Holdup, Flooding, and Pressure Drop in Packed Columns During Countercurrent Flow of Mercury and Water

The hydrodynamics of countercurrent flow of liquids with a high density difference cannot be predicted reliably from correlations developed with data on fluids having low densities (usually water and organic solvents). Dispersed-phase holdup, flooding rates, and pressure drop during countercurrent flow of mercury and water were studied with several packing materials. Results show that, for a given packing, flooding rates and holdup can be correlated in terms of a single parameter, the superficial slip velocity. For the mercury-water system, this parameter is shown to be proportional to the packing diameter and packing void fraction for Raschig rings and solid cylindrical packing.

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SCOPE

The hydrodynamics of countercurrent flow of mercury and water in packed columns was studied, and correlations were developed for fluids having high densities and a large density difference. These data should be useful in evaluating and designing liquid-liquid extraction systems using molten salts and/or liquid metals. It was found that existing flooding rate and holdup correlations based on liquid-liquid systems having much smaller density differences could not be extrapolated reliably to the conditions of this study. The correlations resulting from the present study are based upon data covering a relatively narrow range of density differences, and the dependence of flooding rate on density difference has not been accurately established.

The present study provides data on countercurrent column behavior under conditions far removed from those encountered with conventional systems. Although the data have intrinsic value, they will also contribute significantly to the development of more general correlations as data covering a wider range of physical properties become available. The experimental measurements include dispersed-phase holdup, flooding rates, and pressure drop in the continuous phase. Nonwet plastic (polyethylene and Teflon) Raschig ring and solid cylinder packing having diameters ranging from 0.318 cm (1/8 in) to 1.27 cm (1/2 in) were used in the study. Correlations covering the range of parameters used were developed.

CONCLUSIONS AND SIGNIFICANCE

Flooding rates and dispersed phase holdup during the countercurrent flow of mercury and water in packed columns were found to be significantly different from those predicted by previously reported correlations. Dispersed-phase holdup could be correlated in terms of the superficial slip velocity which is defined as

$$V_s = \frac{V_d}{X} + \frac{V_c}{1-X}$$

The superficial slip velocity was essentially a constant, within the scatter of the data, for a given packing material and was more nearly constant than a characteristic velocity $[V_s/(1\text{-}X)]$ used previously to describe holdup in conventional systems.

For a system in which the superficial slip velocity remains constant up to flooding conditions, the flooding curve can be represented by the relation

$$V_{c,f}^{1/2} + V_{d,f}^{1/2} = V_s^{1/2}$$

Flooding data measured in the present study are adequately predicted by this equation using measurements taken at flow rates well below flooded conditions. Correlation of flooding rates and holdup with a single parameter is useful in characterizing hydrodynamic performance with relatively few measurements. In principal, only one flooding or holdup measurement would allow estimation of both quantities over a wide range of conditions. This may be especially useful in large equipment where provisions are not normally made for making holdup measurements.

The superficial slip velocity was found to be proportional to the packing void fraction and to the packing diameter in the present study. No attempt was made to predict the dependence of slip velocity on changes in physical properties of the fluids involved since only one pair of fluids was used. Flow of high density liquids in packed columns deserves further study, and such efforts are planned. Data are needed over a wider range of physical property values, especially density difference, in order that more general correlations can be developed.

The hydrodynamics of countercurrent flow of liquids having high densities and a large density difference in packed columns must be considered in the evaluation and design of contactors for processing molten-salt breeder reactor fuel. The proposed processing methods (McNeese, 1971) involve extraction of protactinium and rare-earth fission products from the molten fluoride fuel salt into liquid bismuth containing reductant. Preliminary experiments by the authors and experience elsewhere (Johnson, et al., 1971) have shown that conventional correlations (at least of flooding rates) derived from data on aqueous-organic systems do not apply to liquid metal-water systems. Likewise, these correlations are not expected to apply to liquid metal-molten salt systems. The difficulties are believed to result largely from the high density difference that occurs with a liquid metal-molten salt combination. Also, the increased interfacial tension between liquid metals and many other fluids, as compared with that for aqueous-organic systems, and the higher viscosity of the continuous phase could contribute to the observed discrepancies.

A study has been carried out on the hydrodynamics of countercurrent flow of mercury and water in columns containing packing materials having several sizes and shapes. The study included measurements of dispersed-phase (metal) holdup, flooding rates, and pressure drop. The objectives were to demonstrate the differences in behavior between conventional and high-density systems and to describe, on a semitheoretical basis, the behavior of a particular system (mercury-water) that has properties similar to those of liquid metal-molten salt systems. Since only one set of physical properties was used in this study, general correlations are not possible; however, the results that were obtained demonstrate the danger involved in extrapolating correlations based on low-density liquids to conditions involving high-density liquids.

REVIEW OF THE LITERATURE

The hydrodynamic property most frequently studied in the case of packed liquid-liquid columns is the column capacity or flooding rate. Breckenfeld and Wilke (1950) measured flooding rates for 0.635 cm (¼ in) Raschig rings and Berl saddles with several fluids. Their data, along with earlier data, were used to develop a flooding rate correlation that can be expressed as

$$(V_{c,f}^{1/2} + V_{d,f}^{1/2})^2 = 32.5 \frac{\Delta\rho^{0.98}\ \epsilon^{1.98}}{a^{0.82}\ \mu_c^{0.32}\ \sigma^{0.26}} \qquad (1)$$

A plot of $V_{c,f}^{1/2}$ versus $V_{d,f}^{1/2}$ yielded a straight line with a slope of -1. The left side of Equation (1) has units of velocity and can be regarded as a measure of column flow capacities. Using additional data for larger Raschig rings, Crawford and Wilke (1951) developed two similar equations. For Reynolds numbers larger than 50, that is,

$$\frac{(V_{c,f}^{1/2} + V_{d,f}^{1/2})^2\ \rho_c}{a\mu_c} > 50$$

the following relation was developed:

$$(V_{c,f}^{1/2} + V_{d,f}^{1/2})^2 = \frac{69.4\ \Delta\rho\epsilon^{1.5}}{\rho_c^{0.8}\ a^{0.5}\ \sigma^{0.2}} \qquad (2a)$$

For Reynolds numbers less than 50

$$(V_{c,f}^{1/2} + V_{d,f}^{1/2})^2 = \frac{79.7\ \Delta\rho^{1.33}\ \epsilon^2}{\rho_c^{0.73}\ a\ \mu_c^{0.33}\ \sigma^{0.27}} \qquad (2b)$$

Ballard and Piret (1950) used 0.635 cm (¼ in) and 1.27 cm (½ in) Raschig rings with several liquids to develop a somewhat different correlation which can be written as

$$\left[V_{d,f}^{1/2} + 1.7\left(\frac{\rho_c}{\rho_d}\right)^{0.3} V_{c,f}^{1/2}\right]^2 = \frac{0.3025 g^{0.55}\ \Delta\rho^{0.93}}{\rho_d^{0.83}\mu_d^{0.1}}\left(\frac{\epsilon}{a^{0.65}}\right)\left(\frac{\sigma_{da}+\sigma_{ca}}{\sigma}\right)^{0.4} \qquad (3)$$

In this form, one can see that a plot of $V_{d,f}^{1/2}$ versus $V_{c,f}^{1/2}$ will still produce a straight line; however, the slope will not necessarily be -1. The importance of several physical properties, especially ρ_c, μ_c, and interfacial and surface tension, is notably different in the correlation.

Dell and Pratt (1951) studied several packing materials with several fluids. They proposed a correlation that can be written as

$$\left[V_{c,f}^{1/2} + 0.835\left(\frac{\rho_d}{\rho_c}\right)^{1/4} V_{d,f}^{1/2}\right]^2 = C_2^2\left(\frac{a}{g\epsilon^3}\right)^{-1/2}\left(\frac{\rho_c}{\Delta\rho}\right)^{-1/2}\sigma^{-1/8} \qquad (4)$$

Again, this expression gives a straight line for a plot of $V_{d,f}^{1/2}$ versus $V_{c,f}^{1/2}$; however, the slope is not -1. C_2 is a constant that is dependent on the type and size of packing material used.

Hoffing and Lockhart (1954) proposed a different type of expression as follows

$$V_c = \left[\frac{\phi\left(\frac{V_{d,f}}{V_{c,f}}\right)\Delta\rho^{1/2}}{\rho_d^{0.22}\ \rho_c^{0.1}\ \mu_d^{0.08}\ \mu_c^{0.1}\left(\frac{\sigma}{\sigma_{ca}}\right)^{0.5}\left(\frac{a}{\epsilon^{1.2}}\right)^{0.67}}\right]^{1.25}\left(\frac{V_{d,f}}{V_{c,f}}\right)^{1/4} \qquad (5)$$

where the function $\phi\left(\frac{V_{d,f}}{V_{c,f}}\right)$ is as defined in their paper.

This expression does not yield a straight line on a plot of $V_{d,f}^{1/2}$ versus $V_{c,f}^{1/2}$.

Nemunaitis et al. (1971) recently reviewed several of these correlations and compared the results with data from Intalox saddles, Pall rings, and Raschig rings. They suggested use of the Crawford-Wilke correlation [Equation (2)] for the design of packed columns; however, the more complex Hoffing-Lockhart correlation [Equation (5)] gave an equally good fit to their data.

Care must be exercised in using these equations under conditions far removed from the conditions for which they were developed. For instance, Equation (2) predicts that the flooding rate depends upon the difference in densities of the liquids ($\Delta\rho$) to the first power (or the 1.33 power in the case of low Reynolds numbers), while Equation (4) predicts a ½-power dependence. The $\Delta\rho$ dependencies in the other correlations fall between these extremes. For small changes in $\Delta\rho$, such as those observed with most organic solvents and water, the correlations remain within reasonable agreement. However, the density difference between mercury and water is one to two orders of magnitude higher than that between water and organic solvents, and the predictions made by the correlations for this system are not in agreement.

Dispersed-phase holdup was studied by Gayler et al. (1953), and the following equation was proposed for correlating the data

$$\frac{V_d}{X} + \frac{V_c}{1-X} = \epsilon V_0 \ (1 - X) \qquad (6)$$

where V_0 is a characteristic velocity. This equation was suggested from experimental data on the rate of hindered settling of solids. Wicks and Beckmann (1955) proposed an expression of the form

$$X = AV_d^r + BV_dV_c^s \qquad (6a)$$

where A, B, r, and s are constants that depend on the packing size. Since this equation was only tested with toluene-water data, it would not be expected to be sufficiently general to extrapolate to mercury-water conditions.

The pressure drop in the continuous phase increases and is of more interest when fluids with high density differences are used. Johnson et al. (1971) studied pressure drop in packed columns during countercurrent flow of Wood's metal and water. They correlated their results with the following equation:

$$\frac{\Delta P}{A/\epsilon^3} = \alpha \ \mu_c \ AV_c + \beta \ \rho_c V_c^2 \qquad (6b)$$

where

$$\frac{A}{\epsilon^3} = B + CV_d^{1.31}$$

Again, since only one set of fluids was used, no attempt was made to extrapolate the results to other fluid systems.

In addition to the studies just mentioned, there is a larger body of literature on hydrodynamic properties of countercurrent flow in gas-liquid systems. This literature has not been reviewed because, in most cases, the packing is wet by the dispersed phase. Usually, this is not the most effective way to operate liquid-liquid systems (Nemunaitis et al., 1971); also, wetting has been shown to alter significantly the behavior of a given column.

EQUIPMENT

Glass columns that were 60.96 cm (2 ft) long and had inside diameters of either 2.54 or 5.08 cm (1 or 2 in) were used in the present study. Expanded end sections having diameters equal to twice the column diameter provided space for inlet liquid lines and for reducing entrainment in the effluent streams. The packing materials were held in the column by screens having openings only slightly smaller than the packing dimensions. Screens having different mesh sizes were used with each packing diameter to minimize the potential for flooding to occur at the screen. Packing was placed in the upper expanded end section and, in some cases, in the lower expanded end section. There was no evidence that packing in the lower end section affected the measurements.

Ball valves were required at the upper and lower ends of the packed column for holdup measurements. When opened, these valves had essentially the same inside diameter as the column and thus generated no flow disturbance. The inside of each valve was devoid of packing, and a valve design that minimized the length of the unpacked section was selected. The length of an unpacked valve section was approximately 1.5 times the inside diameter of the column in each case. With one packing material, pressure drop and flooding measurements made with and without the unpacked ball valve sections showed no detectable differences.

Mercury was pumped into the column with a diaphragm pump, and the flow rate was adjusted by setting the length of the pump stroke. Two pumps were used in the study: a Master Line pump manufactured by the Hills-McCanna Company, Carpenterville, Illinois, and a Lapp-CPS-3 pump manufactured by the Lapp Insulator Company, Le Roy, New York. Pulsations in the mercury flow rate were reduced by placing a surge chamber between the pump outlet and the column inlet. Some fluctuation in the flow rate of metal entering the column could be detected in the expanded section above the column; however, the packing in the upper end section appeared to damp fluctuations in the metal flow rate and thus maintain a steady flow within the column.

Distilled water was circulated through the system by a small centrifugal pump (Eastern model D-11); the flow rate was measured with rotameters. A small fresh water inlet and a bleed stream were used to remove impurities and heat generated by the pumps from the system.

Six packing materials made of either polyethylene or Teflon (that is, materials not wet by mercury) and ranging from 0.318 to 1.27 cm (1/8 to 1/2 in) in diameter were used in this study. The ratio of the column diameter to the packing diameter varied from 4 to 8. It is true that wall effects cannot be neglected at the lowest ratio; however, the column diameter was limited by the mercury supply and the capacity of the mercury pump. To resolve this problem, one packing material (0.635 cm solid cylinders with a length-to-diameter ratio of unity) was evaluated in both the 2.50- and 5.08-cm-I.D. (1- and 2-in-I.D.) columns (that is, columns with column-to-packing diameter ratios of 4 and 8). The results, which showed no significant differences in the two cases, suggest that wall effects are minor. The column void fractions were essentially the same, and the average superficial slip velocity between the phases (the method adopted in this study for correlating holdup) in the two columns differed by less than one standard deviation.

EXPERIMENTAL TECHNIQUE

Quantitative measurements were made of the dispersed-phase holdup, flooding rate, and pressure drop for a range of liquid flow rates. In all cases, the columns were operated with water as the continuous phase. The experimental techniques for the three types of measurements is given below.

Dispersed-Phase Holdup. The volume of the dispersed phase (metal) present in the column was determined by suddenly and simultaneously closing two ball valves located at the top and the bottom of the column, respectively. This isolated the materials present in the column, and the volume of mercury thereby trapped was determined either by measuring the position of the settled metal-water interface or by draining the metal from the column and subsequently measuring the volume of the metal. The total holdup of the dispersed phase is the sum of (1) a static holdup that does not normally drain from the packing and (2) a dynamic holdup that drains readily. The measured values reported in this study are for the dynamic holdup. The static holdup was small (probably $< 3\%$) for the packing materials used.

Flooding Rate. Flooding rates were determined at various metal flow rates by slowly increasing the water flow rate until indications of incipient flooding were observed. Flooding could be observed visually or could be determined by a sharp increase in the pressure drop across the column. The usual evidence of flooding was an accumulation (with time) of mercury in the column. This caused an increase in pressure drop which was usually evident before flooding could be detected visually. A column was not considered to be flooded if constant water and mercury flow rates could be maintained through the column for 15 min with a constant pressure drop. A column was considered to be flooded when the flow of water could not be maintained at a constant rate without an attendant continual increase in pressure drop across the column.

Pressure Drop. The continuous-phase pressure drop was determined by measuring the depression of the metal-water interface at the bottom of the column. The interface was maintained at the bottom of the column by use of a jackleg on the metal outlet from the column. The vent to the jackleg was connected with the top of the column and was filled with water. With no flow through the column, the interface was located at the jackleg

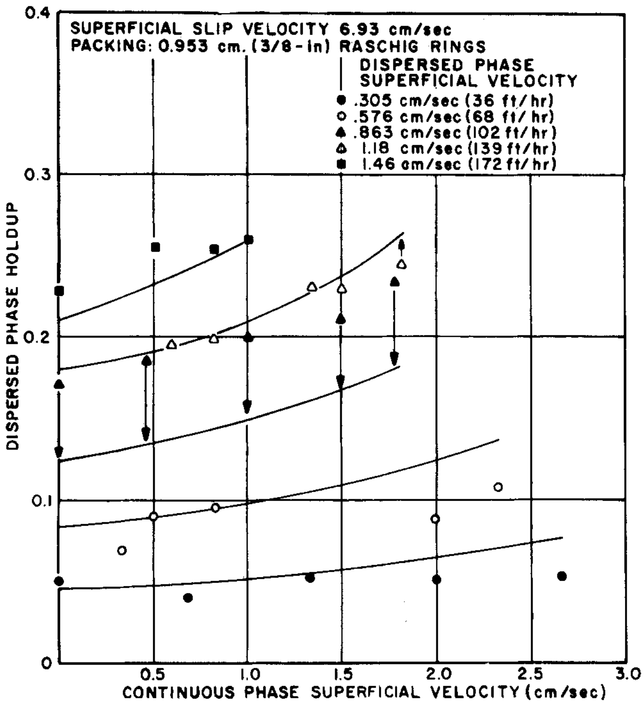

Fig. 1. Predicted and measured dispersed phase holdup in packed columns during countercurrent flow of mercury and water.

elevation. As the flow rate of either phase was increased, the interface was depressed below the level of the jackleg; and the extent of depression was used as a measure of the pressure drop.

RESULTS AND DISCUSSION

Dispersed-Phase Holdup. A typical set of dispersed-phase (mercury) holdup data is shown in Figure 1, where the fraction of the column void volume occupied by mercury is plotted as a function of the superficial velocity of the continuous phase (water). The data are for a 5.08-cm (2 in) diameter column packed with 0.953-cm (⅜ in) diameter Raschig rings. Separate curves are shown for each metal flow rate used. At low metal and water flow rates, holdup is essentially proportional to the metal flow rate. The continuous-phase flow rate becomes important only in the region where flooding conditions are approached. The holdup data shown in Figure 1 and similar data for other packing materials studied can be correlated in terms of a single parameter, the superficial slip velocity, which is characteristic of a given packing material for a particular combination of continuous and dispersed phases. The slip velocity, V_s, is defined as

$$V_s = \frac{V_d}{X} + \frac{V_c}{1 - X} \tag{7}$$

Slip velocity values calculated for each holdup measurement showed no significant trend with either the continuous-phase flow rate or the dispersed-phase flow rate. The average slip velocity values were used to calculate the predicted dispersed-phase holdup for given water and mercury flow rates, and the curves shown in Figure 1 were obtained in this manner. The agreement of the proposed correlation with the individual data points is satisfactory. No explanation can be given for the high results at 0.864 cm/s metal flow. Those results are believed to be in error since they appear to be inconsistent with the remaining data.

The average superficial slip velocities for the packing materials studied, along with the standard deviations of these values, are given in Table 1. The standard deviations are between 5 and 20% of the average slip velocity values; for packing materials having diameters of 0.635 cm (¼ in) or greater, the standard deviations were less than 16% of the respective superficial slip velocities. The scatter in the data appears to be random as illustrated in Figure 2, where the superficial slip velocity is plotted as a function of dispersed-phase holdup for 0.635 cm (¼ in) diameter Raschig ring packing. Differences in the slip velocity values fall within the scatter of the initial holdup data, and no trend is confirmed by similar plots for other packing materials. Thus, for the mercury-water system, dispersed-phase holdup can be correlated over a wide range of water and mercury flow rates by a single parameter V_s. On the other hand, Gayler et al. (1953) have reported that the superficial slip velocity is not constant for aqueous-organic systems which they studied. They defined another characteristic velocity, V_0 [see Equation (6)], which appeared to be more nearly constant. This quantity is related to the slip velocity as

$$V_0 = \frac{V_s}{1 - X} \tag{8}$$

Values for V_0 from the mercury-water system are plotted in Figure 2 and tabulated in Table 1. The scatter in these values is greater than that for the respective values for V_s (see Table 1); also, a significant trend with dispersed-phase holdup is evident (see Figure 2). Thus, it appears that holdup data obtained with high-density fluids are more closely correlated by the superficial slip velocity than by the characteristic velocity proposed by Gayler et al. (1953). In both cases, there is some evidence that the characteristic velocities V_0 or V_s for a given metal rate

TABLE 1. SLIP VELOCITIES WITH MERCURY-WATER

Packing size, cm	Type	V_s cm/s	Standard deviation cm/s	Standard deviation %	V_0 cm/s	Standard deviation cm/s	Standard deviation %	Void fraction
0.318	Solid[1]	2.01	0.408	20.3	4.17	2.67	64.0	0.37
0.476	Rings	6.11	1.17	19.2	7.47	1.0	13.4	0.67
0.635	Solid[1]	2.67	0.14	5.4	4.72	0.61	13.0	0.39
0.635	Rings	6.19	0.61	10.0	8.61	2.17	25.0	0.76
0.953	Rings	6.93	1.02	14.7	8.17	0.99	12.1	0.69
0.953	Rings	8.5	0.96	11.0	11.5	1.69	15.0	0.69
1.27	Rings	12.6	2.05	16.2	15.3	2.66	17.4	0.71

[1] Right circular cylinders.

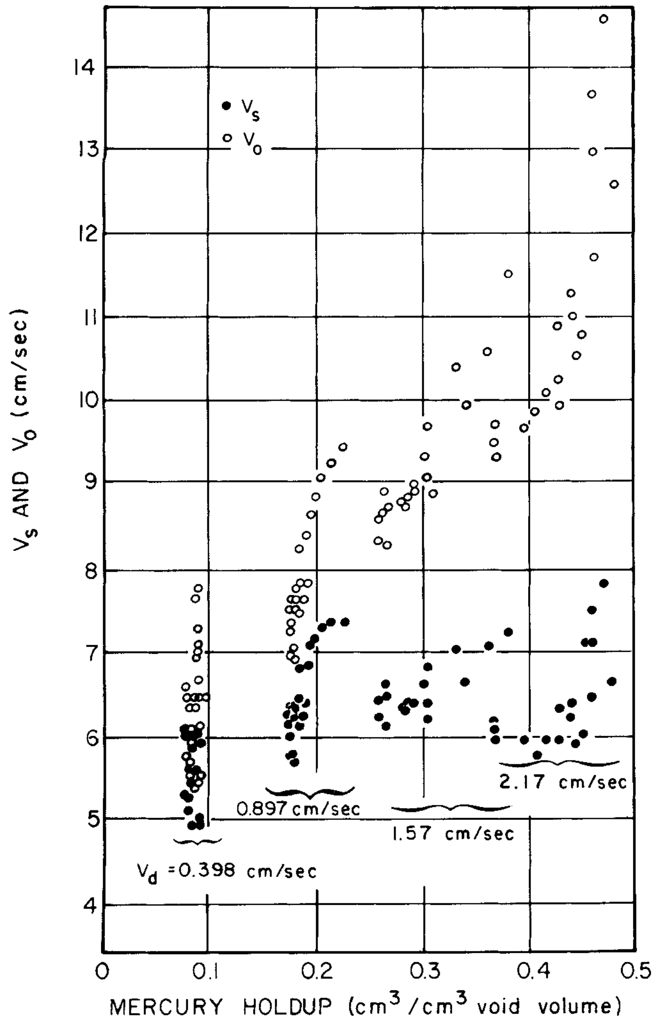

Fig. 2. Variation of V_s and V_0 with mercury holdup in columns packed with 0.635 cm (¼ in) Raschig rings.

increase with V_c, but this trend is far more evident with V_0 than with V_s. The greater horizontal spread of data at high metal rates results because the holdup becomes increasingly dependent on V_c (see Figure 1).

For a given packing diameter, the slip velocity V_s appears to be proportional to the packing void fraction. This is illustrated in Table 1, which shows slip velocities for 0.635 cm (¼ in) Raschig rings and 0.635-cm-diam solid cylindrical packing. The proporti^nality is believed to hold for Raschig rings having a range of wall thicknesses, solid cylinders, and spheres. One of the reported flooding rate correlations discussed earlier [see Equation (3)] indicates that V_s is approximately proportional to ϵ while two others [see Equations (2a) and (4)] indicate that V_s is proportional to $\epsilon^{1.5}$ and two others [see Equations (1) and (2b)] indicate that V_s is proportional to ϵ^2.

The effect of packing diameter on slip velocity is shown in Figure 3, where the slip velocity divided by the packing void fraction is plotted as a function of the packing diameter. The data yield a straight line having a slope of unity on a log-log plot. Consequently, the slip velocity appears to be proportional to the packing diameter as well as to the packing void fraction. The data shown in Figure 3 include results for two solid cylindrical packings and four sizes of Raschig rings. It is believed that this correlation allows the prediction of slip velocity (and hence dispersed-phase holdup) for packing materials within the range of conditions tested. Literature correlations described earlier for flooding rates give an indication of the dependence of slip velocity on packing diameter. Several do not specify diameter directly as a parameter, but they do use area per unit volume in this respect. Also, the slip velocity is not given explicitly; however, in the next section, one can see how it can be inferred from Equations (1) through (5). For similarly shaped packing materials, the area term a is inversely proportional to the packing diameter. Therefore, a diameter dependence near unity (0.82 to 1.0) is predicted by Equations (1), (2b), and (4). (The Dell-Pratt correlation contains a constant that depends upon packing diameter, and the variation of this constant must also be taken into account). Equations (2a) and (3) predict a power dependence near ½.

Flooding Rate Correlation. The superficial slip velocity appears to be constant for a given packing material over a wide range of mercury and water flow rates. A useful correlation for flooding rates can be obtained by assuming that the superficial slip velocity remains constant up to the flooding point. It is assumed that the conditions at flooding can be described by the following relation

$$\frac{\partial V_c}{\partial X} = \frac{\partial V_d}{\partial X} = 0 \tag{9}$$

Combining Equations (7) and (9) yields the following expression

$$V_{c,f}^{1/2} + V_{d,f}^{1/2} = V_s^{1/2} \tag{10}$$

which relates the superficial velocities of the continuous and discontinuous phases at flooding to the superficial slip velocity for the packing under consideration. This relation states that a plot of the square root of the dispersed-phase superficial velocity versus the square root of the continuous-phase superficial velocity should yield a straight line having a slope of −1 and intercepts (on both axes) equal to the square root of the superficial slip velocity. It should be noted that a slope of −1 is predicted by many of the existing flooding correlations. Equation (10) relates these flooding curves to the slip velocity. This equation was used to estimate the diameter dependence

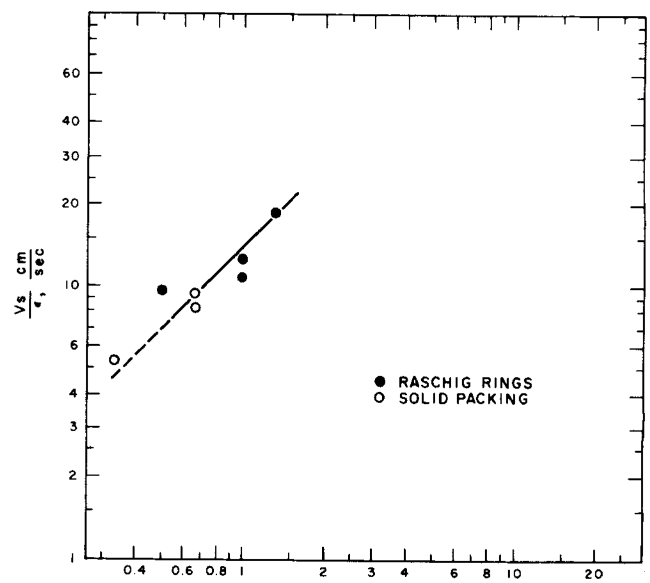

Fig. 3. Effect of packing diameter on superficial slip velocity for Raschig ring and solid cylindrical packing.

of slip velocity observed by previous investigators (as discussed in the previous section).

In Figure 4, which shows a typical flooding curve, the square root of the dispersed-phase flow rate at flooding is plotted as a function of the square root of the continuous-phase flow rate at flooding. The data points shown were obtained with 0.953 cm (⅜ in) diam Raschig rings and represent conditions where flooding was observed. The intercepts for the line shown represent the average superficial slip velocity determined from holdup data, as indicated in Table 1; hence, the line is based upon data obtained with mercury and water at flow rates considerably below flooded conditions. Two slip velocity values are reported in Table 1 for 0.953 cm (⅜ in) Raschig ring packing. The difference in the reported values is believed to result from repacking the column and likely reflects changes in the packing orientation rather than changes in the packing void fraction. It is believed that the use of larger column-to-packing diameter ratios will minimize this effect. The data obtained with a particular packing of the column appear to be self consistent. The slip velocity value of 6.94 cm/sec represents initial data and is based upon fewer experimental data points than the value of 8.5 cm/s. The agreement between the experimentally determined and the predicted flooding rates is satisfactory for the packing materials tested. Within the precision of these measurements (and within the precision needed for most applications), dispersed-phase holdup and flooding can be estimated from a single parameter, the superficial slip velocity, which can be obtained from Figure 3 for the range of packing sizes studied.

CONTINUOUS-PHASE PRESSURE DROP

Curves representing data for pressure drop in the continuous phase resemble holdup curves in many respects. This is illustrated in Figure 5, where the pressure drop across a column packed with 0.953 cm (⅜ in) Raschig rings is plotted as a function of the continuous-phase flow rate for a number of dispersed-phase flow rates. The similarity between Figures 1 and 5 is apparent. Such agreement is to be expected since interaction between the continuous phase and the dispersed phase constitutes a large fraction of the observed pressure drop. The pressure drop data from packing diameters of 0.635 cm (¼ in) or larger are shown in a normalized plot in Figure 6. The ordinate in this figure is the ratio of the measured pressure drop to the mass of mercury held up in the column per unit area of column, that is, the quantity $\Delta P/(XL\Delta\rho)$. The ordinal variable can be interpreted as the fraction of the dispersed phase that is supported by interaction with the continuous phase under conditions where the dispersed phase is not accelerated in passing through the column. If the column con'ained no packing and there was no interaction with the column wall, the value of this quantity would be unity. The fraction of the metal phase that is not supported by interaction with the continuous phase and with the wall is supported by interaction with the packing. It is believed that interaction between the continuous phase and the packing and column wall is responsible for a negligible fraction of the total column pressure drop, and pressure drop measurements made with no metal flow suggest that this assumption is valid.

The abscissa is the ratio of the continuous-phase flow to the superficial slip velocity. The data for two sizes of Raschig rings can be represented by the relation

$$\frac{\Delta P}{gXL\Delta\rho} = A\ D_p + 0.71 \left(\frac{V_c}{V_s}\right) \tag{11}$$

The holdup can be estimated from Equation (7). The intercept of the line defined by Equation (11) is proportional to the packing diameter (for similarly shaped

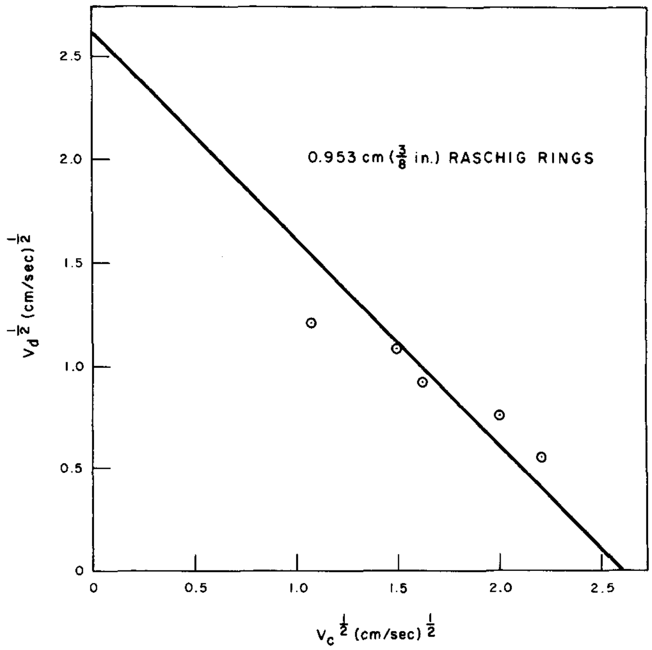

Fig. 4. Predicted and measured flooding rates during countercurrent flow of mercury and water in a 5.08-cm (2-in)-diam column packed with 0.952 cm (⅜ in) Raschig rings.

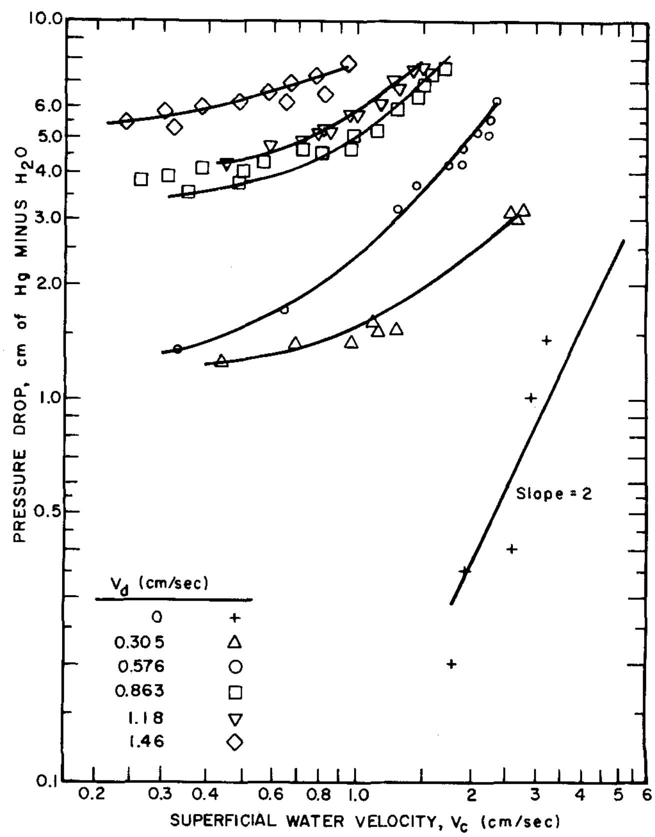

Fig. 5. Variation of column pressure drop with superficial velocities of the continuous and dispersed phases in a 5.08-cm (2-in)-diam column packed with 0.952 cm (⅜ in) Raschig rings.

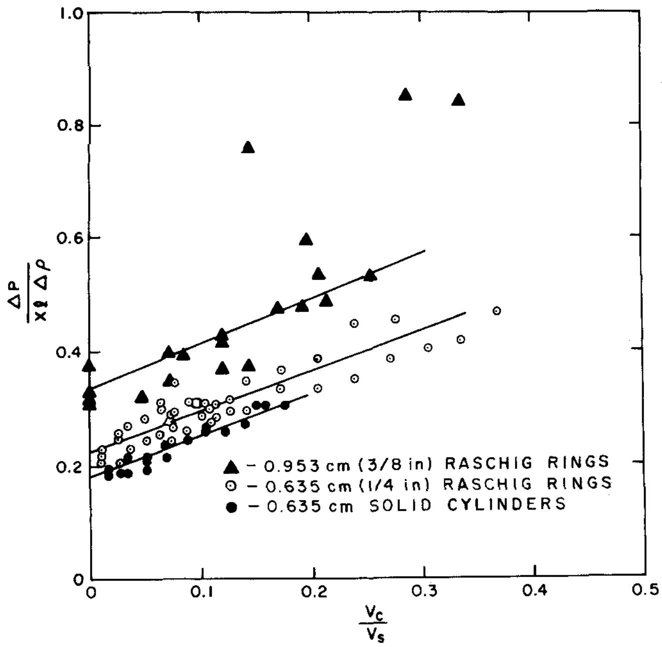

Fig. 6. Ratio of pressure drop to mass of mercury held up in a packed column versus the ratio of the continuous phase superficial velocity to the superficial slip velocity.

packing) or inversely proportional to the packing surface area per unit volume. The constant A has the value 0.36 cm^{-1} (0.92 in^{-1}) for Raschig ring packing. The fraction of the metal holdup supported by the packing with no net continuous phase flow is thus apparently proportional to the packing surface area per unit column volume. The fraction of the metal supported by the packing then decreases (and the fraction supported by the continuous phase increases) linearly with the continuous-phase flow rate. Equation (11) provides a better fit for the present data than does Equation (6b); however, this equation has not been tested for a wide range of physical property variation and, therefore, should be used for other systems with caution.

Critical Packing Size for Obtaining Dispersion of the Metal Phase. Qualitative observations of the behavior of the metal phase during countercurrent flow of mercury and water were also made with the packing materials used in this study. In the case of the larger packing materials [packing diameters of 0.635 cm (¼ in) or greater], the mercury flowed down the column in the form of small droplets. This condition is illustrated in Figure 7 for a column packed with 0.635 cm (¼ in) diam. Raschig rings. The interfacial area between the dispersed and continuous phase was quite large. When the packing diameter was reduced to 0.476 cm (3/16 in) or less, the type of metal flow changed dramatically, as shown in Figure 8. With the smaller packing, the metal phase was largely coalesced and traveled down the column in channel flow. The interfacial area obtained with this mode of flow was much less than that obtained with larger packing. It is believed that the mass transfer behavior would be less favorable with the small packing than with larger packing.

Dell and Pratt (1951) reported a transition in the mode of dispersed-phase flow during countercurrent flow of aqueous and organic streams in columns packed with materials wet by the dispersed phase. The transition was reported to occur at a critical packing diameter D_p, given by the relation

$$D_p^* = 2.42 \sqrt{\frac{\sigma}{g\Delta\rho}} \qquad (12)$$

The transition point predicted by this equation is below a packing diameter of 0.476 cm (3/16 in); however, data from the present study indicate that the transition point lies between the two packing diameters of 0.476 cm and 0.635 cm. Since only one set of physical properties was used in this study, the reported correlation cannot be tested over a significant range of conditions; the data obtained, however, suggest a larger value (approximately 3) for the dimensionless constant.

The flow pattern for the dispersed phase was also affected by the rates of flow of both the dispersed phase and the continuous phase. The droplets of dispersed phase began to coalesce with greater frequency as flooding conditions were approached. Nevertheless, this change in behavior was not as dramatic as that noted in the vicinity of the critical packing diameter; the metal droplets were never as completely coalesced as those shown in Figure 8.

SUMMARY AND CONCLUSIONS

Packed columns were operated with a single set of liquids, mercury, and water, that have a large difference in density and that do not wet the packing material. Results show that the hydrodynamic properties of this system are considerably different from those predicted by

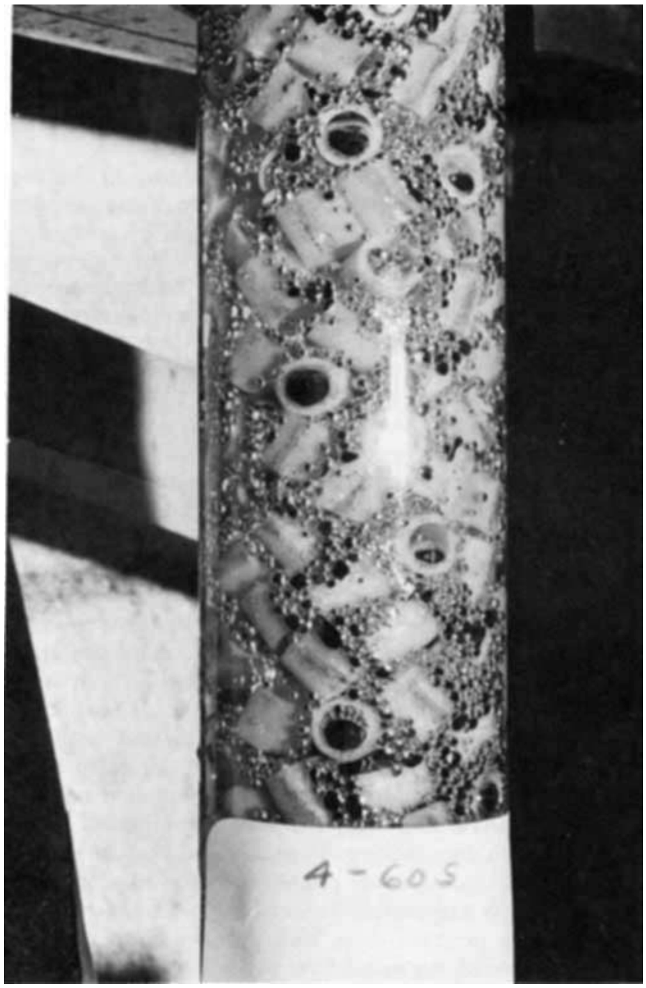

Fig. 7. Countercurrent flow of mercury and water through a 2.54-cm (1-in)-diam column packed with 0.635 cm (¼ in) Raschig rings. Superficial water and mercury velocities were 0.466 and 1.57 cm/s, respectively.

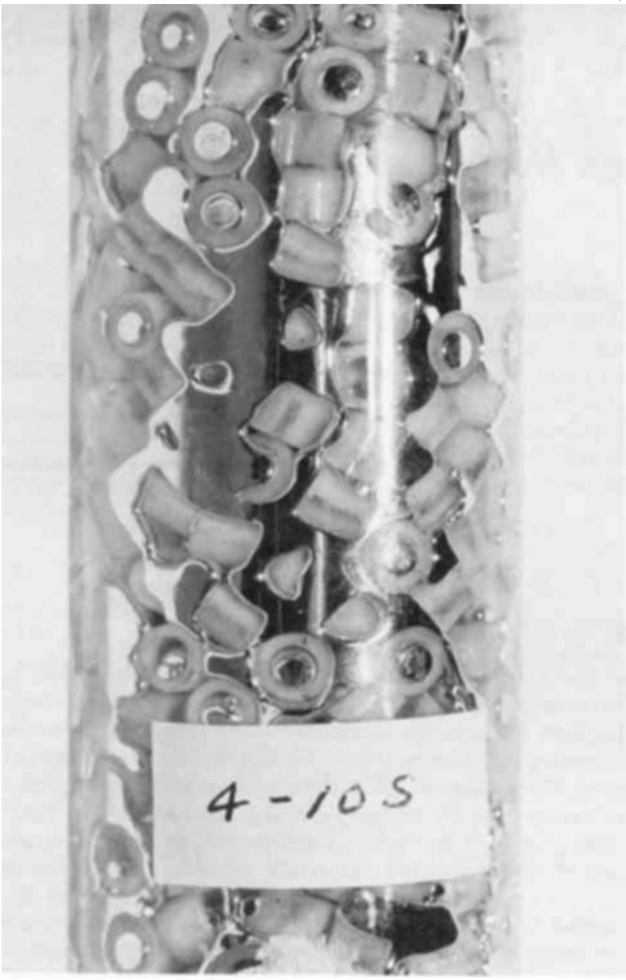

Fig. 8. Countercurrent flow of mercury and water through a 2.54-cm (1-in)-diam column packed with 0.476 cm (3/16 in) Raschig rings. Superficial water and mercury velocities were 0.0787 and 1.57 cm/s, respectively.

correlations developed for liquids having a low density difference. It was found that holdup of the dispersed phase and flooding rates can be correlated over a wide range of water and mercury flow rates by a single parameter, the superficial velocity. A correlation is given which allows this parameter to be predicted from the packing diameter and the packing void fraction. A relation is given which allows calculation of the column pressure drop over a range of conditions. A sharp transition in behavior of the metal occurs during countercurrent flow of mercury and water at a packing diameter between 0.476 and 0.635 cm (3/16 and ¼ in). Larger packing diameters result in improved dispersion and a greater interfacial area between the continuous and dispersed phases.

Further studies, using other systems, are recommended in order to extend this investigation of the effects of physical properties of the continuous and dispersed phases during countercurrent flow of liquids having a large difference in density.

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NOTATION

a = cm^2 of packing surface/cm^3 of packing volume
A, B, C, r, s = constants used in particular correlations
D_p = diameter of packing
D_p^* = critical diameter of packing, cm
g = gravitational acceleration (980 cm/sec^2)
L = length of column, cm
V_c = superficial velocity of the continuous phase, cm/s
V_d = superficial velocity of the dispersed phase, cm/s
V_0 = characteristic velocity, cm/s
V_s = superficial slip velocity, cm/s
$V_{c,f}$ = superficial continuous-phase velocity at flooding, cm/s
$V_{d,f}$ = superficial dispersed-phase velocity at flooding, cm/s
X = fraction of the void volume of the column occupied by dispersed phase, dimensionless

Greek Letters

α, β = constants used in particular correlations
ΔP = pressure drop in the continuous phase, dynes/cm^2
$\Delta\rho$ = difference in densities of dispersed and continuous phases, g/cm^3
ϵ = void fraction of the packed column, dimensionless
μ = viscosity, poise
ρ = density, g/cm^3
σ = interfacial tension between the continuous and dispersed phases, dynes/cm (subscripts *ca* and *da* refer to the interfacial tension between the continuous or dispersed phase and air, for example, surface tension)

Subscripts

c, d = subscripts denoting continuous and dispersed phases, respectively

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