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DESIGNING TRAYS FOR SELECTIVE TREATING

Ralph H. Weiland[1], Nathan A. Hatcher[2] and Jaime L. Nava[3]
[1] Optimized Gas Treating, Inc., P.O. Box 125, Clarita, OK, USA, Email: ralph.weiland@ogtrt.com
[2] Optimized Gas Treating, Inc., 311 Bayou Bend, Buda, TX 78610, Email: nate.hatcher@ogtrt.com
[3] Optimized Gas Treating, Inc., 7719 View Park Ln, Houston, TX 77095, Email: jaime.nava@ogtrt.com

Abstract
Field performance data from eight different gas treating plants are used to show how certain tray design parameters can be selected to improve contactor performance radically by ensuring the trays operate hydraulically in the spray regime. A case study is also presented in which both CO_2 and H_2S removal specifications are met by using multi-pass trays even though satisfactory hydraulic performance can be had from a single-pass design.

Keywords: Absorption, selectivity, spray, trays, multi-pass

1. Introduction

Trays, random packing, and structured packing each have their place, uses, advantages and disadvantages, and the reasons for choosing one internal over another are wide and varied. Structurally, trays are robust, they allow easy introduction and removal of mid-tower feeds and side-draws, they can handle the high L/G ratios common in gas treating and they offer good turndown. If pressure drop must be minimized (vacuum systems, CO_2 capture from power plant flue gases) or the columns are extremely small or large in diameter, packing often makes more sense. In systems with small L/G ratios (e.g., glycol dehydration), structured packing is favoured over any other type of internals. In revamps for increased capacity, the higher throughputs possible with structured packing favour it as a replacement for trays. However, structured packing is almost impossible to clean *in situ*, is more susceptible to plugging by entrained solids, and is inherently more difficult than random packing to remove from a column for cleaning. But these are guidelines, not rules, and it sometimes happens that trays, for example, should be used in a very low L/G ratio acid gas removal application even when conventional thinking would have recommended packing.

As mass transfer or separation devices, by their very nature these three types of tower internals have inherently different mass transfer characteristics. In any separation application, the efficiency or behaviour of a given internal is a function not just of the mechanical construction of the device but also of the hydraulic state of the fluids — gas and liquid — flowing through it and being contacted. In gas treating, mass transfer is nowhere near as simple as just counting the number of equilibrium stages and amending the result by applying some kind of efficiency (trays) or HETP (packing) value. Gas treating, especially using amines, is highly non-ideal and can be predictively simulated only by a mass transfer rate based model. In the context of reactive absorption, this type of model has been extensively described elsewhere[1] and warrants no further discussion beyond the reminder that absorption rates depend on mass transfer coefficients and concentration (or activity) driving forces. Enhancement factors account for the effect of chemical reaction kinetics and sometimes reaction equilibria on transport rates. The size of mass and heat transfer coefficients depends to a very great extent on the hydraulic state of flow of the fluids being contacted.

This paper describes the way absorbers intended for selective H_2S removal behave when operated outside the range common in generic gas treating, in particular at unusually low liquid loads. In 2009 we[2] reported on what appeared to be the impossibly-high selectivity observed and validated in two selective treating plants, one in Iowa and the other in New Mexico, USA. In this paper, we report on six additional cases, show that all eight cases are completely in line with each other, and then use the results to design a tray capable of producing extraordinary selectivity in a particular application.

2. Tray Hydraulics

The diameter of a tray column is determined by the tray's jet-flood and downcomer choke-flood limits.

The Souders-Brown factor ($C_S = u_S \sqrt{\rho_V/(\rho_L - \rho_V)}$ is a measure of the vapour-handling capacity, where u_S is superficial vapour velocity and ρ is density). C_S is typically below 0.12 m/s (0.4 ft/s). Tray vendors still struggle with reliably calculating downcomer choke-flood limits, although progress is being made.

Perhaps the most important factor in deciding the mode of operation of a tray is the liquid weir load. Numerically, the weir load, q_L, is the volumetric flow rate, Q_L, of clear liquid over the weir divided by the physical length of the weir, L_W:

$$q_L = Q_L / L_W \tag{1}$$

Weir loads considerably over 200 gpm/ft have been achieved although more typically 150 gpm/ft is considered a fairly high weir load. Between roughly 45 to 50 m^3/m·hr (60 or 70 gpm/ft) and 110+ m^3/m·hr (150+ gpm/ft), the biphase is a well-mixed froth of discontinuous gas dispersed in a more or less continuous liquid (froth regime). As the weir load falls below the lower end of the froth regime, the mode of operation changes gradually from discontinuous-gas in continuous-liquid to discontinuous-liquid in a continuous-gas. The froth gives way to a spray. The transition is anything but sharp and takes place over a considerable range of weir loads. However, when the weir load becomes low enough the flow regime becomes unmistakably a spray of liquid droplets projected across the tray in a rising continuous gas phase, with the drops finally bouncing into the downcomer. From the standpoint of selective gas treating, the question is what effect the flow regime has on the individual gas- and liquid-side mass transfer coefficients.

In the froth regime, where most trays operate in gas treating, the liquid is ripped apart by the gas jetting through the tray perforations and is highly agitated (turbulent) even on a "micro" level. High turbulence intensity greatly assists the movement of components to and from the interface into the bulk liquid. In other words, liquid-side mass transfer coefficients are much higher than they would be if the liquid were less turbulent or indeed were quiescent altogether. Because CO_2 absorption is controlled almost entirely by resistance in the liquid, a conventionally-operated tray is an excellent contacting device for CO_2 removal, *but not for CO_2 slip*. The status of the gas flow is perhaps less clear cut; however, it is the state of turbulence right near the liquid interface that is important. The gas enters the liquid in rather intense bursts and slugs of large bubbles and broad jets. Near the interface its flow is not especially turbulent so H_2S transfer is not greatly promoted.

In the spray regime, the liquid flow rate is low relative to the gas, and the liquid on the tray exists in the form of small droplets, of about 1 mm diameter. The droplets are projected through the vapour space, bounce their way across the tray and find themselves in the downcomer in only a few hops. Within small drops, the liquid *is nearly completely stagnant* and transport of material takes place almost solely by molecular diffusion, a very slow process compared with turbulent transport. Mass transfer coefficients inside the drops are therefore very small, absorption of CO_2 is necessarily severely retarded, and the *CO_2 slip should improve dramatically*. To maximize selectivity, this is exactly what one would like. As for the gas phase, it is now continuous but in a bulk sense it is still only moderately turbulent. However, the gas flows past the drops at Reynolds numbers that are at least 500. Flow past spheres is laminar region at Reynolds numbers below unity and is fully turbulent above a Reynolds number of about 1,000. Thus, the gas flow past the drops is almost fully turbulent, and the turbulence is on the same scale as the drop size because it exists mainly on the downstream side of the drop. In other words, the turbulence is at its maximum effectiveness. *When fully in the spray regime, the H_2S absorption is maximized and CO_2 absorption is minimized—the perfect combination for the best possible selectivity*.

The weir liquid load primarily determines the flow regime in which the tray is operating, and exactly where it is operating within that regime. Thus, to see abnormal selectivity it is useful to look for practical cases in selective gas treating that span a spectrum from fully spray to just inside the froth regime part of the operating envelope. The selectivity observed in such cases should be compared with the selectivity that would be expected from a froth-regime hydraulic model to see if operating regime has any effect and, if so, how much. Expected selectivity has been calculated using ProTreat™, a commercial process simulator using a mass and heat transfer rate-based column model.

3. Field Performance Data Under Low Weir Load Conditions

In 2008, Weiland[2] reported two sets of commercial operating data taken on small-diameter columns operating at low weir loads. In both cases the raw gases were low in H_2S and with CO_2 either below or only slightly above 2% so requiring essentially the greatest possible CO_2 slip (minimum removal) to meet North American treating specifications. Because of the small amount of acid gas removal, the absorbers in these plants were operated at small liquid rates and very low weir loads. Simulations fell far short of agreeing with the field data. Eventually it was realized that the absorbers were well into the spray regime and ProTreat's mass transfer coefficient correlations were inapplicable because they were developed from data on trays operating in the froth regime. To reproduce the performance data, the vapour-side mass transfer coefficients had to be increased by upwards of a factor of ten or more, and the liquid-side coefficients had to be correspondingly decreased.

Since then, six more commercial tower performance data sets with absorbers at low weir load have come to light. The only non-proprietary set of measurements is from a plant operated by Signalta Resources near Forestburg, Alberta, Canada[3]. These eight data sets are from plants in Canada, USA and India and span the full spectrum of weir loads from about 2.2 m^3/m·hr (3 gpm/ft) to 45 m^3/m·hr (60 gpm/ft). Each plant was simulated first using ProTreat's database correlations for tray mass transfer coefficients (froth regime), using the flowsheet shown in Figure 1. Simulations were repeated for various values of a constant factor multiplying the gas-side mass transfer coefficient (the same factor divided the liquid coefficient) until agreement with the performance data was obtained.

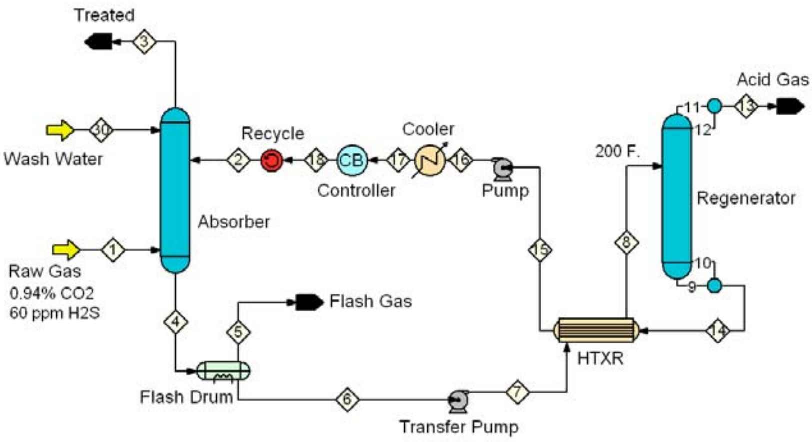


Figure 1. Typical PFD for Process Simulation

Figure 2 shows how the results compare with each other and how the correction changes with changing weir load. The plot shows a truly remarkable degree of correlation, especially in view of the fact that these results are derived from actual field data from eight different operating plants in three countries, some using generic *N*-methyldiethanolamine (MDEA), others using specialty amines, and one unintentionally using a diethanolamine (DEA)-MDEA mixture.

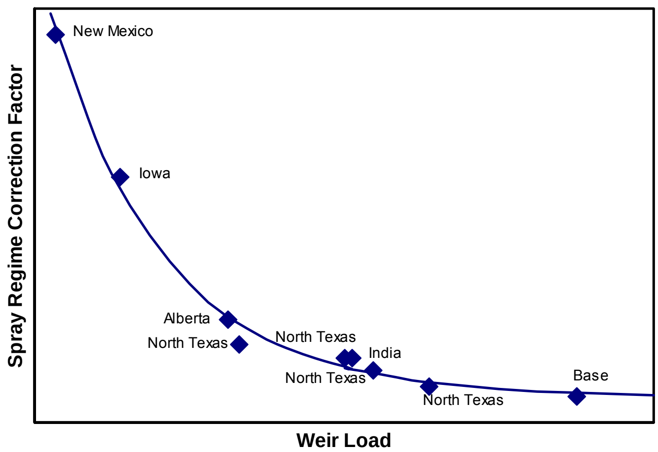


Figure 2. How the Correction Factor for Spray Regime Operation Varies with Weir Liquid Load

The correction factor is always greater than one. It multiplies the gas-side coefficient and divides the liquid coefficient; hence, the lower the weir load, the faster the absorption of H_2S, and the slower the absorption (higher the slip) of CO_2. Quantitatively, how important is weir load in determining H_2S leak and CO_2 slip from a column? For the Iowa plant (see data point in Figure 2), simulation using froth regime mass transfer indicated that the treated gas should have been 27 ppmv H_2S with 68% CO_2 slip. The plant was actually treating to 1 ppmv H_2S with 93% CO_2 slip and these performance numbers were accurately matched by using a correction factor appropriate to the operating weir liquid load. If this absorber had been properly designed according to conventional, well-accepted procedures, it would not have had the two-pass trays that it did (it was a resurrected column), the weirs would have been a lot shorter and this contactor would have failed to meet its treating goal by a very wide margin. It turns out that in each of the eight cases examined, the contactors were all meeting their treating goals. In fact, often they were significantly over performing, an accident with a very happy outcome. The next section will show how good tray design can be used to achieve otherwise unachievable outcomes, intentionally rather than by accident.

4. Designing Trays for Selectivity: A Case Study

This section looks at how tray re-design can be used to turn a failed plant into a success at quite minimal cost apart from the lost revenue associated with down-time of a large gas processing facility. The plant was originally designed to treat 330 MMSCFD of high-pressure gas containing 750 ppmv H_2S and 2.5% CO_2. Table 2 lists the design parameters and relevant equipment sizes used. The treating goal was 4 ppmv H_2S and 2% CO_2.

Table 2. Original Design Parameters and Operating Limits

Parameter	Value	Parameter	Value
Gas:		Absorber:	
Pressure (barg)	65	Diameter (mm)	3200
Maximum Temperature (°C)	43	Trays	12
CO_2 (mol %)	2.5	Tray Spacing (mm)	610
H_2S (ppmv)	750	Number of Passes	1
Flow (1000's SCMH)	156	Regenerator:	
Solvent:		Diameter (ft)	1675
MDEA (wt%)	50	Trays	20
Pump Capacity (m^3/hr)	80	Reboiler Duty (MW)	7
Maximum Temperature (°C)	49	Flash Pressure (barg)	4

Despite both the gas and lean amine being more than 15°F (8°C) colder than design, this plant as-built failed to deliver on-specification gas at more than 60% of design capacity *even when the gas contained only 400 ppmv H_2S*. Simulation of the complete plant using ProTreat showed that at *design* conditions of temperature, pressure, flow and composition, the best the plant could possibly achieve was 24 ppmv H_2S, and CO_2 would be removed to 1.62 mol%, well below the pipeline company's specifications for gas. In fact, at 60% gas rate, the optimal solvent flow was found to be 55.5 m^3/hr (240 gpm). Under actual plant operating conditions of colder gas and solvent, simulation indicated the plant should treat the 94,000 SCMH (200 MMSCFD) of 400 ppmv H_2S raw gas to 3.6 ppmv H_2S and 1.7% CO_2. This compares very favourably with the values measured at the pipeline header of 2.8 ppmv H_2S and 1.8% CO_2. In fairness, it should be noted that the weir load on the absorber trays was 30 m^3/m·hr (40 gpm/ft) so a small credit was taken for the operation being somewhat into the spray regime. The agreement between simulated and measured performance lends confidence in the ability of this simulation tool to predict performance with high accuracy.

The question remains as to what, and how much, improvement might be achieved by various strategies. In terms of revamp options to allow design rates to be reached, three main approaches were investigated: (1) using more trays in the absorber, (2) changing the tray design to take advantage of lower weir loads, and (3) altering the solvent rate. Simulation showed that a few more real trays could make a sizeable difference to the H_2S leak and, furthermore, that excessive CO_2 removal loads the solvent to much higher CO_2 content than necessary. High CO_2 causes higher H_2S

backpressure throughout the absorber, and lowers H_2S removal. However, the available tower height limits the number of additional trays that can be added without exceeding the jet flood limit. In other words, as more trays are added, the tray spacing must be lowered to fit the additional trays into the column, and this causes flooding to occur at lower vapour velocities.

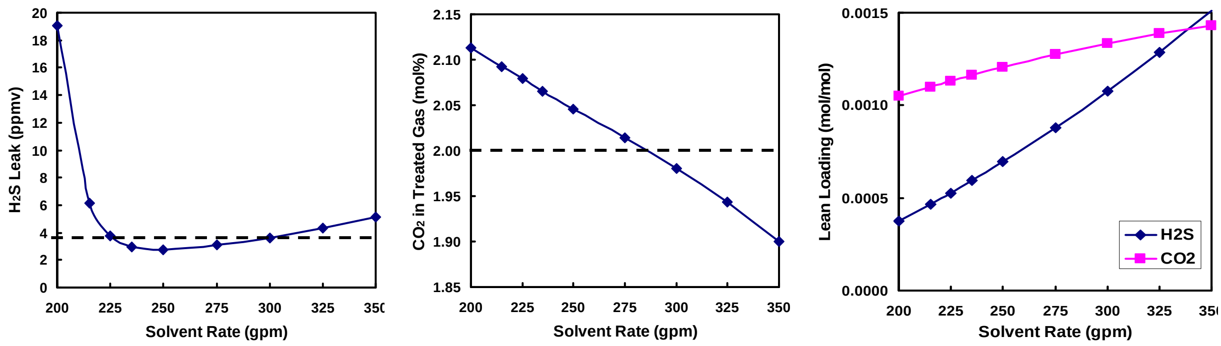
It is possible to replace 12 trays on 24-in tray spacing with 18 trays on 16-in spacing and not encroach into the head space in the absorber. Simulation of these 18 one-pass trays under design conditions predicted that the extra six trays (of the same design as originally installed) would take the H_2S level from 24 to 17 ppmv, but would drop the CO_2 content of the treated gas even further, from 1.62% to 1.45%. In and of itself, more trays help H_2S removal, but not nearly enough. Note that under design conditions with one-pass trays, the trays operate near the edge of the spray regime (weir liquid load = 48 m^3/m·hr or 65 gpm/ft), but not in it.

The next approach was to see what benefit might be gained from using multi-pass trays. Normally, multi-pass trays are used to reduce weir loads on heavily liquid-loaded trays so that excessive liquid backup on the trays is avoided, and premature jet and downcomer flood do not occur. This column certainly does not fall into that category, and multi-pass trays normally would not be recommended. However, in amine treating where tray efficiencies are low *and selectivity is controlled by the mass transfer characteristics of the trays*, there is potentially a large separations benefit from going to multiple tray passes. A 3200-mm (10.5-ft) diameter column is big enough to house 4-pass trays, and that is what was used in the next simulations. Simulation of 18 four-pass trays under the worst design conditions (highest temperatures, maximum gas and liquid flows, and maximum reboiler duty) predicted treated gas having 5.2 ppmv H_2S and 1.9% CO_2. Only a conservative credit for low weir load was taken. The gas still does not meeting the pipeline's 4 ppmv specification on H_2S but is much closer to the CO_2 target. The H_2S profile suggests that if only a couple more trays could be squeezed in, 4 ppmv H_2S might be reached. However, simulation shows the suggestion to be incorrect. Even one more tray causes higher CO_2 pickup, resulting in worse H_2S leak. Eighteen trays appear to be optimum. It would possibly be beneficial to use a lower solvent lean H_2S loading to squeeze another two or three ppmv H_2S from the gas, but the reboiler is under maximum load and stripping cannot be improved, unless… maybe a *lower* solvent rate can be applied beneficially.

Although there are a number of additional parameters that might be manipulated to improve the outcome, and in a final redesign they would be examined, the remaining process variable studied was the solvent circulation rate. Varying the solvent rate was an attempt to lower the solvent lean loading, especially with respect to H_2S. Because the reboiler was already operating at maximum design duty, lowering the solvent rate was the most obvious (the only?) way to achieve lower loadings. However, the efficacy of lowering the solvent rate depends on whether the absorber is lean-end or rich-end pinched. In this case, calculations showed conclusively that H_2S absorption was *not* limited by conditions at the rich end, i.e., by solvent capacity, but rather was lean-end pinched. Once again, a series of simulations using the ProTreat simulator was run at several circulation rates from 80 m^3/hr (350 gpm) right down to 45 m^3/hr (200 gpm) but keeping the reboiler duty constant at maximum rate. Figure 3 shows the results. Figure 3(c) shows that the lean solvent H_2S loading decreases strongly with decreasing solvent rate—this is at least partly responsible for better H_2S removal. However, as the circulation rate is decreased tray operation is thrown increasingly into the spray regime and this too favours selectivity by increasing the mass transfer coefficient in the gas phase (improving H_2S absorption) and decreasing it in the liquid phase. As Figure 3(b) shows, this decreases CO_2 removal (increases CO_2 rejection) which, of course, helps H_2S absorption too because CO_2 loads the solvent less, leaving more solvent capacity for H_2S. As shown in Figure 3(a), there is a fairly narrow range of solvent rates over which both the H_2S and CO_2 treats can be met, with the best treating being obtained at about 250 gpm (56 m^3/hr) where the H_2S leak is 3 ppmv and the treated gas is right at 2% CO_2. It must be stated that no simulator has the kind of accuracy needed to guarantee these concentrations, so looking at additional variables would certainly be warranted. A sensitivity analysis ought to be a normal part of any final revamp design, and looking at sensitivity to all the parameters would undoubtedly reveal other ways to squeeze out just a little more performance.

In this plant, *guaranteeing* the ability to meet pipeline specifications at the very limit of its design operating range is problematic in a commercial sense. But at the next level of complexity, it is always possible to use a specialty amine. In the present case, if the lean loading could be reduced even further, better treat is assured. But this cannot be done by increasing the reboiler duty or by going beyond four tray passes, especially in a column of this diameter. Also, the solvent rate cannot be further reduced because of the barrier imposed by the solvent's capacity limit and the excessive CO_2 rejection that it causes. It has become established practice in tail gas treating to partially neutralize

MDEA with a very small amount of phosphoric acid or other inorganic acidic chemical in order to overcome the limitation imposed by insufficiently stripped amine. Only a few thousands of parts per million are needed to drop H_2S leaks by a factor of ten or more. However, these approaches are outside the original scope of this paper, although subsequent simulations have shown their value.



(a) H_2S Leak (b) CO_2 Leak (c) Lean Loadings

Figure 3. Effect of Solvent Rate on Treating Quality

5. Conclusions

Factors influencing the mass transfer performance of amine contactors have been reviewed with an emphasis on those parameters that specifically impact selectivity for H_2S removal and promote CO_2 slip. Earlier literature includes a patent[4] concerning the description of a tray specifically intended to keep the liquid flow quiescent while enhancing turbulence in the gas. This patented tray was intended to maximize selectivity by designing-in the right hydraulic characteristics. Thus, the notion that selectivity might be purposefully influenced by tray hydraulic design has been known for 20 years.

Further plant performance data have been obtained that validate the effect of spray regime operation on mass transfer. The data are of sufficiently high quality to permit *predictions* to be made with considerable confidence.

The case study has pointed out the tremendous benefits that can be realized by deliberately operating an underperforming amine contactor in the spray regime. Instead of building an entirely new amine plant, or having to install much larger reboilers and regenerators to reduce lean amine acid gas loadings, it was found that the absorber in this particular case could simply be retrayed. Retraying with properly designed trays would allow the unit to meet not only the originally intended design specification on H_2S but to operate with precisely the targeted CO_2 slip. And this can be done without recourse to the use of specialty solvents. Similar opportunities may exist in Claus tail gas treating and in acid gas enrichment applications, areas where good H_2S removal is required with minimal CO_2 pickup.

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