A Model for Pressure Drop in Two-Phase Gas-Liquid Downflow Through Packed Columns

V. G. RAO and
A. A. H. DRINKENBURG

Department of Chemical Engineering
Rijksuniversiteit Groningen
9747 AG Groningen, The Netherlands

The nature of the interaction between the flowing phases in a cocurrent gas-liquid downflow through packed beds depends on the type of the flow regime. The interaction is poor and geometric in nature in gas-continuous flow and becomes high and dynamic in pulse flow due to gas dispersion, acceleration, and mixing of the liquid in the pulses. Models to calculate pressure drop in each of the flow regimes are presented, taking into account the respective interactions. Experimental data on pressure drops and liquid holdups were measured in gas-continuous flow for 3 mm glass spheres and 6 mm Raschig rings. An air-water system is used. The literature data on pressure drops and the experimental data, covering liquid velocities from 0.001 m/s to 0.029 m/s and gas velocities from 0.097 m/s to 2 m/s, were compared with the calculated values. It was found that the pressure drop due to dynamic interaction can be as low as 10% and as much as 80% of the total pressure drop for the data examined in this work. An empirical correlation for holdup in gas-continuous flow is given for Raschig rings.

SCOPE

Industrial trickle-bed reactors generally operate in gas-continuous flow and sometimes in or near to the pulse flow regime. Operating a reactor in the pulse flow regime offers higher heat transfer rates (Weekman and Myers, 1965), higher mass transfer rates (e.g., Hirose et al., 1974; Gianetto et al., 1973), less axial dispersion in the liquid phase (Lerou et al., 1980; Fukushima and Kusaka, 1977) and, very essentially, reduces the formation of local hot spots due to increased wetting of the catalyst particles.

Pressure drop and liquid holdup have been used increasingly to correlate mass transfer rates (Hirose et al, 1974). However, almost all published pressure drop correlations, especially in the high interaction regime (pulse and dispersed bubble flow) are empirical; no reliable theoretical model has been given yet. The interaction between the phases in gas-continuous flow is poor and geometric in nature. The pulse flow regime is characterized by a high interaction between the phases. We then observe pistonlike plugs of liquid-rich mixture moving from top to bottom, separated by parts of the bed that seem to be in normal trickle flow condition. The flow pattern in the low density (gas-rich) part is gas-continuous flow and the interaction between the phases is geometric. The flow pattern in the high-density pulses (liquid-rich part or pulsing part) corresponds to dispersed bubble flow. The interaction between the phases in this part becomes high and dynamic due to various physical processes such as gas dispersion, acceleration, and mixing of liquid occurring in the pulse.

In this study the geometric interaction model considered by Sweeney (1967) and Rao (1979) was modified based on the pressure drop of the gas in prewetted beds, thus in the presence of the static holdup, to calculate δ_{LG} in gas-continuous flow. The model for the pressure drop in pulse flow is based upon the added contributions from the gas-continuous part by geometric interaction and from the pulsing part by both geometric and dynamic interactions. The dynamic interaction pressure drops were calculated by simple mathematical models with the help of hydrodynamic properties of pulses. The single-phase pressure drops of gas on wet packing (in the presence of static holdup) and on dry packing were measured for the packings of 3 mm spheres, and 2.5, 4, and 6 mm Raschig rings in a column diameter of 0.05 m with an air-water system. Some experimental data on pressure drops and liquid holdups in gas-continuous flow were measured for 3 mm glass spheres and 6 mm glass Raschig rings.

CONCLUSIONS AND SIGNIFICANCE

The nature of the interaction between the flowing phases depends on the type of the flow regime and has a major influence on the pressure drop. Models for the pressure drop are presented in gas-continuous flow and pulse flow. The pressure drops in gas-continuous flow as calculated by our modified geometric interaction model give better results than those of the existing geometric interaction model. The pressure drop data obtained in this work for 3 mm spheres and 6 mm Raschig rings and the data obtained by Specchia and Baldi (1977) for 2.7 and 5.4 mm cylinders were compared with the values calculated by the modified geometric interaction model. Almost all the data lie within ± 25% of the calculated values with a relative root mean square deviation of 17%.

Correspondence concerning this paper should be directed to A. A. H. Drinkenburg.

The pressure drop in pulse flow is calculated taking into account both geometric and dynamic interactions. Dynamic interactions are bubble formation, liquid acceleration, and liquid turbulence. Model calculations are compared to a large amount of data obtained by Blok (1981) for 2.5 and 4 mm Raschig rings in column diameters of 5, 10, and 20 cm and for the data obtained by Rao and Drinkenburg (1983) for 3 mm spheres and 6 mm Raschig rings in a column diameter of 5 cm. The comparison between the calculated values and the experimental values is satisfactory with almost all the experimental data falling within ±30% of the calculated values. The pressure drop due to bubble dispersion and the pressure drop due to acceleration of the liquid in the pulses are comparable to each other at low liquid rates (low pulse frequencies). At higher liquid rates (higher pulse frequencies) the bubble dispersion pressure drop dominates over the acceleration pressure drop. The mixing pressure drop is not significant. Its contribution to calculated values of δ_{LG} is less than 1% for Raschig rings and a maximum of 3% for spheres. The dynamic interaction pressure drop dominates over the pressure drop due to geometric interaction at high liquid rates and at low to moderate gas rates.

The liquid holdup data in gas-continuous flow for 3 mm glass spheres agreed with the correlations proposed by Specchia and Baldi (1977) and Rao (1979), but the liquid holdup data for 6 mm glass Raschig rings did not agree with the correlations. In view of this a new correlation for the data of 6 mm Raschig rings and for the data obtained by Blok (1981) for 2.5 and 4 mm Raschig rings is presented.

INTRODUCTION

Pressure drop and liquid holdup are significant parameters in the design and operation of two-phase cocurrent gas-liquid downflow packed columns. Pressure drop is obviously connected with the dissipated power in the reactor. A large number of publications have appeared on this subject and several empirical or semiempirical correlations have been proposed. In their excellent review on trickle-bed hydrodynamics, Gianetto et al. (1978) presented most significant correlations of pressure drop and liquid holdup together with their range of validity and comments about their limitations. Owing to the complex behavior of two-phase flow in packed columns, a reliable theoretical model has not been given yet. In addition, different hydrodynamic mechanisms exist in the poor interaction regime (such as trickle or gas-continuous flow) and in the high interaction regime (such as pulse and dispersed bubble flow).

The interaction between the phases is geometric in nature in the poor interaction regime, for which a few models have been proposed (Sweeney, 1967; Specchia and Baldi, 1977; Rao, 1979). Rao extended the geometric interaction model to the high interaction regime such as pulse flow and dispersed bubble flow. The additional pressure drop in pulse flow and dispersed bubble flow was estimated by proposing a mechanism of bubble breakage and redispersion. It should be noted, however, that the constants in the correlating equations were calculated from the experimental pressure drop data. Rao and Drinkenburg (1983) proposed a model in the pulse flow regime in which the pressure drop is viewed as being contributed to by the gas-continuous part outside the pulses and by the pulses themselves. The pressure drop in the gas-continuous part (outside the pulses) was estimated by the geometric interaction model (Rao, 1979) and the pressure drop due to the pulses was estimated using pulse properties and experimental two-phase pressure drop.

From the foregoing, we may conclude that no model based on the hydrodynamic mechanism involved, especially in the high interaction regime, has been put forward which could estimate δ_{LG} from first principles. In this work, an attempt is made in this direction. We also reexamined the geometric interaction model (Rao, 1979) in gas-continuous flow. We compared our data on pressure drop and liquid holdup, supplemented by experimental data from literature, with the proposed correlation.

THEORY

Gas-Continuous Flow

According to the geometric interaction (GI) model (Rao, 1979; Rao and Drinkenburg, 1983) the two-phase pressure drop, δ_{LG}, for a cocurrent downward flow through a packed column is given by the following equation:

$$\delta_{LG} = \frac{\delta_L^\circ}{\beta^3} - \rho_L g = \frac{\delta_G^\circ}{(1-\beta)^3} - \rho_G g \tag{1}$$

δ_L° and δ_G° are the single-phase pressure drops of liquid and gas, respectively, through the dry bed; β is the total liquid holdup. Equation 1 was derived based on the assumption that the friction coefficient between the packing and either of the phases that comes in contact with the packing is the same, be it in single-phase flow or two-phase flow. The problem remains that the structure of the gas capillaries in a dry bed differs from that in a prewetted bed by the presence of static holdup in the latter case. The problem can be greatly reduced if we employ the single-phase pressure drop of the gas phase on wet packing instead of the dry packing pressure drop in Eq. 1. A similar approach has been taken by Specchia and Baldi (1977) in so far that they also start from prewetted bed pressure drop. Their equations, however, are not based on a constant friction coefficient but on a constancy of the coefficients in the well-known Ergun equation, independent of liquid irrigation. The geometric interaction (the effect of the presence of one phase on the other) can then be accounted by the dynamic liquid holdup. With these observations, Eq. 1 for the gas phase is modified and rewritten for δ_{LG} as follows:

$$\delta_{LG} = \frac{\delta_{GW}^\circ}{(1-\beta_d)^3} - \rho_G g \tag{2}$$

δ_{GW}° is the single phase pressure drop of the gas phase on wet packing and β_d is dynamic liquid holdup. The model represented by Eq. 2 is referred to as the modified geometric interaction (MGI) model.

Two-Phase Pressure Drop in Pulse Flow—The Model

The pulse flow regime is characterized by low density and high density slugs of gas and liquid mixtures flowing successively through the column. The flow pattern in the low density part is more like gas-continuous flow and the flow pattern in a high density slug corresponds to dispersed bubble flow. The holdup in the low density gas-continuous part is called the base holdup, β_b, and the holdup in the high density slug is referred to as the pulse holdup, β_p. It is obvious that the nature of the interaction between the phases continually changes along the length of the column when pulses pass through. The interaction in the gas-continuous part of the column is poor and geometric in nature; the interaction in the pulsing part of the column is high, due to various physical processes occurring in the pulse, and is dynamic in nature. Therefore, the pressure drop in the pulse flow regime can be divided into two parts: 1) the pressure drop in the gas-continuous part of the column, and 2) the pressure drop in the pulsing part of the column.

1. *Pressure drop in the gas-continuous part (outside the pulses).* The pressure drop in the gas-continuous part of the column can be conveniently estimated by the modified geometric inter-

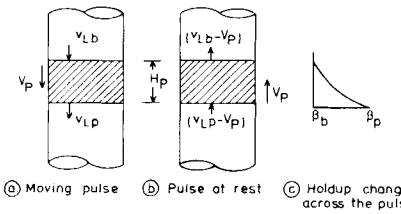

Figure 1. Representation of a pulse in a column.

action model using dynamic base holdup $\beta_{b,d}$, as shown in Eq. 3:

$$\delta_{LG,GC} = \frac{\delta^o_{GW}}{(1-\beta_{b,d})^3} - \rho_G g \tag{3}$$

2. *Pressure drop in the pulsing part.* The interaction in this flow regime is not only geometric but also dynamic due to bubble dispersion, mixing, and acceleration of liquid in a pulse. Chow et al. (1979) observed a minimum pressure gradient between pulses in the column, corresponding to the gas-continuous part. Any further increase in pressure drop while the pulse passes the position of the detector was due to frictional losses in the pulse and the momentum transfer to the liquid film picked up by the pulse. While the pulse is traveling down the column a portion of the liquid is taken up at its front and some portion of the liquid forming a slow moving film is left behind. In general the pulse velocity is of the order 1 m/s, approximately an order of magnitude higher than the real liquid velocity. The real gas velocity (based on average pulse holdup) is usually higher than the pulse velocity (Blok, 1981; Rao and Drinkenburg, 1983), which means there is a net transport of gas through the pulse. This phenomenon together with the complex nature of the pulse itself imparts a certain momentum, accelerating the liquid in the pulse. Moreover, the turbulence in the pulse promotes mixing. The pressure drop due to the above mentioned interactions is rather difficult to calculate by rigorous theoretical treatment but an estimate may be made with the help of an overall momentum balance together with some mathematical models based on analogy with simple systems as shown in the following sections.

Consider a pulse of height H_P and a velocity V_P in a column as shown in Figure 1a. The typical variation of holdup across the pulse height is shown in Figure 1c. β_p and β_b are the pulse and base holdups respectively at the front and back of the pulse. v_{Lp} and v_{Lb} are the real liquid velocities based on pulse holdup and base holdup, respectively.

While the pulse is moving down the column, it is assumed that the pulse picks up some amount of liquid at its front and leaves behind the same amount of liquid, which means the pulse is kept at steady state conditions. It may be useful to consider the pulse at rest. This may be accomplished by applying a negative velocity V_P to the pulse as depicted in Figure 1b. The total pressure drop across a pulse can be obtained by identifying the pressure drops due to various mechanisms in the pulse and writing down the momentum balance for the conditions as show in Figure 1b.

$$\Delta P_A + \Delta P_L + \Delta P_B + \Delta P_M = \Delta P_P \tag{4}$$

The various terms in Eq. 4 may be identified as follows: ΔP_P is the total pressure drop over a pulse. $\Delta P_L (= \Delta P_{LF} - \rho_{LG} H_p)$ is the frictional pressure drop in the liquid phase due to geometric interaction minus gravity forces in the pulse. ΔP_B is the extra pressure drop in the gas phase due to bubble surface enlargement and reduction. ΔP_M is the extra pressure drop in the liquid phase due to the mixing process. ΔP_A is the pressure drop due to liquid acceleration in the liquid phase in the pulse and is equal to

$$\Delta P_A = \rho_L \epsilon \beta_p (v_{Lp} - V_p)^2 - \rho_L \epsilon \beta (v_{Lb} - V_p)^2 \tag{4a}$$

Equation 4 presumes that the partial pressure drops are additive and thus independent. This is not necessarily so for ΔP_M. As will be shown, the contribution of ΔP_M to the total pressure drop is negligible. The two-phase pressure drop, δ_{LG}, per unit height of the packing by the various mechanisms as described above can be calculated separately as follows.

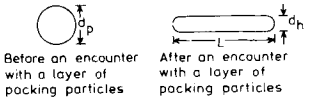

Figure 2. The model for bubble dispersion.

a). *Pressure drop in the pulsing part due to geometric interaction.* Assuming that the pressure drop in a pulse is the same for each of the phases, the two-phase pressure drop due to geometric interaction per unit height of the pulse can be calculated by the MGI model, replacing the total dynamic holdup by the average dynamic pulse holdup as in Eq. 5:

$$\delta_{LG,P} = \frac{\delta^o_{GW}}{(1-\overline{\beta}_{p,d})^3} - \rho_G g \tag{5}$$

The actual number of pulses in a column of one unit height is given by

$$N_p = f_p / V_p \tag{6}$$

where f_p is the pulse frequency and V_p is the pulse velocity. Therefore, the height of the column occupied by the pulses (or the pulsing fraction) per unit height of the column is

$$H_{PT} = N_p H_p \tag{7}$$

where H_p is the pulse height. The product of Eqs. 5 and 7 gives the two-phase pressure drop due to geometric interaction in the part of the column occupied by pulses.

b). *Pressure drop due to bubble dispersion.* Assuming all the gas is dispersed as bubbles within the pulse, we propose that when a gas bubble encounters a layer of packing particles the bubble shape changes while moving from one spacing to the next; i.e., a process of surface reduction and enlargement takes place. The spaces between the particles of a packed column normally are the same size as the packing particles themselves. Therefore the bubbles in the liquid have a maximum spherical diameter of the same order. Moving from one space to the next, however, means that the bubble has to split up and recoalesce, or at least elongate very much to pass through the restrictions set by the layer of the packing particles. The energy dissipated through the gas bubble in the liquid by the repeated surface enlargement and reduction can be estimated as follows.

Let us say that t_p is the residence time of the gas bubble within a pulse of height H_p, that v_G is the real gas velocity, and V_p is the pulse velocity. The distance traveled by the pulse in the time t_p is $V_p t_p$ and the distance traveled by the gas in the time t_p is $v_G t_p$. Therefore,

$$t_p = H_p / (v_G - V_p) \tag{8}$$

Suppose that when the gas bubble encounters a layer of packing particles the bubble changes from a spherical diameter d_p (particle diameter) to a cylindrical diameter d_h which is equal to the hydraulic diameter of the packing, as shown in the Figure 2. The length of the cylindrical gas bubble can be calculated by the equal-volume relationship of the gas bubble at these two states and is then given by

$$L = (2/3)(d_p^3/d_h^2) \tag{9}$$

The difference in surface energy for a bubble in these two states is

$$(\Pi d_h L - \Pi d_p^2)\sigma_L = \Pi d_p^2 \sigma_L \left(\frac{2}{3}\frac{d_p}{d_h} - 1\right) \tag{10}$$

in which the end faces of the cylindrical bubble are neglected. The energy difference is considered to be dissipated during each cycle in the form of heat. The process of surface enlargement and reduction is repeated whenever the gas bubble encounters a layer of packing articles. The number of particle encounters of the gas bubble during its residence time t_p in the pulse is given by

$$n_p = \frac{v_G t_p}{d_p} = \frac{H_P}{d_p}\frac{1}{\left(1 - \frac{V_P}{v_G}\right)} \tag{11}$$

Therefore, the surface energy dissipated within the pulse is given by the product of Eqs. 10 and 11 and this is equal to the volume of the bubble, $V_B(= \Pi/6d_p^3)$, multiplied by the pressure drop with the pulse, ΔP_B, due to bubble surface enlargement and reduction. Therefore the extra pressure drop of the gas phase, ΔP_B, in a pulse is given by

$$\Delta P_B = \frac{6H_P\sigma_L\left(\frac{2}{3}\frac{d_p}{d_h} - 1\right)}{d_p^2\left(1 - \frac{V_P}{v_G}\right)} \tag{12}$$

A gas volume, during its residence time in one meter of the column, encounters a pulse more than once and the number of such encounters (certainly less than the actual number of pulses in one meter of the column) is given by

$$n_B = \frac{f_p}{V_P}\left(1 - \frac{V_P}{v_G}\right) \tag{13}$$

Therefore, the total excess pressure drop in the gas phase due to bubble dispersion in all the pulses per unit height of the column is given by the product of Eqs. 12 and 13:

$$\delta_{LG,B} = n_B \Delta P_B \tag{14}$$

c). *Pressure drop due to mixing.* The mixing in a pulse is largely due to the turbulence in the liquid phase. The process of mixing in the pulse seems rather fast and actually decreases the axial mixing in the liquid phase compared to the gas-continuous flow (Lerou et al., 1980; Fukushima and Kusaka, 1977). The pulses greatly activate the stagnant parts of the liquid (Blok, 1981) and renew the surface of the liquid. Turbulence in a liquid creates primary eddies which disintegrate into smaller eddies until the energy is lost to heat by viscous dissipation associated with the smallest eddies. Assuming that a local homogeneous isotropic turbulence exists in the liquid phase of the pulse, the size of eddies for which the energy dissipation is maximum can be taken as the microscale of turbulence as given by:

$$\ell = (\mu/\rho)^{3/4}(E')^{-1/4} \tag{15}$$

where E' is the rate of energy dissipated per unit mass of the liquid. The characteristic length of a surface renewal eddy, as a first approximation, can be found from the "film" thickness calculated from the base holdup and pulse holdup measurements, as given by Eq. 16:

$$\ell = \epsilon(\beta_p - \beta_b)/a_s \tag{16}$$

From Eqs. 15 and 16 we get the extra rate of energy, E', dissipated in the form of heat per unit mass of the liquid. The extra pressure drop in the liquid phase, ΔP_M, due to mixing in a pulse can be obtained multiplying E' by the residence time of the liquid volume in the pusle and the density of the liquid. Thus:

$$\Delta P_M = \frac{\mu^3}{\rho^2}\left(\frac{H_P}{V_P - v_L}\right)\frac{a_s^4}{\epsilon^4(\beta_p - \beta_b)^4} \approx \frac{\mu^3}{\rho^2}\frac{H_P}{V_P}\frac{a_s^4}{\epsilon^4(\beta_p - \beta_b)^4} \tag{17}$$

since the pulse velocity, V_P, is always very much higher than the real liquid velocity, v_L.

The process of energy dissipation in the form of heat due to mixing repeats itself whenever the liquid volume encounters a pulse. The number of such encounters of the liquid with a pulse is approximately given by the product of pulse frequency, f_p, and the residence time of the liquid in the column. The residence time of the liquid in a column of one unit height is $1/v_L$ where v_L is the average real liquid velocity. Therefore, the number of encounters of a liquid volume with a pulse per unit column height is given by

$$n_M = \frac{f_p}{v_L}\left(1 - \frac{v_L}{V_P}\right) \approx \frac{f_p}{v_L} \tag{18}$$

The product of Eqs. 17 and 18 now gives the total pressure drop in the pulses due to mixing per unit column height; therefore,

$$\delta_{LG,M} = n_M \Delta P_M \tag{19}$$

d). *Acceleration pressure drop.* As described earlier, when a liquid element encounters a pulse it is accelerated and later is left behind again as a slow moving liquid. A measure of this acceleration pressure drop for each encounter of the liquid with a pulse is given by the momentum equation (Eq. 4a):

$$\Delta P_A = \rho_L \epsilon\beta_P(v_{Lp} - V_p)^2 - \rho_L \epsilon\beta_b(v_{Lb} - V_p)^2 \tag{20}$$

The number of encounters of the liquid element with a pulse in a unit column height is again given by Eq. 18. This number, n_M, multiplied by ΔP_A as given by Eq. 20, gives the total extra acceleration pressure drop, $\delta_{LG,A}$, due to all pulses in a unit column height:

$$\delta_{LG,A} = n_M \Delta P_A \tag{21}$$

Finally, by adding all the contributions from Eqs. 3, 5, 14, 19, and 21 we get the two-phase pressure drop per unit length, δ_{LG}, in the pulse flow regime:

$$\delta_{LG} = (1 - H_{PT})\delta_{LG,GC} + H_{PT}\delta_{LG,P} + \delta_{LG,B} + \delta_{LG,M} + \delta_{LG,A} \tag{22}$$

The first term on righthand side of Eq. 22 is the pressure drop contribution due to geometric interaction in the gas-continuous part of the fraction $(1 - H_{PT})$ of the column height. The second term is the pressure drop contribution due to geometric interaction in the pulsing part of the fraction H_{PT} of the column height.

EXPERIMENTAL

The experimental set up is schematically represented in Figure 3 and was the same as reported earlier (Rao and Drinkenburg, 1983). The two-phase data of pressure drop, holdup, and pulse properties reported earlier by Blok (1981) and Rao and Drinkenburg (1983) were used. Some additional data of pressure drop and liquid holdup in the gas-continuous regime were measured for packings, namely 6 mm Raschig rings and 3 mm spheres covering a range of liquid velocities from 0.0014 to 0.0147 m/s and gas velocities from 0.184 to 2 m/s. An air-water system was used.

The single-phase pressure drops of gas both on dry packing and on wet packing (in the presence of static holdup) were measured in a 0.05 m diameter glass column of 1 m length using 3 mm spheres, and 6, 4, and 2.5 mm Raschig rings. The use of 6 mm rings is the largest diameter permitted; above a ratio of $D/d_p = 8$, wall effects increasingly distort the results. The measurement of the single-phase pressure drops on wet packing was as follows. The gas was saturated with water in a prewetted bed before it was allowed to flow through the test column. The packing was completely wetted, operating the bed at high liquid and gas rates Then the desired gas rate and an arbitrary liquid rate were set and the two-phase pressure drop

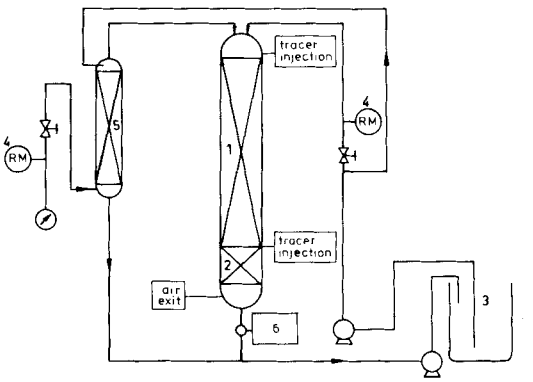

Figure 3. Schematic diagram of the equipment: 1. Packed column; 2. Test section; 3. Liquid tank; 4. Rotameters; 5. Humidifier; 6. Colorimeter.

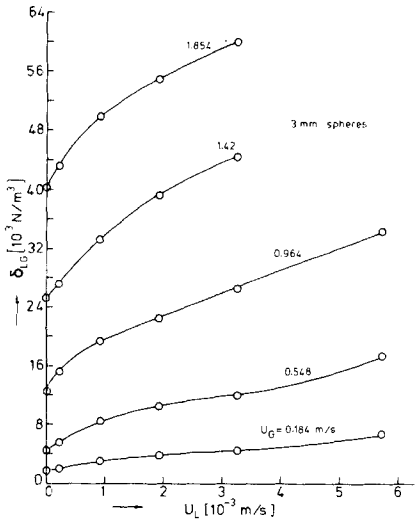

Figure 4. Pressure drop vs. liquid velocity near zero liquid velocities.

was measured. The liquid rate was then decreased in steps to zero and the steady state pressure drop was measured at each rate step, including the one at zero liquid rate. This procedure was repeated for other gas velocities.

The hydrodynamic properties of the pulses were determined previously in the same equipment by means of a set of two electrical conductivity cells. The two cells were mounted at the bottom of the column, 5 cm apart. Both cells consisted of two wide-mesh screen electrodes. The dynamic response of both cells was sampled by a PDP-11/04 computer. From the response of one of the cells, after calibration, the local liquid holdup in the pulses and between pulses could be followed, as could pulse frequency, interval times between pulses, and pulse height. Responses from both cells together provided pulse velocity.

The static holdup in the column was measured by the usual procedure. The bed was filled first with a known amount of liquid and then allowed to drain for about 20 minutes. The drained amount of liquid was measured. The static holdup is then the difference between the known amount of the liquid filled in and the amount of liquid drained out of the bed.

RESULTS AND DISCUSSION

Single phase pressure drop

The typical behavior of the pressure drop of 3 mm spheres as a function of liquid velocity at low liquid rates at a constant gas velocity is shown in Figure 4. The curves of different gas velocities extrapolated to zero liquid rate correspond reasonably well with the measured values of the pressure drop on wet packing. The measured values at zero liquid rate are then taken as single-phase pressure drops on the wet packing. The single-phase pressure drops of gas on wet packing are higher than the corresponding single-phase pressure drops on dry packing due to the presence of static holdup. The dry packing pressure drops did not agree with Ergun's equation (1952); the measured values were always higher.

The single-phase pressure drops of gas on dry packing ($\beta_s = 0$) and on wet packing (in the presence of β_s) were then fitted to an Ergun-type equation written as:

TABLE 1. CONSTANTS K_1 AND K_2 IN EQ. 23 AND STATIC HOLDUP FOR AIR-WATER SYSTEM

Packing	ϵ	Dry Packing K_1	Dry Packing K_2	Wet Packing K_1	Wet Packing K_2	β_s
2.5 mm Raschig rings	0.57	335	3.22	316	4.0	0.07
4 mm Raschig rings	0.68	456	3.17	517	3.4	0.061
6 mm Raschig rings	0.76	313	3.19	384	3.4	0.057
3 mm spheres	0.39	196	1.11	227	1.52	0.102

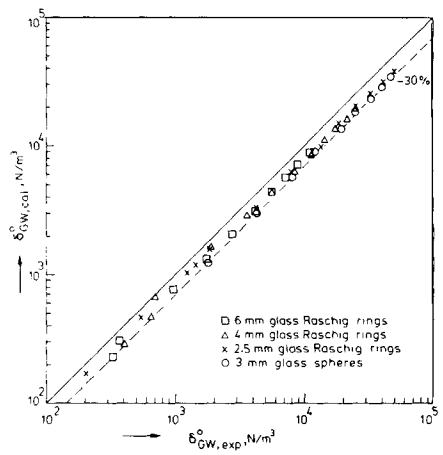

Figure 5. Comparison of calculated and experimental wet packing pressure drops of gas phase.

$$\delta^o_{GW} = K_1 \frac{[1-\epsilon(1-\beta_s)]^2}{d_e^2\epsilon^3(1-\beta_s)^3}\mu_G U_G + K_2 \frac{[1-\epsilon(1-\beta_s)]}{d_e\epsilon^3(1-\beta_s)^3}\rho_G U_g^2 \tag{23}$$

The value of constants K_1 and K_2 were then evaluated by the linear least squares method and are listed in Table 1 together with the static liquid holdup.

An estimate of the single-phase pressure drop of gas on wet packing was made from the dry packing pressure drop data by the geometric interaction model, replacing the total liquid holdup β in Eq. 1 by the static liquid holdup β_s, as in Eq. 24:

$$\delta^o_{GW} = \frac{\delta^o_G}{(1-\beta_s)^3} - \rho_G g \tag{24}$$

The calculated values from Eq. 24 and the experimental values are compared in Figure 5. The calculated values are consistently lower than the experimental values. This may be attributed partially to the fact that the assumption made in formulating the geometric interaction model as described by Eq. 1 is not true; this again is in favor of an attempt to reduce this uncertainty by using the modified geometric interaction model (MGI), based on the wet packing pressure drop of gas as described in Eq. 2.

GAS-CONTINUOUS FLOW

Two-Phase Pressure Drop

The two-phase pressure drops δ_{LG} were calculated based on both single-phase dry packing and wet packing pressure drops of gas

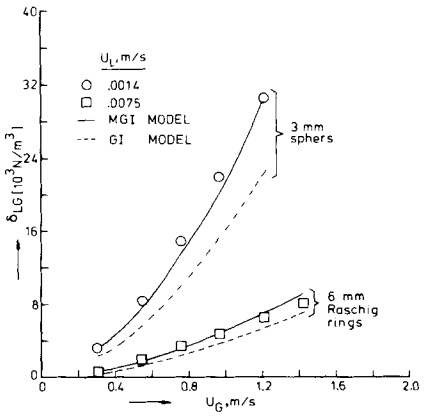

Figure 6. Comparison of experimental pressure drops with GI and MGI models for gas-continuous flow.

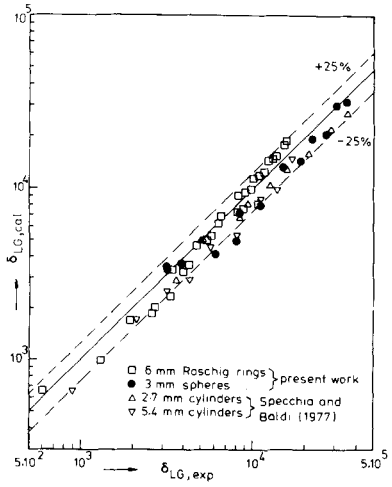

Figure 7. Comparison of calculated and experimental two-phase pressure drops in gas-continuous flow.

by Eqs. 1 and 2, respectively. The typical variation of δ_{LG} with gas velocity for 3 mm class spheres and 6 mm glass Raschig rings is plotted in Figure 6. The calculated δ_{LG} values by the MGI model of Eq. 2 and the experimental values are compared in Figure 7. The data of Specchia and Baldi (1977) on 2.7 and 5.4 mm cylinders are also included in Figure 7. The wet packing pressure drops of gas on 2.7 and 5.4 mm cylinders were calculated using the constants in the Ergun-type equation and static holdups as given by Specchia and Baldi (1977).

As can be seen in Figure 6, δ_{LG} values calculated by the MGI model of Eq. 2 are closer to the measured values and certainly an improvement over the GI model given by Eq. 1. As shown in Figure 7, a satisfactory agreement is obtained between the pressure drops calculated by the MGI model and the experimental values, most of the data lying within ±25% error limits. A total of 59 experimental points were examined and the relative root mean square deviation for all the data is 17%. The experimental δ_{LG} values were obtained for $0.001 \leq U_L \leq 0.0147$ m/s and $0.097 \leq U_G \leq 2$ m/s.

HOLDUP

The holdup data for 3 mm spheres and 6 mm glass Raschig rings are compared with the correlations proposed by Rao (1979) for total liquid holdup and Specchia and Baldi (1977) for dynamic liquid holdup as given by Eqs. 25 and 26 respectively:

$$\beta = 0.045\, a_s^{1/3}[Re_L/Re_G]^{1/5}$$
$$0.02 \leq (Re_L/Re_G) \leq 20 \qquad (25)$$

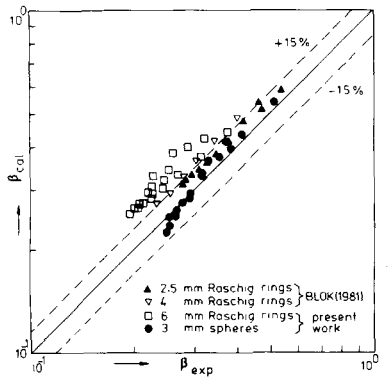

Figure 8. Comparison of total liquid holdup with the correlation of Rao (1979); Eq. 25.

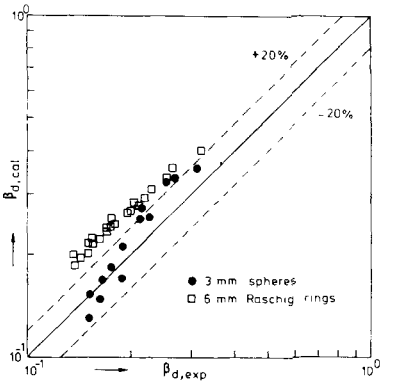

Figure 9. Comparison of dynamic liquid holdup with the correlation of Specchia and Baldi (1977); gas-continuous flow, Eq. 26.

$$\beta = 3.86\, Re_L^{0.545}(Ga^*)^{-0.42}\left(\frac{a_s d_p}{\epsilon}\right)^{0.65} \qquad (26)$$

The comparison of total liquid holdup, β, is made in Figure 8 and the dynamic liquid holdup β_d is made in Figure 9. As can be seen from these figures, the data for 3 mm glass spheres agree reasonably well, but the data for Raschig rings differ very much with the correlations given by Eqs. 25 and 26. It should be noted, however, that Eq. 25 was proposed based on a large amount of data for spheres and cylinders and few data for Raschig rings and Berl saddles. In view of this, an equation similar to Eq. 25 for the total liquid holdup with a different constant is proposed for the data of Raschig rings, Eq. 27:

$$\beta = 0.037\, a_s^{1/3}(Re_L/Re_G)^{1/5} \qquad (27)$$

The holdups calculated by Eq. 27 and the exerimental holdups are plotted in Figure 10. The data of Blok (1981) for 2.5 and 4 mm Raschig rings and the data of Rao (1979) for 9.54 mm Raschig rings in the gas-continuous flow regime are also presented in Figure 10. As can be seen from this figure, Eq. 27 correlates the data well; all lie within ±15% error limits.

PULSE FLOW

Two-phase pressure drop δ_{LG} in pulse flow was calculated by Eq. 22. The pressure drop contributions due to geometric interaction in the gas-continuous part and pulsing part were calculated using the modified geometric interaction (MGI) model. The pressure drop contributions due to bubble dispersion ΔP_B were calculated by Eq. 12 in which hydraulic diameters of the packings were based on external porosities in the case of Raschig rings; i.e., Raschig rings were treated as if they were solid cylinders. Figure

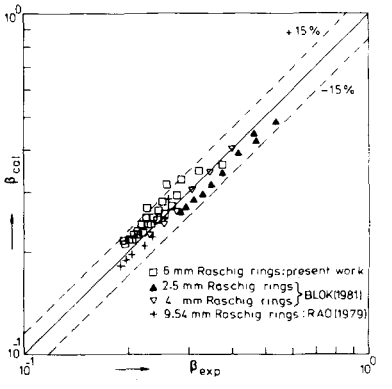

Figure 10. Comparison of total liquid holdup for Raschig rings with the present correlation; gas-continuous flow, Eq. 27.

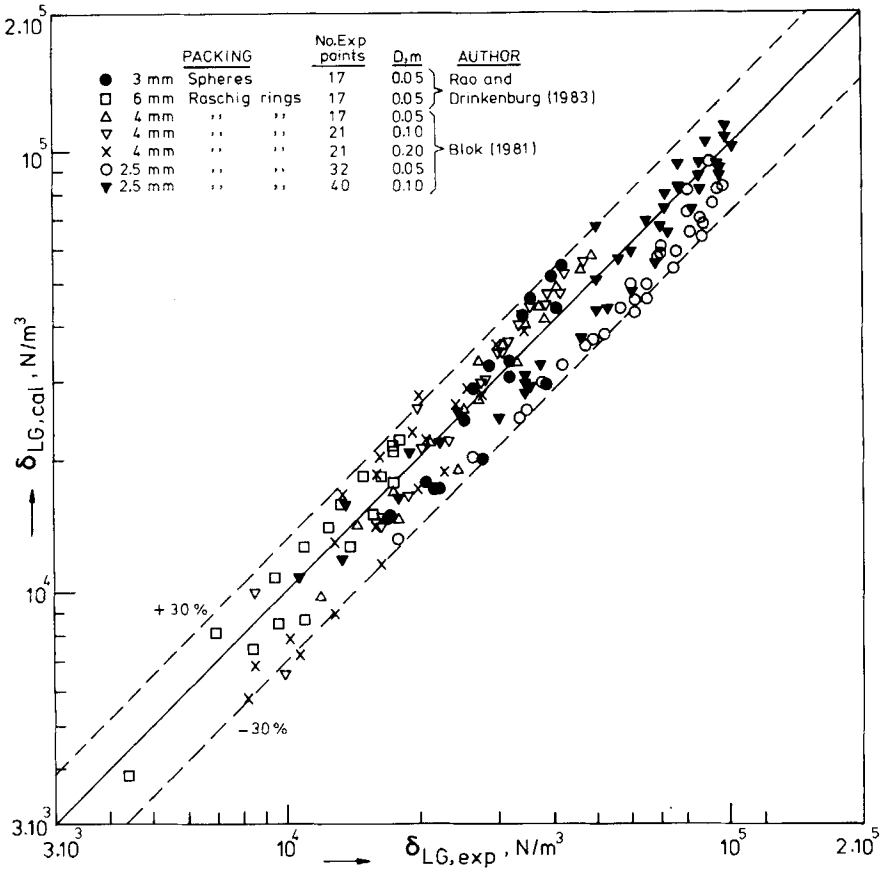

Figure 11. Comparison of calculated and experimental pressure drops in pulse flow.

11 shows a comparison between δ_{LG} values calculated by Eq. 22 based on the MGI model and experimental data obtained by Rao and Drinkenburg (1983) for 3 mm spheres and 6 mm Raschig rings in a column diameter of 5 cm, and by Blok (1981) for 2.5 and 4 mm Raschig rings in column diameters of 5, 10, and 20 cm. The experimental δ_{LG} values were obtained for $0.0057 \leq U_L \leq 0.029$ m/s and $0.1 \leq U_G \leq 1.91$ m/s. A total of 165 experimental points are compared; almost all data fall between ±30% of the calculated values. The relative root mean square deviation for all the data is 18%.

Two-phase pressure drop, δ_{LG}, calculated by Eq. 22 can be broadly divided into (a) geometric interaction pressure drop (added contributions from gas-continuous part and pulsing part), and (b) dynamic interaction pressure drop. The fractions of geometric interaction pressure drop, x_{GI}, in $\delta_{LG,cal}$ were calculated for all the data; the typical variation as a function of pulse frequency is shown in Figures 12 and 13 for various packings and column diameters. It should be noted however that the pulse frequency increases with increasing liquid and gas velocities, and that holdups (β_b and β_p) are only a function of gas velocity for a given packing (Blok and Drinkenburg, 1982; Rao and Drinkenburg, 1983).

Figure 12 shows the variation of the fraction of the total pressure drop due to geometric interaction, x_{GI}, at a constant liquid velocity, as a function of pulse frequency (therefore as a function of gas velocity). The increase in gas velocity increases both the geometric and the dynamic interaction pressure drops. However the increase in geometric interaction pressure drop dominates over the increase in dynamic interaction pressure drop (due to increase in pulse frequency) and the net result would be an increase in x_{GI} as shown in Figure 12. Again x_{GI}, at a constant gas velocity, is plotted against pulse frequency (therefore, as a function of liquid velocity) in Figure 13. As can be seen from Figure 13, x_{GI} decreases rapidly at low pulse frequencies (i.e., low liquid rates) and then the decrease in x_{GI} becomes gradual for higher pulse frequencies. Thus, Figures 12 and 13 clearly illustrate quantitatively the variations of geometric and dynamic interaction pressure drops in the pulse flow regime. The dynamic interaction pressure drop varies from 10 to 80%, depending on the flow rates of the phases and the packing properties, for the data examined in this work. The pressure drop due to bubble dispersion and acceleration pressure drop are comparable to each other at low liquid rates (low pulse frequencies). At higher liquid rates (higher pulse frequencies) the bubble dispersion pressure drop dominates over the acceleration pressure drop. The mixing drop is not significant. Its contribution to cal-

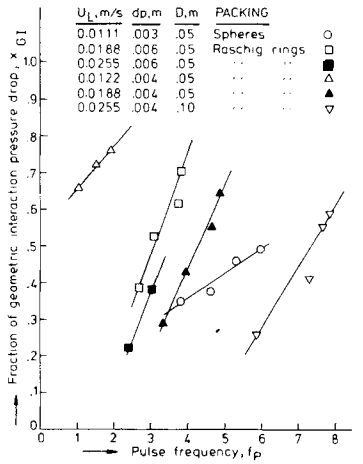

Figure 12. Variation of the fraction of geometric interaction pressure drop with pulse frequency at constant liquid velocities.

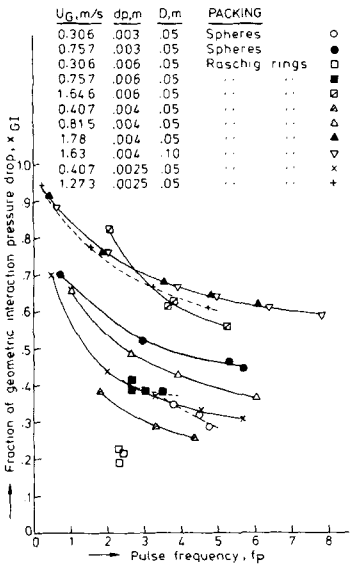

Figure 13. Variation of the fraction of geometric interaction pressure drop with pulse frequency at constant gas velocities.

TABLE 2. TYPICAL VALUES OF PRESSURE DROP ACROSS A PULSE

Packing	D, m	ΔP_{PE}, N/m² Rao & Drinkenburg (1983)	ΔP_{PE}, N/m² This Work
6 mm Raschig rings	0.05	1,300–1,500	600–975
4 mm Raschig rings	0.05	1,700–2,900	2,600–3,850
4 mm Raschig rings	0.1	1,800–2,400	2,500–3,900
2.5 mm Raschig rings	0.05	3,000–8,400	4,200–9,000
2.5 mm Raschig rings	0.10	3,200–9,000	4,800–9,300
3 mm spheres	0.05	2,200–2,500	2,700–4,000

culated values of δ_{LG} is less than 1% for Raschig rings and a maximum of 3% for spheres. Table 2 compares the pressure drops across a pulse calculated by the present model with the pressure drops across a pulse calculated from the experimental data by Rao and Drinkenburg (1983).

NOTATION

a_s = specific surface area of the bed, m^{-1}
d_e = equivalent diameter of the packing [$= 6(1-\epsilon)/a_s$], m
d_h = hydraulic diameter of the packing, m
d_p = nominal diameter of the packing, m
D = column diameter, m
E' = energy dissipated to heat per unit mass of the liquid, m/s^2
f_p = pulse frequency, s^{-1}
g = acceleration due to gravity, m/s^2
Ga^* = modified Galileo number [$= d_p^3\rho_L(\rho_L g + \delta_{LG})/\mu_L^2$]
H = column height, m
H_P = pulse height, m
H_{PT} = fraction of the pulsing part in the column
ℓ = size of an eddy, m
n = number of pulse encounters
N_p = number of pulses in the column
ΔP = pressure drop, N/m^2
ΔP_{PE} = extra pressure drop over a pulse [$= \Delta P_A + \Delta P_B + \Delta P_M$], N/m^2
ΔP_p = total pressure drop over a pulse [$= \Delta P_{PE} + \Delta P_L$], N/m^2
Re = Reynolds number [$= \rho U d_p/\mu$]
t_p = residence time of gas in a pulse, s
U = superficial velocity, m/s
v = real velocity, m/s
V_B = volume of the bubble, m^3
V_P = pulse velocity, m/s
x = fraction

Greek Letters

β = liquid holdup, fraction of void volume
δ_{LG} = two-phase pressure drop per unit height, N/m^3
δ_L^o, δ_G^o = single-phase pressure drops in a dry bed per unit height, N/m^3
δ_{GW}^o = single-phase pressure drop of gas on wet packing per unit height, N/m^3
μ = viscosity, Ns/m^2
σ = surface tension, N/m
ϵ = porosity of dry bed
ρ = density, kg/m^3

Subscripts

A = acceleration
B = bubble
b = base
d = dynamic
F = friction
G = gas
GC = gas-continuous
GI = geometric interaction
L = liquid
LG = two-phase (liquid-gas)
M = mixing
P,p = pulse (p is also used for packing size)
s = static

APPENDIX

Deviation of Geometric Interaction Model

(Rao 1979, Rao and Drinkenburg, 1983)
The following assumptions are made:

1. Each of the two phases is continuous.
2. The flow is steady.
3. The voidage and holdup are constant and uniform.
4. The static pressure drop in two-phase flow does not vary across the cross section of the column and is equal to the pressure drop in each of the phases.
5. The friction coefficient in two-phase (TP) flow is the same as in single-phase (SP) flow.

The pressure drop due to friction in each of the two phases for two-phase flow is then written as follows:

For the liquid phase:

$$\frac{(\text{cross-sectional area})_{TP}\,\Delta P_L}{(\text{cross-sectional area})_{SP}\,\Delta P_L^o} = \frac{(\text{shear stress})_{TP}\,(\text{area of contact})_{TP}}{(\text{shear stress})_{SP}\,(\text{area of contact})_{SP}} \quad \text{(A1)}$$

or

$$\beta(\Delta P_L/\Delta_L^o) = \alpha_L\left[\left(\frac{1}{2}\rho_L V_L^2\right)_{TP}\cdot f_{TP}\right]\Big/\left[\left(\frac{1}{2}\rho_L V_L^2\right)_{SP}\cdot f_{SP}\right] \quad \text{(A2)}$$

or

$$\Delta P_L = \alpha_L(\Delta P_L^o/\beta^3) \quad \text{(A3)}$$

The corresponding equation for the gas phase is:

$$\Delta P_G = \alpha_G[\Delta P_G^o/(1-\beta)^3] \quad \text{(A4)}$$

For the downward flow, the total pressure drop in each of the phases is then given by

$$\Delta P_{LT} = \Delta P_L - \rho_L g H = \alpha_L(\Delta P_L^o/\beta^3) - \rho_L g H \quad \text{(A5)}$$

$$\Delta P_{GT} = \Delta P_G - \rho_G g H = \alpha_G[\Delta P_G^o/(1-\beta)^3] - \rho_G g H \quad \text{(A6)}$$

and according to assumption 4 above,

$$\Delta P_{LG} = \Delta P_{LT} = \Delta P_{GT} \quad \text{(A7)}$$

NOTATION

f = friction factor
ΔP = pressure drop, N/m^2

Greek Letters

α = ratio of area of contact in TP to SP

Subscripts

G = gas
L = liquid
LG = two-phase (liquid-gas)
SP = single-phase
TP = two-phase
T = total

Superscripts

o = single-phase

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