Using Structured Packing for CO_2 Removal in LNG Plants

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SUMMARY

Treating natural gas in an LNG plant to reduce CO_2 to a level sufficient for liquefaction of the gas (typically 50 ppmv) is a classic deep CO_2 removal process that often uses an absorber containing either random or structured packing. Process simulation is shown to predict the performance of a CO_2 removal unit in an LNG plant before and after revamping from trays to structured packing. Structured packing of various sizes is compared with trays, and its profound effect on absorber performance is shown. There is an optimal packing size for each application. Specifying too large a packing will result in failure to meet the treating goal. Choosing a packing size that is unnecessarily small is not only costly because of higher packing cost, but it invites plugging and reduces tower capacity, too. A quantitative and reliable approach to determining the "right" size is provided.

INTRODUCTION

One of the most neglected areas in gas treating is the correct selection of tower internals in both absorbers and regenerators. The literature is replete with data on vapor-liquid equilibrium in a host of aqueous amine systems containing both single amines and mixtures. Considerable data also exist on a variety of physical, thermal, and transport properties such as solution density, viscosity, heat of reaction, heat capacity, and diffusion coefficients. The kinetics of the reaction between dissolved CO_2 and various amines has been measured and reported in terms of Arrhenius parameters numerous times for all the commonly-used amines. There is no question that such parameters are important in interpreting laboratory measurements of absorption rates and all of them have been used in that setting. Far fewer of these parameters have been applied in the design of commercial equipment using traditional methods such as equilibrium stage calculations, for the simple reason that ideal stages know nothing about what, if anything at all, is in the column. However, acid gas absorption and solvent regeneration are carried out commercially in columns *with real internals*. Apart from hydraulic considerations, the mass transfer performance of tower internals unfortunately has tended to be almost completely ignored. This is despite the fact that the mass transfer characteristics of the internals plays a central role, and are at least as important in setting tower performance as phase equilibrium and reaction heat. The translation from numbers of ideal stages to actual trays counts and to the required depths of structured or random packing has traditionally been done solely on the basis of experience. This approach works quite well in light hydrocarbon separations, for example, where tray efficiencies are fairly constant and well known (except for very high purity) and where vendor data exist on HETPs and HTUs for various packings for the systems of interest. Amine treating, however, is undoubtedly one of the processes least amenable to extrapolation into areas where experience is lacking. When parts-per-million specifications must be met on product gases, selecting the wrong packing size or bed depth can result in a failed design.

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For many years, packing has had a bad reputation in absorption and distillation at high pressure. Part of the reason is inattention to proper distributor design. Another is the persistent and still unresolved difficulty in translating ideal stages to actual packed bed depths and the selection of a particular commercial packing. However, packing is now being used increasingly in gas processing for several reasons. For a given size, packed columns tend to permit higher throughput than trays. And in offshore operations such as FPSO and FLNG, columns using structured packing are much less susceptible to the effects of rocking motion caused by wave action. It is particularly critical to select the *right* packing type and size in FLNG because of high cost associated with weight and footprint, so the need for reliability and accuracy is even greater.

It is no longer necessary to engage in any form of guesswork when it comes to designing towers containing one or more packings from a large array of possible packing types and sizes. The key is to simulate the column as the mass transfer device it really is. This goes well beyond hydraulic or capacity calculations and entails a mass transfer rate approach to the process itself. Although rate calculations require knowledge of the mass transfer characteristics of the internals (mass transfer coefficients for both phases, and the interfacial area) this kind of information is available in the literature as well as within the ProTreat® amine treating simulator. As we shall see, ProTreat simulation makes packing performance just as easy *to predict* as trays. The emphasis here is on *spot-on prediction* because absolutely no parameters need to be guesstimated by the engineer to come up with the right answer. The simulation is out-of-the-box reliable and accurate.

In what follows, attention is on the performance of tower packings, first by comparing simulation with performance measured in an LNG plant, and then by considering the effect of packing size for a particular family (brand) of structured packing used in the same service.

PREDICTING PERFORMANCE OF RANDOM AND STRUCTURED PACKING

The selection of tower internals for distillation has been well reviewed by Pilling and Holden (2009). In CO_2 removal in LNG plants, packing has tended to be used less frequently, but there are several reasons why packing may be preferable to trays:

- Pressure drop is usually lower,
- Tower capacity is often higher/ Smaller diameter towers,
- Foaming tends to be less severe, if it exists at all,
- In applications subject to rocking motion such as FPSO and FLNG, structured packing offers better resistance to upsets caused by periodic tower tilt,
- In low liquid load applications where the trays become dry and operate in the spray regime,
- In columns of less than 750-mm diameter where trays are impractical.

A cautionary note is that random and structured packing should *not* be used in applications where solids are present or if fouling is a concern.

For the low to modest liquid loads typical of LNG applications where the CO_2 content of the inlet gas is not extremely high, structured packing has advantages over its random brethren. Increased gas handling capacity can be a very significant factor in high pressure towers in situations where excessive weight and footprint have severe cost penalties. This is particularly the case in FPSO and FLNG where, indeed, tightening a design can yield large cost advantages. The smaller column diameter offered by packing, coupled with a high capacity specialty amine solvent, is certainly beneficial, but so is using only the packing depth actually required. The trick is determining this depth reliably! Tower diameter is determined by hydraulics, and hydraulic performance is well documented and well understood. The same cannot be said for packed bed depth—this is determined by mass transfer, and the mass transfer performance of structured packings with chemical reactions is still a very uncertain and uncomfortable area for many practitioners.

Packed columns seem always to have presented a challenge to designers, perhaps because there are so many varieties, types, and sizes of packing and perhaps even more because the experience base is so small, especially in gas treating with amines. However, today there is no reason why packed columns cannot be designed with just as much certainty and confidence as trays. The processes taking place in absorption and regeneration towers are just normal mass transfer processes. As long as one has access to the basic mass transfer characteristics as embodied in mass transfer coefficient correlations for the particular internals of interest, packed columns are no harder to specify and design than their trayed counterparts. The fundamental correlations contained within the ProTreat® simulator's information base have been developed from literature, vendor and research data and have been shown repeatedly to allow very accurate and reliable *predictions* of column performance without recourse to guestimating artificial parameters such as tray efficiencies or fictitious residence times on theoretical stages or tray thermal efficiencies. Before embarking on a case study to show the effect of the size of the structured packings within a particular vendor's portfolio, it may lend conviction to the analysis to demonstrate first ProTreat's ability to predict performance in a commercial unit.

Comparison with Commercial Data

The demonstration case involves the revamp of the amine section of an LNG plant using GAS/SPEC*2020* solvent to treat a feed gas with 2.24% CO_2 at about 4 MPa. The unit was built originally with trayed columns but was unable to achieve more than 70% of the nameplate capacity, purportedly because of foaming. The process flowsheet was completely conventional with the usual absorber-regenerator combination connected to each other through a flash tank, cross exchanger, trim cooler and pumps. Analysis of the treated gas (27.7°C) showed 21.2 ppmv CO_2. Using all the known plant conditions plus the tray details, ProTreat predicted 18.2 ppmv at 27.7°C. This was what one might call an "out-of-the-box" prediction in that absolutely no parameters were guessed or estimated. The simulation data consisted of tray and column vendor drawings along with process flow, temperature and pressure measurements taken directly from the plant's DCS. A *true prediction* to within a couple of parts per million of the measured value is certainly encouraging.

The cause of foaming (if indeed there really was foaming) was never determined. However, even at only 70% of the design capacity, the regenerator was running very close to the recommended 85% hydraulic flood limit so there is a question as to whether the plant was being prevented from operating at full capacity because the regenerator was perhaps undersized, or if maybe there were other problems with its trays. Because both absorber and regenerator were designed with the trays inaccessible for inspection, the real cause was never identified. Regardless of the root cause of the capacity bottleneck, the decision was taken to replace both towers with somewhat larger diameter versions, and to replace the trays with structured packing. The packing was of local manufacture, but from photographs (see the photograph in Figure 1) its appearance is similar to several well-known commercial brands. The crimp size had to be estimated from photographs and it was found to be around 25 mm from peak to peak. Full-capacity plant performance data were taken in mid-2012, again using GAS/SPEC CS-2020 solvent. The treated gas was reported to be 7 ppmv CO_2. Out-of-the-box ProTreat® simulation indicated the unit should have been producing 1.2 ppmv CO_2 with the absorber and regenerator running at 23% and 36% of flood, respectively, and at actual design conditions. This was more discrepancy than we would have expected based on past experience using standard packings supplied by commercial vendors (usually predictions are within 1–2 ppm of measured performance), so we set out to assess the possible cause(s). The CO_2 absorber was running in the completely mass transfer rate controlled regime[1]. When mass transfer rate controls absorption, and all the process parameters such as flow rates, compositions and temperatures have been verified, the reason for discrepancies must be sought in either mass transfer or sensitivity to some process condition. All that could be determined for this particular packing was a very rough estimate of the crimp size (18 mm) and that the packing sheets were perforated and embossed, a treatment that promotes liquid spreading. Proper embossing is critical for reliable packing performance and it is surmised that the packing surface area, which is calculated from the estimated crimp size with the assumption of correct crimping, was probably responsible for the discrepancy. In addition, scatter in wetted surface areas measured even under carefully-monitored laboratory conditions is known (Lewis et al., 2006) to be within only is $\pm$12 to 15%. In commercial installations, variance is likely to be greater still. Surface area for gas-liquid contact has a large effect on the treated gas purity.

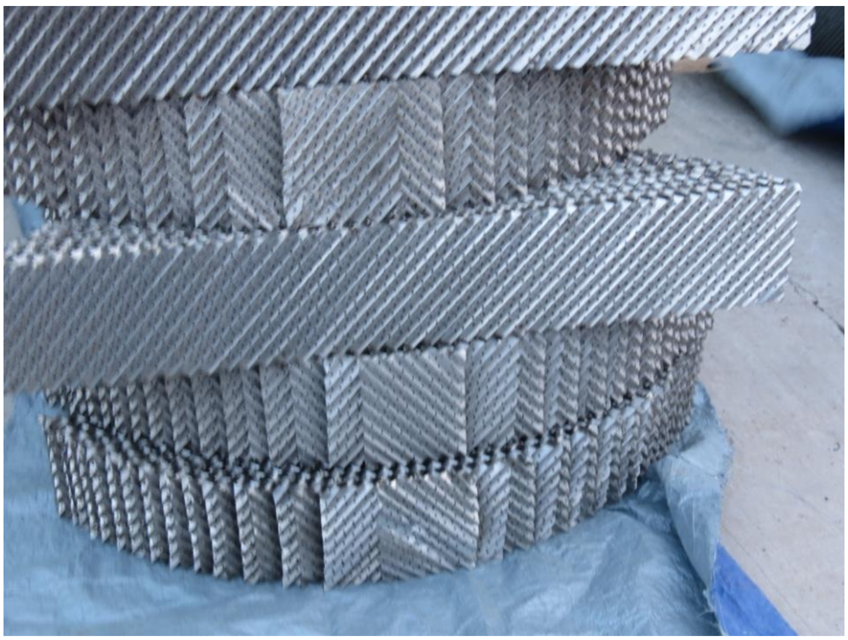

Figure 1 Structured Packing Bricks Used in Revamp

Another factor that pertains to the packing (one that is impossible to quantify) is the efficacy of the distributor used in the column. Imperfect liquid distribution will never generate higher interfacial area or cause better performance. A perfect match between reported and simulated CO_2 content of the treated gas (and a perfect match with all other measured data) can be achieved by reducing the wetted area of a roughly equivalent standard commercial packing by about 20%.

In light of these factors and the inherent uncertainty in process plant measurements, the 6 ppm discrepancy between simulation and measurement is certainly within the bounds of plant measurement accuracy and our inability to do more than roughly estimate the packing size. Simulation yields very satisfactory performance from a gas quality point of view. These simulated results are *pure predictions*, and are certainly close enough to actual measured performance to give us considerable confidence in

[1] CO_2 in the treated gas was not limited to a value set by the lean solvent CO_2 loading (lean end pinched) and it was not limited to a value set by too low a solvent flow, i.e., limited by the solvent capacity (rich end pinched).

ProTreat's ability to predict the effect of packing type and size, for example, on CO_2 removal using reactive amines.

Effect of Packing Size on CO_2 Removal in an LNG Facility

The effect of packing size on treating for CO_2 removal can be seen by considering a range of structured packings within a particular brand series, in this case Koch-Glitsch FLEXIPAC 1Y, 1.4Y, 2Y, 3Y and 4Y (Y is the common designation for a crimp angle of 45°). The FLEXIPAC brand is merely representative of structured packing in general, and it was selected arbitrarily and without prejudice. In the order written above, this packing series is in increasing crimp size and decreasing dry specific surface area. For the same gas and liquid flow rates, they also have somewhat different liquid-film mass transfer coefficients and, therefore, the same chemical reactions affect mass transfer rates to different extents.

Table 1 describes the raw gas common to all the cases in the study. The solvent was 50 wt% GAS/SPEC CS-1160 solvent flowing at 204 m^3/h and 50°C. The regenerator contained 13.7 m of type FLEXIPAK 3X structured packing in all cases. The absorber contained 15.25 m of various crimp sizes of FLEXIPAC structured packing as described above. In all cases, both columns were sized for 70% flood regardless of the packing. The regenerator was 1875 mm diameter while the absorber diameter ranged from 2825 mm diameter with the finest packing (1X) to 1885 mm diameter with the coarsest (4X). Reboiler duty was held constant at 13.5 MW and the molar stripping ratio was typically 1.12 at the regenerator overhead.

Table 1 Raw Gas Used in Case Study

Conditions	
Temperature (°C)	37.2
Pressure (bara)	64.4
Flow (Nm^3/d)	6,700,000

Composition (mol%)			
H_2S	0.0001	**iC4**	0.020
CO_2	2.000	**nC5**	0.006
C1	94.331	**iC5**	0.010
C2	1.900	**nC6**	0.030
C3	0.170	**CH_3SH**	0.0007
nC4	0.030	**N_2**	1.500

Table 2 is a synopsis of the simulated treating performance with 15.25 m of each packing size. The lowest size designation has the largest specific (dry) area and also treats the gas to the lowest CO_2 level. Note that although there is an inverse relationship between area and treated gas CO_2 content (just as one should expect), it is anything but inversely linear—treated gas quality is a *very* strong function of dry area, i.e., packing size. As ever coarser packing is used the temperature bulge moves closer to the top of the column. What may be surprising is that it also grows in size until at very large packing sizes it starts to fall again. It may also be interesting to note that the ratio of wetted area to dry area of the packing grows with packing size, and can exceed unity by a considerable fraction. The same liquid flow has much larger area to spread across for small packings, thus leaving more of the packing in the dry state. But for large packings, the available area for spreading is more restricted. The wetted area can exceed the dry area because all liquid flow is not restricted just to the mechanical surface of the packing when the film becomes thick. A thick film becomes quite disrupted, large waves form and a certain amount of sparging of the gas through the liquid probably occurs.

In many ways, *tray* performance is close to the performance of the smallest packing, but this is definitely *not* because of higher surface area for mass transfer. Indeed, in this case, the equivalent surface area based on the volume between any two trays is around 130 m^{-1} whereas the column-average wetted area for 1X packing is twice as high at about 270 m^{-1}. Instead, the intense agitation on the trays gives a mass transfer coefficient almost four times larger for trays than for the 1X packing (This also turns out to be true for all the packing sizes in the FLEXIPAC family).

Table 2 Simulated Treating Performance, Bulge Temperature, and Bulge Position

FLEXIPAK®	Dry Area	Treated Gas CO_2	Bulge Temperature	Bulge Position from Top	Wetted/Dry Area Ratio
Packing Size	(m^2/m^3)	(ppmv)	(°C)	(m or Tray No.)	(unit less)
1X	440	0.45	88.9	13.4	0.614
1.4X	340	0.46	96.9	13.1	0.741
2X	220	1.79	114.8	9.0	0.973
3X	110	108	110.3	7.0	1.332
4X	55	516	105.4	7.0	1.691
25 Trays		0.93	88.9	Tray 20	

Several points emerge from this. First, structured (and random) packings are no more challenging to a true mass transfer rate based simulation than trays. Secondly, one cannot simply scale up the effect of packing size in any simple or ad hoc arithmetic way. Packing performance is a complex function of packing size, hydraulics, and chemical reaction kinetics. Third, the effective wetted area active on a structured packing is not limited to the packing's dry area, so scale-up based on dry area could be wrong by several fold. In short, scale-up based on random and structured packing *size* is simply not feasible; for example, one cannot predict the performance of 2X packing from knowing how 1X performs. One must inevitably conclude that the only way forward is with a mass transfer rate-based simulation capability such as that offered by ProTreat®, soundly based on principles of mass transfer.

The response in performance that accompanies various packing sizes is described in greater detail in the plots of Figures 2 and 3. In Figure 2, the gas-phase CO_2 profiles for 1X and 1.4X packing are closely coincident. Thus, for small-crimp packing the final treating level is determined by the partial pressure of CO_2 in equilibrium with the entering lean amine, not by mass transfer rates. In other words, the absorber with very fine packing is completely lean-end pinched. The treated gas CO_2 content is almost identical between 25 trays on 600 mm tray spacing and 15 m of fine packing, but the trayed absorber does not exhibit quite the same *degree* of lean-end pinching as the packing (although it is still pinched because the top 6 trays reduce the CO_2 content by less than 1 ppmv). However, with 2X and larger packing, treating ceases to be lean-end pinched altogether.

As Figure 3 shows, coarser packing results in a larger temperature bulge which moves up towards the center of the column. The largest packing simply does not have sufficient area to allow rapid enough CO_2 absorption to achieve satisfactory treating. The temperature bulge is much larger though, because a lot of CO_2 is being absorbed locally into a relatively small volume of liquid. Insufficient physical supporting structure (i.e., dry packing surface area) for the liquid results in lower holdup volumes, therefore temperatures are higher, backpressure of CO_2 goes up and absorption rates suffer. Actually, the absorber with 2X packing is bulge pinched. This can be seen from Figure 4 where the actual CO_2 concentration in the gas at various positions almost coincides with the equilibrium values along the lower half of the absorber. Figure 5 is a similar plot for a much larger packing size. In both cases, there is almost no driving force for absorption. Once past the bottom metre or so of packing, the gas has to wait until it is nearly half way up the column before significant absorption rates can resume. It is the intensified temperature bulge that is responsible for this type of pinch.

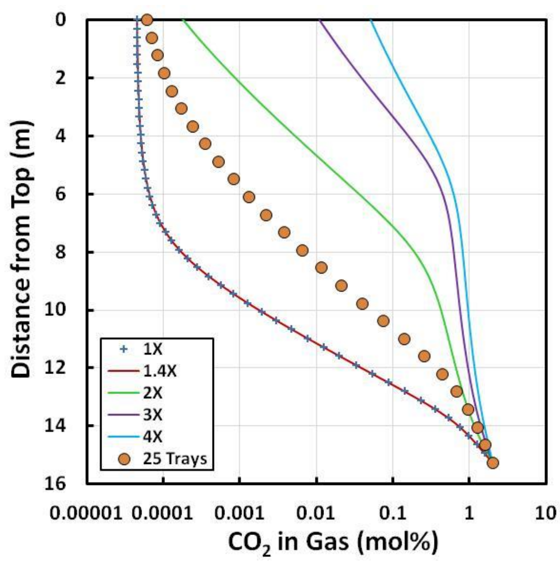

Figure 2 Absorber CO_2 Profiles in the Gas for Various Packing Sizes and for Trays

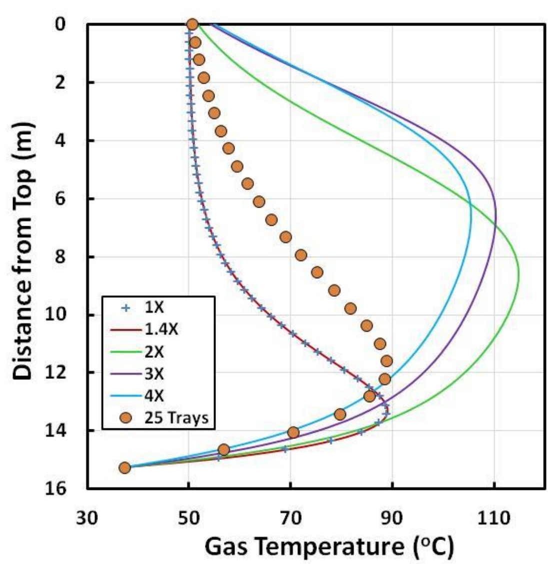

Figure 3 Absorber Temperature Profiles for Various Packing Sizes and for Trays

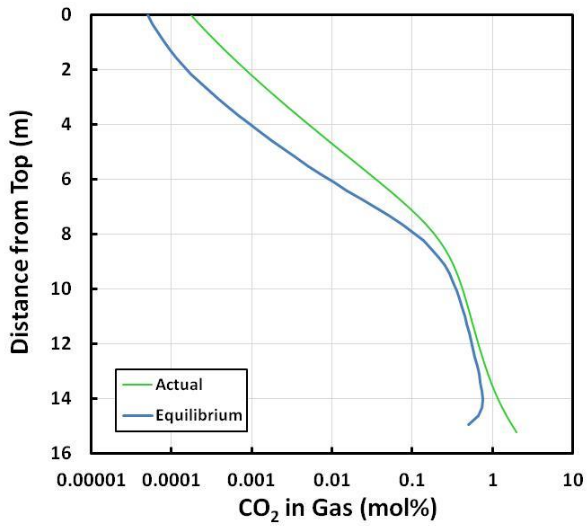

Figure 4 **Actual and Equilibrium CO_2 Concentrations in the Gas at Various Positions in the Absorber. Packing is FLEXIPAC® 2X.**

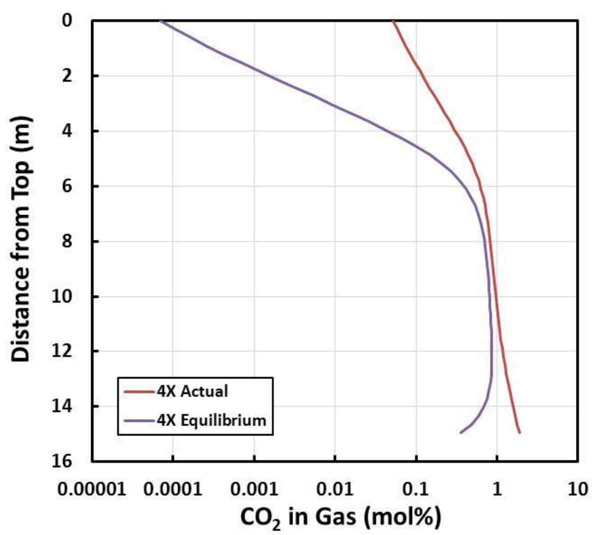

Figure 5 **Actual and Equilibrium CO_2 Concentrations in the Gas at Various Positions in the Absorber. Packing is FLEXIPAC® 4X.**

ProTreat's mass transfer rate model is able to match field data closely without fitting artificial parameters such as tray efficiencies or hypothetical residence times on theoretical stages. This is a good indication that the simulator's predictive power can be relied upon to give the right answers with confidence for other applications. As long as accurate parameters pertinent to the particular packing of interest are in the simulator's database, that packing's performance can be reliably predicted and just the right packed depth can be determined. For the ProTreat® mass transfer rate-based simulator, structured packing performance can be predicted just as easily and reliably as for trays.

USING STRUCTURED PACKING IN GAS TREATING

In the last few years, engineers have shown increasing interest in using structured packing coupled with specialty solvents in amine-based gas treating applications. Consequently, structured packing is being applied more and more widely. Nevertheless, the idea is still new enough that questions are often asked as to whether structured packing should or should not be considered in a given application.

One of the most obvious application areas in which the use of structured packing is almost mandatory is in columns subject to periodic tilting motion as on floating structures such as FPSO and FLNG platforms. An advantage of using a specialty solvent such as GAS/SPEC CS-1160 and CS-2020 is the lower circulation requirement. This can result in a smaller plant and lower operating costs. Structured packing resists liquid maldistribution brought about by rocking motion better than random packing. Trays have very poor resistance to the sloshing and seiching induced by lateral back and forth motion. (An exception is trays that rely on confined centrifugal motion during contacting, e.g., ConSep™ and ULTRAFRAC® trays, although these kinds of trays tend to be more expensive.) In offshore applications structured packing should always be considered. Especially in the context of periodic tilting motion, however, care must be taken to use the right kind of liquid distributor. The distributor should have no free liquid surfaces and should be high pressure drop type, not a gravity flow device such as a trough distributor. This also mandates that solid amine hygiene be practiced (i.e., filtration and corrosion management).

There are very few reasons to exclude structured packing from consideration. One such reason is fouling. If the system is a fouling one, the deposits that will inevitably occur on the surfaces of the packing will be almost impossible to remove and operations may soon become plagued by plugging problems. On the other hand, unless structured packing is used too close to the flood point where liquid holdup becomes high, it is naturally resistant foaming. It should be recognized, however, that if the system is a *bad* foamer, structured packing may not be the answer—instead the root cause of the foaming should be determined and alleviated. Even a good design is no match for poor amine hygiene.

In a revamp for higher capacity, the naturally higher vapor handling ability of structured packing may recommend it as a way to achieve higher capacity in the same shell. Except in tail gas treating and acid gas enrichment, pressure drop is not usually an issue. However, if it is, structured packing can almost always be made to work at lower pressure drop. To that end, the largest possible crimp consistent with being able to achieve the target separation within the height of the existing tower shell should be used. Again, finding out what that crimp size is can be facilitated greatly by using mass transfer rate based simulation.

SUMMARY

Packed absorption columns can operate in various modes of pinching or be mass transfer rate controlled throughout. There is just no way to tell beforehand which mode will prevail, and with what packing type and size. This makes it almost impossible to develop a design that is truly as optimized as it should be in FPSO and FLNG applications using any approach other than one with a mass transfer *rate* basis. Currently, only the ProTreat® simulator has this proven capability, as witnessed by repeated validation with real plant performance data.

A real mass transfer rate model is constructed from components that are soundly based in fundamental sciences and engineering, and not on approximations made to avoid what used to be impossibly complex and arduous hand computations. The enormous power of even desktop and laptop computers has turned computer time into a non-issue. Rigor can be achieved for the meager cost of computing times measured in tens of seconds. The computer models that result can be accurately described as virtual plants in which it is quite easy to investigate very involved what-if scenarios.

Because of their wide range of sizes and the somewhat laterally compartmentalized flows, structured packings offer a great deal of flexibility in gas treating which allows them to be used where conventional trays are very difficult, if not impossible, to apply. Possibly two of the greatest barriers to using structured packing in gas treating have been (1) the very small experience base and (2) the resulting difficulty in translating the results of more-conventional, approximate calculations into real internals. Today, the experience base is sufficient to have allowed ProTreat® to be benchmarked in a wide range of operations using structured packing, and computing power now makes approximate methods completely unnecessary—all calculations can be done quickly, reliably, and in the fullest possible detail on a laptop computer.

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