Enhancement of Large-Particle Gas-Fluidization by Adding Liquid

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There are circumstances where fluidization of particles by a gas can be promoted by the addition of small quantities of liquid, contrary to many reported cases where liquid impedes gas-solid fluidization. Enhancement occurs only when the particles are larger than about 3 mm in diameter, the liquid and particles have similar densities (within ~25%), and the particles are poorly wetted by the liquid. When these conditions are met, the liquid causes the minimum gas fluidization velocity U_{gmf} *to decrease and particle motion to be more vigorous. For low liquid loadings,* U_{gmf} *and the pressure drop across the bed are then predicted well by a "modified liquid-perturbed gas model."*

Introduction

It is well known that the addition of small quantities of liquids to most gas-fluidized beds (with small and high-density particles) can lead to immobilization of the bed due to bridging and interparticle forces sufficient to nullify the drag provided by the gas. Some work on the immobilization of fluidized beds by liquids has been reported (for example, Gluckman et al., 1976; Seville and Clift, 1984; Nemoto et al., 1997; Seville et al., 1998). There have been no reports of enhancement of fluidization by the addition of liquid from above (except for fine particle beds where static electricity can be reduced by humidification). Recently, the hydrodynamic lubrication effect has been studied in a slightly wetted bed (water content $\alpha < 0.9$ vol. %, Kuwagi et al., 2000) for which the minimum gas fluidization velocity increased with increasing water content, similar to conventional results.

The present study involves a novel fluidized-bed system. One of the authors (Yokogawa, 1999) recently invented a human bathing/massage system, which uses a gas-fluidized bed of large low-density particles to which a small quantity of water is added. In this system human washing and massage are caused by the collision and abrasion of the fluidized particles. In the bed, large low-density particles, such as 6 mm polystyrene spheres, are used as the bed material. When a modest volume (5–20 vol. %) of liquid such as water is added to the bed, a unique phenomenon, never, to our knowledge, previously reported for conventional gas-fluidized beds, is observed, that is, promotion and enhancement of fluidization appears in a dramatic manner. The vigorous particle motion in this bed appears to be very effective for human washing and massage/relaxation. There seems to be a possibility of developing a new fluidized-bed process using the ability of the liquid to mobilize the particles, such as for reactors, heat exchangers, and some industrial washers.

In this article, the influence of the properties of the particles and added liquids on the fundamental characteristics of fluidization is investigated and the conditions of fluidization

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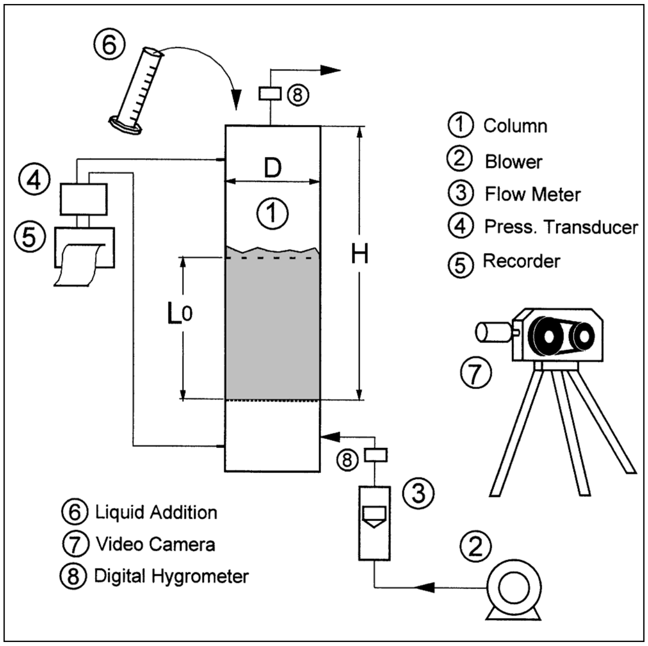


Figure 1. Experimental setup.

promotion (enhancement) are given. To identify the mechanism of fluidization enhancement, a "modified liquid-perturbed gas model" is presented, which does not involve the influence of interfacial properties such as wettability and surface tension.

Equipment and Experimental Method

The experiments were carried out in the apparatus shown in Figure 1 with particles whose properties are given in Table 1. In the table, the noncoated glass beads were standard commercially-supplied beads, while the coated glass beads were sprayed with Teflon at ambient conditions. The relevant properties of the added liquids appear in Table 2. Four transparent acrylic columns were used: a full column of 180 mm inside diameter, a half-column of the same diameter, and full columns of 120 and 60 mm inner diameters. The larger columns were mainly used to observe the fluidization and to obtain measurements for systems where the liquid was water (WTR) and the particles were polystyrene (PLST). The intermediate and small columns were used for all other cases. Each distributor was composed of a perforated plate with 2 mm diameter holes (open area 1.3%) covered by No. 400 wire mesh.

Table 2. Properties of Added Liquids at Room Temperature (25°C)

	Water	Phosphoric Acid	Barium Sulfate Solution	Methylene Bromide
	WTR	PAC	BAS	MBR
Density ρ_l (kg/m^3)	1,000	1,670	1,900	2,500
Viscosity μ_l (mPa·s)	0.890	41.1	103.7	0.968
Surface tension τ_l (N/m)	0.072	0.0762	0.0440	0.0379

Fluidization experiments were carried out for L_0 (static bed height)/D (bed diameter) = 1.5. Each experiment started upon the addition, by pouring from above, of a small quantity of liquid into the gas-fluidized bed. The drying rate was measured separately before the test runs in order to maintain constant liquid content. In the results below, the liquid content α is defined as

$$\alpha = V_l/V_{B\cdot \mathrm{blk}} \tag{1}$$

where V_l = added liquid volume and $V_{B\cdot \mathrm{blk}}$ = bulk bed volume.

Conditions for Fluidization Enhancement

(1) Qualitative evaluation and classification of fluidization condition

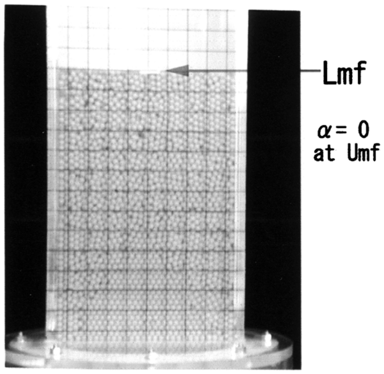
The change of the fluidization character is shown in Figure 2 after 10 vol. % ($\alpha = 0.1$) colored water was added to an air-fluidized bed of large low-density particles (6 mm dia. PTSL). Fluidization was seen to change from a dry-bed at U_{mf} (Figure 2a) to the liquid-added bed (Figure 2b). As soon as 10 vol. % dyed water was added to the bed, it converted rapidly to intense fluidization at the same air flow rate. The superficial gas velocity at minimum fluidization was about 39% lower than for the dry bed.

Figure 3a indicates that, in the bed of the relatively poorly wetted polystyrene particles, the liquid was not completely continuous, and it was maldistributed within the bed, causing particle aggregates of intermediate scale. (In Figures 3 to 6 and Figure 9, darker spots indicate the liquid, colored by ink.) On the other hand, in a bed of fully wettable glass beads, the liquid was completely connected throughout the whole bed,

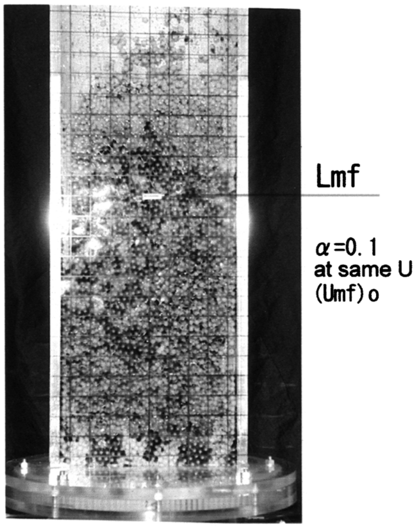
Table 1. Properties of Particles

			Glass beads			
	Polystrene		Noncoated			Teflon-Coated
	PLST-1	PLST-2	GB1	GB2	GB3	GB3′
Mean Dia. d_p (mm)	3.2	6.0	1.0	2.1	6.0	6.0
Contact * Angle (deg)	105		26			101
Shape	Cylindrical		Spherical			
Density ρ_s (kg/m^3)	1,010		2,450			

*Contact angle between water and plate at room temperature.



(a) Dry bed



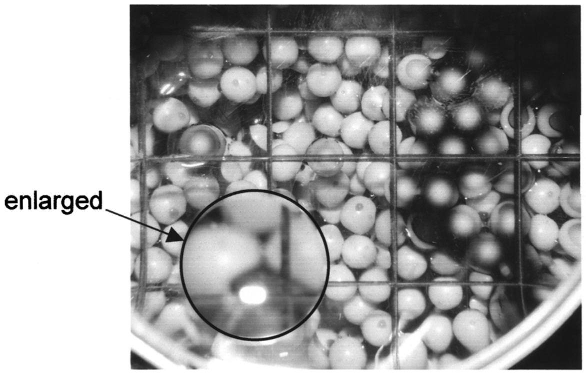
(b) Water-added bed

Figure 2. Images showing effects of liquid-addition for 6 mm dia. PLST.

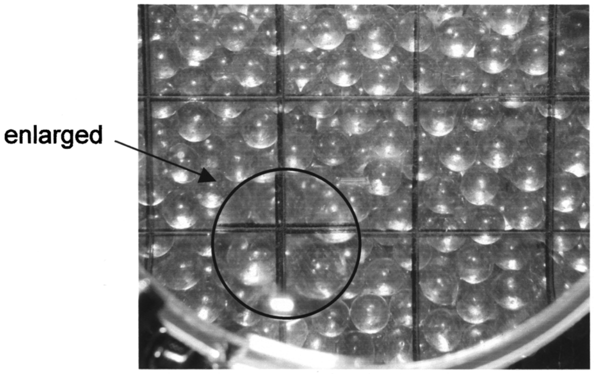
and, therefore, fluidization could be halted by interparticle forces associated with liquid bridges, as shown in Figure 3b.

It was confirmed in this study that wettability is one of the principal factors influencing defluidization. However, for large dense particles like the 6-mm glass beads in this study, another factor arises. The influence of wettability for large and heavy-particle beds is observed by comparing Figures 4 and 5. Figure 4 shows an example of good wettability (noncoated glass beads), while Figure 5 shows a poorly wetted bed (Teflon-coated glass beads). Although water gradually penetrated the bed of noncoated glass beads from the top, for Teflon-coated glass beads, it never percolated into the bed because the high-velocity air held the water at the bed surface. Even when water was delivered forcibly at low gas velocity, once the superficial gas velocity exceeded ~0.2–0.3 U_{mf}, all water migrated to the bed surface for the Teflon-coated glass beads. Therefore, fluidization was not promoted in poorly wettable high-density bed materials.

The influence of liquid density can be distinguished by comparing Figures 4 and 6. Figure 6 shows glass bead beds after addition of a high-density liquid, phosphoric acid ($\rho_l = 1{,}670\ \mathrm{kg/m^3}$). The phosphoric acid easily and quickly permeated into the core of the bed (promoting fluidization) compared with the lower-density liquid, water, for the same gas velocity.



(a)PLST+WTR maldistribution due to poor wettability



(b)GB+WTR uniformly distributed and bridged water due to good wettability

Figure 3. Views of liquid-distribution in bed at $U_g = U_{mf}$.
(a) 6 mm dia. PLST + water; (b) 6 mm dia. GB + water.

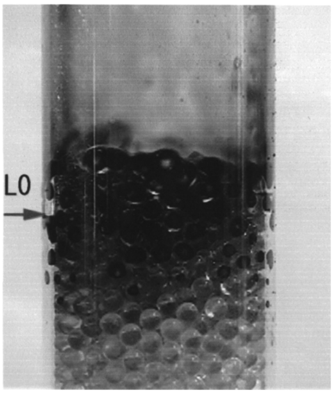


Figure 4. Behavior for 6 mm dia GB (wettable) + water.

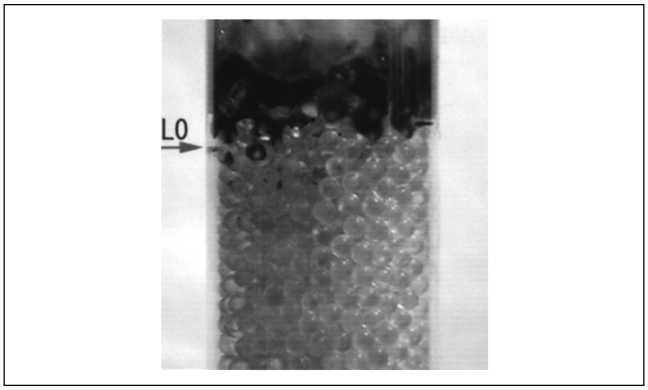


Figure 5. Behavior for 6 mm Teflon-coated GB (nonwettable) + water.

The key qualitative observations are summarized in Table 3. The terms used to characterize fluidization quality in the table are defined as follows:

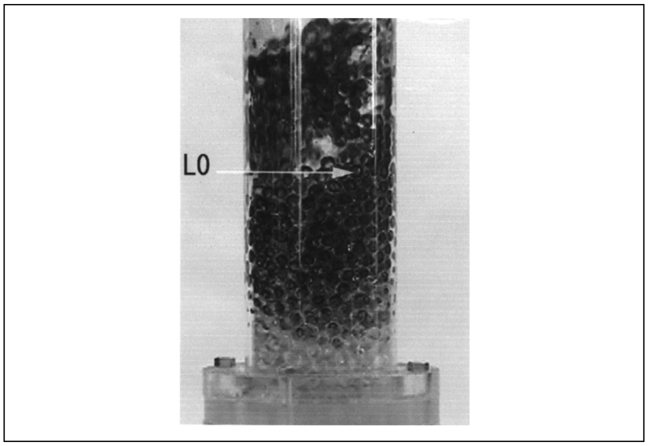


Figure 6. Behavior for 6 mm dia GB (wettable) + PAC.

VG: “Very Good” denotes immediate onset of vigorous fluidization (fluidization enhancement) upon addition of small quantities of liquid (from a few percent to 10% of bed volume) at the minimum fluidization condition.

G: “Good” signifies that fluidization enhancement occurs in a similar manner, but a few minutes are required for the liquid to penetrate into the whole bed.

SI: “Some Improvement” corresponds to cases where fluidization enhancement occurred only when a large amount liquid (greater than 20 vol. % of the bed volume) was added to the bed at minimum fluidization.

P: “Poor” designates cases where there was no fluidization enhancement, or where the bed was immobilized when any amount of liquid was added.

When fluidization is promoted by the addition of a liquid, the difference between the particle and liquid densities, that is, $(\rho_s - \rho_l)$, particle size, liquid viscosity, and wettability all appear to be important variables. Observations suggest that fluidization can be promoted only when the particles are relatively large, the density difference between the liquid and solid particles is small, such as $(\rho_s - \rho_l)/\rho_l < 0.25$, and wettability is poor. In such cases the added-liquid disperses itself throughout the entire bed. Liquid is contained within aggregates, but liquid bridges do not connect the aggregates. Hence, particle aggregates of moderate size are formed, with liquid connected only within these aggregates.

Where fluidization has been found to be terminated due to liquid addition in previous work (for example, Gluckman et al., 1976; Seville and Clift, 1984), denser particles like glass beads were used. However, in the cases considered in this article, fluidization is promoted when the difference in densities between the liquid and solids is small.

The influence of added liquids differs greatly according to the gas velocity and height of injection. For small-particle-fluidized beds, liquids like water, added from above, penetrate readily into the bed so that all particles are wetted successfully. Fluidization then decelerates or stops altogether due to liquid-bridging. Added liquid is then an important factor leading to defluidization. For large and heavy particles, top-added low-density liquids, such as water, are not able to

Table 3. Fluidization Caused by Liquid Addition

Particles	Liquid	Evaluation*	Fluidization Situation	Fig.
PLST-2	WTR	VG	Fluidization greatly promoted	2b
PLST-1	WTR	SI	Fluidization stopped for $\alpha = 0.1$ to 0.2; fluidization promoted for $\alpha \geq 0.3$	
PLST-1	PAC	P	Viscosity is more important than liquid density; some fluidization promotion occurred for $\alpha \geq 0.3$	
GB-3′ (coated)	WTR	P	Liquid does not permeate because of high gas velocity and poor wettability; no promotion of fluidization	5
GB-3	WTR	P	Liquid does not permeate because of high gas velocity; after forced delivery of liquid, fluidization stopped due to liquid bridging	4 3b
GB-3	PAC	SI	Fluidization is promoted in the portion reached by liquid, although liquid needs considerable time to permeate	6
GB-3	BAS	G	Fluidization is promoted	
GB-3	MBR	G	Fluidization is promoted	
GB-2	WTR	P	Fluidization stops within a few minutes	
GB-2	BAS	SI, (P)	Quasi-fluidization for $\alpha \geq 0.2$	
GB-2	PAC	P	Intermittent quasi-fluidization for $\alpha \geq 0.2$	
GB-1	WTR	P	Fluidization stops immediately	

*VG = very good; G = good; SI = some improvement; P = poor.

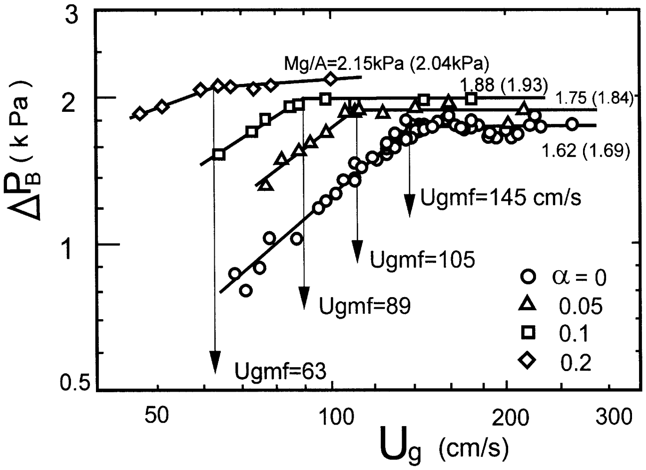


Figure 7. **$\Delta P_B - U_g$ diagram for 6-mm PLST/water system in 180-mm column.**

Numbers in brackets represent ΔP_{sus}.

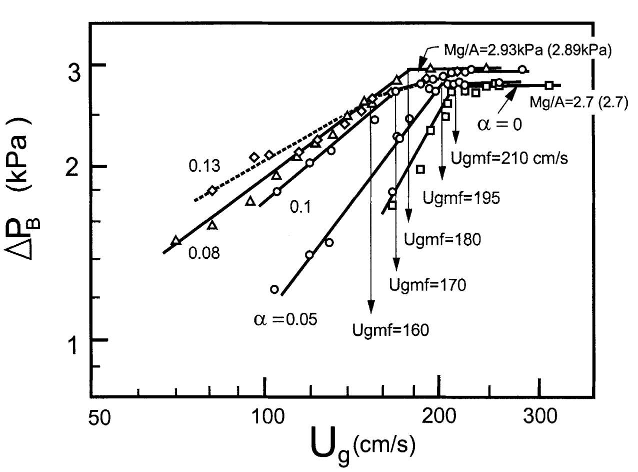


Figure 8. **$\Delta P_B - U_g$ diagram for 6-mm GB/phosphoric acid system.**

Numbers in brackets represent ΔP_{sus}.

permeate into the bed from above against the high air velocity. Since liquids cannot penetrate into the bed, the particles are not wetted and, therefore, neither fluidization promotion nor defluidization occur. However, if the liquid is injected from below or within the bed, liquid can impede or promote fluidization depending on the other factors identified above.

(2) Conditions for fluidization enhancement

From the above, the conditions for fluidization enhancement appear to be as follows:

(1) The added liquid must be able to reach the core of the bed and then to enhance the drag due to gas flow.

(2) The added liquid forms moderate-size aggregates of solids and liquids rather than forming a bridged liquid network throughout the entire bed.

In order to satisfy (1), the particles and liquid should have similar densities (within ~25%). To satisfy (2), the particles should be poorly wettable and/or large (that is, with low surface area per unit volume), so that the forces causing binding between particles are not significant.

(3) Fluidization diagram (ΔP_B-U_g diagram)

A ΔP_B-U_g diagram for the largest column (dia. 180 mm) is shown in Figure 7. The bed material was polystyrene with a diameter of 6 mm. When liquid (water) was added, fluidization was clearly enhanced as α increased, with U_{gmf} decreasing by 28%–57% for $\alpha = 0.05$ to 0.20, where the minimum fluidization gas velocity U_{gmf} is defined from a ΔP_B vs. U_g diagram obtained with decreasing gas velocity. (Mg/A), that is, the particle plus liquid weight divided by the cross-sectional area, is the value which corresponds to ideal fluidization where particles are supported fully by drag. In this figure, the experimental ΔP_B required for fluidization (ΔP_{sus}) is almost equal to (Mg/A). This indicates good fluidization conditions, with liquid uniformly dispersed over the whole bed, while aggregates consisting of liquids and particles are of moderate size. However, for large α, the system approaches solid-liquid fluidization. Therefore, the profile of the ΔP_B-U_g line changes to a smooth curve with a gradual transition (such as for $\alpha = 0.2$). This trend becomes more noticeable for dense particles and dense liquids.

Figure 8 shows the ΔP_B-U_g diagram for the 6-mm GB/PAC system in the 120-mm diameter column. Due to safety considerations, all test runs involving liquids other than water were carried out in this column. As described above, for large glass beads (6 mm dia.), fluidization can be decelerated by water addition, while, for the smaller particles (2.1 and 1.0 mm diameter), fluidization may even stop. On the other hand, fluidization is promoted by the addition of phosphoric acid ($\rho_l = 1{,}670$ kg/m^3), barium sulfate ($\rho_l = 1{,}900$ kg/m^3), and methylene bromide ($\rho_l = 2{,}500$ kg/m^3), cases in which the liquid density is closer to the particle density. In Figure 8, similar fluidization enhancement appears as for the (PLST/WTR) system. The decrease of U_{mf} with increasing α and the change of the ΔP_B-U_g profile to a smoother and more rounded curve with increasing α are seen in the figure. In this (GB/PAC) system, fluidization becomes less stable, and it is difficult to determine a clear U_{gmf} value once α exceeded 0.15.

Modified Liquid-Perturbed Gas Model

The dispersion of added liquid in the 6-mm PLST/WTR system at a constant gas flow rate is shown in Figure 9. Clusters or patches of polystyrene particles held together by water were dispersed throughout the bed when a small quantity of water ($\alpha = 0.05$) was added, while a large connected network was observed with more water ($\alpha = 0.2$) added.

To explain these observations and the conditions of fluidization, a liquid-perturbed gas model is proposed. In this model, the interstitial gas velocity is increased and fluidization is thereby promoted because of the reduction of open area for gas flow due to the presence of the liquid and the formation of solid-liquid clusters in the bed. A gas-perturbed liquid model was originally developed by Zhang et al. (1995) for systems predominantly composed of liquid and solids, and

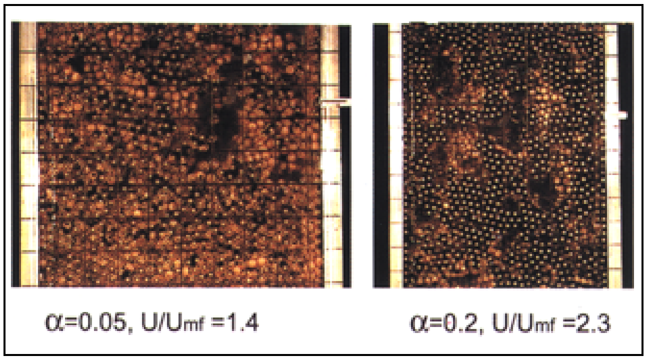


Figure 9. Dispersion of added liquid in 6-mm PLST/ WTR system at same gas-flow rate.

then inverted by Zhang et al. (1998) for the opposite case where a small flow of liquid perturbs a gas-fluidized bed. In the latter case, the minimum fluidization gas velocity U_{gmf} and the pressure drop through the bed ΔP_B are given, respectively, by

$$(\rho_s - \rho_g)(1 - \epsilon_{mf})g = \frac{150 U_{gmf}\mu_g(\epsilon_{smf})^2}{\phi^2 d_p^2 (\epsilon_{gmf})^3} + \frac{1.75\rho_g (U_{gmf})^2(\epsilon_{smf})}{\phi d_p (\epsilon_{gmf})^3} \tag{2}$$

where

$$\epsilon_{mf} = \epsilon_{gmf} + \epsilon_{lmf}$$

and

$$\Delta P_B = (\rho_s - \rho_g)(1 - \epsilon_{mf}) g L_{mf} \tag{3}$$

This liquid-perturbed gas model assumes that full support of the solids is provided by the gas, the velocity of which is increased by the presence of the liquid. The gas interstitial velocity (and, hence, the drag) are increased due to the volume occupied by the liquid. Therefore, these equations do not involve the liquid weight on the lefthand side of Eq. 2 and righthand side of Eq. 3. However, as can be seen in Figures 7 and 8, bed pressure drop ΔP_B increases when there is an increase in the ratio α of added water to dry-bed volume.

Hence, the liquid-perturbed gas model is modified to include the influence of the liquid weight. It is postulated that the added liquid uniformly coats each particle surface, although this assumption is undoubtedly oversimplified, especially for large α. In this system, the frictional pressure gradient at minimum fluidization is equal to the weight of liquid-coated solids per unit bed volume corrected for buoyancy, as given by the Ergun (1952) equation applied to the gas-solid system. In an analogous manner to Zhang et al. (1995, 1998), we can then obtain the following equations for the minimum fluidization gas velocity U_{gmf} and the pressure drop through the bed ΔP_B for liquid-added gas-fluidized beds

$$(\bar{\rho}_s - \rho_g)(1 - \epsilon_{gmf})g = \frac{150 U_{gmf}\mu_g(\epsilon_{smf} + \epsilon_{lmf})^2}{\phi^2 \bar{d}_p^2 (\epsilon_{gmf})^3} + \frac{1.75\rho_g (U_{gmf})^2(\epsilon_{smf} + \epsilon_{lmf})}{\phi \bar{d}_p (\epsilon_{gmf})^3} \tag{4}$$

$$\Delta P_B = (\bar{\rho}_s - \rho_g)(1 - \epsilon_{gmf}) g L_{mf} \tag{5}$$

where $\bar{d}_p = (d_p^3 + 6\alpha V_{B\cdot \mathrm{blk}}/\pi N_p)^{1/3}$ and $\bar{\rho}_s = (\epsilon_{smf}\rho_s + \epsilon_{lmf}\rho_l)/(\epsilon_{smf} + \epsilon_{lmf})$ denote the diameter and density of the liquid-coated particles, respectively.

Predictions of the model are compared with experimental results in Table 4. For both U_{gmf} and ΔP_B, the prediction and experiments agree well up to $\alpha \approx 0.15$. At greater liquid volume fractions, the accuracy of prediction becomes worse, probably because the assumption of uniform delivery of liquid over the whole bed is seriously in error at high liquid-loadings. (Note that liquid occupies about half the nonparti-

Table 4. Experimental vs. Predicted Bed Properties.

α	ϵ_{mf}^*	L_{mf}^* mm	$\Delta P_B)_{\mathrm{exp}}$ kPa	$U_{gmf})_{\mathrm{exp}}$ m/s	$\Delta P_B)_{\mathrm{cal}}$ kPA	$U_{gmf})_{\mathrm{cal}}$ m/s	δ No. %
PLST + WTR							
0.00	0.401	(273)	1.69	1.45	1.62	1.23	−15
0.05	0.417	281	1.84	1.05	1.75	1.14	+9
0.10	0.441	293	1.93	0.89	1.88	1.06	+19
0.20	0.503	330	2.04	0.63	2.15	1.03	+63
GB + PAC							
0.00	0.376	(180)	2.70	2.10	2.70	1.84	−12
0.05	0.402	188	2.74	1.95	2.84	1.68	−14
0.08	0.424	195	2.89	1.80	2.93	1.65	−8
0.10	0.438	200	2.65**	1.70	2.99	1.64	−4
0.13	0.418	193	2.60**	1.60	3.08	1.27	−21
0.15							
0.20			Less Stable Fluidization				

exp = experimental value; cal = calculated value; *in wetted beds except at $\alpha = 0$; No. = absolute deviation between experimental and calculated U_{gmf} values, based on experimental; **at U_{gmf} point.

cle volume of the bed when $\alpha = 0.2$.) Therefore, the fluidization becomes less stable. Another reason is the effect of wettability between the solid surfaces and liquids. Especially for light particles and relatively light liquids (that is, PLST/WTR in this study), wettability has a profound effect and the differences between predictions and experimental results are large. The interaction between the solid surface and liquid as affected by wettability and surface tension will be considered in future work.

Conclusions

Under some conditions, it is possible for the addition of a liquid to enhance the fluidization of gas-fluidized beds. This occurs when the particles are relatively large (>3 mm), the liquid and particles have similar densities (within ~25%), and the particles are poorly wetted by the liquid. When fluidization is promoted in this manner, the minimum fluidization velocity is decreased significantly, and particle motion is enhanced.

A "modified liquid-perturbed gas model" gives good predictions for a volumetric liquid loading up to ~0.15. Above that, predictions become unsatisfactory, probably due to nonuniform distribution of liquid within the bed.

Acknowledgments

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Notation

A = cross-sectional area of column, m^2
d_p = equivalent-volume sphere particle diameter, mm or m
$\bar{d}_p$ = mean particle diameter after being coated by added liquid, $\bar{d}_p = (d_p^3 + 6\alpha V_{B\cdot\mathrm{blk}}/\pi N_p)^{1/3}$, mm or m
g = acceleration of gravity, m/s^2
L_0 = static bed height, m
L_{mf} = bed height at minimum fluidization condition, m
M = mass of particles and liquid in the bed, kg
N_p = number of particles
U_g = superficial gas velocity, m/s
U_{mf} = superficial minimum fluidization gas-velocity in dry beds, cm/s or m/s
U_{gmf} = superficial minimum fluidization gas-velocity in liquid-added beds, cm/s or m/s
$V_{B\cdot\mathrm{blk}}$ = bed bulk volume, m^3

Greek letters

α = volumetric ratio of added liquids to dry bulk bed volume
ΔP_B = total bed pressure drop, Pa
ΔP_{sus} = pressure drop through a bed at U_{mf}, Pa
δ = deviation, %
ϵ = voidage
ϵ_g = gas holdup
ϵ_l = liquid holdup
ϵ_s = solids holdup
μ = viscosity, Pa·s
ρ = density, kg/m^3
$\bar{\rho}_s$ = density of particles after being coated with liquid, $(\epsilon_{smf}\rho_s + \epsilon_{lmf}\rho_l)/(\epsilon_{smf} + \epsilon_{lmf})$, kg/m^3
σ = surface tension, N/m
ϕ = particle sphericity

Subscripts

g = gas
l = liquid
mf = minimum fluidization
s = solid particle

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