PERFORMANCE OF PACKED COLUMNS

I. Total, Static, and Operating Holdups

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Total and static holdups have been measured for ½-, and 1-in. ceramic Berl saddles, ½-, 1-, and 1½-in. ceramic Raschig rings, and 1-in. carbon Raschig rings with air rates from 100 to 1,000 lb./(hr.) (sq. ft.) and water rates from 1,000 to 10,000 lb./(hr.) (sq. ft.).

The holdup measurements and motion picture observations of the flow of dye solutions through packings provide an explanation for the great differences observed when gas-phase mass transfer rates are measured by absorption and vaporization methods. If the effective interfacial area for vaporization is assumed to be proportional to total holdup and the area for absorption is assumed proportional to operating holdup, the ratio of the two mass transfer rates should be equal to the ratio of the two holdups.

The departure from equality of the two ratios can be explained by the observation that the static holdup is displaced slowly, resulting in additional effective area for absorption over that expected from the operating holdup alone.

In recent years investigations of mass, heat, and momentum transfer in fluid-soild systems have indicated that the free space, or void fraction, ε, is an important variable in the correlation of data(*1, 4, 5, 6, 10, 12*). To apply these findings to an analysis of more complex systems such as those occurring in packed absorption and distillation columns, one must know the total liquid holdup to determine the void fraction available for gas flow under operating conditions. A knowledge of liquid holdups is also of interest in the study of batch distillation and effective interfacial areas for diffusional operations employing packed columns.

Three different types of liquid holdup have been discussed in the literature(*8, 11*). The *total holdup*, h_t, defined as the total liquid in the packing under operating conditions, is expressed as cubic feet of liquid per cubic foot of packing. The *static holdup*, h_s, as used in this work is defined as the liquid in the packing which does not drain from the packing when the liquid supply to the column is discontinued and is also expressed as cubic feet of liquid per cubic foot of packing. The *operating holdup*, h_o, defined as the difference between the total and static holdups, represents the liquid which will drain from the packing and is also a measure of the liquid flowing through the packing when the column is in operation. The relation between the three holdups is given by

$$h_t = h_s + h_o. \qquad (1)$$

Several investigators(*2, 9, 13, 15, 19, 22*) have measured or estimated liquid holdups, and two extensive studies have been reported by Elgin and coworkers(*3, 11*). Unfortunately the previous investigations have dealt with operating holdups almost exclusively and no investigation has been reported of the three types of liquid holdup in packings for which extensive mass transfer data are available, namely, Raschig rings and Berl saddles.

The object of the present work is the determination of the three types of liquid holdup for 0.5-, 1.0-, and 1.5-in. unglazed white porcelain Raschig rings, 0.5-, and 1.0-in. unglazed white porcelain Berl saddles, and 1.0-in. carbon Raschig rings. These data will be used to explain the differences observed in gas-phase mass transfer rates when vaporization and absorption techniques are used. In Part II of this paper the data will be applied to

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TABLE 1.—CHARACTERISTICS OF PACKING USED FOR HOLDUP MEASUREMENTS

Type Manufacturer Material	Raschig rings (U. S. Stoneware Co.) Unglazed white porcelain			Berl saddles (Maurice A. Knight Co.) Unglazed white porcelain		Raschig rings (National Carbon Co.) Carbon
Nominal size, in.	0.5	1.0	1.5	0.5	1.0	1.0
Void fraction, dry	0.605	0.726	0.715	0.660	0.695	0.700
Specific gravity, dry	2.38	2.41	2.36	2.36	2.44	1.57
Pieces/cu. ft	10,900	1,370	430	15,000	1,810	1,470
Surface area, sq. ft./cu. ft.	116	58.5	40.9	133	62.6	62.7
Surface area/piece, sq. ft.	0.01063	0.0427	0.0952	0.00888	0.0346	0.0427
Diameter of equivalent sphere, ft.	0.0582	0.1167	0.1740	0.0532	0.1050	0.1167

the problem of separating the volumetric mass transfer coefficients (k_Ga and k_La) into their components, the effective interfacial area, a, and the mass transfer coefficients, k_G and k_L.

EQUIPMENT

The equipment used for these studies, shown schematically in Figure 1, is the same as that described in detail in a recent paper by Shulman and DeGouff(18) except for minor modifications, which will be discussed. A water tank and pump were installed to permit adjustment of water temperature and recycling of water. Two calibrated rotameters were installed to replace the orifice meters previously used to meter the air. The 10-in.-diam. by 36-in. packed glass column was arranged so that it might be weighed with its contents while in operation. This was done by supporting the column by means of four 0.25-in. steel rods connected at the top by a yoke and at the bottom by a steel ring on which the glass column and the four legs of the packing support plate rested. In operation the glass column was suspended in air except for a few inches at the bottom which were immersed in a water seal. The column and its contents were counterbalanced by weights on a pan connected to the yoke at the top of the column by the lever arm and knife edges obtained from a platform scale. The pan of weights rested in turn on the pan of a 20-kg.-capacity platform scale which could be read to within 1 g. The weighing system was capable of detecting a change in weight of the column of as little as 3 g., and it was therefore possible to determine holdups to within 1% under the poorest conditions, i.e., static-holdup determinations of the larger packings. The column was open at the top to the atmosphere, and so a draft gauge employed for reading the pressure at the base of the column measured the pressure drop across the packing. The weighings were corrected for the buoyancy effect of the portion of the column in the water seal and for the upward thrust due to the pressure drop across the column, which was operated at all times with 28 in. of packing using water at 19° to 25°C. and saturated air of approximately the same temperature to prevent vaporization of water.

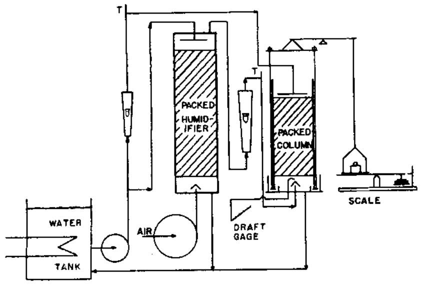

FIG. 1. SCHEMATIC DIAGRAM OF APPARATUS.

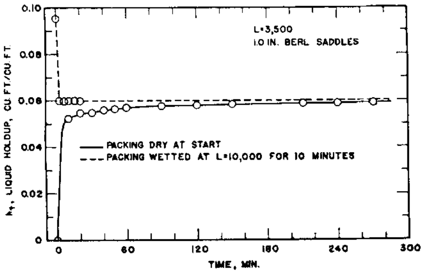

FIG. 2. TOTAL HOLDUP VS. TIME AT $L = 3,500$ FOR 1.0-IN. BERL SADDLES.

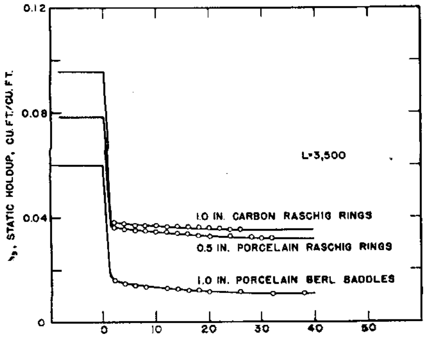

FIG. 3. STATIC HOLDUP VS. DRAINAGE TIME.

The water distributor, which was supported independently of the column approximately 1/2 in. above the packing, consisted of eight arms extending radially from a special fitting and was 9 in. in diameter. It had a total of 160 0.1-in. holes evenly spaced in three rows on four alternate arms and in a single row on the remaining arms. Several holes were plugged with solder as the result of tests made to ensure uniform distribution of liquid for the liquid rates employed.

PROCEDURE

Preliminary tests made possible the establishment of a procedure which gave reproducible data even when the column was emptied and repacked. When the column was packed with dry packing and the water rate was set at a fixed value, the total holdup was found to increase with time until a constant equilibrium value was reached. The same equilibrium value could be reached in a much shorter time by supplying water at a very high rate for a short time, to wet the packing thoroughly, and then running at the desired rate. Figure 2 shows the total holdup for 1.0-in. Berl saddles as a function of time when the two methods are employed. The effect of time is even more noticeable with the smaller packings, which have greater holdups. The buildup with time is believed to be due to the gradual accumulation of water in pockets at points of contact, inside rings, or on portions of the surface which are not continually covered by flowing liquid. The splashing of liquid as it falls from one piece of packing to another and the random motion of the moving liquid over the surface of the packing not only causes this gradual accumulation, until an equilibrium value is reached, but also results in a slow turnover of the liquid in what might otherwise be stagnant pockets. Observations based upon motion picture studies of the flow of dye solutions in packings will be discussed later in connection with the interpretation of mass transfer data.

The total holdup was found to vary with the density of the packed bed

TABLE 2.—VARIATION OF HOLDUP WITH PACKING DENSITY

Packing: 1.0-in. porcelain Raschig rings

Liquid rate, lb./(hr.) (sq. ft.)	3,500	3,500	3,500	3,500	3,500	3,500
Gas rate, lb./(hr.) (sq. ft.)	0	0	300	300	600	600
Void fraction, dry	0.726	0.709	0.726	0.709	0.726	0.709
Pieces/cu. ft., N	1,370	1,460	1,370	1,460	1,370	1,460
h_t, cu. ft./cu. ft.	0.0539	0.0567	0.0543	0.0574	0.0592	0.0724
$(h_t/N)\times 10^5$	3.94	3.88	3.96	3.93	4.32	4.96

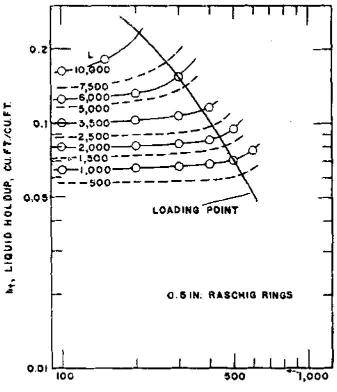

FIG. 4. TOTAL HOLDUP IN 0.5-IN. RASCHIG RINGS.

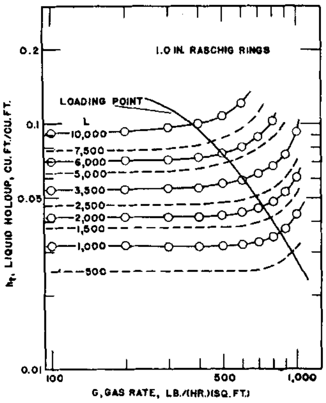

FIG. 5. TOTAL HOLDUP IN 1.0-IN. RASCHIG RINGS.

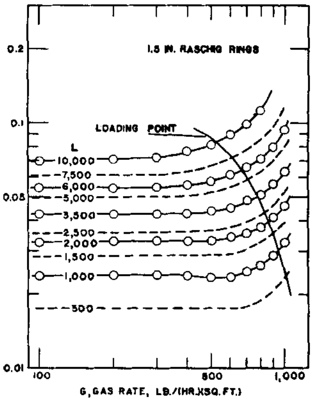

FIG. 6. TOTAL HOLDUP IN 1.5-IN. RASCHIG RINGS.

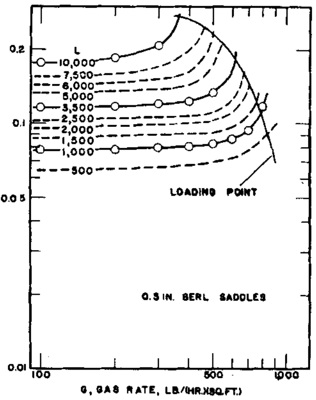

FIG. 7. TOTAL HOLDUP IN 0.5-IN. BERL SADDLES.

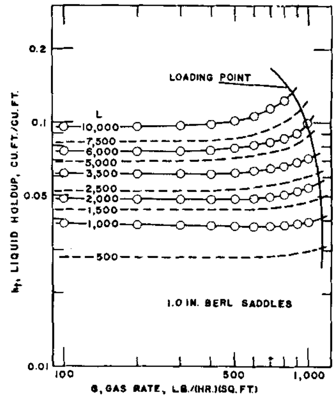

FIG. 8. TOTAL HOLDUP IN 1.0-IN. BERL SADDLES.

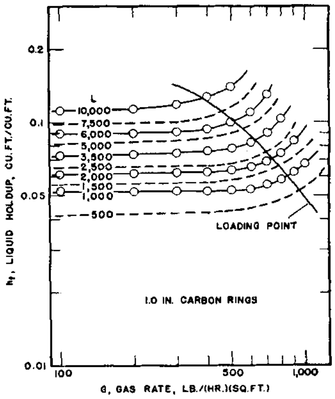

FIG. 9. TOTAL HOLDUP IN 1.0-IN. CARBON RINGS.

when the column was repacked several times with the same packing. For this reason the holdups reported apply only to packing with the characteristics listed in Table 1. The data in Table 2 show that the total holdups are approximately proportional to the number of pieces of packing per cubic foot for a given packing. This observation provides the simplest correction for packing densities other than those listed in Table 1.

To determine the static holdup, h_s, the water supply was cut off after equilibrium conditions were reached, the column was permitted to drain, and a record of column weight vs. time was made. Figure 3 illustrates several drainage curves. It will be noticed that different packings require different lengths of time to drain to fairly constant weight.

On the basis of these preliminary tests the following procedure was adopted to ensure obtaining reproducible data. The air was saturated and cooled to the temperature of the water in the tank. The weight of the column and the dry packing was obtained and the packing was thoroughly wetted by setting the water rate up to over 10,000 lb./(hr.)(sq.ft.) for a minimum of 1 hr. The water rate was then decreased to the rate to be investigated and the air rate was set at 100 lb./(hr.)(sq.ft.) When the platform scale indicated constant weight for more than 3 min. the readings of weight, pressure drop, and temperature were taken and the air rate was increased to the next higher value. For each packing a series of runs was made in this fashion at constant liquid rates with increasing gas rates. The highest liquid rate, 10,000 lb./(hr.)(sq.ft.), was used first, and the gas rate was increased up to 1,000 lb./(hr.)(sq.ft.) or the flooding point, whichever was reached first. The lowest liquid rate employed was 1,000 lb./(hr.)(sq.ft.) because it was felt that good liquid distribution could not be ensured at lower rates.

For the static holdup tests a similar procedure was followed, but the water supply was cut off when equilibrium was reached and data for a drainage curve were recorded. It was soon found that static holdup was independent of liquid and gas rates when this procedure was employed, and so it was not necessary to investigate the two ranges so thoroughly as for total holdup.

EXPERIMENTAL RESULTS

Total Holdup. The data obtained from the total holdup measurements are plotted in Figures 4 to 9 for the six packings studied. The experimental points are shown, and additional lines, obtained by interpolation, extrapolation, and cross plotting, have been added to make the plots more useful for estimating total holdups in the ranges of gas and liquid rates covered. The loading-point line on each plot was obtained from the data of Tillson (*21*) for the same packing. The shapes of the curves are quite similar to those obtained by Elgin and Weiss (*3*) for operating holdups. This is to be expected because the two holdups differ by a constant, the static holdup, as will be shown later. At low liquid rates the total holdup is almost independent of gas rate up to the loading point, but for higher liquid rates, especially for the smaller packings, and for gas rates at approximately the loading point the effect of gas rate cannot be ignored. This sudden increase in holdup as gas rate increases causes the break in the pressure-drop curve which has been taken as the definition of the loading point. It is interesting to note that the total holdups for 1.0-in carbon rings are greater than those for porcelain rings of the same size. This difference is accounted for by the differences in static holdup for the two packings; thus the operating holdups are of the same magnitude. Apparently the nature of the surfaces causes a greater accumulation of semistagnant water in carbon than in porcelain; therefore the total and static holdups reported here probably do not apply to surfaces other than ceramics similar to unglazed

TABLE 3.—CONSTANTS FOR EMPIRICAL EQUATIONS FOR TOTAL AND STATIC HOLDUPS

Type of packing material	Raschig rings Porcelain	Raschig rings Carbon	Saddles Porcelain	Equation
α	2.25×10^{-5}	7.90×10^{-5}	2.50×10^{-5}	2
γ	0.965	0.706	0.965	3
δ	0.00104	0.00250	0.00032	4
θ	0.376	0.376	0.376	3
λ	1.21	1.21	1.56	4
D_P, 1.5-in. packing, ft.	0.174	0.178	0.155	2, 3, 4
D_P, 2.0-in. packing, ft.	0.238	0.235	......	2, 3, 4

porcelain. The operating holdups, however, seem to be independent of the nature of the surface.

For purposes of estimating the total holdups of rings and saddles larger than those investigated in this study the following empirical equations are recommended below *the loading point:*

$$h_t = \frac{\alpha L^{\beta}}{D_P^{2}} \qquad (2)$$

$$\beta = \gamma D_P^{\theta} \qquad (3)$$

The constants, α, γ, and θ, are given in Table 3. These equations fit the experimental data very well up to loading and have been found useful for estimating the holdups for 2.0-in. rings and 1.5-in. saddles.

Static Holdup. The experimental data for the static holdups, summarized in Table 4, show the holdups to be independent of varying gas and liquid rates. In Figure 10 the average value of static holdup for each packing is plotted vs. the equivalent diameter, D_p. Although an insufficient number of packings of each type have been studied to give a good correlation of the data, it is evident that the static holdup is a function of the material of construction, the shape of the packing, and the size of the packing. The lines on Figure 10 may be used to estimate the static holdups of packings which have not been studied, or the following equation for the lines may be used.

$$h_s = \delta D_P^{-\lambda} \qquad (4)$$

The constants, δ and λ, are given in Table 3.

The static holdup, which is a measure of the accumulated semistagnant liquid, may play an important, but hitherto unknown, role in the interpretation of mass transfer studies in packing. It can easily be seen that this semistagnant liquid may be as effective as moving liquid for vaporization work, but relatively ineffective for absorption or desorption operations. A more detailed analysis of this problem is given in another section of this paper.

Operating Holdup. The operating holdup is determined by taking the difference between the total and the static holdups, as indicated by Equation (1). The operating holdups derived from the present studies are in fair agreement with those obtained by previous investigators. The differences may be due to the use of different materials of construction of the packing, slightly different packing dimensions, differences in methods of packing the column, and different drainage times. Thus Furnas and Bellinger (*9*) drained for 3 min., Jesser and Elgin (*11*) for 10 min., and the authors for each packing to a constant weight.

Serious errors may be made in estimating operating holdups by using the methods presented by previous investigators and adopted by various texts and handbooks presenting these data. In the past it has been assumed that operating holdup is independent of gas rate up to the flooding point and so operating holdups were in many cases measured at zero gas rate. These data are then plotted as straight lines with logarithmic coordinates and extrapolated to very high liquid rates approaching 100,000 lb./(hr.)(sq.ft.) in some cases. From Figures 4 to 9 it may be seen such a procedure would give erroneous operating holdups for all but very low gas rates. It is recommended that by means of Figures 4 to 10 and Equation (1) operating holdups be determined at the actual gas and liquid rates employed.

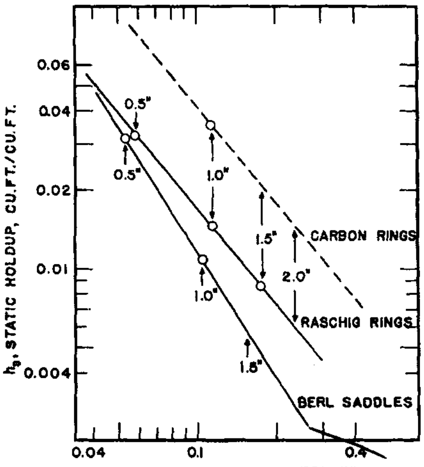

FIG. 10. STATIC HOLDUP OF PACKINGS.

TABLE 4.—SUMMARY OF STATIC HOLDUP DATA

Static holdup, *hs*, cu. ft./cu. ft.

Type of packing material		Raschig rings Unglazed porcelain			Berl saddles Unglazed porcelain		Raschig rings Carbon
Nominal size, in.		0.5	1.0	1.5	0.5	1.0	1.0
L	*G*						
10,000	0	0.0322	0.0150	0.00884	0.0315	0.0108	0.0358
6,000	0	0.0328	0.0149	0.00895	0.0315	0.0110	0.0357
3,500	0	0.0326	0.0150	0.00895	0.0319	0.0110	0.0359
2,000	0	0.0326	0.0149	0.00899	0.0318	0.0111	0.3539
1,000	0	0.0324	0.0148	0.00893	0.0318	0.0110	0.0359
3,500	300	.....	.....	0.00896	0.0318		
3,500	300	.....	0.0152				
3,500	600	.....	.....	0.00867			
3,500	600	.....	0.0151				
6,000	200	0.0325					
6,000	300	.....	.....	......	.....	0.0111	0.0359
Average h_s		0.0325	0.0150	0.00890	0.0317	0.0110	0.0358

APPLICATIONS TO MASS TRANSFER

The primary reason for obtaining the holdup data was a desire to determine the void fraction in packings under operating conditions in order to separate the mass transfer coefficients, k_G and k_L, from the volumetric transfer coefficients, k_Ga and k_La. This work is reported in Part II and will not be discussed here.

Figure 2 emphasizes a fact which has been reported occasionally by investigators on the basis of their experience: it is desirable to wet a packing thoroughly before attempting to determine mass transfer coefficients or the equivalent. This is particularly important when small packings are employed at low liquid rates because it may take several hours of operation under such conditions before the equilibrium total holdup is reached. Failure to observe this precaution undoubtedly accounts for widely scattered data, which are difficult to interpret and impossible to reproduce. If in addition, poor liquid distribution and end effects are added to the usual analytical problems it is easy to understand why the literature contains a considerable number of investigations, the results of which may never be fully explained.

The results of the holdup studies, presented in Figures 4 to 10, may offer an explanation of several mass transfer anomalies which have arisen in recent years. The first is concerned with the differences observed when gas-phase mass transfer coefficients, k_Ga, are determined by vaporization and absorption methods. Excellent discussions of this problem are provided by Pigford and Colburn (*14*) and Sherwood and Pigford (*17*). These authors point out that the most reliable data for k_Ga, obtained by vaporization and absorption measurements, are in disagreement by as much as 300% and no simple explanation is available to account for such large differences. One possibility suggested by these authors is that the ammonia absorption data, which are believed to be reliable, should be interpreted as though a chemical reaction takes place when ammonia dissolves in water and the reaction rate is slow enough to cause an abnormally high liquid-phase resistance. This suggestion was based on the work of Vivian and Whitney (*23* and *24*) on the absorption of chlorine and sulfur dioxide where a mechanism of this sort seemed to explain the data; however, the same authors compared the gas-phase mass transfer coefficients obtained from the sulfur dioxide work with those obtained by ammonia absorption and found them to be in reasonable agreement, and so it is rather unlikely that the chemical reaction mechanism can explain such large differences as have been observed.

An explanation for this mass transfer problem can be offered on the basis of observations of the flow of dye solutions through packed columns. The equipment used for the holdup studies was arranged so that a concentrated dye solution might be injected into the water line several inches before the liquid distributor. With the equipment in operation at a fixed liquid rate the dye solution was injected at a continuous rate for a short period of time and then cut off. By use of 1.5-in. Raschig rings, it was possible to observe the displacement of clear water by dye solution and then the displacement of dye solution by clear water through the glass column. It was found that a considerable portion of the water was not displaced immediately; i.e., there was no sharp line of demarcation between water and dye solution as dye was added or when the dye was cut off. Instead there were pockets of what might be described as semistagnant liquid and splashing, and the random motion of liquid over the packing surface deposited or removed dye from these areas by means of a slow and random dilution process. Thus when dye was injected for about 20 sec. some of the pockets picked up dye, which was not completely washed out by the following clear water until as much as 5 min. had passed. The water in these pockets corresponds to the static holdup, and the rate at which water enters or leaves these areas can be judged qualitatively from Figure 2, which shows the buildup of total holdup when dry packing is used. It can be concluded that there exists in the packing a quantity of water, with a corresponding interfacial area, the composition of which would change rather slowly even if the composition of the liquid entering the column changed rapidly.

If a packed column is used for vaporization, the effective interfacial area consists of the surface area of the moving liquid as well as of the water in the semistagnant pockets. If the column is used for absorption the semistagnant pockets tend to become saturated in a short time, their surface area becomes ineffective, and so the effective interfacial area is substantially that of the moving liquid alone. Of course, the observed volumetric mass transfer coefficients, k_Ga, for the two cases will be different because the effective areas are different. This explanation can be tested quantitatively if the effective area for vaporization is assumed to be proportional to the total holdup, h_t, and that for absorption proportional to the operating holdup, h_o, which represents the moving liquid.

This same line of reasoning can be extended to predict, in part, the behavior of packed columns used for absorption followed by an irreversible chemical reaction such as the absorption of ammonia in acid or of sulfur dioxide and chlorine in alkali solutions. For example, if ammonia is absorbed in water or very dilute acid, the effective area will be that of the moving liquid. As the acid concentration is increased, the semistagnant liquid, even with its slow turnover, will have an increasing capacity to absorb ammonia and at high enough acid concentrations this liquid may be as effective as the moving liquid. Thus one would predict a plot of k_Ga vs. acid concentration which would have the k_Ga value for water absorption at zero acid concentration, and then k_Ga would increase as acid concentration increased until the limiting value corresponding to the k_Ga to be expected for vaporization, corrected for diffusivity, was reached. It should be noted that this explanation provides the two extreme values of k_Ga but cannot, by itself, predict the shape of the intermediate portion of the curve because the relative rates of chemical reaction and diffusion must be taken into account as well as the changing effective area. For the same reason, any theory of absorption and chemical reaction in packed columns which does not take account of the variable effective area could not predict quantitatively the effect of concentrations. It should be noted that the concentration of the solute in the gas phase will influence the effectiveness of the semistagnant liquid. The greater this concentration, the lower the effectiveness because the acid in the pockets will be neutralized at a faster rate than at lower concentrations. As both acid concentration in the liquid and solute concentration in the gas must be considered when a reaction occurs with or without a changing effective area, it may be possible to take into account the effect of these concentrations on both the rates and areas at the same time. Sherwood and Pigford (*17*) provide an excellent discussion of simultaneous absorption and chemical reaction.

To test the explanations offered, as suggested, it was necessary to search the literature for reliable mass transfer data obtained with the Raschig rings and Berl saddles for which holdup data are available. Unfortunately, there is a very

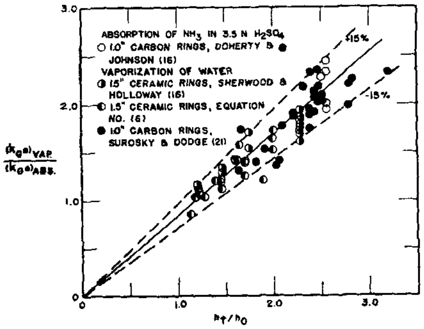

FIG. 11. $(k_Ga)_{vap}/(k_Ga)_{abs}$ vs. h_t/h_o.

limited amount of data suitable for this purpose. An excellent set of data given by Fellinger(*7*) for ammonia absorption in water can be corrected for liquid-phase resistance by means of the Sherwood and Holloway(*16*) correlation and for gas diffusivity to the 2/3 power to provide k_Ga for absorption for all the comparisons desired. Reliable vaporization data are difficult to obtain because end effects are extremely important when the short packing heights required are employed. Surosky and Dodge(*20*) give water-vaporization data for 1.0-in. carbon rings which have been corrected for end effects. Sherwood and Holloway(*16*) report water vaporization data for 1.5-in. ceramic rings for which end effects are estimated to be 35 to 40%. An equation was given for the uncorrected data by Pigford and Colburn (*14*) which is equivalent to

$$k_Ga = 0.0341\, G^{0.69}\, L^{0.33} \qquad (5)$$

Applying a correction of 37.5% based on the investigators' estimate of end effects results in the corrected equation

$$\kappa_Ga = 0.0213\, G^{0.69}\, L^{0.33} \qquad (6)$$

This equation as well as the corrected experimental data can be used for the comparisons. Some data for the absorption of ammonia in sulfuric acid by use of 1.0-in. carbon rings were obtained by Doherty and Johnson and reported by Sherwood and Holloway(*16*). The experimental points of the four sources mentioned were used if the combination of liquid and gas rates fell in the regions investigated in the holdup work reported in Figures 4 to 9. It was felt that excessive extrapolation of the holdup curves was not justified because poor liquid distribution at low liquid rates and rapidly changing holdups at gas and liquid rates above loading would add to the scattering of the original data and result in an inconclusive test of the proposed explanation.

Figure 11 is a plot of the ratio $(k_Ga)_{vap}/(k_Ga)_{abs}$ vs. the holdup ratio h_t/h_o where $(k_Ga)_{vap}$ is the value obtained from the vaporization measurements and absorption runs with high acid concentrations and $(k_Ga)_{abs}$ is the corresponding value for ammonia absorption in water at the same gas and liquid rate, as obtained by Fellinger(*7*). The ammonia and water data were corrected to a common basis by correcting for gas diffusivity to the 2/3 power, employing the values of 0.236 (cm.sq.)/(sec.) for ammonia and 0.256 (cm.sq.)/(sec.) for water at 25°C. and 1 atm. It can be seen that the points fall in a band which is relatively narrow when one considers that the magnitude of some of the ratios represents otherwise unexplainable differences of well over 200%. The best line through the points can be represented by

$$\frac{(k_Ga)_{vap}}{(k_Ga)_{abs}} = 0.85\,\frac{h_t}{h_o} \qquad (7)$$

The broken lines on the diagram 15% above and below the best line indicate the magnitude of the agreement of most of the points. The average deviation from the line given by Equation (7) is ± 8%. The inequality of the two ratios may be caused by the failure of the effective areas to be directly proportional to the holdups as assumed, a different proportionality for the two areas, surface temperature variations making one area less effective than the other, and the possibility that the slow, but finite, turnover of the semistagnant liquid makes some of its area effective for absorption with water work. The departure from equality is not great, however, and it seems as if Equation (7) can be used empirically with Fellinger's data and the holdups to predict mass transfer rates for vaporization and absorption with concentrated absorbents.

A test of the ability of Equation (7) to predict the limiting values of k_Ga for a k_Ga vs. acid concentration plot is shown in Figure 12. The acid-absorption K_Ga data are plotted, and Fellinger's water-absorption value of k_Ga as well as the k_Ga obtained by multiplying it by 0.85 (h_t/h_o) are shown as limiting values. It can be seen that all the experimental data fall between the two as expected, and at high concentrations there is close agreement with the limiting value.

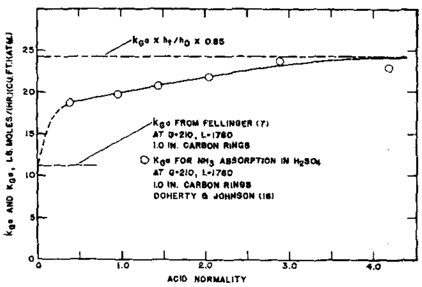

FIG. 12. AMMONIA ABSORPTION IN SULFURIC ACID.

Another packed-column mass transfer anomaly which may be explained eventually with holdup data is the reason for the different effects of gas diffusivity obtained when vaporization and absorption techniques are employed. A large amount of mass transfer data obtained with all sorts of materials and techniques indicates that the gas-phase mass transfer rates should be proportional to gas diffusivity raised to the 2/3 power. However, two seemingly reliable sets of data obtained by vaporization techniques by Surosky and Dodge(*20*) and Mehta and Parekh as reported by Sherwood and Holloway(*16*) indicate the power to be 0.15 to 0.17. The vaporization technique assumes that the effective interfacial area is the same when different liquids wet the packing. In view of the fact that static holdups are a function of surface properties such as interfacial tensions, as illustrated by the differences obtained with carbon and porcelain, one would expect liquids with different physical and chemical properties to wet solid surfaces differently. At the present time this explanation cannot be tested; however, work underway to study the effects of surface tension, viscosity, and the nature of solid surface on holdups may provide the required data.

SUMMARY

Total, static, and operating holdups, obtained for six ring and saddle packings, are represented by Figures 4 to 10 and Equation (1). Equations (2), (3), and (4) may be used to estimate holdups up to loading conditions for rings and saddles larger than those investigated. Total holdups are approximately proportional to the number of pieces of packing per cubic foot. Static holdups are independent of gas and liquid rates but are dependent upon the nature of the surface of the packings; operating holdups are independent of the packing surface.

The holdups can be used to explain the differences between gas-phase mass transfer rates obtained by vaporization and absorption techniques and to provide the limiting mass transfer rates for low and high absorbent concentrations when absorption is followed by an irreversible chemical reaction.

NOTATION

a = effective interfacial area, sq. ft./cu.ft.
D_p = diameter of sphere possessing the same surface area as a piece of packing, ft.
G = superficial gas rate, lb./(hr.)(sq.ft.)
h_o = operating holdup, cu.ft./cu.ft.
h_s = static holdup, cu.ft./cu.ft.
h_t = total holdup, cu.ft./cu.ft.
k_G = gas-phase mass transfer coefficient, lb. moles/(hr.)(sq. ft.)(atm.)
k_L = liquid-phase mass transfer coefficient, lb. moles/(hr.)(sq. ft.)(lb. mole/cu.ft.)
L = superficial liquid rate, lb./(hr.)(sq.ft.)
N = pieces of packing/cu.ft. of packing

Subscripts

vap = obtained by vaporization or absorption in very concentrated absorbents
abs = obtained by absorption in water or extremely dilute absorbents

Greek Letters

α = constant in Equantion (2)
β = constant in Equation (2)
γ = constant in Equation (3)
δ = constant in Equation (4)
ε = void fraction, cu.ft./cu.ft.
θ = constant in Equation (3)
λ = constant in Equation (4)

LITERATURE CITED

1. Chu, J. C., J. Kalil, and W. A. Wetteroth, *Chem. Eng. Progr.*, **49**, 141 (1953).
2. Cooper, C. M., R. J. Christl, and L. C. Perry, *Trans. Am. Inst. Chem. Engrs.*, **37**, 979 (1941).
3. Elgin, J. C., and F. B. Weiss, *Ind. Eng. Chem.*, **31**, 435 (1939).
4. Ergun, S., *Chem. Eng. Progr.*, **48**, 89 (1952).
5. Ergun, S., *Chem. Eng. Progr.*, **48**, 227 (1952).
6. Evans, G. C., and C. F. Gerald, *Chem. Eng. Progr.*, **49**, 135 (1953).
7. Fellinger, L., Sc.D. thesis, Mass. Inst. Technol. (1941).
8. Fenske, M. R., C. O. Tongberg, and D. Quiggle, *Ind. Eng. Chem.*, **31**, 435 (1939).
9. Furnas, C. C., and F. M. Bellinger, *Trans. Am. Inst. Chem. Engrs.*, **34**, 251 (1938).
10. Gamson, B. W., *Chem. Eng. Progr.*, **47**, 19 (1951).
11. Jesser, B. W., and J. C. Elgin, *Trans. Am. Inst. Chem. Engrs.*, **39**, 277 (1943).
12. McCune, L. K., and R. H. Wilhelm, *Ind. Eng. Chem.*, **41**, 1124 (1949).
13. Payne, J. W., and B. F. Dodge, *Ind. Eng. Chem.*, **24**, 630 (1932).
14. Perry, J. H., "Chemical Engineers' Handbook," 3rd ed., Section 10, McGraw-Hill Book Company, Inc., New York (1950).
15. Piret, E. L., C. A. Mann, and T. Wall, *Ind. Eng. Chem.*, **32**, 861 (1940).
16. Sherwood, T. K., and F. A. L. Holloway, *Trans. Am. Inst. Chem. Engrs.*, **36**, 21 and 39 (1940).
17. Sherwood, T. K., and R. L. Pigford, "Absorption and Extraction," 2nd ed., McGraw-Hill Book Company, Inc., New York (1952).
18. Shulman, H. L., and J. J. DeGouff, *Ind. Eng. Chem.*, **44**, 1915 (1952).
20. Simmons, C. W., and H. B. Osborn, *Ind. Eng. Chem.*, **26**, 529 (1934).
21. Surosky, A. E., and B. F. Dodge, *Ind. Eng. Chem.*, **42**, 1112 (1950).
22. Tillson, P., S.M. thesis, Mass. Inst. Technol. (1939).
23. Uchida, S., and S. Fujita, *J. Soc. Chem. Ind. (Japan)*, **39**, 432 (1936); **40**, 238 (1937).
24. Vivian, J. E., and R. P. Whitney, *Chem. Eng. Progr.* **43**, 691 (1947).
25. Whitney, R. P., and J. E. Vivian, *Chem. Eng. Progr.*, **45**, 323 (1949).

II. Wetted and Effective-interfacial Areas, Gas- and Liquid-phase Mass Transfer Rates

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A study was made of separating the volumetric mass transfer coefficients, k_Ga and k_La, into their components k_G, k_L, and a so that the effects of variables might be determined separately for each component. Mass transfer rates for four packings, ½- and 1½-in. Raschig rings and ½-in. and 1-in. Berl saddles, made of naphthalene, were determined by vaporization into air at gas rates from 100 to 1,000 lb./(hr.) (sq. ft.).

The correlation for k_G was used to determine the wetted areas of those packings when irrigated with water and to calculate the effective interfacial areas, a, from Fellinger's data for ammonia absorption. These effective areas were then used to evaluate k_L from previously published k_La data, and a correlation was obtained for all packings.

The correlations for k_G and k_L and the effective-interfacial-area data make possible a more rigorous method for the design of packed columns than was heretofore available.

To predict the performance of columns employing ring and saddle packings for design purposes reliable data such as those of Fellinger(*4*) for volumetric gas-phase coefficients, k_Ga, and of Sherwood and Holloway(*8*) for volumetric liquid-phase coefficients, k_La, are used. Such coefficients can be estimated for aqueous systems from these sources of data and combined by the following relation to give for a limited number of packings the over-all mass transfer coefficients desired for design.

$$\frac{1}{K_Ga} = \frac{1}{k_Ga} + \frac{1}{Hk_La} = \frac{1}{HK_La} \quad (1)$$

Although these sources of data are

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