Operating Holdup on Film-Type Packings

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Liquid holdup is one of the most significant basic operating parameters for irrigated packed columns. Because of its influence on gas-phase pressure gradient and on the course of chemical reaction in a column, there is a need for a reliable method for predicting holdup.

Buchanan (1967) has offered a general form of equation for operating holdup below the loading point on packings of the type used in industrial absorption and distillation columns. In that work it was shown that there are two limiting regimes of film flow to be considered: a gravity-viscosity regime in which the film number is the controlling parameter, and the gravity-inertia regime in which the Froude number controls. The film number, Fi, is $\mu u/\rho g d^2$, a ratio of viscous forces to gravity forces; the Froude number, Fr, is u^2/gd, a ratio of inertial forces to gravity forces. Real flows are usually in a mixed regime between these limits and it was found that a good correlating equation for operating holdup could be formed by adding the separate holdup contributions in an equation

$$h_o = AFi^{1/3} + BFr^{1/2} \tag{1}$$

A large body of literature data for ceramic Raschig rings was examined and the coefficients A and B were established to be 2.2 and 1.8, respectively, for this packing.

The most reliable earlier correlation was that of Otake and Okada (1953). It was found that Eq. 1, with only two arbitrary coefficients, whose values could be predicted with fair accuracy from simple theoretical models, described the data over a range of nearly five orders of magnitude in Reynolds number with a precision only slightly less than that of the equations of Otake and Okada, which employ four arbitrary constants in each of two equations—one equation for each of two ranges of Reynolds number.

In this work, some deficiencies of the earlier correlation are noted and explained as probably being caused by the neglect of changing wetted area. A new correlation is developed. A correlation of somewhat similar form recently proposed by Saez and Carbonell (1985) is examined and is found to be unsatisfactory for packings of this type.

Development of Correlation

When applied to some new experimental results, the correlation defined by Eq. 1 was found to give a good description of the data as a whole; but results for varied flows of a liquid of viscosity 0.25 Pa · s, which was much higher than any viscosity studied before, showed a strong trend across the correlating line. The same trend could be discerned to a less marked degree, in results for a liquid of viscosity 0.04 Pa · s. For small Reynolds numbers the influence of liquid rate is greatly underestimated by Eq. 1. This observation was verified in the original data and is illustrated in Figure 1; the effect is exaggerated by the scales chosen, but it can be seen that for small Reynolds numbers, the lines fitted to sets of points run across the correlating line quite sharply.

The exponent on the film number in Eq. 1 comes from the well-known equations for fully developed laminar film flow down an inclined plane. In the development of this term it was shown that for small Reynolds numbers

$$h_o = \text{const } Fi^{1/3}(a_w d)^{2/3} \tag{2}$$

but, in the absence of a simple equation for wetted area, the influence of liquid rate on wetted area was neglected. Since wetted area does increase with increase of liquid rate and since the film number is the controlling parameter in this regime, there is warrant for using a rather larger exponent on the film number to take account of the wetted-area effect.

When an attempt was made to improve the correlation by the use of a larger exponent on the film number, the points for small Reynolds numbers were successfully realigned; but it now appeared that for large Reynolds numbers the effect of liquid rate had been overestimated—the exponent on the Froude number seemed too great.

The exponent ½ on the Froude number in Eq. 1 arose from a model, developed in that paper, of interrupted flow of a falling film unaffected by viscosity. Frictional effects were ignored. The model should apply exactly to free-falling drops but it seems not entirely suitable to describe a film flow that might well still be affected by friction even at large Reynolds numbers.

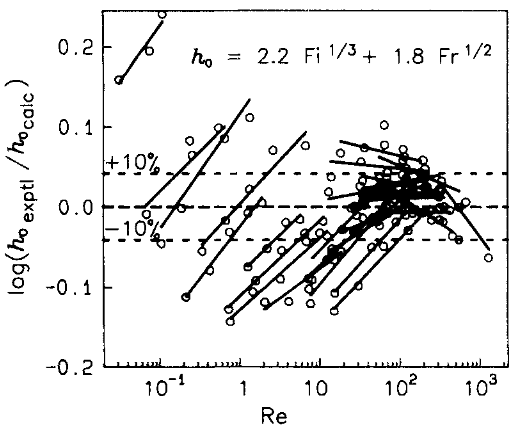

Figure 1. Operating holdup on Raschig rings.
Earlier correlation with lines of best fit for sets of experiments

A perhaps more convincing model has been proposed by Bemer and Kalis (1978). Assuming that the film flow is affected by friction and that, as in pipe flow, the friction factor approaches a constant value for large Reynolds numbers, they advance a holdup equation of form:

$$h_o = \text{const } Fr^{1/3} \tag{3}$$

Because it fails to allow any influence of liquid viscosity, Eq. 3 is not a satisfactory general equation. It cannot and does not correlate the existing data for small Reynolds numbers. But as the limiting case for large Reynolds numbers it gives a better description of the experimental facts than does Eq. 1.

The original work (Buchanan, 1967) assumed a constant wetted area in considering the effect of the Froude number; Bemer and Kalis made the same assumption in their work. Again, this assumption is unlikely to be completely valid and, in fact, in the course of deriving their equation Bemer and Kalis found a relation equivalent to

$$h_o = \text{const } Fr^{1/3}(a_w d)^{2/3} \tag{4}$$

but thereafter they ignored the possibility of wetted area changing with flow rate. Froude number is the controlling parameter in this regime and it appears that, to take account of the influence of liquid rate on wetted area, the exponent on the Froude number should be greater than ⅓.

Thus, with these modifications, a more flexible holdup equation is proposed:

$$h_o = AFi^n + BFr^m \tag{5}$$

The exponents n and m are each expected to be somewhat larger than ⅓.

The constants for Eq. 5 were established by a reexamination of the data used in the 1967 study. The sources and the principles by which the data were selected are described at length in that work. The new data that prompted this study did not quite meet the requirement for high column-to-packing size ratio established earlier and they were not used in the correlation, although in fact they fit it very well.

A simple search method was employed in which a range of possible values of the exponents n and m was explored and for each pair of exponents the coefficients A and B were calculated by a least-squares technique. Because the data were not distributed in any regular way, it seemed unnecessary—even undesirable—to insist upon an overall statistical optimization. Instead, the constants were chosen subjectively to give the best looking correspondence of the lines for different sets of measurements with the trend of the whole line. In fact, the constants finally chosen were only slightly different from the statistical optimum for the data. The final equation for ceramic Raschig rings is

$$h_o = 9.25Fi^{0.48} + 0.805Fr^{0.36} \tag{6}$$

The correlating line, the points employed in the correlation, and the lines of best fit for sets of points, where applicable, are shown in Figure 2. The root mean square deviation of the points from the correlating line is 10.6% (or rather a factor of 1.106, either multiplying or dividing), considerably better than that for Eq. 1 or for the equations of Otake and Okada. Equation 6 is recommended for the estimation of holdup on ceramic Raschig rings and the general form, Eq. 5, should apply, below the loading point, for any packing of the film type. For any particular packing shape, the coefficients A and B and the exponents n and m should be constants. For different shapes, they could be expected to take on different values.

The values found for the exponents n and m imply that for small Reynolds numbers $a_w \propto Fi^{0.22}$ and for large Reynolds numbers $a_w \propto Fr^{0.04}$.

Equation of Saez and Carbonell

Equations 1 and 6 show a strong family resemblance to an equation for the prediction of holdup on granular materials presented recently by Saez and Carbonell (1985):

$$\delta = [180(Re^*/Ga^*) + 1.8(Re^{*2}/Ga^*)]^{0.41} \tag{7}$$

where δ is called the reduced saturation of an irrigated bed and is defined by

$$\delta = h_o/(\epsilon - h_s) \tag{8}$$

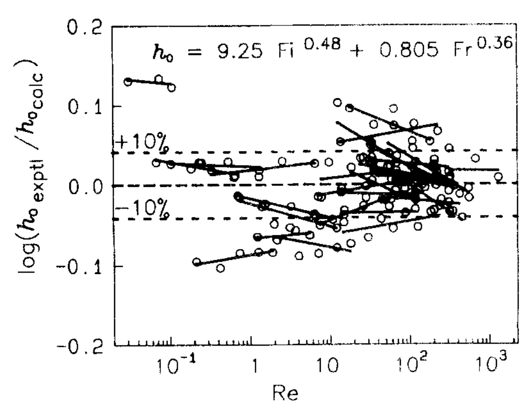

Figure 2. Operating holdup on Raschig Rings.
New correlation with lines of best fit for sets of experiments

In the terms used here, the equation may be rewritten as

$$h_o = (CFi + DFr)^{0.41} \tag{9}$$

where

$$C = 180(\epsilon - h_s)^{2.43}(d/d_e)^2(1 - \epsilon)^2/\epsilon^3 \tag{10}$$

$$D = 1.8(\epsilon - h_s)^{2.43}(d/d_e)(1 - \epsilon)/\epsilon^3 \tag{11}$$

and

$$d_e = 6 \times \text{particle volume/external area of particle} \tag{12}$$

The equations are not strictly comparable with Eqs. 1 or 6, but the appearance of the sum of functions of the film number and the Froude number, one or the other tending to dominate according to the value of Reynolds number, shows the essential similarity of the two approaches.

The numerical coefficients in Eq. 7 are not arbitrary but are the experimentally determined coefficients from Ergun's equation for pressure gradient in single-phase flow through packed beds. Only the exponent 0.41 was derived from holdup experiments.

This approach suffers from the disadvantage that the quantities d_e, ϵ, and h_s are often not available. More seriously, the equation gives very poor predictions for operating holdup on column packings.

The holdup experiments described by Shulman et al. (1955a, b) were carried out in a column of 30 cm ID using a range of flows of a variety of liquids irrigating several sizes of ceramic Raschig ring and Berl saddle packings. They are exceptional in recording all of the packing properties needed to check the Saez-Carbonell equation. But the reported experimental values for operating holdup are consistently two to three times those predicted by Eq. 7. The Raschig ring data form a large part of the data set used to derive Eq. 6 and they are well correlated by it.

It seems that the Saez and Carbonell equation, although apparently successful for granular particles, may not be suitable for application to the large, high-voidage, manufactured shapes of packings used in industrial mass transfer operations.

Acknowledgment

The author gratefully acknowledges the hospitality of the Department of Chemical Engineering of the University of Texas at Austin where this work was done.

Notation

a_w = wetted interfacial area, m^2/m^3
A, B, C, D = constants
d = nominal packing size, diameter/height of Raschig rings, m
d_e = spherical equivalent packing size, Eq. 12, m
Fi = film number $\mu u/\rho g d^2$
Fr = Froude number u^2/gd
g = local gravitational acceleration, m/s^2
Ga^* = Galilei number $\rho^2 g d_e^3 \epsilon^3/\mu^2(1 - \epsilon)^3$
h_o = operating holdup, m^3/m^3
h_s = static holdup, m^3/m^3
n, m = empirical exponents
Re = Reynolds number $\rho u d/\mu$
Re^* = modified Reynolds number $\rho u d_e/\mu(1 - \epsilon)$
u = superficial liquid velocity, m/s

Greek letters

δ = reduced saturation
ϵ = voidage (dry)
μ = liquid viscosity, Pa · s
ρ = liquid density, kg/m^3

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Manuscript received July 2, 1987, and revision received Sept. 14, 1987.