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Energy Dissipation Rate and Pressure Fluctuations in a Three Phase Fluidized Bed with a Large Column Diameter

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Abstract−The effects of liquid (0.02-0.10 m/s) and gas (0.0-0.10 m/s) velocities and particle size (1.0, 2.3, 3.0 mm) on the pressure fluctuations and energy dissipation rate in three phase fluidized beds were determined in a large column (0.376 m-I.D.×2.1 m high). The standard deviation of pressure fluctuations and energy dissipation rate increase with gas and liquid velocities but, decrease in the radial direction of three phase fluidized beds. The energy dissipation rate was well correlated with dimensionless groups as: $E_d=16.788Fr_l^{0.183}Fr_g^{0.139}(1-\psi)^{0.442}+1.265Fr_g^{0.143}Re^{0.181}$.

Key words: Pressure Fluctuation, Energy Dissipation Rate, Three-phase, Fluidization

INTRODUCTION

Recently, the applications of three phase fluidized bed reactors have increased in the chemical, petrochemical and biochemical industries [Fan, 1989; Kwon and Kim, 1990; Kim and Kang, 1997, Kang et al., 1999]. Hydrodynamic properties such as pressure fluctuations in the bed are needed in order to provide the basic information for designing fluidized bed reactors. In that regard, several studies [Lirag and Littman, 1971; Verloop and Heertjes, 1974; Fan et al., 1984; Lee and Kim, 1988; Park and Kim, 2001] have been reported on the pressure fluctuations in fluidized beds. Lirag and Littman [1971] used the frequency calculated from the power spectral density function of pressure fluctuations to estimate the bubble size, and reported that the frequency decreases but the amplitude increases with bed height and particle size because of bubble coalescence. Verloop and Heertjes [1974] derived an expression that relates the major frequency of pressure fluctuations to the bed height. Fan et al. [1984] used an online approach to analyze the pressure fluctuations statistically in which statistical properties such as auto-correlation and cross-correlation functions, probability distribution and powder spectral density function have been determined. Svoboda et al. [1984] concluded that the mean amplitudes of pressure fluctuations increase almost linearly with the relative gas velocity and the dominant frequency decreases steeply with the relative gas velocity. Jin [1985] presented the effect of gas velocity, liquid velocity and particle size on the pressure spectrum in bubble columns and three phase fluidized beds. Kitano and Ikeda [1988] pointed out that the component of pressure fluctuation signals below 10 Hz was significantly affected by bubble behavior. Lee and Kim [1988] proposed that the statistical properties such as mean amplitude, fluctuation interval, standard deviation, flatness and skewness can be utilized to determine the transition velocity from the bubbling to the turbulent flow regimes in gas-fluidized beds. Park and Kim [2001] applied both Fourier transform and wavelet transform to pressure signals in a three phase fluidized bed to identify flow regimes. However, information on energy dissipation rate and the pressure fluctuations in three phase fluidized beds is relatively sparse.

In the present study, pressure fluctuations in three phase (liquid-gas-solid) fluidized beds were determined in a 0.376 m-I.D.×2.1 m high Plexiglas column, and the energy dissipation rate based on the pressure spectrum was determined.

EXPERIMENTS

Experiments were carried out in a pilot scale (0.376 m-I.D.×2.1 m high) Plexiglas column as shown in Fig. 1. Sixteen pressure taps

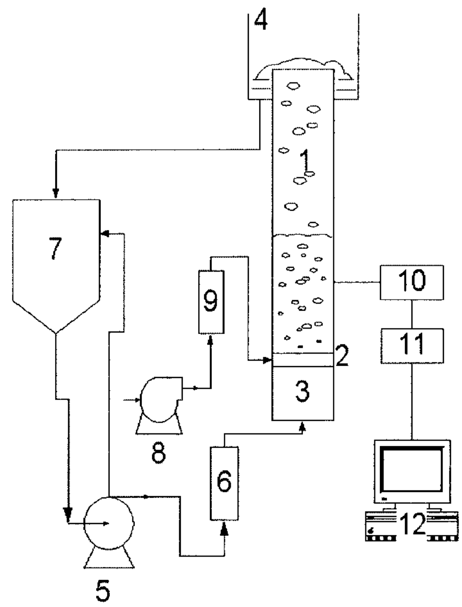

Fig. 1. Schematic diagram of experimental apparatus.

1. Main column	7. Liquid reservoir
2. Distributor	8. Air compressor
3. Calming section	9. Flowmeter
4. Weir	10. Pressure transducer
5. Pump	11. Data acquisition system
6. Flowmeter	12. PC

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were mounted flush with the wall of the column from 70 mm to 1,610 mm above the distributor. The solid particles were supported on a perforated stainless steel plate with 786 evenly spaced holes of 3 mm-I.D. was used as a liquid distributor. The distributor was situated between the main column section and 0.4 m-I.D.×0.55 m high stainless steel distributor box into which water was introduced.

The pressure fluctuations were measured with a pressure transducer located at 0.4 m above the distributor, and the fluctuations were measured at six different radial positions with the sampling time of 10 ms. The transducer produced a voltage proportional to the pressure fluctuations, and the signals were amplified and stored in a data acquisition system. The obtained digitized data were used to calculate the statistical properties of the pressure fluctuations.

The energy dissipation rate can be determined from the pressure spectrum as follows:

From a pressure fluctuation signal, P(t), its probability density function ϕ_N(p) can be calculated from

$$\phi_N(p)\Delta p \equiv \lim_{T\to\infty}\frac{1}{T}\sum(\Delta t) \tag{1}$$

The r-th central moment of P(t) about its mean μ_r, is defined as:

$$\mu_r = \int_{-\infty}^{\infty}(p-\mu)^r\phi_N(p)dp \tag{2}$$

The second central moment is the variance of P(t) and its root square of second central moment is a standard deviation:

$$\sigma = \sqrt{\mathrm{Var}} \tag{3}$$

$$\mathrm{Var} = \int_{-\infty}^{\infty}(p-\mu)^2\phi_N(p)dp \tag{4}$$

The power spectral density function (PSDF) of P(t) is the Fourier transform of its auto-correlation function as:

$$\phi_{pp}(\tau) = \lim_{T\to\infty}\frac{1}{T}\int_{-T/2}^{T/2}p(t)p(t+\tau)dt \tag{5}$$

$$\mathrm{PSDF} = \int_{-\infty}^{\infty}\phi_{pp}(\tau)e^{-j2\pi f\tau}d\tau \tag{6}$$

The PSDF expresses the behavior of a signal in the frequency domain rather than in the time domain, and the distribution of energy with frequency. The energy dissipation rate was determined from the energy spectrum by Tennekes and Lumley [1973]. The energy dissipation rate can be expressed as:

$$E_d = 2\nu\int_0^{\infty}\omega^2E(\omega)d\omega \tag{7}$$

The relationship between the pressure spectrum, S_p(w), and energy spectrum, E(w), has been given by Frost and Moulden [1977].

$$S_p(\omega) = k\rho^2\omega E^2(\omega) \tag{8}$$

where the constant k is 0.49 from the theory of Hinze [1959].

Therefore, the energy dissipation rate can be calculated from the above equations.

$$E_d = \sqrt{\frac{4\nu^2}{k\rho^2}}\int_0^{\infty}\sqrt{\omega^3S_p(\omega)}d\omega \tag{9}$$

RESULTS AND DISCUSSION

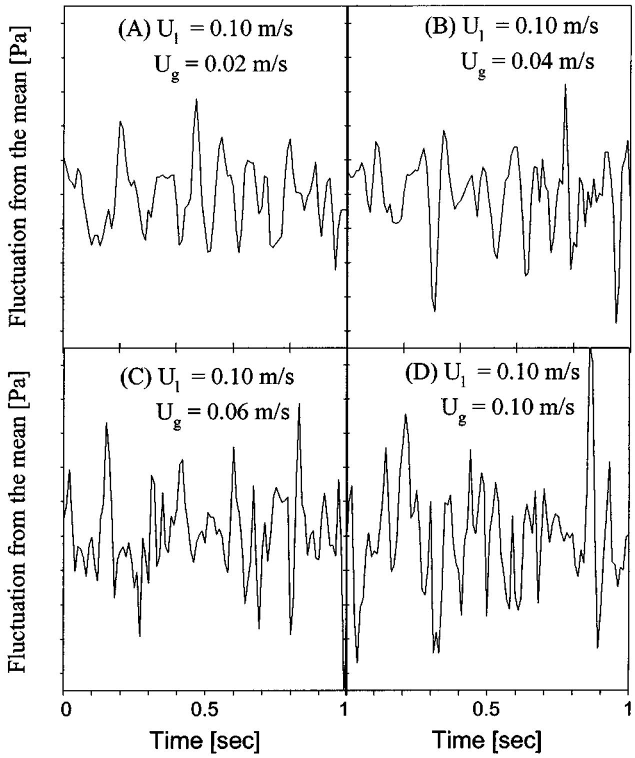

Fig. 2. Pressure fluctuations from mean value in a three phase fluidized bed (dp=3 mm).

The effect of gas velocity on the pressure fluctuations at the center of the column in the three phase fluidized bed is shown in Fig. 2. As can be seen, the amplitude and the frequency of the pressure fluctuation increase with increasing gas velocity due to the bubble coalescence. Jin [1985] and Davidson and Harrison [1978] reported that the amplitude linearly increases with bubble size. Therefore, it may reflect that the bubble coalescence provides an increase in amplitude of pressure fluctuation. Also, the increase of bubble frequency

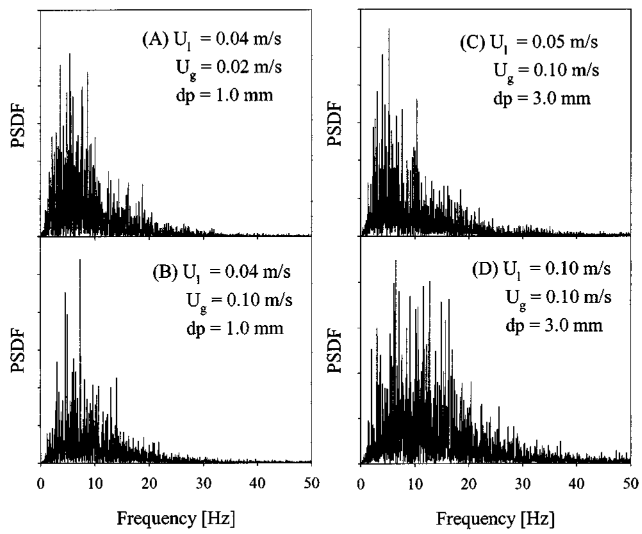

Fig. 3. Power spectral density functions of pressure fluctuations in three phase fluidized bedss.

produces an increase in frequency of the pressure fluctuation.

The typical PSDF of pressure fluctuations in the three phase fluidized beds of 1 and 3 mm glass beads at the center of column is shown in Fig. 3. It can be seen that the peak of PSDF is distributed from 0 to 40 Hz and the main frequency is located at about 10 Hz. This may reflect that the pressure fluctuations are mainly generated by the rising bubbles in the bed since the frequency of pressure fluctuation is nearly the same as of the bubble frequency [Yu, 1989; Fan et al., 1986]. As can be seen in the Fig. 3(A and B), the dominant frequency of the pressure signal decreases with an increase in gas velocity since the large bubbles have low frequencies [Lirag and Littman, 1971; Fan et al., 1986]. The disintegration of larger bubbles is more pronounced with higher particle momentum generated from liquid turbulence with increasing liquid velocity. Therefore, the distribution of PSDF becomes more flattened with an increase in liquid velocity as can be seen in Fig. 3(C and D).

The effect of gas velocity on the standard deviation of pressure fluctuation in three phase fluidized beds of 1 and 3 mm glass beads at the center of column is shown in Fig. 4. The standard deviation increases with gas velocity irrespective of particle size since the bubble size and its distribution increase with gas velocity [Yu and Kim, 1988]. It has been known that the bubble size in the beds of smaller particles is larger than that of larger particles [Yu and Kim, 1988; Kim et al., 1975]. Consequently, the standard deviation of pressure fluctuation is found to be larger in the bed of 1 mm (Fig. 4(A)) than that in the bed of 3 mm glass beads (Fig. 4(B)). As can be shown in Fig. 5, the energy dissipation rate exhibits about the same trends as the standard deviation. This may indicate that the energy dissipation in the bubble wake region is dominant since the eddy motion of the liquid phase in the wake is very active. Since the wake phase holdup increases with gas velocity due to the increase of bubble size, the energy dissipation rate increases with an increase in gas velocity.

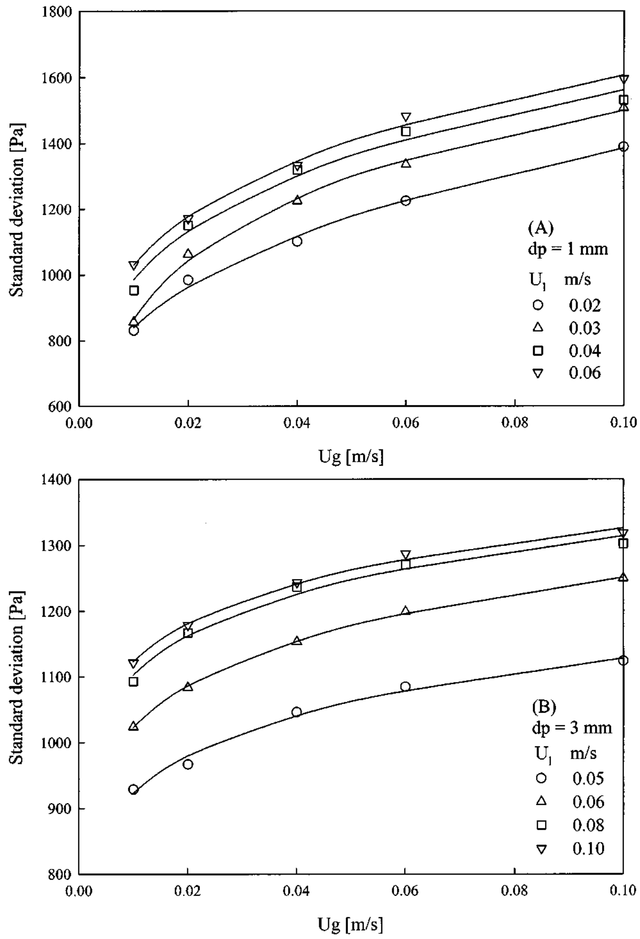

Fig. 4. Effect of gas velocity on standard deviation of pressure fluctuations in three phase fluidized beds.

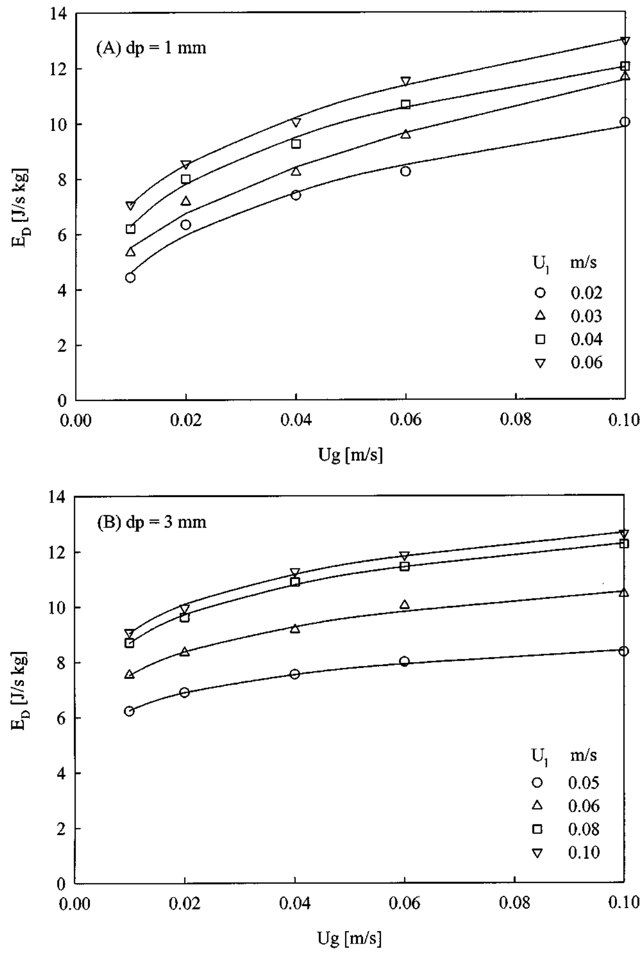

Fig. 5. Effect of gas velocity on the energy dissipation rate in three phase fluidized beds.

The circulation velocity or the turbulence intensity of the liquid phase increases with an increase in liquid velocity [Hinze, 1959; Joshi, 1980]. Thus, it may be expected that the standard deviation of pressure fluctuation increases with an increase in liquid velocity. As can be seen in Fig. 6, the standard deviation increases with liquid velocity in the beds of 1 and 3 mm glass beads at the center of column. However, the rate of increase in standard deviation decreases with liquid velocity since the large bubbles are easily broken up by the liquid turbulence. The probability of bubble breakage would be higher in the beds of larger particles than that of smaller ones. Therefore, the rate of increase in standard deviation is less pronounced in the bed of 3 mm particle than that of 1 mm particles. A similar trend can be observed in the energy dissipation rate (Fig. 7). The energy

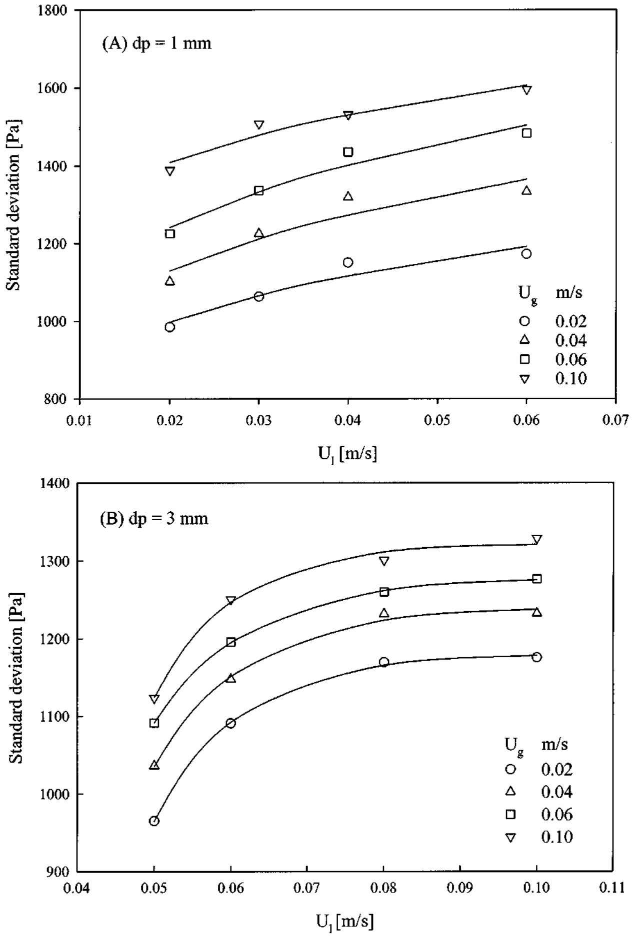

Fig. 6. Effect of liquid velocity on standard deviation of pressure fluctuations in three phase fluidized beds.

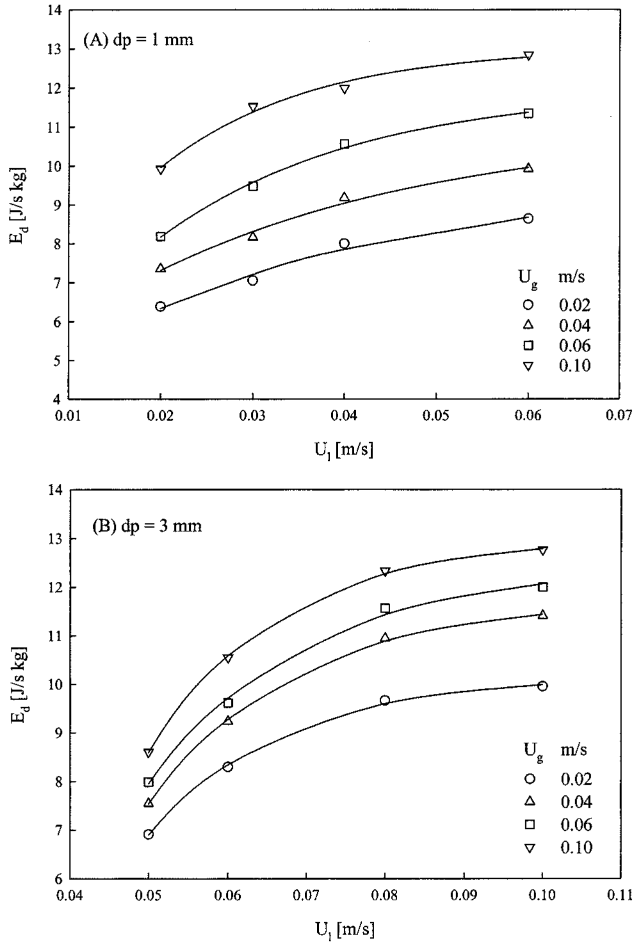

Fig. 7. Effect of liquid velocity on energy dissipation rate in three phase fluidized beds.

dissipation rate increases with increasing liquid velocity since the eddy velocity may increase with liquid velocity [1973]. Since bed porosity and the movement of particles increase with liquid velocity, the large bubbles may disintegrate with an increase in liquid velocity. Therefore, the rate of increase in energy dissipation rate decreases with liquid velocity.

The radial distribution of the standard deviation and energy dissipation rate in the bed of 3 mm glass beads is shown in Fig. 8. As in the case of local gas holdup, bubble size decreases with an increase in the radial distance [Yu and Kim, 1988]. Hence, as can be seen in Fig. 8(A), the standard deviation of pressure fluctuation also decreases along the radial direction. Since large bubbles tend to rise along the center of the column due to wall effect and the liquid recirculation flow exists in a fluidized bed [Morooka et al., 1982], the bubble velocity in the peripheral region would be far lower than that in the center region of the column due to the inhibition effect of liquid down flow on small bubbles and the bubble velocity decreases with an increase in radial direction [Yu and Kim, 1988]. For these reasons, the energy dissipation rate decreases with an increase in the radial direction as can be seen in Fig. 8(B).

1. Correlation

The energy dissipation rate in three phase fluidized beds has been correlated in terms of the Froude and Reynolds numbers and the dimensionless radial distance (ψ=r/R):

$$E_d=16.788Fr_l^{0.183}Fr_g^{0.139}(1-\psi)^{0.442}+1.265Fr_g^{0.143}Re^{0.181}$$

This correlation covers the range of variables $0.341\times10^{-2}<Fr_g<1.020$; $4.082\times10^{-2}<Fr_l<0.443$; $20<Re<300$; $0<\psi<1$ with the correlation coefficient of 0.926 and the relative standard deviation of 16.6% for 294 points. The goodness of fit between the calculated and the experimental values of the energy dissipation rate is shown in Fig. 9.

CONCLUSIONS

The following conclusions can be drawn on the pressure fluctuations and energy dissipation rate. According to analysis of pressure fluctuation signals by statistical variables and power spectrum, the hydrodynamics of three phase fluidized beds is mainly affected by bubble behavior. The energy dissipation rate and the standard deviation of pressure fluctuations increase with increasing gas and liquid velocities but decrease in the radial direction of the column in three phase fluidized beds. The energy dissipation rate and standard deviation of pressure fluctuation in three phase fluidized beds have similar trends with operation variables. Also, the dimensionless correlation of the energy dissipation rate has been expressed in terms of gas and liquid Froude numbers, Reynolds number and ratio of radial distance.

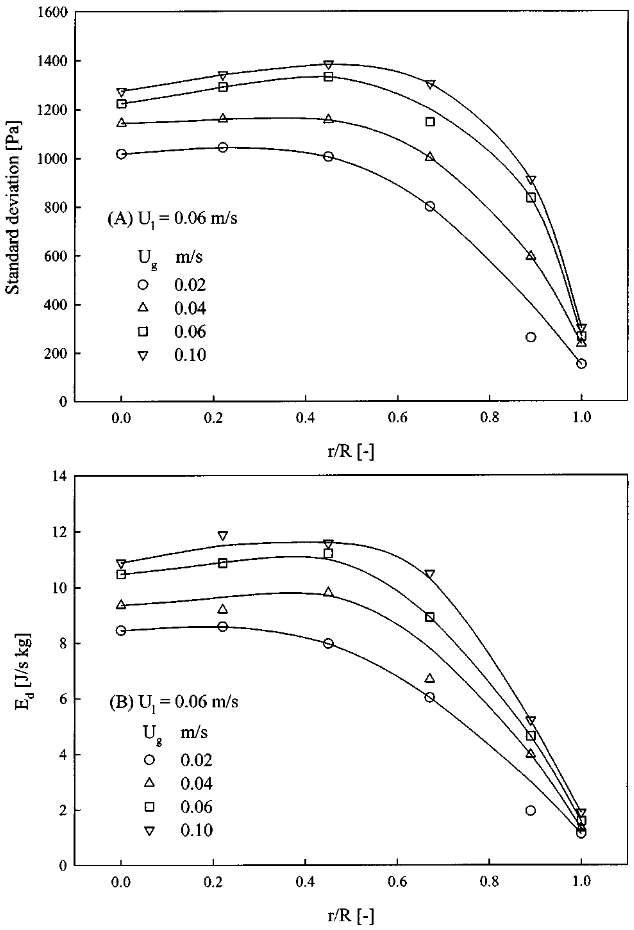

Fig. 8. Radial distribution of standard deviation and energy dissipation rate in three phase fluidized beds.

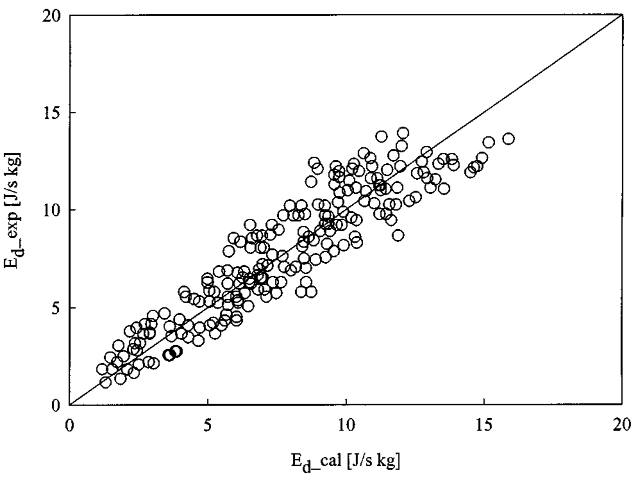

Fig. 9. Comparison between the calculated and experimental values of energy dissipation rate.

ACKNOWLEDGMENT

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NOMENCLATURE

dp : particle diameter [m]
E_d : energy dissipation rate [J/s kg]
$E(\omega)$: energy spectrum
f : frequency [Hz]
Fr : Froude number [U^2/g dp]
g : gravitational acceleration [m/s^2]
P(t) : pressure fluctuation [Pa]
PSDF(f) : power spectral density function
r : radial distance [m]
R : column diameter [m]
Re : Reynolds number [dp U ρ/μ]
$S_p(\omega)$: pressure spectrum
T : time [s]
U : superficial velocity [m/s]
Var : variance

Greek Letters

μ_r : r-th central moment
ϕ : auto-correlation function
ϕ_N : probability density function
ρ : density [kg/m^3]
σ : standard deviation [Pa]
ψ : dimensionless radial distance [r/R]

Subscripts

g : gas phase
l : liquid phase
s : solid phase

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