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Recent Developments and Current Practices in

Odor

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Introduction

One popular method for removing odors from exhaust gas streams is by packed tower scrubbing. The odorous component in the gas is absorbed into liquid in the tower by intimately mixing the gas and a thin film of the liquid in the tower packing. The liquid is then separated from the gas stream, leaving only clean exhaust gas. The few small droplets that become airborne are removed in a droplet filter.

However many odors are objectionable at even very low concentrations. Additionally, many odors are complex mixtures, not just one chemical. This presents serious difficulties for packed tower scrubbing. At low concentrations the gradient across the gas-liquid interface will be relatively small making absorption relatively slow. Any level of control can be achieved by lengthening the time the gas and liquid are in contact, but that means increasing the height of the tower and, consequently, the pressure drop across the tower. The complex chemistries of odors can also be overcome, but often at the cost of sequential towers with different scrubbing liquids. For example, ammonia requires an acid scrubbing solvent, hydrogen sulfide (H_2S) a very basic solvent, and dimethyl disulfide a neutral solvent.

When large volumes of air must be cleaned the fan power costs due to the high pressure drop across a tall tower or two towers may make the packed tower a very expensive solution. For this reason, manufacturers are constantly exploring packings with lower pressure drop. The amount of pressure drop through a packed tower is determined, primarily, by the amount of liquid supported by the air flow through the tower and, secondarily, by the frictional forces of the air flow through the tower packing.

Two main types of packings are available today: random dumped packing and structured packing. Structured packing has less void space than random dumped packings. Thus, less liquid is held up in the structured packing resulting in lower pressure drops through the packed tower. However, structured packing can be expensive to manufacture and time consuming to install. Monolithic packing is a simpler structured packing. It is less expensive to manufacture, easy to install, and can be operated at a much lower pressure drop than random dumped packings. This paper reports a study of the pressure drop and mass transfer rates of a recently available monolithic packing and compares it to a widely used random dumped packing.

Theory

The mass transfer coefficient is a measure of the tendency of a minor gas constituent, in this case a strong odor, to transfer from the gas phase into the liquid phase. It is dependent on the operating conditions of the packed tower, the chemistry of the pollutant/scrubbing liquid combination, and the amount of surface area created by the tower packing. In order to calculate the value of the mass transfer coefficient, it is necessary to evaluate the driving force which causes the odor to move from the gas phase into the liquid phase. The driving force is a function of the concentrations of odor in both the gas stream and the scrubbing liquor. If there is a chemical in the scrubbing liquor that reacts with the odor, the concentration of the solute (i.e., odorous compound in solution) in the liquid phase is essentially zero.

In this study, H_2S was absorbed using a scrubbing liquor of sodium hydroxide (NaOH) and water. This system was chosen so previous studies reported in the literature would provide a basis for comparison of the results. Future studies will involve other odors and other liquors.

REMOVAL OF ODORANT COMPOUNDS BY PACKED TOWER SCRUBBING

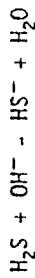
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A pilot-scale wet scrubber has been constructed to make comparative tests of a new monolithic packing and a conventional random dumped packing. Both odor removal efficiency and pressure drop were measured at various gas and liquid flow rates. Hydrogen sulfide was removed from an air stream with a basic scrubbing liquor of sodium hydroxide and water at a pH of 12.5.

While the pressure drop through the monolithic packing was about one-tenth of that through an equal height bed of random dumped packing, the mass transfer coefficient was higher for the random dumped packing. Combining these two measurements, the pressure drop per transfer unit was found to be significantly lower for the monolithic packing. Thus, the monolithic packing will be more cost efficient over the life of the packing.

The sodium hydroxide dissociates in water, forming a sodium ion (Na⁺) and a hydroxide ion (OH⁻). The H₂S then reacts with the dissociated hydroxide ion:



Since the dissociation equilibrium drives to the right the concentration of solute in the liquid phase is essentially zero, and the mass transfer driving force approaches the product of inlet pollutant concentration and system pressure. Where the total system pressure remains constant, a log mean average driving force can be used:

$$\Delta P_{lm} = P \frac{y_1 - y_0}{\ln(y_1/y_0)} \quad (1)$$

The solute transferred may be expressed in terms of the overall gas-phase mass transfer coefficient, $K_g A$, as:

$$N = AZK_g A P \Delta P_{lm} \quad (2)$$

When very low concentrations of solute are being removed from the gas phase, the amount of solute transferred from the gas phase is:

$$N = G_m (y_1 - y_0) \quad (3)$$

Equations (1), (2), and (3) can be combined to give:

$$G_m = \frac{AZK_g A P}{\ln(y_1/y_0)} \quad (4)$$

The concentrations of odor in the gas and in the liquid change from the bottom to the top of the tower. A decrease in the odor concentration in the gas by 1/e is termed one transfer unit. This has a given physical height for a specific system. Thus as the height of a transfer unit decreases, the number of transfer units in a given tower increases, and the amount of mass transfer increases. With 6 transfer units, the odorous gas concentration will be reduced by better than 99.9%.

For an absorption system in which the pollutant gas is so soluble that there is no equilibrium vapor pressure of the pollutant over the scrubbing liquid due to the solute, the number of transfer units can be expressed as:

$$N_{TU} = \ln(y_1/y_0) \quad (5)$$

The height of a transfer unit can then be calculated as:

$$H_{TU} = \frac{Z}{N_{TU}} = \frac{Z}{\ln(y_1/y_0)} \quad (6)$$

Substitution of equation (6) into equation (4) and solving for the mass transfer coefficient gives:

$$K_g A = \frac{G_m}{A P H_{TU}} \quad (7)$$

This equation was used to calculate the mass transfer coefficient in this paper.

Equipment and Materials

A wet scrubber pilot plant was built in order to test the different packings. The tower was designed for countercurrent flow with a packing depth of 3 feet and a diameter of 10 inches. The diameter of the tower is sufficient that wall effects are minimal. The gas flow was measured by a calibrated venturi. A rotameter was used to measure the liquid loading rate. A mist eliminator was used to collect any scrubbing liquor being carried out with the gas. Manometers were used to measure the pressure drop across the packed bed and the mist eliminator.

Two types of packings were tested: 1 inch Jaeger Tri-Packs* and a monolithic packing. The 1 inch Tri-Packs were selected as the most appropriate to the 10 inch diameter tower.

The scrubbing liquor was applied to the packing from a single nozzle at the center of the tower cross-section. Two different nozzles were used to give the best full cone spray at different liquid flow rates. The chemistry of the scrubbing liquor was maintained by a pH sensor and a metering feed pump, which added NaOH to the scrubbing liquid.

H₂S gas was injected into the ambient air stream upstream of the fan so it would be well-mixed with the inlet air. Samples of the polluted gas were collected in Tedlar bags. A Jerome 621 H₂S analyzer was used to measure the concentration of the H₂S in the gas upstream and downstream of the packed tower.

A diagram showing the arrangement of the wet scrubber pilot plant is provided in Figure 1.

Experimental Procedure

The first task was to measure the liquid holdup and pressure drop across the packed bed for each of the packings. These were measured at gas loading rates ranging from 1000 to 3200 lb/ft² hr and liquid loading rates varying from 2000 to 6000 lb/ft² hr. Water was used as the scrubbing liquor with approximately 1 to 2% NaOH added to bring the pH to about 12.5. Ambient air was used as the gas through the scrubber. Many of the higher flow rates measured for the monolithic packing could not be duplicated with random dumped packing because the pressure drop exceeded the capacity of our fan. The range was extended slightly by multi-linear regression on all the data collected for the random dumped packing. This provided an estimate of the pressure drop at higher gas loading rates. This regression analysis was also done for the data collected from the monolithic packing for comparison.

Next, each packing was tested for its efficiency in removing H₂S from ambient air. For each test, the inlet H₂S concentration was varied between 1 and 4 ppm. To determine the inlet and outlet concentrations, the air was sampled directly by filling up Tedlar bags through valves at points immediately downstream of the fan and between the packing bed and the mist eliminator. Before each reading of the bag with the H₂S analyzer, the bags

* Tri-Packs is a registered trade mark of Jaeger Products, Inc.

through the random dumped packing. The liquid holdup experiment verified these results with the liquid holdup of the random dumped packing approximately five times the liquid holdup of monolithic packing. The pressure drop and amount of liquid hold up increases with both increasing gas flow and increasing liquid flow. This can be seen in Figures 2 and 3.

The pressure drop through the packed bed is caused by any restriction to the movement of gas. This will include the shape of the packing, the amount of liquid being held up in the packing, and the viscosity of the liquid. Thus, if liquid is being held up in the packing, that liquid is narrowing the free air passages and restricting air flow. A packed bed can be modeled as a series of parallel, small diameter tubes of equal length and diameter. Because the monolithic packing is structured packing, the theoretical tubes are of a larger diameter than in the random dumped packing. There is both lower wall friction loss and less wall for the liquid to be spread upon. The random dumped packing "tubes" are many and short, while with the monolithic packing, the tubes are continuous from the bottom to the top.

Not only does the increase in pressure drop increase the cost of operation, but it limits the useful range of the scrubber because of flooding. Flooding occurs when the liquid and gas phases invert. At this point the fan cannot overcome the large amount of liquid holdup in the packing, resulting in minimal flow and a large increase in pressure drop. Packed towers are usually operated at 60 to 75 percent of the flooding gas flow rate. From the Figure 3, it appears that flooding is occurring in the random dumped packing at gas flow rates greater than about 1800 lb/ft² hr. This is apparent by the sudden increase in liquid holdup at that point. Also in Figure 3, the liquid holdup in the monolithic packing is still increasing slowly with increasing gas loading rate, indicating the system is not flooding at any of these gas flow rates. Thus, the random dumped packing cannot be operated at as high a gas flow rate as the monolithic packing.

Another problem caused by increased liquid holdup is clogging of the packing by precipitates of the scrubbing liquor. When there is a lot of liquid held up in the packing, a residue can form on the packing which clogs the packing and increase the pressure drop. We observed this in the random dumped packing in our tower over the short time this study was underway. The intricate design of the packing made it more susceptible to clogging, and there was more opportunity for precipitation due to much liquid holdup.

Figure 4 shows the mass transfer coefficient variation as the liquid flow rate is increased at a constant gas flow rate of 2240 lb/ft² hr. The $K_G a$ for the monolithic packing is about one-fourth of the $K_G a$ through the random dumped packing. This translates into a removal efficiency of approximately 85% for the 3 feet of monolithic packing as compared to 99% for the random dumped packing. One would expect that the mass transfer rate would increase with increasing liquid flow rate, given the greater liquid available for the pollutant to be absorbed into. The random dumped packing does behave in this manner. However, for the monolithic packing, it appears there is an optimal liquid flow rate of 3500 lb/ft² hr at which maximum mass transfer occurs.

Figure 5 shows the mass transfer coefficient variation with increasing gas flow rate at a constant liquid loading rate of 5070 lb/ft² hr. It is apparent from the graph that the $K_G a$ of the monolithic packing again is about one tenth of the $K_G a$ of the random dumped packing. But note that the monolithic packing behaves different from our expectations. One would expect the mass transfer coefficient to increase with increasing gas flow rate up to a point of

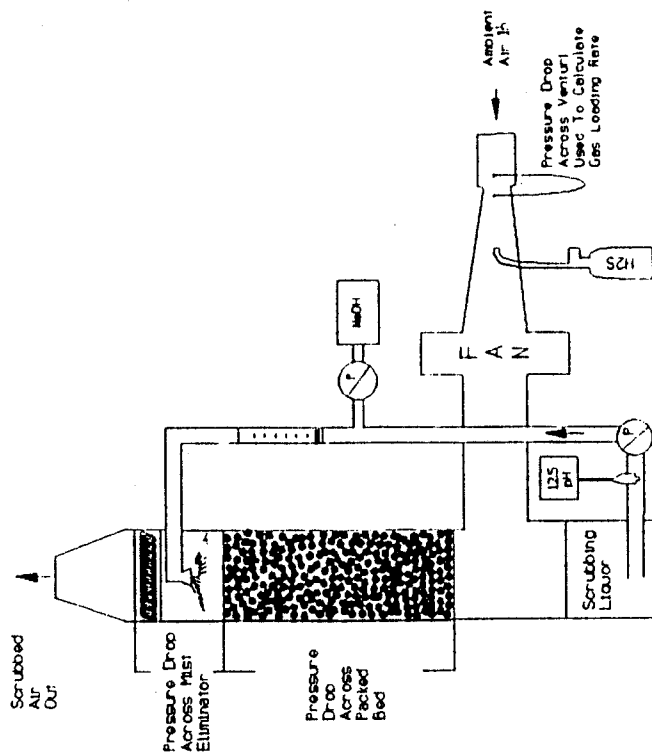


Figure 1. Diagram of wet scrubber pilot plant.

were agitated so that the H₂S would be well mixed with the air. To increase the accuracy of the measurements, three readings were taken from each bag.

Other measurements necessary for the calculation of the mass transfer coefficient were also recorded. The system pressure at the top of the tower was measured to provide the log mean estimate of the pressure through the packing. Also, the air temperature was recorded to convert the measured gas flow rate to standard conditions. The ambient pressure was assumed to be 1 atm for all test runs.

To keep the NaOH concentration constant in the scrubbing liquor, the pH was maintained at 12.5. Because the system was operating as a batch reactor rather than with constant overflow, after about three runs of 6 upstream and downstream samples each, the scrubbing liquor was flushed out and replaced with fresh water and NaOH. This kept the concentration of HS⁻ in the scrubbing liquid at sufficiently low levels.

Each packing was tested at the same liquid and gas loading rates. First, the gas loading rate was kept constant at 150 cfm (2240 lb/ft² hr), while the liquid loading rate was varied from 1.6 gpm (1475 lb/ft² hr) to 5.5 gpm (5070 lb/ft² hr). Second, the liquid loading rate was kept constant at 5.5 gpm (5070 lb/ft² hr), while the gas loading rate was varied from 150 cfm (1244 lb/ft² hr) to 370 cfm (3070 lb/ft² hr). Lastly, the liquid and gas loading rates were kept constant at 150 cfm and 5.5 gpm, while the pH of the scrubbing liquor was varied by controlling the amount of NaOH added to it.

Results and Discussion

The results of the pressure drop experiment found the pressure drop through the monolithic packing to be about one tenth of the pressure drop

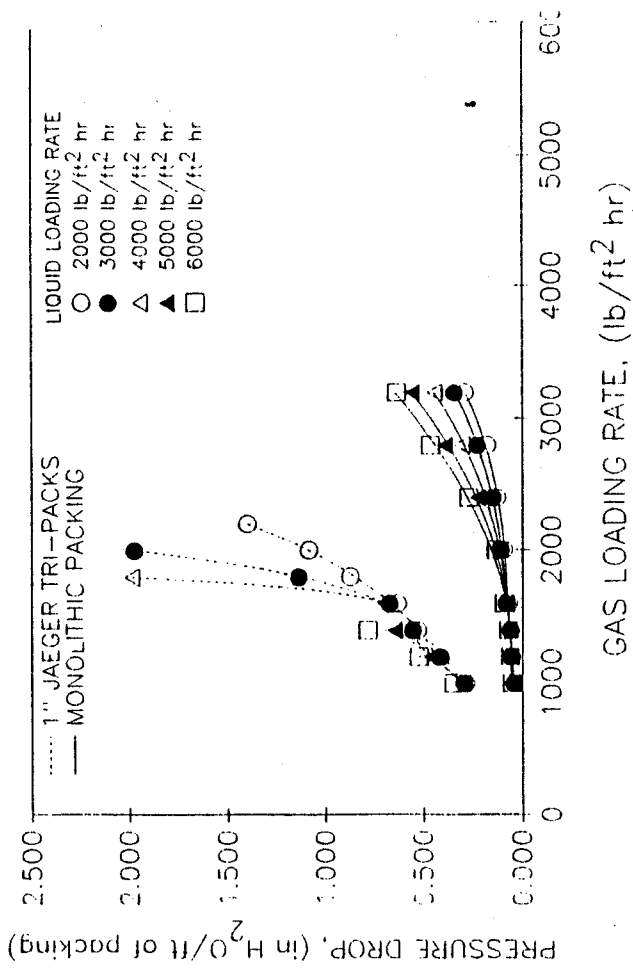


Figure 2. Comparison of pressure drop with random dumped packing and monolithic packing.

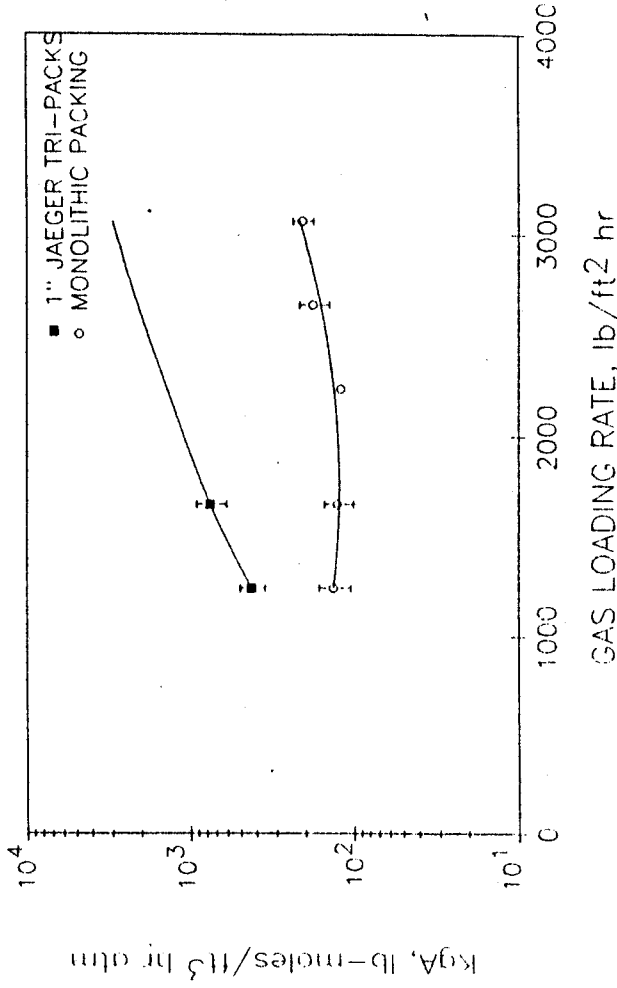


Figure 4. Comparison of mass transfer coefficient for random dumped packing and monolithic tower packing at a liquid loading rate of 5070 lb/ft² hr and pH = 12.5.

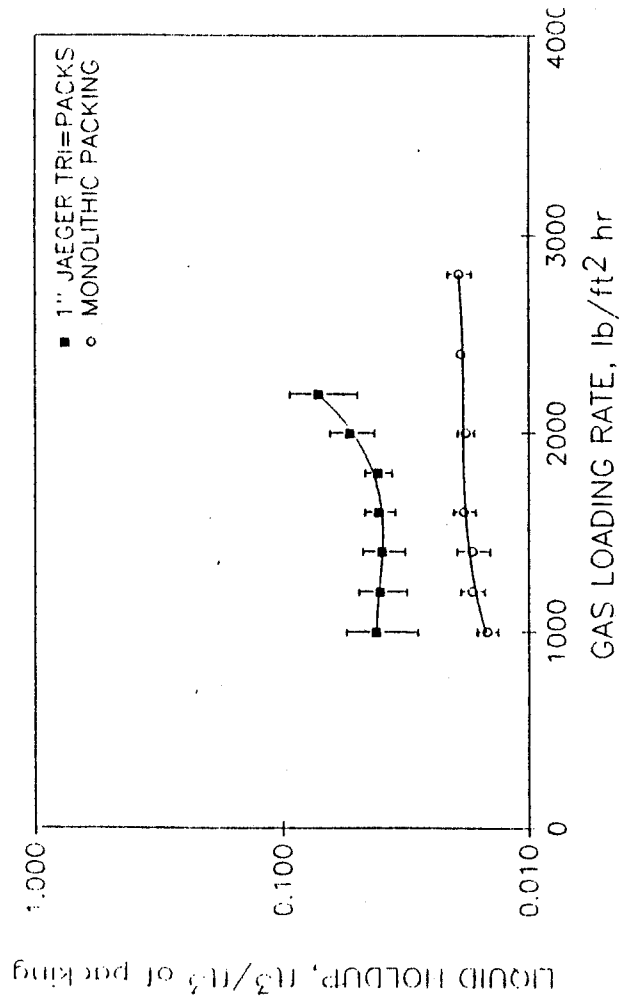


Figure 3. Comparison of liquid holdup for random dumped packing and monolithic packing at a liquid loading rate of 2000 lb/ft² hr.

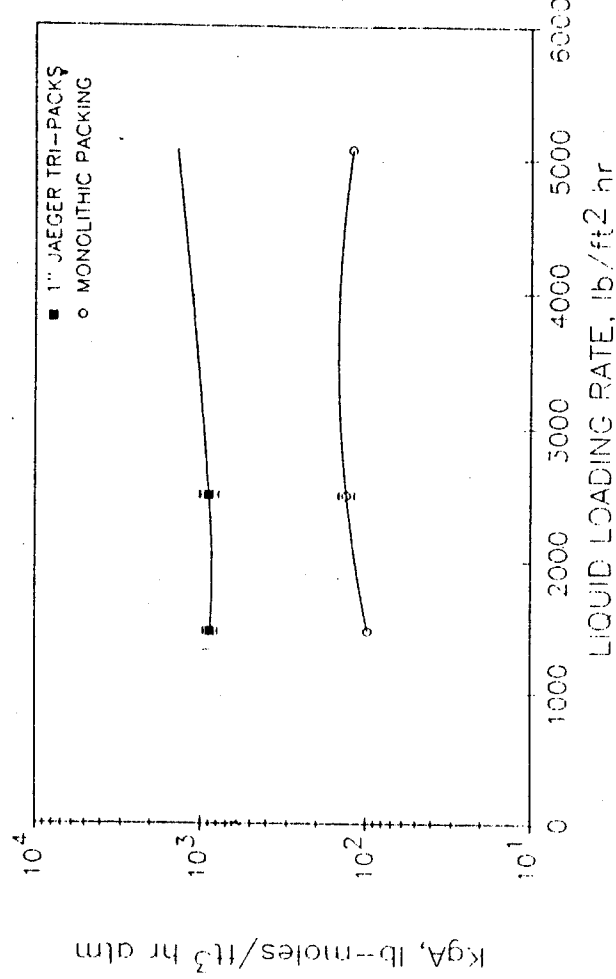


Figure 5. Comparison of mass transfer coefficient for random dumped packing and monolithic packing at a gas loading rate of 2240 lb/ft² hr and pH = 12.5.

saturation. This was the behavior of the random dumped packing. However, the mass transfer through the monolithic packing decreased with increasing gas flow rate up to a point where it then began to increase.

One reason for the difference in behavior of the K_gA in the two packings may be the differences in the paths through the two packings. As stated above, the paths through the random dumped packing are short in length and small in diameter. So, when the polluted air is moving through the packed tower, it is constantly brought into contact with the wetted packing as it moves through the many different paths it takes to get to the top of the packed tower. The paths in monolithic packing, on the other hand, are nearly straight, large diameter paths from the bottom of the packed tower to the top. This feature accounts for the lower pressure drop but it also provides less contact between the wetted surface and the polluted gas.

If we calculate the Reynold's number for the monolithic packing, we see that laminar flow can be expected until the gas flow reaches about 1900 lb/ft² hr. and will not be fully turbulent for gas flow rates less than 2100 lb/ft² hr. During laminar flow, the bulk flow of the gas is in the same direction, in this case from bottom to top through the tower. Also, the greatest velocity occurs in the center of the flow tube. The momentum of the air moving at the greatest velocity pulls the air moving at slower velocities toward the center of the tube. As the velocity of the gas increases, the momentum force pulling the slower velocity gas towards the center of the tube also increases. Thus, while in laminar flow, as the gas loading rate increases, less and less gas comes into contact with the sides of the flow tubes, allowing less mass transfer to occur. When the flow enters the transitional stage, the direction of micro-movement of the gas changes. It begins to move in different directions as the flow approaches turbulent flow. Thus, more and more contact occurs between the polluted gas and the wetted sides of the tubes. Once the flow is fully turbulent, the mass transfer coefficient through the monolithic packing begins to increase.

In determining the mass transfer rate through each packing, the pH was kept constant at 12.5. This value was chosen from information available in the literature for the removal of H₂S using NaOH and water. To verify that this value of pH would yield the highest rates of mass transfer, the mass transfer coefficient for varying values of pH were determined for each of the packings. From the graph of pH vs. K_gA , one can see that the mass transfer coefficient through each packing increased at the same rate as the pH increased. K_gA peaks at a pH of about 12.3, and then seems to remain fairly constant. Thus, using a pH of the scrubbing liquor of 12.5 yielded approximately the highest values of mass transfer coefficient for removal of H₂S using NaOH and water as the scrubbing liquor. This is shown in Figure 6.

All the test runs at pH = 12.5 were included in a multi-linear regression analysis for K_gA for the random dumped packing and the monolithic packing. The results are given in Table I. The L^2 term that appears in both the pressure drop and K_gA equations for the random dumped packing emphasizes the size differences in the theoretical flow tubes. The effect of the initial pollutant concentration is small, but larger than the L^2 term. One explanation for this effect may be a violation of the assumptions in equations (3) or (5) at higher pollutant concentrations.

Conclusions and Recommendations

The random dumped packing achieves high mass transfer at the cost of a higher pressure drop. This results in a lower value for the height of a transfer unit (H_{TU}) and thus a shorter tower. A tower packed with monolithic

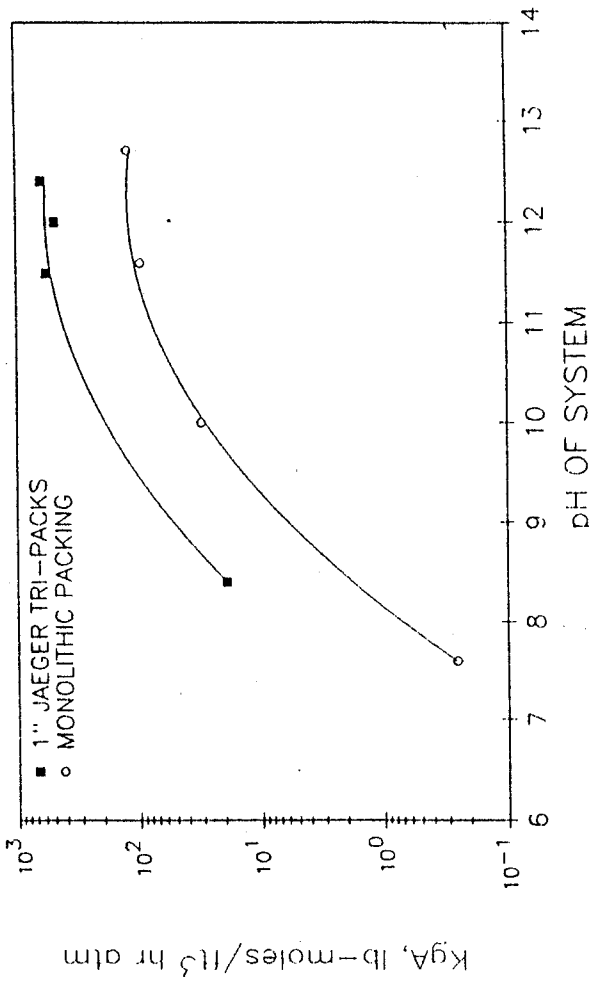


Figure 6. Comparison of mass transfer coefficient for random dumped packing and monolithic packing with change in liquid phase pH.

packing, however, has a low pressure drop, but the height of each transfer unit is greater, requiring a taller tower. Since total pressure drop is a function of the actual tower height for a given required removal, the proper comparison between the two packings is the pressure drop per transfer unit. This is the pressure drop that will occur at the tower height required for a specified mass transfer to occur.

This comparison is provided by the curves in Figure 7. We can see that not only is the pressure drop per transfer unit of the monolithic packing much less than that of the random dumped packing, but it also appears to be increasing at a slower rate than the random dumped packing at the higher gas loading rates. This tells us the monolithic packing will be the more cost efficient packing over the life of the scrubber.

Table I. Multilinear Regression Equations

Variable	Multi-linear Regression Equation	Correlation Coefficient
Monolithic Packing		
Pressure Drop =	$EXP(2.00 + (5.03 \times 10^{-5})L + (4.44 \times 10^{-4})G)$	0.973
$K_gA =$	$265.09 - (0.19)G + (5.17 \times 10^{-5})G^2 - (3.87 \times 10^{-3})ppm + (7.05 \times 10^{-3})L$	0.572
1" Jaeger Tri-Packs		
Pressure Drop =	$EXP(1.51 + (1.19 \times 10^{-4})L + (7.11 \times 10^{-4})G - (9.91 \times 10^{-5})L^2)$	0.903
$K_gA =$	$287.85 - (0.19)G + (5.36 \times 10^{-5})G^2 - (4.41 \times 10^{-3})ppm + (9.18 \times 10^{-7})L^2$	0.563

Note: L = liquid loading rate (lb/ft² hr), G = gas loading rate (lb/ft² hr), and ppm = inlet concentration of H₂S (ppm)

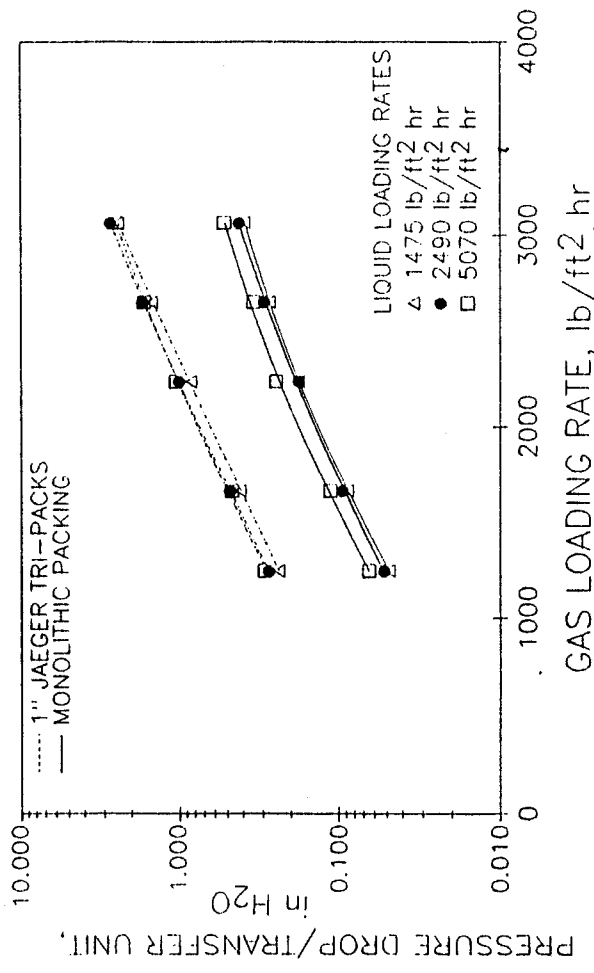


Figure 7. Comparison of pressure drop per transfer unit for random and monolithic tower packing.

The results presented here suggest several additional lines of inquiry. The K_gA may continue to increase at still higher gas loading rates. Depending on the increase of pressure drop the optimum design velocities may be still higher. The light weight of the monolithic packing suggests the construction of very large diameter chambers. It would be useful to compare the resulting designs against towers with random dumped packing using larger-sized packing, which has a lower pressure drop.

Nomenclature

- A = cross-sectional area of tower, ft^2
- ΔP_{tm} = log mean pressure driving force, atm
- G_m = gas phase flow, lb-mole/hr
- H_{TU} = height of a transfer unit, ft
- K_gA = overall mass transfer coefficient, lb-mole/hr ft^3 atm
- N_s = solute transferred, lb-mole/hr
- N_{TU} = number of transfer units
- P = system pressure, atm
- y_i = mole fraction of solute in inlet gas
- y_o = mole fraction of solute in outlet gas
- Z = height of packed tower, ft

References

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