Effect of Liquid-Packing Surface Interaction on Gas Absorption and Flooding in a Packed Column

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Gas absorption, pressure drop, liquid holdup, and loading behavior in a packed column have been investigated using packing materials almost geometrically identical but fabricated from three different materials (ceramics, Saran, and polyethylene). For the absorption of oxygen into sodium sulfite solution, observed values of the liquid-side, composite, overall mass transfer coefficient, K_La, were about 25% larger for the ceramic packing than for the polymeric packings. It was also observed that liquid loading occurs more readily in the case of the polymeric packing materials and it appears that the usual type of correlation is inadequate for predicting loading when polymeric packings are employed. In the case of liquid operating holdup no differences were observed from packing to packing. These observations are discussed in terms of the nature of the interaction between liquid and packing surface and it is pointed out how these phenomena may be fundamentally different from those of previous investigations, which relied upon surface-active agents added to the liquid.

Ceramic and stoneware tower packings continue to enjoy wide application in the process industries. However, the availability of new materials within recent years now permits more flexibility and latitude in the choice of tower packings, particularly those made of polymeric materials which can be easily fabricated in a wide variety of shapes, hitherto unavailable. Considerable data and many useful correlations exist for the purpose of estimating mass transfer efficiency, capacity, and pressure drop in towers containing ceramic and stoneware packings of different sizes and shapes. Not nearly so much information is available for the newer types of polymeric tower packings. Within this state of knowledge and development, the work reported here was undertaken to investigate the performance of polymeric tower-packing materials as compared to the more conventional stoneware and ceramics. Because of the wide variety of packing shapes available in these materials it did not appear profitable to investigate geometry; rather, attention has been focused upon the nature of the packing material itself.

The primary function of a tower packing is to provide a skeleton over the surface of which liquid flows in the form of a thin, preferably turbulent, film. Because mass transport takes place across the interface between this film and a vapor phase, it would appear that transport should be enhanced by increasing the surface area of the packing. While this is roughly true it does not constitute a quantitative rule of proportionality because, no matter how much packing area is available, this area becomes effective for mass transport only if it is wetted by the liquid.

Besides the often studied liquid and vapor flow rates, other factors that play an important role in the wetting of a packing are the surface tension of the liquid and the affinity of the solid for wetting by the liquid. One measure of this wetting interaction between solid and liquid is the contact angle, Θ, defined as the angle made with a uniform, flat, solid surface by the edge of a liquid drop resting on the surface. This angle depends on the values of the surface tensions of the solid and the liquid as well as on the value of the interfacial tension between solid and liquid. The following equation relating these quantities follows directly from a force balance within the plane of contact of solid and liquid:

$$\cos\Theta = \frac{\gamma_S - \gamma_{SL}}{\gamma_L} \qquad (1)$$

This equation is valid for contact angles up to 90 deg.

Some aspects of the wetting problem have received attention in the past. For example, Sherwood and Holloway (*1*), Newton, et al. (*2*), and Jesser and Elgin (*3*) have studied how varying liquid surface tension affects efficiencies, capacities, and holdup in packed columns. Sherwood, et al. (*1*) observed that the addition of wetting agents to the liquid resulted in reduced coefficients for desorption of carbon dioxide from water but produced no changes when only the evaporation of water was studied. They concluded that the wetting agent affected only the liquid side coefficient, presumably by interfering with transport across the interface. The same workers also noted that a thin coating of paraffin on the packing reduced K_La for the carbon dioxide-water system by a smaller amount than it reduced K_Ga for the vaporization of water. Newton, et al. (*2*) observed increased tendency toward flooding when surface tension was decreased by the addition of a surface active agent to the liquid. Jesser and Elgin (*3*) found that changes in liquid surface tension had little effect on liquid holdup at low liquid flow rates but that at larger flow rates decreases in surface tension led to increases in holdup. One difficulty in most studies like these is that surface tension of the liquid can be varied only by changing the nature of the liquid itself, by adding a surface-active substance to the system or by allowing corresponding variations in liquid temperature. Moreover, changes in liquid surface tension affect the nature of the interaction not only between liquid and solid but between liquid and gas as well. In any case, changes in liquid surface tension are almost always accompanied by changes in the transport properties of the liquid phase, either within the liquid or at the liquid-vapor interface. Therefore, observed phenomena which accompany changes in surface tension within such systems may be caused by simultaneous changes in transport properties of the liquid, and changes at the gas-liquid interface, as well as by changes at the liquid-packing interface. Resolution of these three effects is not easily accomplished.

The wetting of a tower packing depends not only on the nature of the liquid, but also on the type of surface offered by the packing. The investigation reported here was devoted to studying how variation only in the nature of the packing surface affected the efficiency, capacity and liquid holdup in a packed gas-absorption tower. Although other investigations, like those cited before, have been concerned with variations in liquid surface tension (involving different systems, different viscosities, and diffusivities, added surface-active agents, etc.), the author is aware of no previous work, other than that of Sherwood and Holloway (*1*), that has focused on variation in surface properties of the packing. Up to now, it appears that no other investigation has been designed to study only the effects of the nature of the packing material on tower performance, while attempting to maintain other system variables and parameters constant.

EXPERIMENTAL PROCEDURE

Three different types of packing material were employed in this work: Saran (a copolymer of vinyl and vinylidene chloride), polyethylene and ceramic Raschig rings. All rings had outside dimensions of approximately ⅜ in. and wall thickness of about 1/10 in. The ceramic rings were purchased as standard tower-packing material and the polymeric rings were fabricated by cutting tubing to the proper size. The Raschig rings were packed into a 5 ft. glass column of 3 in. I.D. by dropping them into the column already filled with water, as recommended by Eckert (*4*). Values of the void fraction, ϵ, were computed from the volume of water displaced. Void volumes and dimensions of well formed ring specimens were as follows:

	Saran	polyethylene	ceramic
ϵ	0.70	0.61	0.63
O.D., cm.	1.0	1.0	1.1
length, cm.	1.0	1.0	1.0
wall thickness, cm.	0.20	0.21	0.28

The value of ϵ usually employed for ⅜ in. Raschig rings (*13*) is 0.68.

The polymeric rings were more uniform than the ceramic rings; some of the latter were of shorter length, some stuck together and some were broken. The differing values measured for ϵ in this study indicate that the materials packed differently within the column. The larger wall thickness of the ceramic rings suggests that they may have packed differently from the polymeric rings; polyethylene, which has a density smaller than that of water, did not settle through the water and the ceramic and Saran rings settled at different rates. Thus the differing values measured for ϵ are not unexpected.

The column and associated equipment is shown on the schematic flow diagram in Figure 1. Liquid was supplied to the top of the column from a pipe that always extended to within 1 in. of the packing. The liquid flow rate to the column was measured by a calibrated rotameter and controlled by a quick-closing valve arrangement. Compressed air was supplied to the column through a water saturator maintained at 70°F. The air flow was metered by a calibrated rotameter and controlled by a needle-valve arrangement. The pressure drop across the column was measured by a calibrated water manometer connected to the pressure taps indicated in the figure.

The mass-transfer system employed was air-sodium sulfite solution (5% by weight) in which simultaneous chemical reaction takes place as oxygen is absorbed by the solution and oxidizes the sulfite ion to sulfate. The air-sodium sulfite solution system has been thoroughly studied in the past (*5*, *6*) and mass transfer is easily measured in this system by titration of sulfite with iodate ion. In this investigation the sodium sulfite solution contained 4g. of cobalt chloride per pound; the latter compound acted as an oxidation catalyst.

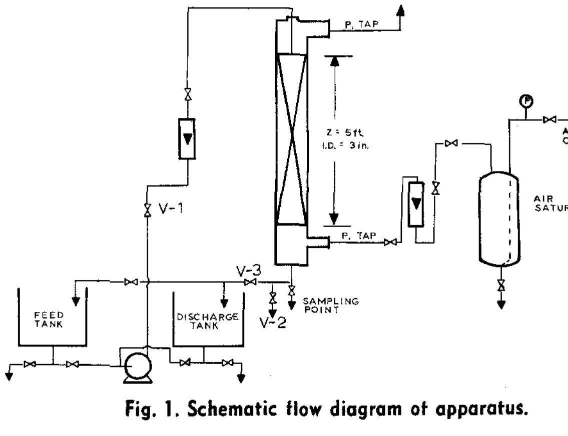

Fig. 1. Schematic flow diagram of apparatus.

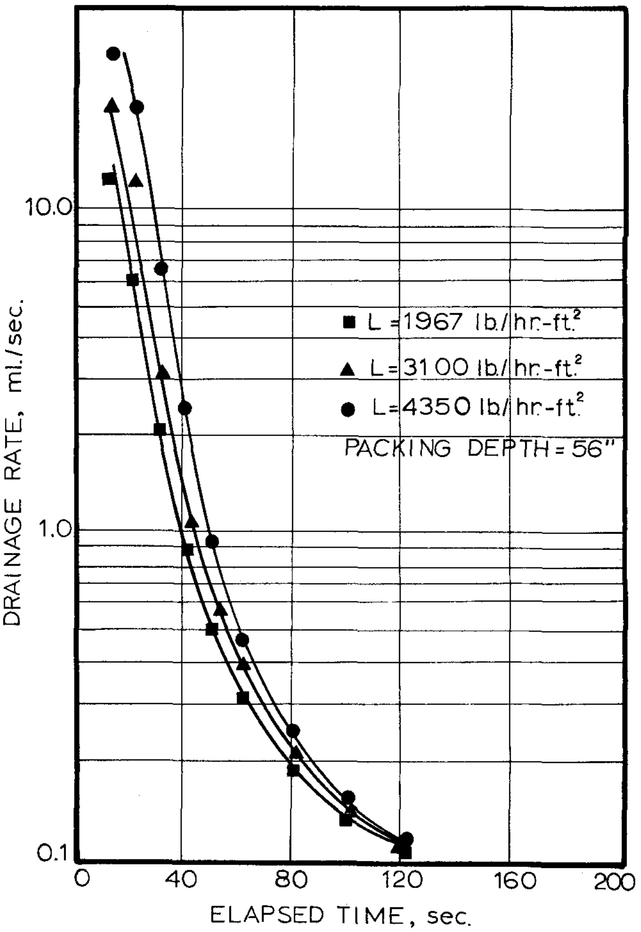

Fig. 2. Determination of drainage time for operating holdup; ceramic Raschig rings.

During experiments, flow rates were held constant by manual control. Liquid flow rates were investigated over the range of 650 to 5,650 lb./hr.-sq.ft. and air flow rates between 84 and 300 lb./hr.-sq.ft. For mass transfer measurements the operation was first allowed several minutes to attain the steady state after the desired gas and liquid flow rates had been established. Steady state operation was confirmed by the constancy of two successive sets of analytical measurements. At the discharge end of the column, liquid was kept at a constant level by adjusting the flow rate through valve V-3 to prevent gas bubbles from leaving with the exit liquid. For each measurement, a set of liquid samples was drawn every 3 min. from the feed and from the base of the packing through the sampling tap indicated in Figure 1. Eight such sets of samples were collected at selected steady state operating points and analyzed for sodium sulfite by titration with sodium iodate solution. Standard deviation of sample means of concentration were smaller than about 2%. Temperatures were maintained as close to 70°F. as possible; the feed and exit liquid never differed in temperature by more than 2°F. Mass transfer measurements with each packing material were conducted at three different packing heights to assess the magnitude of end effects.

Liquid holdup in the packing was determined by the following procedure which is similar to that used by Jesser and Elgin (*3*). After steady state has been attained for a given liquid flow rate, valves V-1 and V-3 were closed and valve V-2 opened, all simultaneously. Thereafter liquid drainage rate from the packing was measured as a function of time; incremental volumes were collected for measured time periods by using a graduated cylinder. This procedure was repeated for different liquid rates and typical results are shown plotted in Figures 2 and 3. After sufficient time had elapsed, the drainage rate for a particular kind of packing became independent of the original liquid flow rate, as is evident from

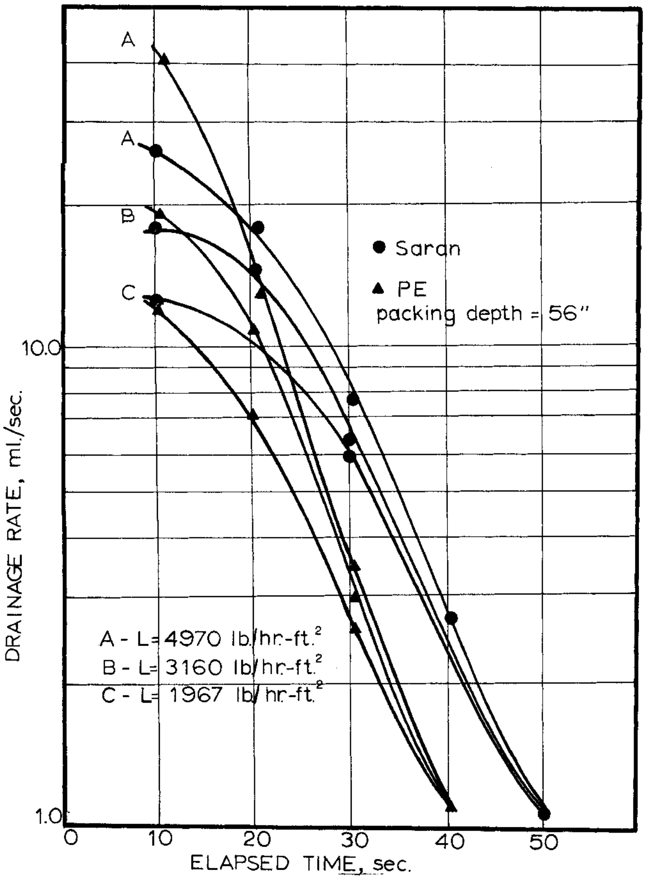

Fig. 3. Determination of drainage time for operating holdup; polymeric packing.

the merging of the drainage curves in Figures 2 and 3. The time, corresponding to the junction of the drainage curves for a particular packing, may be designated the *drainage time for operating holdup* and the total liquid holdup in an operating column may be thought of as made up of an operating holdup which drains from the packing in this time period, and a static holdup which drains beyond this time period and for which the drainage rate is independent of the initial liquid rate during operation. This procedure may be thought of as defining operating and static holdup. It would be possible to take operating holdup as equal to the time integral of the functions shown in Figures 2 and 3 between zero time and the point of merger of the drainage curves for each packing. However, once the drainage time for operating holdup was determined as described above, it was more convenient to experimentally collect the total liquid drained from the packing during this time period after feed to the column had been shut off. Determinations were made in this way from operating steady states in which gas also flowed through the column; thereby the dependence of operating holdup on gas rate could be determined in the case of each different type of packing.

Loading point was indicated by an abrupt increase in pressure drop across the column as the gas flow rate increased beyond a certain value. To determine loading points, constant liquid flow rate to the column was established and the air flow rate was then increased slowly until a sudden increase in pressure drop was noted at the loading gas velocity for a particular liquid flow rate. This was carried out for each different type of packing over a range of liquid flow rates.

RESULTS AND DISCUSSION

Yoshida and Akita (*5*) have shown that for the system composed of air and sodium sulfite solution, with cupric ion as catalyst, the gas-phase resistance to transport is negligible and that the transport of oxygen in the liquid is the controlling process. They reached this conclusion from the fact that their data for K_La did not depend on whether runs were made with air or with pure oxygen. In the present work with cobaltous ion catalyst, the value of $\sqrt{M}$ was estimated as equal to about five, based on the reaction rate constant data of Harris and Roper (*6*) and the values of k_L for oxygen absorption without chemical reaction reported by Garner and Porter (*16*). Based on the sulfite concentrations employed and the equilibrium oxygen solubility, this value of $\sqrt{M}$ indicates (*17*) that the present value of k_L^* may have been about five times larger than k_L in the absence of chemical reaction. Nevertheless, for the measurements of the present study, mass transfer was not sensitive to gas flow rate below the loading point in accord with the findings of Yoshida and Akita (*5*). This suggests that the liquid-phase resistance still predominated in spite of the large value of $\sqrt{M}$. Measured changes in sodium sulfite concentration across the column are plotted as a function of liquid flow rate in Figure 4 for different depths of ceramic packing. For a given depth of packing, the data appear to be independent of gas flow rate. This Figure also shows the effects of loading on mass transfer in that, for the larger gas and liquid flow rates, there was an increase in the rate of oxygen absorption. Treybal (*7*) and Vivian, et al. (*8*) also note that mass transfer is independent of gas flow rate until loading occurs in a system in which the major transport resistance resides in the liquid phase.

Figure 4 also shows the effect of type of packing material on mass transfer when all other operating variables are identical. It is clear from Figure 4 that superior mass transfer rates were obtained with ceramic packing, whereas there was no identifiable difference between the performances of the two polymeric packing materials. It is clear that the differences in mass transfer rates obtained with the different packing materials do not show the same trend as the different values of ϵ measured for these packings. Similar behavior is also indicated by the composite mass transfer coefficients computed from the data and discussed below.

Since the sodium sulfite solutions employed were dilute and only small amounts of oxygen were transferred in the experiments, both operating and equilibrium lines may be regarded as linear and the equilibrium relationship may

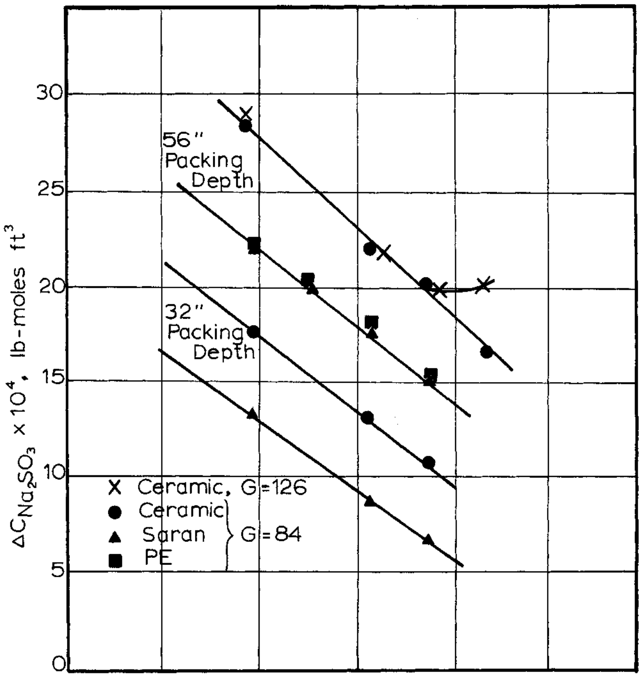

Fig. 4. Change in sodium sulfite concentration as a function of liquid flow rate. Comparison of packing materials and effect of packing depth.

be described by Henry's Law (5). In light of these considerations, the number of transfer units may be computed from

$$N_{OL} = \int_{x_1}^{x_2} \frac{(1-x)_{\text{lm}}\, dx}{(1-x)\,(x-x^*)} \approx \frac{x_2 - x_1}{(x-x^*)_{\text{lm}}} \tag{2}$$

and the overall composite mass transfer coefficient is then given by:

$$K_L a = \frac{L'}{ZA_c} \cdot \frac{x_2 - x_1}{(x-x^*)_{\text{lm}}} \tag{3}$$

Values of N_{OL} and $K_L a$ discussed below were computed from the above equations and the Henry's Law equilibrium relationship (5) for oxygen in water. In the equations above, x_1 and x_2 were taken as equal to total dissolved oxygen concentration, that is equivalent to the quantity of sulfite ion consumed. An alternative approach, based on assuming zero oxygen concentration in the bulk liquid phase, results in values of N_{OL} and $K_L a$ which show similar trends but scatter more; therefore total dissolved oxygen concentration was used instead. The use of total dissolved oxygen concentration appears to be in accord with the report (5) that mass transfer resistance in this system resides primarily in the liquid phase. The latter finding suggests that the reaction of dissolved oxygen with sulfite ion was slow compared to liquid residence time in the apparatus.

End effects appeared to be negligible in this investigation as indicated by measurements made using three different packing depths (ranging from 32 to 56 in.). When the results were plotted as N_{OL} vs. packing depth, straight lines passing through the origin were obtained for each of the three packings thereby indicating negligible end effects on mass transfer rate. Typical results are shown for ceramic packing in Figure 5.

The composite, overall, mass transfer coefficient, $K_L a$, is also shown plotted vs. liquid flow rate in Figure 5 for the cases of the different packing materials. Straight lines have been fit through the data points of this Figure yielding the following empirical expressions:

$$K_L a = 2.1 \times 10^{-3}\ L^{0.452} \quad \text{(for ceramic packing)}$$

and (4)

$$K_L a = 1.7 \times 10^{-3}\ L^{0.452} \quad \text{(for polymeric packing)}$$

In these expressions the exponent of L is identical to that found by Furnas and Bellinger (9) for similar packings. The reproducibility of the data shown in Figure 5 and represented by Equations (4) was checked by removing the packing from the column, repacking the tower and conducting repeat measurements. In no case were appreciable differences noted after the tower had been repacked.

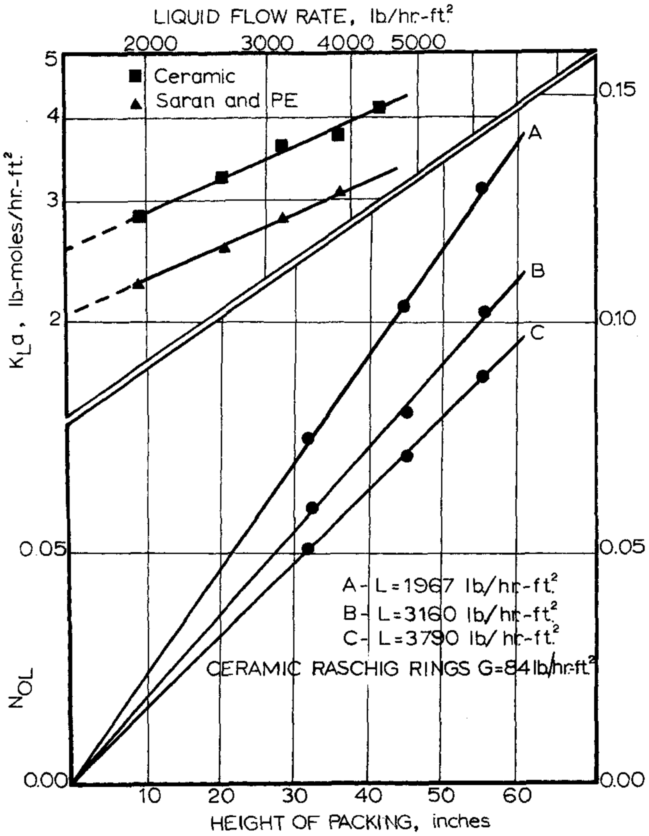

Fig. 5. Test for end effects and liquid phase overall mass transfer coefficients.

One possible interpretation of Figure 5 is that the difference between $K_L a$ in the cases of ceramic and polymeric packing resides solely in differences in the interfacial area, a. It has been shown (10) that the mass transfer performance of a packed column depends on the wetted area of the packing. In the case at hand, the more easily wetted ceramic packing might be expected to produce the greatest interfacial area between liquid and gas in the column. As mentioned above, the values of ϵ were found to be different for each type of packing with the Saran and polyethylene displaying the greatest difference in this quantity. These differences in ϵ suggest differences in surface area but the results for $K_L a$ do not show the same trend as ϵ for the various packings. Thus, although the different packings may have stacked differently, producing different values of ϵ, these differences do not correlate with the differences observed for $K_L a$. Change in interfacial area may not be the only phenomenon that is caused by differences in packing material. The nature of liquid flow over a solid surface would be expected to be influenced by substantive differences in the interaction between liquid and the solid, as was the case in the present investigation. The possibility cannot be discounted that the degree of convective transport within the liquid might also have been affected by the nature of the interaction between the liquid and the solid surface. Evidence of this has already been observed by Sherwood and Holloway (1). The fact that their work showed paraffin-coated packing reduced $K_L a$ more for an aqueous system in which the gas side resistance controls than for an aqueous system in which the liquid side resistance controls, indicates that poor wetting of the packing may cause increased agitation of the liquid thereby partially offsetting the decrease in a. Another statement of this position is that coating the packing surface with paraffin caused a greater decrease in the long lifetime surface than in the short lifetime surface. In the present work, operating holdup (at the same liquid rate) was about the same for each kind of packing material. This is discussed in more detail and may not be immediately evident from a comparison of Figures 2 and 3 where the scales are somewhat different. The equality of operating holdup from packing to packing suggests that wetted surface area may not have been very much different in each case. Thus the observed differences in mass transfer rates may lie more in differences of lifetime of liquid surface than in differences of wetted surface area. Further indication of possible increases of liquid agitation is provided by the face that the operating holdup drainage rates in the present experiments were considerably larger for the polymeric packings. As is evident from Figures 2 and 3 the drainage time period for operating holdup was 120, 50, and 40 sec. for ceramic, Saran, and polyethylene packings, respectively. This trend in drainage times is in accord with the aqueous contact angles [measured by using a telescope with a goniometer eyepiece-method of Zisman (11)] on the packing materials as shown in Table 1.

As would be expected, less thoroughly or less easily wet packing surfaces (higher contact angles) provided the

Table 1.

	PACKING MATERIAL		
	ceramic	saran	polyethylene
contact angle reported for pure water (*11*)	—	80 deg.	95 deg.
contact angle measured for water used in this study	0.0 deg.	71 deg.	84 deg.
contact angle measured for Na_2SO_3 solution in this study	0.0 deg.	66 deg.	78 deg.
drainage time	120 sec.	50 sec.	40 sec.

shortest drainage times. In the case of the ceramic Raschig rings, wetting was complete, more liquid was retained and the liquid adhered thoroughly to the surface, forming a film on it (*3*) thereby increasing the drainage time.

The measurements of pressure drop across the column may be summarized as follows. Considering pressure drop as a function of gas flow rate, with constant liquid rate through the column, no appreciable differences in behavior were detected among the three packing materials. This indicates that pressure drop per unit packed height was the same for the ceramic and plastic packings with the normal gas and liquid flow rates used in these experiments. The dependence of pressure drop on flow rate observed in the present work was very similar to other results (*13*) for ⅜ in. ceramic Raschig rings in a 3 in. column, except that the pressure drops were somewhat larger in the work reported here. However, when there was no liquid flowing through the column but the packings were wet, the ceramic packing displayed a greater (by about 30%) pressure drop than that through the polymeric rings. This observation is in accord with the expected differences in *static* holdup among packings which are wet or not wet by the liquid. Apparently there is little correspondence between static holdup and operating holdup since the latter quantity appeared to be independent of packing material as stated above and reported more fully below. No material difference was noted between pressure drops observed for wet polyethylene packing and wet Saran packing. The difference in behavior between polymers and ceramics can be explained by the stronger adhesion of water to the ceramic packing. A film of water remained and covered the surface of this packing and offered resistance to gas flow either by constriction or by adsorbing energy from the gas stream to produce ripples or waves in the adhering water film. The water remaining on the polymeric packings, however, was not spread over the entire packing surface and, due to poor adhesion, was probably free to migrate to locations of minimum resistance to gas flow.

The dependence of operating liquid holdup on liquid and gas flow rates was also investigated. For constant liquid rate, it was found that operating holdup in the column was not affected by changes in gas flow rate up to the point of loading; this permitted further investigation of operating holdup as a function of liquid flow rate to be carried out at zero gas flow rate with confidence that the results describe behavior up to the loading point. The dependence of operating holdup on liquid rate measured at zero gas rate was found to be independent of the type of packing material used. Essentially the same values of holdup and the same gradual (almost linear) increase in operating holdup was found as the liquid rate increased, regardless of which packing material was employed. As pointed out above, this independence of operating holdup on packing material is not immediately apparent from the curves of Figures 2 and 3, which are plotted on different scales. The dependence of operating holdup on liquid flow rate observed in the present work was quite similar to results for ⅜ in. Raschig rings previously reported (*13*); the values of holdup measured in the present experiments were a few percent smaller, however. These results also served to verify the reproducibility of the holdup data as well as to demonstrate that liquid operating holdup was independent of the surface characteristics of the packing materials employed in this study. These results are interesting in light of the findings of Jesser and Elgin (*3*) who observed increases in holdup for the larger liquid flow rates as liquid surface tension decreased, although surface tension appeared to have no effect on holdup at lower liquid flow rates in their work. However, the present experiments indicate that changes in contact angle at constant liquid surface tension do not appear to affect holdup, even at the larger liquid rates; this suggests that the dependence of holdup on liquid surface tension observed by Jesser and Elgin may have little to do with wettability of the packing and may have been caused by changes in the nature of the interaction at the liquid-gas interface.

The loading characteristics of the column in this work were found to depend on the nature of the packing material. This is interesting in light of the fact that there appeared to be no difference among packings in the functional relationship between pressure drop and flow rate below the loading point. Because of this, it may be dangerous to generalize further from the few experiments reported here. With the polymeric materials, loading occurred at lower flow rates than observed with the ceramic Raschig rings. The gas and liquid flow rates at the experimentally observed loading point are plotted in Figure 6. These results are also displayed in this figure in the form of a generalized pressure-drop correlation (*12, 13*) commonly used to predict loading and flooding points. It is interesting that the experimental loading points were identical for the two polymeric packings. However, the curves for these packings based on the generalized correlation are separated due to the different values of ϵ measured for the two polymeric materials in this work.

The difference in loading characteristics between polymeric and ceramic packing is evident from Figure 6. It can be surmised from the results that increased tendency toward flooding is associated with decreased wettability of the packing material. This difference in behavior decreases at larger liquid flow rates which would be expected to cause more extensive and increasing spreading of the liquid over the polymeric packings. It is evident from these results that the usual correlations (*12, 13*) for loading and flooding in packed columns may be inadequate for predicting performance when the packing material is not wetted by the liquid phase.

It is interesting to consider the present results for loading in light of the observations of Newton, et al. (*2*). These workers measured increased tendency to flood with conventional packing materials as the liquid surface tension was decreased by the addition of surface-active agents to the liquid. In their experiments, the packing was presumably well wet regardless of the presence of the surface-active agent. Although Equation (1) does not apply under such circumstances, γ_S remained constant and γ_L was presumably decreased by the added surface active agents. The interfacial tension between solid and liquid, γ_{SL}, could either have increased or decreased depending on the nature of the surface-active agents, their tendency to adsorb and their mode of adsorption on the solid surface. In the present work, increased tendency to flood was observed as Θ increased and γ_S decreased but γ_L remained unchanged. Changes in the quantity γ_{SL} are difficult to predict in the present case, but it is probable that γ_{SL} is smaller (*15*) for the polymer-water interface than for the ceramic-water interface. It is possible that γ_{SL} may not

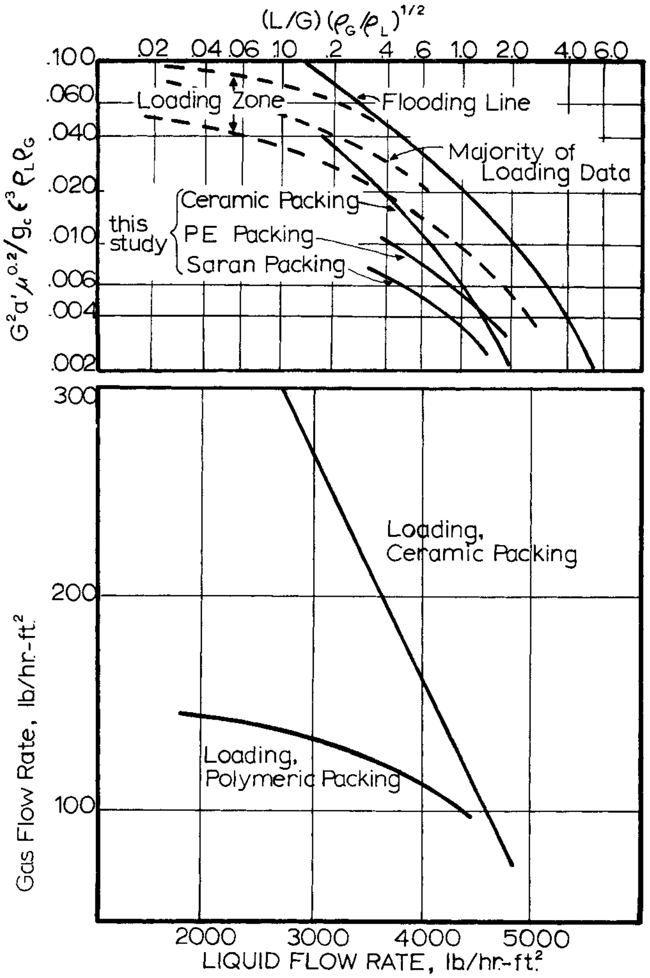

Fig. 6. Loading behavior.

play a large role in flooding behavior and, that in the work of Newton, et al. (*2*), the surface active agents may have enhanced flooding by their effect on the gas liquid interface. In the present work, increased tendency to flood probably corresponds to increased Θ, brought about mainly by decreasing γ_S.

CONCLUSIONS

The results reported here confirm the early observation (*1*) that decreased wetting of the packing in gas adsorption lowers K_La. They have also shown that, under conditions of typical liquid and gas flow rates, pressure drop appears to be independent of packing material. Although there was some indication that static holdup was larger for the ceramic packing, operating liquid holdup was not observed to depend on the nature of the packing material. This result, in light of previous observations (*3*), suggests that the nature of the liquid-gas interface may play a larger role in affecting liquid holdup than the nature of the liquid-packing interface. Finally, it was observed that poor wetting of the packing by the liquid brought about greater tendency toward loading. It appears that this phenomenon is fundamentally different from the increased flooding tendency (*2*) caused by the addition of a surface-active agent to a system in which the packing is already well wet.

ACKNOWLEDGMENT

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NOTATION

a = interfacial gas-liquid surface per unit volume, ft.$^{-1}$
a' = specific packing surface area per unit volume, ft.$^{-1}$
A_c = cross sectional area of column, sq.ft.
C = concentration, lb.-moles/cu.ft.
D = diffusivity, sq.ft./sec.
g_c = gravitational conversion factor, 4.17×10^8 ft.-lb./lb. force, hr.
G = gas flow rate, lb./hr., sq.ft.
k' = second-order chemical reaction rate constant, sq.ft./lb.-mole, sec.
k_L = liquid-phase, mass transfer coefficient in the absence of chemical reaction in liquid phase, lb.-moles/sq.ft., hr.
k_L^* = liquid-phase, mass transfer coefficient accompanied by chemical reaction in the liquid phase, lb.-moles/sq.ft., hr.
K_L = overall, liquid-phase, mass transfer coefficient, lb.-moles/sq.ft., hr.
L = liquid flow rate, lb./hr., sq.ft.
L' = liquid flow rate, lb.-moles/hr., sq.ft.
M = $D_Ak'C_B/k_L^2$, dimensionless
N_{OL} = number of transfer units based on overall, liquid-phase coefficient
x = mole fraction
Z = column height, ft.

Greek Letters

γ = surface or interfacial tension, erg./sq.cm.
ϵ = void fraction or porosity
Θ = contact angle
μ = viscosity, centipoise
ρ = density, lb./cu.ft.

Subscripts and superscripts

A = oxygen concentration
B = sulfite-ion concentration
G = gas phase
L = liquid phase
lm = logarithmic mean
S = solid or packing surface
SL = interfacial tension
1, 2 = conditions at entrance and exit from column
$*$ = equilibrium composition

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