The Hysteretic Behavior of Pressure Drop and Liquid Holdup in Trickle Beds

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Experimental observations are presented concerning the hysteretic behavior of the total holdup and pressure drop in trickle-bed reactors. Evidence for the existence of multiple hydrodynamic states dependent on the prior history of the packed bed was first presented by Kan and Greenfield (1978, 1979). By maintaining a constant liquid flow rate and varying the gas flow rate, the pressure drops and liquid holdups obtained differed by as much as 50 and 10%, respectively, depending on the maximum gas flow rate achieved and whether the gas flow rate was increasing or decreasing. Kan and Greenfield hypothesized that the hysteresis was the result of a change in tortuosity and breakage of liquid bridges transverse to the direction of flow as the gas flow rate was increased; however, when they tried to confirm this explanation by decreasing the surface tension of liquid, no change in the hysteresis was observed. More recently Levec et al. (1986) found that even when the gas flow rate is zero, the liquid holdup for increasing and decreasing liquid flow rates can exhibit hysteresis. They also found a large hysteresis in the pressure drop for increasing and decreasing liquid and gas flow rates. Christensen et al. (1986) attributed the path dependence as being due to liquid flow in two different modes: rivulet flow and film flow. Their measurements were made in a large two-dimensional bed using a microwave attenuation technique for measuring the liquid holdup. Christensen et al. (1986) found higher liquid holdups in the increasing flow regime than in the decreasing flow regime. This result is the opposite of that found by Levec et al., who used a dynamic weighing method to measure liquid holdups in a cylindrical bed. The weighing method is apparently more accurate than the microwave method, and allowed for accurate measurements of the static liquid holdup as well. Sáez and Carbonell (1985), Sáez et al. (1986), and Levec et al. (1986) developed a correlation for liquid holdup and gas phase pressure drop in which the multiplicity of hydrodynamic states was reflected in changes in the liquid phase and gas phase relative permeabilities. The main purpose of this work is to present some new observations based on a detailed experimental study of the hysteretic behavior of the pressure drop and liquid holdup in trickle beds.

Experimental Apparatus and Procedure

The experimental system used in this study is described in detail in a previous paper by Levec et al. (1986). The column had dimensions of 17.2 cm ID, and 130 cm of total packing length. The packing material used consisted of glass spheres of 0.3 cm dia. The bed porosity was 0.375, and the measured static liquid holdup was 0.022. The flow distributor had 550 capillary tubes at 0.6 cm pitch with 0.09 cm ID and 3.0 cm length, through which water was pumped into the column. The capillaries were held between two Pertinax plates. The bottom plate had circular holes around the capillaries; the holes were slightly larger in diameter than the outer diameter of the capillary tubes, the small tolerance allowing for the flow of air introduced to the chamber between the two plates. The top of the packing was 0.5 cm below the distributor. Measurement of the dynamic liquid holdup was accomplished by weighing the column during operation by means of a strain gauge (N/SL from BLH Electronics, USA) with a sensitivity of 360 V/kg, allowing the detection of 5 g weight differences from a total dry column weight of 80 kg. The liquid and gas phases used were water and air.

In the zero gas flow rate experiments, the column was preflooded and then allowed to drain for about 20 min. The liquid flow rate was subsequently increased to the flooding point, and then gradually decreased to the minimum flow rate. In subsequent cycles, the liquid flow rate was increased again to some intermediate value less than the flooding velocity and then decreased. Liquid holdup measurements were taken throughout these cycles.

In the two-phase flow experiments, high liquid and gas flow rates were used to induce pulsing flow at the start of a set of runs to assure complete wetting of the bed. The packed bed was then allowed to drain for 20 min. The gas flow rate was fixed and the liquid flow rate was increased to the desired value and then decreased. Simultaneous measurements of the liquid holdup and the pressure drop were taken. Other experiments were done at a fixed liquid flow rate and variable gas flow rate. Since the holdup is not a strong function of the gas flow rate, only pressure drop changes were recorded in this set of experiments.

Results and Discussion

For the case of zero gas flow rate, experimental results are presented in Figures 1 and 2. In order to test for the possible effect of the maximum liquid flow rate on the hysteresis, the liquid flow rate was increased to maximum liquid Reynolds numbers of 93.92, 70.44, and 41.09 for runs 1, 2, and 3, respectively. Each run consisted of two cycles and the run began with the draining of the column over a 20 min. interval. A cycle started with the lowest Reynolds number (1.17). The liquid flow rate was increased up to the highest Reynolds number and then subsequently reduced to its minimum value to end the cycle. In each run, increasing the liquid flow rate in the second cycle did not show notable hysteresis; the liquid holdups for the second cycles in each run followed the decreasing flow path. As shown in Figure 1, the paths for increasing liquid flow in these three runs were nearly the same. In the decreasing liquid flow operation, however, the greater the maximum liquid Reynolds number was, the higher were the liquid holdup values obtained. In addition, a separate run consisting of three successive cycles increased up to the flooding point Reynolds number (129) illustrated much less pronounced hysteresis once the flooding point was reached. The average mean relative deviation for the decreasing flow rate data compared to the Levec et al. (1986) correlation was 7.3% using 606 data points.

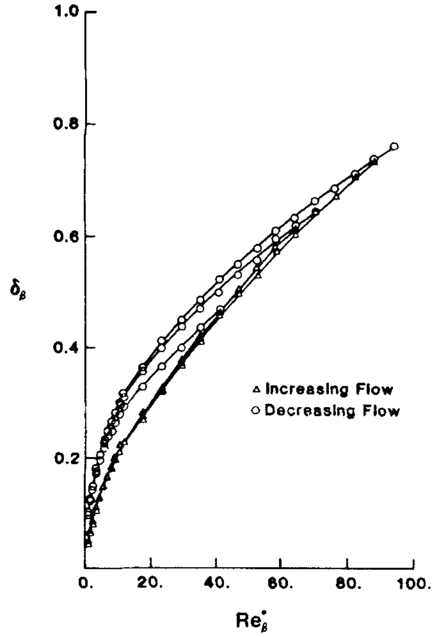

Figure 1. Three cycles of liquid holdup at various liquid Reynolds number.
$Re_g^* = 0$; $Re^*_{\beta,\max} = 93.92, 70.44, 41.09$

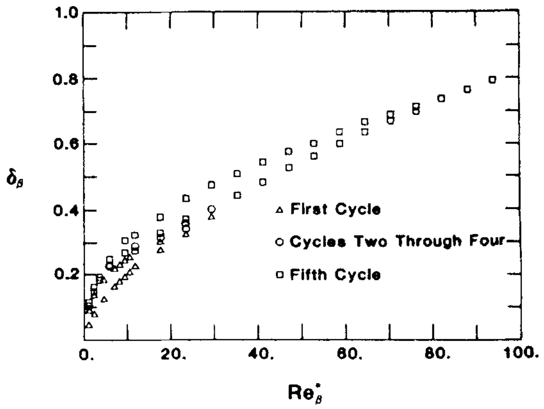

Figure 2. Five cycles of liquid holdup at various liquid Reynolds numbers.
$Re_g^* = 0$; $Re^*_{\beta,\max} = 29.35$ (4 times), 93.92

The indication here is that the liquid holdup is dependent on the hysteretic behavior of the contact angle at the gas-liquid-solid contact line. The contact angle is larger for liquid advancing on a dry solid than for a liquid receding from a wetted solid. The smaller contact angle leads to a higher liquid holdup. It is important to remember that our column does not start out dry during the first cycle, but has been brought to the pulsing regime and then drained over a 20 min period.

Figure 2 shows four cycles with a maximum liquid Reynolds number of 29.35, and then a fifth cycle increasing the liquid Reynolds number to 93.92 and then decreasing it. No draining was done between cycles. The second, third, and fourth cycles show increasing and decreasing liquid holdup values along the same curve as the decreasing curve of the first cycle. The fifth cycle shows increasing liquid holdup values following the same curve as the previous three cycles, up to the Reynolds number of 29.35; it then continues with the same behavior obtained in the first cycle of Figure 1.

Two types of two-phase flow experiments were performed. In the first type a constant gas flow rate was maintained as the liquid flow rate was increased to the pulsing flow regime, and then decreased again to the minimal value. Representative results for the pressure drop at a gas Reynolds number of 41.316 are presented in Figure 3. Measurements of liquid holdup and pressure drop were also made at a gas Reynolds number of 11.268. Average mean deviations with respect to the correlation of Levec et al. (1986) were 4.9 and 9.7% for the liquid holdups, and 25.8 and 64.9% for the pressure drops at gas Reynolds numbers of 11.268 and 41.316, respectively, for 146 data points. In the cycles following the first cycle, the liquid holdup in the increasing and decreasing liquid flow operations follows the same decreasing flow path since no draining is done between cycles, but hysteretic behavior is maintained in the pressure drops. The pressure drops in the decreasing flow operation were significantly higher. It is apparent that the overall dynamic liquid holdup values alone do not completely determine the pressure drop. The indication here is perhaps that the radial distribution of the liquid in the bed changes depending on whether the liquid

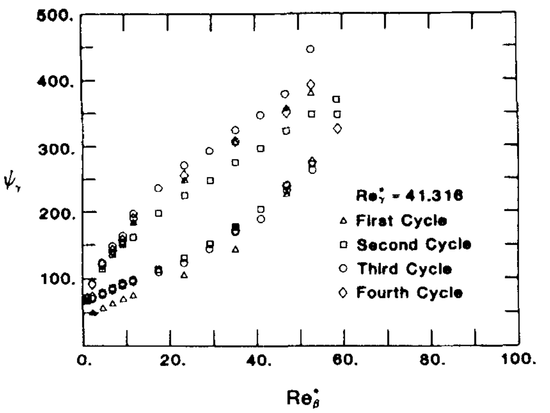

Figure 3. Four cycles of dimensionless pressure drop at various liquid Reynolds numbers.

$Re_\gamma^* = 41.316$; $Re_{\beta,\max}^* = 64.57$; pulsing flow

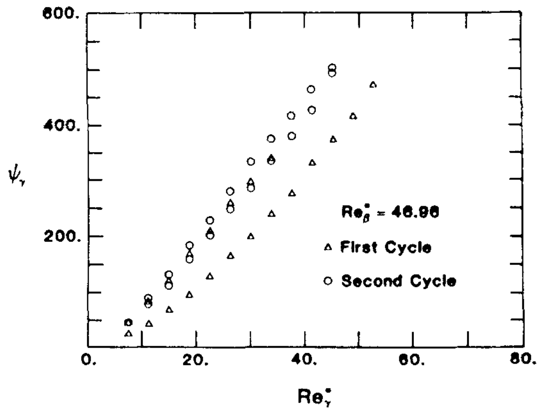

Figure 4. Two cycles of dimensionless pressure drop at various gas Reynolds numbers.

$Re_\beta^* = 46.96$; $Re_{\gamma,\max}^* = 56.340, 56.340$; pulsing flow

flow rate is increasing or decreasing. This is similar to the idea proposed by Christensen et al. (1986) in which the structure of the flow changes depending on the history of operation of the column. The differences in liquid holdup values between the increasing and decreasing liquid flow operations were a maximum of 20 and 42% for the constant gas Reynolds numbers of 11.268 and 41.316, respectively. The differences between pressure drops measured during increasing and decreasing flow rates were 60 and 78% for constant gas Reynolds numbers of 11.268 and 41.316.

In the second type of two-phase flow experiment, a constant liquid Reynolds number was maintained as the gas flow rate was increased to a maximum value not in the pulsing regime, and to a maximum value in the pulsing regime in a subsequent run, Figure 4. The liquid holdup was not measured in these experiments, as its sensitivity to the changes in gas flow rate was close to the limits of experimental error. On the contrary, the pressure drop was very much dependent on the changes in the gas Reynolds number. If pulsing was not reached, hysteresis in pressure drop data still existed; however, it was not nearly as pronounced as when pulsing was reached. In the first cycle shown in Figure 4 for a liquid Reynolds number of 46.96, pulsing was reached and the data display differences up to 47.5% between the increasing and decreasing gas flow rate cases. The second cycle in Figure 4 was not brought to pulsing and the data exhibit a maximum difference of 14.9% between the increasing and decreasing gas flow data. This is perhaps an indication that pulsing flow induces a more uniform distribution of liquid in the bed.

Conclusions

Experimental observations regarding the case of zero gas flow rate in a trickle bed indicate that the liquid holdup depends on the maximum liquid flow rate achieved, its value being larger the greater the maximum liquid Reynolds number reached in the column, up to the flooding point liquid Reynolds number. For the two-phase flow case at constant gas Reynolds number, no hysteresis is observed in the liquid holdup once pulsing has been attained, but hysteresis is observed in the pressure drop. Pressure drops in the decreasing flow operation are significantly higher than in the increasing flow operation. The differences in pressure drop between increasing and decreasing liquid Reynolds numbers are greater the larger the gas flow rate. Pulsing flow may redistribute the liquid, causing different pressure drop values for increasing and decreasing liquid flow rate. The liquid texture (films and rivulets) is changed much more by changes in the liquid flow rate than by changes in the gas flow rate. For the two-phase flow case at constant liquid Reynolds number, notable hysteretic behavior in pressure is observed in cycles in which pulsing flow is achieved. When no pulsing is attained, only very small differences in pressure drop are observed between the increasing and decreasing gas flow rate cases. Pulsing flow may cause an irreversible change in the liquid distribution with respect to subsequent cycles of increasing and decreasing gas flow rate.

Acknowledgment

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Notation

d_e = equivalent diameter of the particles, $6V_p/S_p$
g = gravitational acceleration constant
Re_α^* = Reynolds number for α phase, $\rho_\alpha \langle v_\alpha \rangle d_e/(1-\epsilon)\mu_\alpha$
S_α, S_α^o = saturation of the α phase $(\epsilon_\alpha/\epsilon)$, reduced saturation $(\epsilon_\alpha^o/\epsilon)$
S_p = external surface areas of particles
$\langle v_\alpha \rangle$ = superficial velocity of the α phase
V_p = volume of particles

Greek letters

ϵ = porosity of bed
ϵ_α = volume fraction of bed occupied by α phase
ϵ_β^o = residual or static holdup of liquid in bed
μ_α = viscosity of α phase
ρ_α = density of α phase
ψ_γ = dimensionless pressure drop in gas phase, i.e., pressure drop in gas phase$/\rho_\gamma g$
δ_α = reduced saturation of α phase $(S_\alpha - S_\alpha^o)/(1 - S_\alpha^o)$

Subscripts

β = liquid phase
γ = gas phase
α = β or γ

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Errata

In the paper entitled "The Discharge of Two-Phase Flashing Flow in a Horizontal Duct" [33(3), p. 524, March, 1987], −2 was left out in the denominator of the lefthand side of Eq. 8. This mistake, however, does not affect the final development of the paper. It should read (after multiplying the right side by −2):

$$N = 4f\frac{L}{D} = \frac{2}{G^{*2}}\left[\frac{\eta_1 - \eta_2}{1 - \omega} + \frac{\omega}{(1 - \omega)^2}\ln\frac{(1 - \omega)\eta_2 + \omega}{(1 - \omega)\eta_1 + \omega}\right] - 2\ln\left[\frac{(1 - \omega)\eta_2 + \omega}{(1 - \omega)\eta_1 + \omega}\left(\frac{\eta_1}{\eta_2}\right)\right] \tag{8}$$

We thank Dr. D. A. Shaw of Monsanto Company and Dr. H. Giesbrecht of BASF (Germany) for pointing out the discrepancy.

In the paper entitled "Forced Convection: IV. Asymptotic Forms for Laminar and Turbulent Transfer Rates" [33(12), p. 2008, Dec. 1987, Re < 0 in Eq. 53 should be changed to Re < 10, Re ⟶ 10 in Eq. 54 to Re ⟶ 0. Also, under Eq. B, delete the word "only."