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Transition Velocity and Bed Expansion of Two-Phase (Liquid-Solid) Fluidization Systems

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Abstract−Hydrodynamic transition experiments for two-phase (liquid-solid), both upward and downward, liquid flow systems were performed in a 127-mm diameter column. The particles were 3.2-mm polymer (1,280 kg/m^3), 5.8-mm polyethylene (910, 930, 946 kg/m^3), 5.5-mm polystyrene (1,021 kg/m^3) and 6.0-mm glass (2,230 kg/m^3) spheres, with water, aqueous glycerol solution and silicone oil as liquids. The dimensionless pressure gradient increases initially with increasing liquid velocity, but decreases gradually with increasing liquid velocity beyond U_{lmf} due to bed expansion. The non-dimensionalized pressure gradient using the liquid/solid mixture density increases with increasing liquid velocity and then reaches a constant value close to unity beyond U_{lmf}. The minimum fluidization Reynolds number for liquid-solid system increases with increasing Archimedes number including both heavier and lighter than the density of the liquid phase. U_{lmf} should be the same for both upward and downward fluidization systems since the Ergun equation is based on the main assumption that drag force of the superficial liquid velocity, U_{lmf}, is equal to the net difference between gravitational and buoyancy forces.

Key words: Liquid-Solid Systems, Two-Phase Fluidization, Minimum Fluidization, Bed Expansion

INTRODUCTION

In two-phase (liquid-solid) upward systems, solid particles whose density is larger than that of the liquid are fluidized by upward liquid. When the solid beds have a density lower than that of the liquid, the beds can be fluidized by a downward flow of liquid phase [Muroyama and Fan, 1985]. In both cases, the liquid is the continuous phase and solid particle is dispersed phase.

The application of fluidization technique in biotechnology has become one of the most important areas in bioreactor engineering [Atkinson, 1981; Shugerl, 1989]. Upward fluidized bed bioreactors are among the most efficient reactors for aerobic and anaerobic wastewater treatment [Jeris et al., 1981; Jewell et al., 1981; Choi and Shin, 1999], penicillin production [Oh et al., 1988; Endo et al., 1988], and phenol degradation [Tang and Fan, 1987; Livingston and Chase, 1989]. However, the important problem of biofilm thickness control is the main reason for the limited industrial application of these systems. The control of biofilm thickness within a narrow range is achieved in the downward fluidized bed biofilm reactor [Karamanev and Nikolov, 1992]. It was found that this bioreactor is very efficient both when used for biological aerobic wastewater treatment under bench scale and when scaled up [Nikolov and Karamanev, 1987; Nikolov et al., 1990].

Many studies have been published on hydrodynamics of two-phase (liquid-solid) upward fluidization [Wilhelm and Kwauk, 1948; Ergun, 1952; Richardson and Zaki, 1954; Begovich and Watson, 1978; Epstein et al., 1981; Fan et al., 1985; Kwauk, 1992; Zhang et al., 1995; Lee et al., 1999, 2000b]. However, few studies on the hydrodynamics of two-phase downward fluidization have been published [Fan et al., 1982; Garnier et al., 1990; Karamanev and Nikolov, 1992; Lee et al., 2000a]. Two mathematical models relating the bed expansion to the downward liquid velocity were proposed by Fan et al. [1982]. These models were based on the experimental data obtained from expansion of beds containing solid particles having densities from 822 to 930 kg/m^3 and only one bed with lighter particles with a density of 380 kg/m^3. Particle sizes were 4.76 and 19.1 mm, corresponding to d_p/D_t ratios of 0.062 and 0.25, respectively. Karamanev and Nikolov [1992] reported the bed expansion characteristics of two-phase downward fluidization. They used twelve different expanded polystyrene (Styrofoam) spheres with diameters from 1.31 to 7.24 mm and densities between 75 and 930 kg/m^3, corresponding d_p/D_t ratios from 0.016 to 0.091, respectively.

The main objective of study is to investigate the effects of liquid velocity and the density difference between solid particles and liquid on the transition velocity and bed expansion under the d_p/D_t ratio less than 0.05 in two-phase both upward and downward fluidization systems.

1. Pressure Gradient of Two-Phase (Liquid-Solid) Fixed or Fluidized Beds

With the z-coordinate taken as positive in the upward direction, i.e., in the same direction as the liquid flow, the overall pressure variation in the vertical direction corrected for the frictional pressure gradient is given by

$$\left(-\frac{dP}{dz}\right)_{ls} = \rho_l g + \left(-\frac{dp}{dz}\right)_{f,ls} \tag{1}$$

The frictional pressure gradient in two-phase (liquid-solid) upward systems can be expressed as

$$\left(-\frac{dp}{dz}\right)_{f,ls} = \varepsilon_s(\rho_s - \rho_l)g \tag{2}$$

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Substituting Eq. (2) into Eq. (1) and rearranging, we obtain

$$\frac{1}{\rho_l g}\left(-\frac{dP}{dz}\right)_{ls} = 1 + \varepsilon_s\left(\frac{\rho_s}{\rho_l} - 1\right) \tag{3}$$

For a fixed or moderately expanded bed, $(-dp/dz)_{f,ls}$ can be expressed by the Ergun [1952] equation applied to the liquid-solid interaction, i.e.,

$$\left(-\frac{dp}{dz}\right)_{f,ls} = \frac{150(1-\varepsilon_l)^2 \mu_l U_l}{\varepsilon_l^3 \phi^2 d_p^2} + \frac{1.75(1-\varepsilon_l)\rho_l U_l^2}{\varepsilon_l^3 \phi d_p} \tag{4}$$

Substituting Eq. (4) into Eq. (1) leads to

$$\frac{1}{\rho_l g}\left(-\frac{dP}{dz}\right)_{ls} = 1 + \frac{150(1-\varepsilon_l)^2 \mu_l U_l}{\phi^2 d_p^2 \varepsilon_l^3 \rho_l g} + \frac{1.75(1-\varepsilon_l)}{\varepsilon_l^3}\frac{U_l^2}{\phi d_p g} \tag{5}$$

With the assumptions of bed voidages, particle properties and the superficial liquid velocity are all uniform over the entire bed height, Eqs. (3) and (5) can be applied if the bed height is known from the measurement so that the pressure gradient is also uniform over that interval.

In case of the liquid-solid downward fixed or fluidized beds, the dimensionless pressure gradient as reported by Lee et al. [2000a] is defined as

$$\frac{1}{\rho_l g}\left(-\frac{dP}{dz}\right)_{ls} = 1 - \frac{150(1-\varepsilon_l)^2 \mu_l U_l}{\phi^2 d_p^2 \varepsilon_l^3 \rho_l g} - \frac{1.75(1-\varepsilon_l)}{\varepsilon_l^3}\frac{U_l^2}{\phi d_p g} \tag{6}$$

The frictional pressure gradient at the minimum fluidization condition equal to the net difference between gravitational and buoyancy forces per unit area is given by the Ergun equation [1954].

$$\left(-\frac{dp}{dz}\right)_{f,ls} = \varepsilon_s|(\rho_s - \rho_l)|g = \frac{150(1-\varepsilon_l)^2 \mu_l U_l}{\varepsilon_l^3 \phi^2 d_p^2} + \frac{1.75(1-\varepsilon_l)\rho_l U_l^2}{\varepsilon_l^3 \phi d_p} \tag{7}$$

Rearranging the result, we arrive at

$$Re_{lmf}^2 + \frac{150}{1.75}\frac{1-\varepsilon_{lmf}}{\phi}Re_{lmf} - Ar_l\frac{\phi\varepsilon_{lmf}^3}{1.75} = 0 \tag{8}$$

$$\text{where } Ar_l = \frac{d_p^3 \rho_l |(\rho_s - \rho_l)| g}{\mu_l^2} \tag{9}$$

With simplification of the equation type suggested by Wen and Yu [1966a, b], the Ergun equivalent of Re_{lmf} equation reduced to the more generalized form as

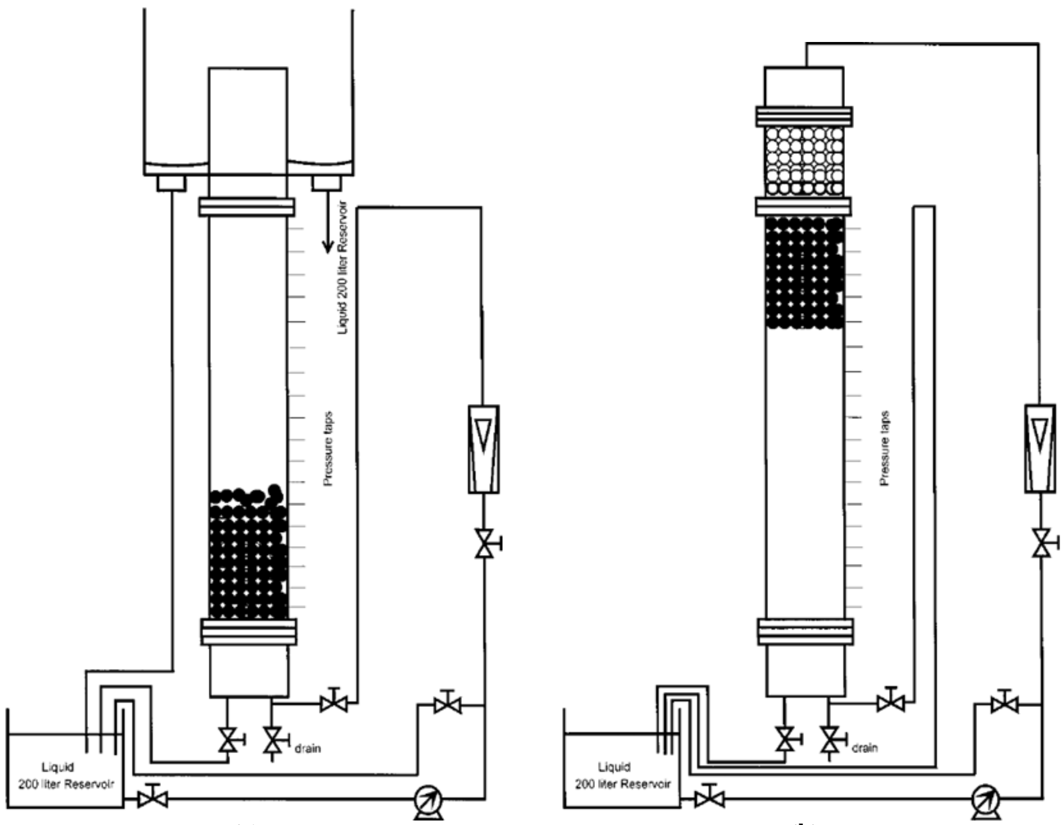
$$Re_{lmf} = \sqrt{C_1^2 + C_2 Ar_l} - C_1 \tag{10}$$

where values of C_1 and C_2 in the literature are summarized in Table 1.

EXPERIMENTAL

Table 1. Values of C_1 and C_2 coefficients from various investigators

Author	C_1	C_2
Wen and Yu [1966a, b]	33.7	0.0408
Richardson [1971]	25.7	0.0366
Grace [1982]	27.2	0.0408



(a) (b)

Fig. 1. Schematic diagrams of experimental equipment (a) Two-phase (liquid-solid) upward systems; (b) Two-phase (liquid-solid) downward systems.

Table 2. Physical properties of solid particles, $\phi \approx 1.0$

Solids	Density ρ_s, [kg/m^3]	Mean diameter d_p, [mm]
Alumina (in silicone oil)	1881	3.2
Glass beads	2230	6.0
Polyethylene (PE)	910	5.8
Polyethylene (PE)	930	5.8
Polyethylene (PE)	946	5.8
Polymer blend (PB)	1280	3.3
Polystyrene (PS)	1021	5.5

Table 3. Physical properties of liquids (20 °C)

Liquid	Density ρ_l, [kg/m^3]	Viscosity μ_l, [mPa·s]
Glycerol solution	1130	7.0
Silicone oil	953	2.4
Water	1000	1.0

Experiments, involving both visual observations and dynamic pressure measurements determined by differential pressure transducer (Omega, PX750-DI) connected to a large number of axially distributed pressure taps, were carried out in a 127-mm diameter Plexiglas column of total 2.74 m, with a 1.83-m high test section. The pressure taps were mounted flush with the wall of the column at 0.1-m intervals starting from 0.05 m above the liquid distributor. The schematic diagrams of the experimental setup, involving two-phase (liquid-solid) both upward and downward systems are shown in Figs. 1(a) and 1(b). The particles were 3.2-mm polymer (1,280 kg/m^3), 5.8-mm polyethylene (910, 930, 946 kg/m^3), 5.5-mm polystyrene (1,021 kg/m^3) and 6.0-mm glass (2,230 kg/m^3) spheres, with water, aqueous glycerol solution and silicone oil as liquids. The liquid flows upward through the beds of solids for upward system, while the liquid flows downward for two-phase (liquid-solid) downward systems. The physical properties of solids particles and liquids are listed in Table 2 and Table 3, respectively. The static bed height, H_{B0}, was always higher than 0.5 m with the particle weights of 3.5-8.54 kg depending on the particle density. Liquid flow rates (U_l) were measured by a flow meter in the range of 0-27.9 mm/s. The liquid was pumped into the plenum chamber of the column (packed with 16-mm plastic intalox saddles) at a constant flow rate and then through a perforated plate containing 34 evenly spaced holes of diameter 4 mm serving as the liquid distributor in the two-phase upward fluidized beds. In the downward system, the liquid pumped to top of the column at a constant liquid flow, then through a perforated containing 34 evenly spaced holes of diameter 4 mm serving as the liquid distributor. A retaining stainless screen (5 mesh) was located below the fluidized-bed liquid distributor section. This section prevented the particles from rising from the bed to the top portion of the column. Pressure signals from the transducer were processed by a personal computer at a sampling frequency of 5 Hz for intervals 180 s. The overall pressure gradients were measured to determine the minimum liquid fluidization velocity of the particles by changing the superficial liquid velocity decreased step-by-step from the initially fluidized state to zero.

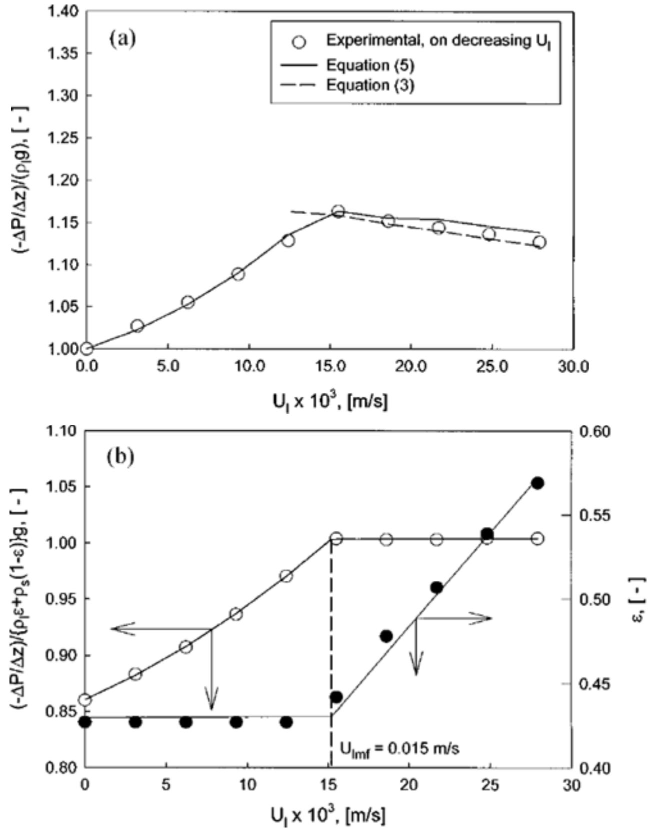


Fig. 2. (a) Dimensionless pressure gradient based on liquid density as a function of liquid velocity for liquid-solid fluidized beds (d_p=3.3 mm, ρ_s=1,280 kg/m^3). (b) Dimensionless pressure gradient based on liquid/solid mixture density as a function of liquid velocity for liquid-solid fluidized beds (d_p=3.3 mm, ρ_s=1,280 kg/m^3).

RESULTS AND DISCUSSION

The minimum fluidization velocity (U_{lmf}) in liquid-solid fluidized beds is a function of particle diameter and density as well as the physical properties of liquid phase such as density and viscosity. The dimensionless pressure gradient in terms of liquid density for water-polymer blend beads is shown in Fig. 2a, together with the predicted hydrostatic pressure gradient [Eq. (3)] and the predicted pressure gradient from Eq. (5). The minimum liquid fluidization velocity is taken as the velocity at which the pressure gradient reaches a maximum. The dimensionless pressure gradient increases initially with increasing liquid velocity, but decreases gradually with increasing liquid velocity beyond U_{lmf} due to bed expansion. The non-dimensionalized pressure gradient in terms of the liquid/solid mixture density for the same system increases with increasing liquid velocity and then reaches a constant value close to unity beyond U_{lmf}, as can be seen in Fig. 2b.

Fig. 3 (with one case also plotted in Fig. 2b) shows the variation of bed voidage with liquid velocity in the various two-phase (liquid-solid) fluidization systems.

The bed voidage is seen to vary linearly with liquid velocity beyond U_{lmf}, i.e.

$$U_l=\varepsilon^n U_t \tag{11}$$

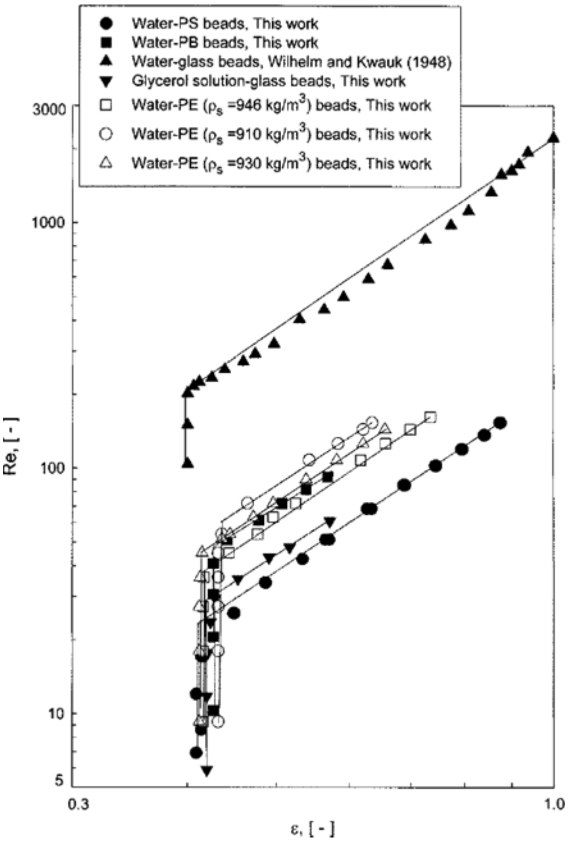


Fig. 3. Relation between bed voidage and liquid velocity for two-phase (liquid-solid) fluidization systems.

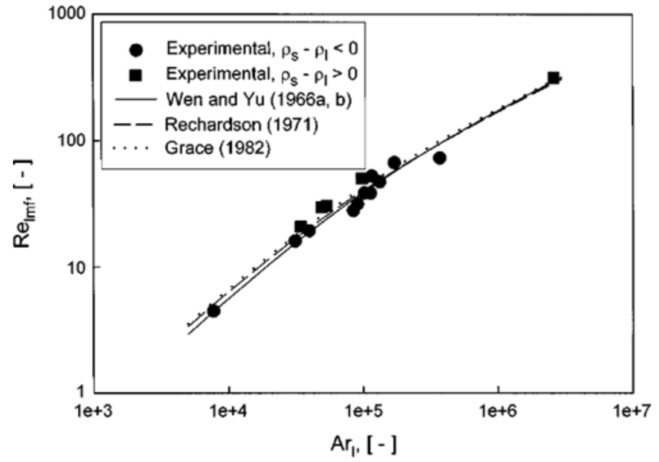


Fig. 4. Dependence of Re_{lmf} on Archimedes number based on minimum fluidization velocity in both cases.

Richardson and Zaki [1954] formulated the sectional correlations of the exponent, n, to the terminal Reynolds number ($Re_t = d_p U_t \rho_l/\mu_l$). Experimental values of U_t and n are listed in Table 4, together with the values of n from the Richardson-Zaki correlations. As can be seen, the agreement between the two sets of n values is good.

The difference between the values of Re_{lmf} and Archimedes number (Ar) is shown in Fig. 4 with the data of Karamanev and Nikolov [1992]. The only U_{lmf} values for which d_p/D_t ratio is less than 0.05 have been chosen due to the wall effect. As can be seen in Fig. 4, the minimum fluidization Reynolds number for liquid-solid system increases with increasing Archimedes number including both the heavier and lighter densities of particles than that of the liquid. Theoretically, U_{lmf} should be the same for both upward and downward fluidization systems since the Ergun equation is based on the main assumption that drag force of the superficial liquid velocity, U_{lmf}, is equal to the net difference between gravitational and buoyancy forces. Theoretical equations from Table 1 predict reasonably well the minimum liquid fluidization velocities for the both cases.

CONCLUSION

For two-phase both upward and downward flow systems, the dimensionless pressure gradient increases initially with increasing liquid velocity, but decreases gradually with increasing liquid velocity beyond U_{lmf} due to bed expansion. A good agreement was obtained between the experimental and the Richardson-Zaki correlations. U_{lmf} should be the same for both upward and downward fluidization systems since the Ergun equation is based on the main assumption that drag force of the superficial liquid velocity, U_{lmf}, is equal to the net difference between gravitational and buoyancy forces.

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NOMENCLATURE

Table 4. Experimental values of terminal velocity U_t and Richardson-Zaki index n for various systems

System	d_p [mm]	U_t expt'*l* [m/s]	n expt'*l* [-]	n R.-Z. correl'n [-]	Source
Glycerol solution-glass beads	6.0	0.26	2.47	2.53	This work
Water-glass beads	5.0	0.44	2.63	2.40	Wilhelm and Kwauk, 1948
Water-polymer blend (PB) beads	3.3	0.11	2.33	2.43	This work
Water-polystyrene (PS) beads	5.5	0.04	2.56	2.57	This work
Water-PE (ρ_s=910 kg/m^3) beads	5.8	0.08	2.41	2.38	This work
Water-PE (ρ_s=930 kg/m^3) beads	5.8	0.07	2.50	2.42	This work
Water-PE (ρ_s=946 kg/m^3) beads	5.8	0.06	2.52	2.45	This work

Ar_l : Archimedes number defined by $\frac{d_p^3\rho_l(\rho_s-\rho_l)g}{\mu_l^2}$ [-]
C_1 : coefficient in Eq. (10) [-]
C_2 : coefficient in Eq. (10) [-]
d_p : qui-volume sphere particle diameter [mm or m]
D_t : column diameter [m]
g : acceleration of gravity [m/s^2]
H_{B0} : static bed height [m]
n : Richardson and Zaki [1954] index [-]
$-\Delta P$: total pressure drop [Pa]
$(-\Delta P/\Delta z)$: total pressure gradient [Pa/m]
$(-dP/dz)_{ls}$: overall pressure gradient in liquid-solid system [Pa/m]
$(-dp/dz)_{f,ls}$: frictional pressure gradient due to liquid-solid interaction [Pa/m]
Re : particle Reynolds number, $\rho_l d_p U_l/\mu_l$ [-]
Re_{lmf} : Reynolds number at minimum fluidization condition, $\rho_l d_p U_{lmf}/\mu_l$ [-]
Re_t : particle Reynolds number at terminal condition, $\rho_l d_p U_t/\mu_l$ [-]
U_l : superficial liquid velocity [m/s]
U_{lmf} : U_l at minimum fluidization [m/s]
U_i : value of U_l when log U_l vs. log ε for liquid-solid fluidization is extrapolated to ε=1 [m/s]

Greek Letters

ε : bed voidage [-]
ε_l : liquid holdup [-]
ε_{mf} : voidage at minimum fluidization [-]
ε_s : solids holdup [-]
μ_l : liquid viscosity [Pa·s or mPa·s]
ρ_l : liquid density [kg/m^3]
ρ_s : particle density [kg/m^3]
ϕ : particle sphericity [-]

REFERENCES

Atkinson, B., "Biological Fluidized bed Treatment of Water and Wastewater," Cooper, P. F. and Atkinson, B., eds., Horwood, E., Chichester, U.K. (1981).

Begovich, J. M. and Watson, J. S., "Hydrodynamic Characteristics of Three-Phase Fluidized Beds," in Fluidization, Davidson, J. F. and Keairns, D. L., eds., Cambridge Univ. Press, U.K. (1978).

Choi, H. S. and Shin, M. S., "Hydrodynamics Study of Two Different Inverse Fluidized Reactors for the application of Wastewater Treatment," *Korean J. Chem. Eng.*, **16**, 670 (1999).

Endo, I., Nagamune, T., Tachi, K. and Kobayashi, T., "Fluidized Bed Bioreactor: Antibiotic Production," Abstr. Int. Biotechnol. Symp., Paris, France, **37** (July 17-22, 1988).

Epstein, N., Leclair, B. P. and Pruden, B. B., "Liquid Fluidization of Binary Particle Mixtures-I. Overall Bed Expansion," *Chem. Eng. Sci.*, **36**, 1803 (1981).

Ergun, S., "Fluid Flow Through Packed Columns," *Chem. Eng. Prog.*, **48**, 89 (1952).

Fan, L.-S., Matsuura, A. and Chern, S.-H., "Hydrodynamic Characteristics of a Gas-Liquid-Solid Fluidized Bed Containing a Binary Mixture of Particles," *AIChE J.*, **31**, 1801 (1985).

Fan, L.-S., Muroyama, K. and Chern, S.-H., "Hydrodynamic Characteristics of Inverse Fluidization in Liquid-Solid and Gas-Liquid-solid Systems," *Chem. Eng. J.*, **24**, 43 (1982).

Garnier, A., Chavaria, C., Andre, G. and Klvana, D., "The Inverse Fluidization Airlift Bioreactor. 1 Hydrodynamic Studies," *Chem. Eng. Comm.*, **98**, 31 (1990).

Grace, J. R., "Fluidized Bed Hydrodynamics," Chap. 8.1 in Handbook of Multiphase Systems, Hetsroni, ed., Hemisphere Publishing Corp., Washington (1982).

Jeris, J. S., Owens, R. W. and Flood, F., "Secondary Treatment of Municipal Wastewater with Fluidized Bed Technology," Biological Fluidized Bed Treatment of Water and Wastewater, Cooper, P. F. and Atkinson, B., eds., Horwood, E., Chichester, U.K. (1981).

Jewell, W. J., Switzenbaum, M. S. and Morris, J. W., "Municipal Wastewater Treatment with the Anaerobic Attached Microbial Film Expanded Bed Process," *J. Water Poll. Control Fed.*, **53**, 482 (1981).

Karamanev, D. G. and Nikolov, L. N., "Bed Expansion of Liquid-Solid Inverse Fluidization," *AIChE J.*, **38**, 1916 (1992).

Kwauk, M., "Fluidization: Idealized and Bubbleless, with Applications," Science Press, Beijing (1992).

Lee, D. H., Epstein, N. and Grace, J. R., "Models for Minimum Liquid Fluidization Velocity of Gas-Liquid Fluidized Beds," Proc. 8th APCChE Congress, **3**, 1699 (1999).

Lee, D. H., Epstein, N. and Grace, J. R., "Hydrodynamic Transition from Fixed to Fully Fluidized Beds for Three-Phase Inverse Fluidization," *Korean J. Chem. Eng.*, **17**, 684 (2000a).

Lee, D. H., Macchi, A., Epstein, N. and Grace, J. R., "Transition Velocities and Phase Holdups at Minimum Fluidization in Gas-Liquid-Solid Systems," *Can. J. Chem. Eng.*, in press (2000b).

Livingston, A. G. and Chase, H. A., "Modeling Phenol Degradation in a Fluidized-Bed Bioreactor," *AIChE J.*, **35**, 1986 (1989).

Nikolov, L. N. and Karamanev, D. G., "Experimental Study of Inverse Fluidized Bed Biofilm Reactor," *Can. J. Chem. Eng.*, **65**, 214 (1987).

Nikolov, L. N. and Karamanev, D. G., "The Inverse Fluidized Bed Biofilm Reactor: A New Laboratory Scale Apparatus for Biofilm Research," *J. Ferm. Bioeng.*, **69**, 265 (1990).

Oh, D. K., Hyun, C. K., Kim, J. H. and Park, Y. H., "Production of Penicillin in a Fluidized Bed Bioreactor," *Biotechnol. Bioeng.*, **32**, 569 (1988).

Richardson, J. F. and Zaki, W. N., "Sedimentation and Fluidization," *Trans. Instn. Chem. Engrs.*, **32**, 35 (1954).

Richardson, J. F., "Incipient Fluidization and Particulate Systems," Chap. 2 in Fluidization, Davidson, J. F. and Harrison, D., eds., Academic Press, New York (1971).

Shugerl, K., "Biofluidization: Application of the Fluidization Technique in Biotechnology," *Can. J. Chem. Eng.*, **67**, 178 (1989).

Tang, W. T. and Fan, L.-S., "Steady-State Phenol Degradation in a Draft Tube, Gas-Liquid-Solid Fluidized-Bed Bioreactor," *AIChE. J.*, **33**, 239 (1987).

Wen, C. Y. and Yu, Y. H., "Mechanics of Fluidization," *Chem. Eng. Prog. Symp. Ser.*, **62**(62), 100 (1966a).

Wen, C. Y. and Yu, Y. H., "A Generalized Method for Predicting the Minimum Fluidization Velocities," *AIChE J.*, **12**, 610 (1966b).

Wilhelm, R. H. and Kwauk, M., "Fluidization of Solid Particles," *Chem. Eng. Prog.*, **44**, 201 (1948).

Zhang, J. P., Epstein, N., Grace, J. R. and Zhu, J., "Minimum Liquid Fluidization Velocity of Gas-Liquid Fluidized Beds," *Chem. Eng. Res. Des.*, **73**, 347 (1995).