the column cross-section, something we are unable to do. But, if the tower's actual mass transfer performance is known, this type of analysis offers the possibility of estimating how much maldistribution might be required to produce it. However, which of the gas or liquid is mechanically maldistributed and which is a consequence of the other will need additional information, e.g., measured distributor out-of-levelness, or perhaps even a CFD study of the gas inlet flow in the tower sump. Two parameters are needed: the relative cross-sectional areas affected, and the deviations of the phase flows from their perfectly distributed values. There is no obvious way to determine the latter, but relative areas might, in principle at least, be roughly estimated using thermal images taken from different orientations. Unfortunately, TGTUs operating selectively do not usually show the large temperature changes exhibited by CO_2 absorbers, for example (see Cooper and Weiland, 2016), probably making thermal imaging unworkable except in the rare instance of a TGTU processing a high-H_2S, low-CO_2 gas, or when maldistribution is extreme. Nonetheless, maldistribution can be a hidden cause of severe failure to properly treat tail gas and meet SO_2 emission regulations, and the parallel column model offers a way to analyze it.

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