**Kinetic Behavior of Solid Particles
in Fluidized Beds**

Final Report

H.O. Kono

June 1990

Work Performed Under Contract No.: DE-AC21-86MC23249

**For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia**

**By
West Virginia University
Department of Chemical Engineering
Morgantown, West Virginia**

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June 1990

ABSTRACT

The overall objectives of this project (DE-AC-86MC23249) are to develop experimental techniques for measuring the forces of fluidized particles, and to predict the solid-gas performance in fluidized beds by using data analysis system, and by elucidating the intrinsic mechanism of erosion and attrition phenomena in fluidized beds. The reduction of erosion and attrition rates is one of the critical engineering problems for the design and operation of fluidized bed combustors. Specifically, the objectives are to: (1) develop the experimental techniques to measure the forces of solid particles prevailing in fluidized beds; (2) measure and characterize the forces of solid particles in various types of fluidized beds with various configurations (conventional and spouted fluidized beds) and with different scales (10, 20, and 30cm) under various fluidization conditions (particle size, bed aspect ratio and gas velocity); (3) find and verify the mechanism of erosion rates of in-bed tubes and attrition rates of fluidized particles by forces of solid particles in fluidized beds.

We developed three different kinds of measurement methods, i.e., fracture sensitive sensor, piezoelectric sensor and gas pressure fluctuation methods. By using these methods the exact forces of solid particles, including the transient corporate in fluidized beds, were systematically measured. Simultaneously, the erosion rates of in-bed tubes and attrition rates of fluidized particles were measured.

The correlation of results from the above three methods indicates that the maximum of transient forces of solid particles should play a decisive role in determining the erosion and attrition rates. This is a very important conclusion to fundamentally understand the erosion and attrition phenomena in fluidized beds.

Based upon these accomplishments, the erosion rates of in-bed tubes and the attrition rate of fluidized particles can be predicted, which will help the design and operation of fluidized bed reactors.

This final report consists of three chapters. They are: chapter 1, Measurement of Transient Forces of Solid Particles in Fluidized Bed by Fracture Sensitive Sensor Method; chapter 2, Measurement of Transient Forces of Solid Particles in Fluidized Bed by Gas Pressure Fluctuation Method; and chapter 3, Measurement of Transient Forces of Solid Particles in Fluidized Beds by Piezoelectric Sensor Method and Comparison of Erosion and Attrition Rates with Transient Forces of Solid Particles Measured.

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CHAPTER 1

MEASUREMENT OF TRANSIENT FORCES OF SOLID PARTICLES IN FLUIDIZED BED BY FRACTURE SENSITIVE SENSOR METHOD

CHAPTER 1 SUMMARY

Experimental techniques have been developed for measuring the forces of solid particles in fluidized beds. The fracture sensitive sensor particle method (using granules with a known mechanical strength), piezoelectric method, and pressure fluctuation method are being employed to evaluate the transient behavior of solid particles and the force distribution in fluidized beds. Generally, erosion and attrition in fluidized beds depend on two factors: transient forces prevailing in fluidized beds, and the physical properties of the fluidized particles and in-bed tubes. To have an intrinsic understanding of this behavior, the effect of the two factors should be elucidated separately. The results of this study will assist the design and operation of fluidized-bed combustors and gasifiers that can minimize erosion and attrition.

In this chapter, the fracture sensitive sensor particle method was developed and experimentally verified. Sensor particles of known mechanical strength, expressed by Rumf and Hirasu's equations, were employed to evaluate the representative forces that cause erosion and attrition in fluidized beds. Several fluidized beds including the two-dimensional bed, three dimensional square bed, circular bed, and spouted fluidized bed were constructed for the force measurement experiments.

The peaks of transient forces of fluidized particles could be affected by the humidity of the fluidizing air if the water vapor in the air condensed on the fluidized particles. A relative humidity of 50 percent at 20°C and 1 atm was experimentally chosen as the fluidizing air condition in this study. The peaks of transient forces of fluidized particles were found to increase with an increase in particle size, superficial gas velocity, and bed height.

The effect of bed diameter on the peaks of transient forces in fluidized particles was found to be not as significant as that of bed height. The bed diameter effect on these transient forces was found to be negligible when the inside diameter (I.D.) was larger than 0.203 m at the same height of the bed.

The presence of large bubbles and unstable fluidization indicates slugging fluidization. Although most fluidized-bed combustion and gasification units are claimed to be at the bubbling fluidization condition, it is more likely to be a combination of bubbling and slugging, depending on the operating conditions and the size of the fluidized beds. Severe bubble coalescence that forms large bubbles and causes unstable fluidization was generally

observed in the coarse-particle fluidized bed, especially for small bed diameters. For relatively large bed diameters, the coarse-particle fluidized bed may perform close to a bubbling bed at low gas velocities. Therefore, the term "slugging" is a measure of the degree of unstable fluidization, and this degree depends on how the gas bubbles grow in the bed. At a lower level of slugging, fluidization can be considered to be bubbling, and the forces of fluidized particles are smaller.

The bed configuration was proven to have a significant influence on the forces of fluidized particles. At the same superficial gas velocity and at the same bed height, experiments showed that a circular bed tends more to slugging and fluidized particles in that bed have higher transient forces than in a square fluidized bed. The degree of slugging in a two-dimensional fluidized bed is lower than that in a square fluidized bed; and the solid particles in a two-dimensional fluidized bed have a lower force than those in a square fluidized bed. Bed configuration may influence the forces of fluidized particles because of the wall effect; however, more investigation is necessary to reach a final conclusion. As for the spouted fluidized bed, the particles have a higher force than those in the same size circular fluidized bed because of the existence of an air jet.

The volumetric flow ratio of fluidizing air through the jet and through the gas distribution in a spouted fluidized bed affects on the transient forces of solid particles. The fluidized particles had largest transient forces at a volumetric flow ratio of 0.5. This indicates that both the jet and the conical perforated gas distributor are responsible for causing transient forces of solid particles in a spouted fluidized bed.

The effect of the gas distributor on the forces of fluidized particles depends the superficial gas velocity. At lower gas velocities, different types of gas distributors do not affect the forces of fluidized particles. However, a gas distributor with a higher pressure drop may cause the fluidized particles to have greater force when the gas velocity is larger than 1.5 m/s. The effect of various types of gas distributor on the behavior of solid particles was elucidated experimentally for the first time.

The breakage of fracture sensitive sensor particles in a two-dimensional fluidized bed was observed by video. The sensor particles seemed to be destroyed as they moved into the bubble-wake area. A so-called "shedding" phenomenon existing in the wake may create transient fluctuations and locally high forces.

1.1.0 INTRODUCTION

1.1.1 Purpose

The transient force of solid particles determines the fundamental characteristics of a fluidized bed. This force also causes attrition of fluidized particles, erosion of vessels and boiler tubes and vibration of fluidization systems. Therefore, a study of the force that fluidized particles have is of vital importance for designing coarse-particle fluidized-bed reactors such as fluidized bed combustors.

Experimental data on the attrition of fluidized particles have been published by Kono (1981) and Vaux and Fellers (1981). However, attrition depends not only on the prevailing forces of solid particles, but also on the physical properties of the particles themselves. To have an intrinsic understanding on this behavior, the effect of these two factors should be investigated separately.

The objectives of this project are to develop experimental techniques to measure the forces of fluidized particles and to predict the performance of solid particles in fluidized beds using data analysis and mathematical modeling. This study will assist in designing and operating fluidized-bed combustors and gasifiers that can minimize erosion and attrition.

1.1.2 Background

Experimental techniques have been presented for investigating particle dynamics in fluidized beds (Marsheck and Gomezplata 1965; Heertjes, Verloop, and Willems 1970; Oki, Walawender, and Fan 1977; Nguyen and Grace 1978; Raso and Tirabasso 1983; Lin, Chen, and Chao 1985). These measurement techniques can essentially be classified into three categories: (1) using a small sensor to detect particle momentum in the flow path, (2) following the track of a tracer particle (i.e., radioactive tracer technique), and (3) statistical correlation of particle movement as observed by optical fibers. However, because of the failure of the experimental idea and the difficulty involved in analyzing the data, none of these techniques has been successfully applied for the systematic measurement of the stochastic and transient forces of fluidized particles. Recently, Kono and coworkers (1987) described a new experimental idea and technique for measuring the forces and the kinetic collision energy in gas-solid fluidized beds using fracture sensitive tracer particles of known mechanical strength. This gives a direct method to evaluate the kinetic performance of fluidized particles.

Solid particles move transiently through a fluidized bed. Their motion is a function of position and time. In other words, the motion of fluidized particles is transient and not periodic. Therefore, a force distribution is imposed in a fluidized bed at

each specific location for a certain time interval. The relatively large forces (near the maximum) in the distribution seem to be responsible for the erosion and attrition in fluidization systems. In this study, the fracture sensitive sensor particle method, piezoelectric sensor method, and pressure fluctuation method will be simultaneously developed to investigate the kinetic behavior of solid particles in fluidized beds. However, the fracture sensitive sensor particle method will be focused in this chapter. Because fracture sensitive sensor particles in a fluidized bed are exposed timewise and locationwise to a wide distribution of forces, the force that destroys the particles will be the prevailing maximum force at a given fluidization condition. This method is appropriate to detect the maximum possible force of solid particles in fluidized beds. Consequently, the peaks of transient force of solid particles will simply be referred to as the "kinetic force." The piezoelectric method (using a Piezorton sensor) measures the local force and its time-dependent fluctuation with respect to a space-fixed probe. The force distribution of solid particles at a specific location in a fluidized bed can be obtained by this method. The pressure fluctuation method provides overall hydrodynamic information on the gas phase.

1.2.0 THE FRACTURE SENSITIVE SENSOR PARTICLE METHOD

In this chapter, the fracture sensitive sensor particle method was developed and applied to investigate the effects of particle size, superficial gas velocity, bed height, bed diameter, and bed configuration on the kinetic behavior of solid particles in fluidized beds. Quantitative data and comprehensive information (including a video observation of the destruction of the fracture sensitive sensor particles in a two-dimensional fluidized bed) were obtained.

1.2.1 Preparation and Calibration of Fracture Sensitive Sensor Particles

Fracture sensitive sensor particles were prepared using a special pelletization technique. This technique is based on the theoretical equations derived by Rumpf (1958) and Hiramatsu et al. (1965) for the preparation of solid-liquid two phase granules. According to Rumpf, the tensile strength of a granule caused by the capillary forces is given by

$$\sigma = 6(1 - \epsilon) \frac{\gamma}{d} \quad (1)$$

where

- σ : tensile strength of fracture sensitive sensor particles [Pa],
- ϵ : porosity of fracture sensitive sensor particles [-],
- γ : surface tension of liquid [N/m], and
- d : diameter of primary particles [m].

Equation 1 was verified experimentally using the tensile-strength measurement equipment in our laboratory. The equipment utilizes a split-cell design by Hartley and Parfitt (1984), and is described as follows:

"The cell is supported on very low friction bearings and connected to a force transducer. One half of the cell is held secure while the other half is pulled away. The force transducer measures the force necessary to separate the cell."

Using this equipment, the tensile strength of glass bead powders ($d = 256, 76, \text{ and } 35 \mu\text{m}$) with binding liquids ($\gamma = 72, 47, \text{ and } 27 \text{ dyn/cm}$) was measured. Figure 1.1 shows the experimental tensile strength versus the theoretical prediction using Rumpf's equation. Figure 1.1 shows the good agreement.

Figure 1.1. Experimental Verification of Rumpf's Equation

Hiramatsu et al. (1965) proposed a correlation to calculate the compressive force that breaks a spherical granule. Hiramatsu's tensile strength data yields the following equation:

$$F = \frac{\pi D^2}{2.8} \sigma, \quad (2)$$

where

$$D = \left[\frac{6}{\pi} \cdot \frac{W}{(1 - \epsilon) \rho_p + \epsilon \rho_L} \right]^{1/3}$$

and where

- F: durable compressive force of the fracture sensitive sensor particle [N],
- D: diameter of the fracture sensitive sensor particle [m],
- σ : tensile strength of the fracture sensitive sensor particle [Pa],
- W: mass of the fracture sensitive sensor particle [kg],
- ρ_p : liquid density [kg/m³], and
- ρ_L : primary particle density [kg/m³].

By combining Equations 1 and 2, the compressive force that breaks a capillary-state granule can be expressed as

$$F[N] = \frac{6}{2.8} \pi (1 - \epsilon) \frac{\gamma}{d} \left[\frac{6}{\pi} \cdot \frac{W}{(1 - \epsilon) \rho_p + \epsilon \rho_L} \right]^{2/3} \quad (3)$$

To prove the validity of Equation 3, a capillary-state granule (fracture-sensitive sensor particle) was prepared and its mechanical strength was measured. The calculated compressive forces from Equation 3 and experimental data are compared in Figure 1.2. They are in good agreement.

Fracture sensitive sensor particles with various strengths (0.3 - 8.6 kPa) were prepared by changing the surface tension of the binding liquid and the primary particle diameter. The surface tension of liquids was controlled by adding surfactant to water. The primary particle size of glass beads forming the granules ranged from 35 to 1000 μ m. The voidage of the particles was experimentally determined at approximately 30 percent for all experiments. The weight of the particles was also controlled to be constant for all experiments. A rotating granulator was used to prepare fracture sensitive sensor particles at the designed mechanical strength.

Figure 1.2. Experimental Verification of Hiramatsu's Equation

1.2.2 Correlation Between the Durable Compressive Force and the Durable Impact Energy of Fracture Sensitive Sensor Particles

The compressive strength of fracture sensitive sensor particles has been determined, but these measurements were made in the static condition. It is necessary to determine the dynamic impact energy that causes the break of fracture sensitive sensor particles during collision (durable impact energy of a granule).

The static compressive force that breaks such a particle (durable compressive force of a granule) was determined using Equation 3. One preweighed, fracture sensitive sensor particle with a known durable compressive force was dropped on a large stainless steel plate. This particle was dropped from an increasingly greater height until a crack appeared on the sensor particle. The effect of air resistance on the dropping granule was neglected, and the durable impact energy was assumed to be the potential energy as given by

$$E = Wgh \quad (4)$$

where

- E: durable impact energy of the fracture sensitive sensor particle [J],
- W: mass of the fracture sensitive sensor particle [kg],

- g: gravitational constant [m/s^2], and
h: minimum height at which first crack appears [m].

Figure 1.3 shows a plot of durable compressive force versus durable impact energy for fracture sensitive sensor particles in a glass bead system. Regression analysis gives the following empirical correlation:

$$E[J] = 5.9849 \times 10^{-3} F[N] \quad (5)$$

Applying Equations 3 and 5, the mechanical properties of a fracture sensitive sensor particle (durable compressive force and durable impact energy) can be obtained. Typical examples of physical and mechanical properties of such particles are shown in Table 1.1.

1.2.3 Experimental Procedure

The experimental setup of the fluidization system is shown in Figure 1.4. The kinetic forces of solid particles in fluidized beds were determined by the following procedure. About 8 to 12 preweighed, fracture sensitive sensor particles (W_i), of uniform size and with known mechanical strength (durable compressive force and durable impact energy), were placed in a fluidized bed at a given fluidization condition. After 2 minutes the air supply was stopped, and the amount of particles that survived in the fluidized bed (W_o) was determined by careful sieving. The fluidizing air was humidified in order to prevent the granules from drying out. The time for fluidization was determined, based on the following considerations:

- (1) The time for fluidization should be short enough that the effect of drying is negligible.
- (2) The time for fluidization should be long enough to ensure that the fracture sensitive sensor particles experience the kinetic forces prevailing in the bed.
- (3) The time for fluidization should be chosen such that the experiment is time efficient.

It was determined by experiment that a period of about 2 minutes was satisfactory.

By plotting U_o/U_{mf} versus W_o/W_i (survival ratio of fracture sensitive sensor particles after fluidization), the minimum value of U_o/U_{mf} at which the particles of known strength were fractured was determined. (See Figure 1.5) At this value of U_o/U_{mf} , the kinetic force in the fluidized bed was considered to be equal to the durable compressive force of the fracture sensitive sensor particle, F . Also at this value of U_o/U_{mf} , the dynamic impact energy of fluidized particles was assumed to be equal to the durable impact

Figure 1.3. Experimental Relationship Between Dynamic Impact Energy and Durable Static Compressive Force

Table 1.1. Physical and Mechanical Properties of Fracture-Sensitive Sensor Particles

d (μm)	$\gamma \cdot 10^3$ (N/m)	D (mm)	σ (kPa)	$F \cdot 10^{-2}$ (N)	$E \cdot 10^4$ (J)
35.0	27	6.2	2.70	8.15	4.88
35.0	47	6.2	4.75	14.34	8.58
35.0	72	6.2	8.64	37.23	22.30
54.0	72	6.2	5.60	24.13	14.40
76.5	72	6.0	3.95	16.07	9.62
107.5	72	6.0	2.81	11.44	6.85
168.5	72	6.4	1.80	8.24	4.93
256.0	72	6.4	1.18	5.42	3.24
362.5	72	6.9	0.83	4.44	2.66
512.5	72	6.6	0.59	2.91	1.74
1015.0	72	6.9	0.30	1.59	0.95

Figure 1.4. Schematic Diagram of the Experimental Apparatus

Figure 1.5. Estimation of the Minimum Value of Dimensionless Gas Velocity at Which Fracture Sensitive Sensor Particles of Known Strength Were Fractured

energy of the fracture sensitive sensor particles, E. By repeating the above experiment with fracture sensitive sensor particles of different strengths, a plot of U_0/U_{mf} versus F can be generated. This experiment will be done at various fluidized particle sizes, bed configurations, and bed aspect ratios.

In this study, three circular fluidized beds (inside diameters of 0.108 m, 0.203 m, and 0.292 m), a spouted fluidized bed (0.108 m I.D. fluidized bed with a 0.0254 m jet opening and 60° conical perforated gas distributor having holes of 1.5 mm diameter), a square fluidized bed (0.108 m x 0.108 m), and a two-dimensional fluidized bed (0.25 m x 0.01 m) were used. A sintering plate with a hole opening of 150 μ m (100 mesh) was usually used as the gas distributor. However, perforated plates with holes 1.0 and 1.5 mm in diameter and a bandage-covered wire screen were also used to study the gas distributor effect on the kinetic forces of solid particles in the fluidized bed. The fluidized media were glass beads, with the properties listed in Table 1.2.

Table 1.2. Physical Properties of Glass Beads

AVERAGE PARTICLE DIAMETER d_p (mm)	PARTICLE DENSITY ρ_p (kg/m ³)	MINIMUM FLUIDIZATION
		VELOCITY U_{mf} (m/s)
2.18	2.49×10^3	1.36
1.0	2.49×10^3	0.46
0.5	2.52×10^3	0.22

1.2.4 The Effect of Fluidizing-Air Humidity on the Force Measurement

The humidity of the fluidizing air was maintained at a 90-percent relative humidity in a previous study (Kono, Soltani-Ahmadi, and Suzuki 1987) to prevent the fracture sensitive sensor particles from drying and to reduce the electrostatic charge of the fluidized media. However, the water vapor in the fluidizing air may have condensed slightly on the surface of the fluidized glass beads at a relative humidity of 90 percent because of temperature variations in the experimental environment. Condensation results in an increase in interparticle forces and retards the motion of the fluidized particles. According to our observation of glass bead systems ($d_p = 0.5 \sim 2.18$ mm), there was no significant electrostatic effect and the drying of sensor particles was negligible when the relative humidity of the fluidizing air was maintained above 50 percent.

Figure 1.6 shows the effect of the relative humidity of the fluidizing air on the survival ratio of fracture sensitive sensor particles (W_o/W_i). The kinetic forces of fluidized particles at relative humidities of 50, 70, and 90 percent were measured using the fracture sensitive sensor particle method in a 0.108 m I.D. fluidized bed. These results are shown in Figure 1.7. The experimental evidence from Figures 1.6 and 1.7 shows that it is appropriate to maintain the relative humidity between 50 and 70 percent while measuring the force in a glass bead system. This will avoid the drying of sensor particles, the electrostatic effect, and water vapor condensation on the fluidized particles. Hereafter, the relative humidity of fluidizing air (at room temperature) will be maintained at 50 percent for all force measurement experiments.

1.2.5 Video Observation of the Destruction of Fracture Sensitive Sensor Particles in a Two-Dimensional Fluidized Bed

A video of the two-dimensional fluidized bed filmed by a high speed camera shows the motion of a fracture sensitive sensor particle and its destruction. The particle seems to be destroyed as it moves into the bubble-wake area. It has been reported that the wake has a different structure than that of the emulsion phase. A so-called "shedding" phenomenon existing in the wake creates transient fluctuations and locally high forces. However, a more detailed investigation into the motion of the bubble and wake is necessary to reach conclusions.

1.3.0 RESULTS AND DISCUSSION

Many measurements of force were made using the fracture sensitive sensor particle method. In general, the transient forces

Figure 1.6. The Effect of the Relative Humidity of Fluidizing Air on the Survival Ratio of Sensor Particles

Figure 1.7. The Effect of the Relative Humidity of Fluidizing Air on the Prevailing Kinetic Forces in a Fluidized Bed

of solid particles (kinetic forces) increase with larger particle sizes, bed heights, and superficial gas velocities, as shown in Figures 1.8, 1.9, and 1.10. A tendency for the transient force to reach a maximum at each fluidization condition as the superficial gas velocity increases can also be seen. When the maximum transient force is reached, the fluidization condition seems to change from slugging (the presence of large bubbles and unstable fluidization) to turbulent. The scale-up effect has been studied at a constant bed aspect ratio (H/D_t), as shown in Figure 1.11. It seems that the transient forces of fluidized particles increase with the bed diameter when the bed aspect ratio remains constant. However, the increase in maximum transient forces of fluidized particles may be caused by an increase in the bed diameter, bed height, or both. Figure 1.12 shows that the maximum transient forces of solid particles ($d_p = 1.0$ mm) were about the same in fluidized beds of 0.108 m, 0.203 m, and 0.292 m I.D. when measured at the same bed height of 0.203 m. But at a bed height of 0.292 m, the maximum transient forces of solid particles in the 0.108 m I.D. fluidized bed were higher than those in 0.203 m and 0.292 m I.D. fluidized beds, as shown in Figure 1.13. This shows that the slugging phenomenon, which is assumed to be responsible for the maximum transient forces of fluidized particles, may be significantly affected by the bed diameter when relatively coarse particles are used at bed heights greater than 0.292 m. However, bed diameter does not appear to significantly affect the maximum transient forces of fluidized particles when it is larger than 0.203 m I.D. It must be noted that the effect of bed diameter on the slugging phenomenon is less than that of bed height, and becomes negligible when the diameter is larger than 0.203 m I.D..

In general, the pressure drop across a gas distributor increases with the superficial gas velocity. The relationship between the pressure drop across a gas distributor and the superficial gas velocity for the three types of gas distributors used in this study is shown in Figure 1.14. At lower gas velocities, different types of gas distributor did not show an effect on the maximum transient forces of solid particles in fluidized beds. (See Figure 1.15.) But at higher gas velocities, the gas distributor affected the transient forces of fluidized particles. (See Figure 1.16.) It can be seen that the pressure drop across the gas distributor can cause a difference in the transient forces of fluidized particles. At high gas velocities, the porous-plate gas distributor (100 mesh) has the same effect on the maximum transient forces of fluidized particles as the perforated-plate gas distributor with holes 1.0 mm in diameter.

The kinetic behavior of solid particles in a 0.108 m I.D. spouted fluidized bed was also investigated. The spouted fluidized bed has a 0.0254 m jet opening and a 60° conical, perforated gas distributor with holes 1.5 mm in diameter. The volumetric flow

Figure 1.8. The Effects of Particle Size, Bed Aspect Ratio, and Gas Velocity on the Prevailing Kinetic Forces in a 0.108 m I.D. Fluidized Bed

Figure 1.9. The Effects of Particle Size, Bed Aspect Ratio, and Gas Velocity on the Prevailing Kinetic Forces in a 0.203 m I.D. Fluidized Bed

Figure 1.10. The Effects of Particle Size, Bed Aspect Ratio, and Gas Velocity on the Prevailing Kinetic Forces in a 0.292 m I.D. Fluidized Bed

Figure 1.11. The Effect of Bed Diameter on the Prevailing Kinetic Forces in Fluidized Beds at a Constant Bed Aspect Ratio

Figure 1.12. The Effect of Bed Diameter on the Prevailing Kinetic Forces in Fluidized Beds at a Bed Height of 0.203 m

Figure 1.13. The Effect of Bed Diameter on the Prevailing Kinetic Forces in Fluidized Beds at a Bed Height of 0.292 m

Figure 1.14. The Relationship Between the Pressure Drop Across Gas Distributors and Superficial Gas Velocity

Figure 1.15. The Effect of the Gas Distributor on Prevailing Kinetic Forces in a Fluidized Bed at Low Gas Velocities

Figure 1.16. The Effect of the Gas Distributor on Prevailing Kinetic Forces in a Fluidized Bed at High Gas Velocities

ratio of fluidizing air through the jet opening (X), fluidized particle size, superficial gas velocity, and bed height were systematically studied with respect to how these parameters affect the kinetic forces of solid particles in a spouted fluidized bed.

Figure 1.17 shows that the effects of fluidized particle size, superficial gas velocity, and bed height are the same on the kinetic forces of solid particles in a spouted fluidized bed as in a circular fluidized bed. However, the effect of the volumetric flow ratio of fluidizing air through the jet opening had a complicated effect on the kinetic forces of fluidized particles. As seen in Figure 1.18, the kinetic forces of solid particles in a spouted bed ($X = 1.0$) are relatively greater than those in a spouted fluidized bed. Also, the kinetic forces of solid particles in the spouted fluidized bed at $X = 0.5$ are greater than those at $X = 0.3$ and 0.7 . This reveals that both the jet and the conical perforated gas distributor are responsible for developing the maximum transient forces of solid particles in a spouted fluidized bed. This observation is consistent with the experimental results, which show that the transient forces of solid particles in both the spouted bed ($X = 1.0$) and the circular bed with a conical perforated gas distributor ($X = 0.0$) are greater than those in regular circular fluidized beds.

The transient forces of fluidized particles in a square

Figure 1.17. The Effects of Particle Size, Gas Velocity and Bed Height on the Prevailing Kinetic Forces in a 0.108 m I.D. Spouted Fluidized Bed at $X = 0.5$

Figure 1.18. The Effect of Volumetric Flow Ratio on the Prevailing Kinetic Forces in a 0.108 m I.D. Spouted Fluidized Bed

Figure 1.19. Kinetic Forces of Solid Particles in a 0.108 m Square Fluidized Bed

fluidized bed were measured. (See Figure 1.19) The general tendency is similar to that observed in the circular fluidized beds. The transient forces prevailing in a two-dimensional bed were also measured. The bed configuration was proven to have an influence on the transient forces of fluidized particles. The results are shown in Figure 1.20. As mentioned earlier, the presence of large bubbles and unstable fluidization indicates slugging. The degree of slugging in a fluidized bed depends on how the gas bubbles grow in the bed. At the same superficial gas velocity and bed height, experiments showed that a circular bed tends to have more slugging and higher transient forces than a square fluidized bed. The degree of slugging in a two-dimensional fluidized bed is lower than that in a square fluidized bed, and the transient forces in a two-dimensional fluidized bed are lower than those in a square fluidized bed. The influence of bed configuration on transient forces may be caused by the wall effect; however, more investigation is necessary to reach a final conclusion. The spouted fluidized bed has higher transient forces than a circular fluidized bed of the same size because of the existence of an air jet.

Figure 1.20. Comparison of Kinetic Forces of Solid Particles in Various Fluidized Beds

1.4.0 CONCLUSION

The transient force of solid particles in fluidized beds has been measured using the fracture sensitive sensor particle method in a wide range of fluidization and in various types of fluidized bed configuration. The peaks of transient force of solid particles, which will cause the erosion and attrition in fluidized beds, were thus obtained experimentally for the first time. Based on a comprehensive understanding of the kinetic behavior of fluidized particles, combined with erosion and attrition experiments in fluidized beds, the technique developed in this chapter can assist in designing and operating fluidized-bed combustors and gasifiers.

1.5.0 NOMENCLATURE

d	Diameter of primary particle
d_p	Diameter of fluidized particle
D	Diameter of the fracture sensitive sensor particle
D_t	Diameter of fluidized bed
E	Durable impact energy of fracture sensitive sensor particle
F	Durable compressive force of sensor particle (kinetic force prevailing in a fluidized bed)
g	Gravitational constant

h	Minimum height at which a crack appears on a granule
H	Height of loosely packed bed
t	Time of fluidization
T	Temperature
U_{mf}	Minimum fluidization velocity
U_o	Superficial gas velocity
W	Weight of the fracture sensitive sensor particle
W_i	Weight of the fracture sensitive sensor particles placed in a fluidized bed
W_o	Weight of surviving fracture sensitive sensor particles in a fluidized bed
X	Volumetric flow ratio of fluidizing air through the jet opening
ϵ	Porosity of the sensor particle
γ	Surface tension of liquid
σ	Tensile strength of fracture sensitive sensor particle
ρ_L	Liquid density
ρ_p	Particle density

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CHAPTER 2

MEASUREMENT OF TRANSIENT FORCES OF SOLID PARTICLES IN FLUIDIZED BED BY GAS PRESSURE FLUCTUATION METHOD

CHAPTER 2 SUMMARY

To estimate the transient forces of solid particles in fluidized beds, a measurement method of the gas phase pressure fluctuation in beds was developed to correlate the gas pressure fluctuation with the maximum transient forces of solid particles obtained by the fracture sensitive sensor method described in chapter 1.

The background of pressure fluctuation measurements was also reviewed. Two different types of gas pressure fluctuation data in fluidized beds were utilized. First, the maxima of transient pressure fluctuation of gas phase (ΔP) and secondly the root-mean-square deviation were used to characterize the phenomena. The optimum data sampling of pressure measurements was experimentally determined, i.e., the sampling rate is 100 per second, and the sampling period is 60 seconds. Both results were used to correlate the maximum of transient force of solid particles with that of the gas pressure fluctuation in fluidized beds. It was found through the experiment that the maximum of transient pressure fluctuation (ΔP) can be correlated with the transient forces of solid particles, which substantially determine the erosion and attrition phenomena in fluidized beds. The significance of this conclusion is that the pressure fluctuation measurement is much more easily applicable to fluidized beds than any direct force measurement at elevated temperature and pressure.

2.1.0 INTRODUCTION

2.1.1 General Remarks

To correlate the transient motion of solid particles in fluidized beds with the gas-phase pressure fluctuations, pressure fluctuation measurements were accomplished under the same fluidization conditions as those of fracture sensitive sensor particle method. The experimental correlation enables the prediction of fluidized-particle forces by the measurement of pressure fluctuations. The advantage of predicting the transient forces of solid particles in fluidized beds is that we can apply this measurement method directly to the high temperature and pressure systems.

Since the correlation between this method and the fracture

sensitive sensors or piezoelectric sensor methods could have been identified, this approach is practically very important.

2.1.2 Background of Pressure Fluctuation Measurements in Fluidized Beds

Pressure fluctuations have been observed in fluidized beds and used to define an index for the quality of fluidization (Schuster and Kisliak, 1952; Winter, 1968). Small and rapid fluctuations are considered to be associated with a good quality of fluidization.

The nature of pressure fluctuations in a fluidized bed is a complex function of particle properties, bed geometry, pressure in the bed, and properties and flow conditions of the fluidizing fluid. The cause of pressure fluctuation in fluidized beds has been studied by several investigators. Tamarin (1964 and Hiby (1967) have concluded that the pressure fluctuations are related to the passage of bubbles through the upper boundary of the bed and to the changes in the height of the bed. Lirag and Littman (1971) have also concluded that the bed height fluctuations, resulting from bubble escaping at the surface of the bed, cause the pressure fluctuations. Kang, et al. (1967), however, have concluded that the action of bubbles causes changes in the mode and condition of gas flow and porosity in the dense phase, and eventually induces the pressure fluctuations. Verloop and Heertjes (1974) indicated that harmonic oscillations of the pressure around its equilibrium value can be observed in shallow gas fluidized beds. They derived correlations to predict the major fluctuation frequency and the transition from homogeneous to bubbling fluidization based on the damping mechanism. Baskakov (1986) reported that the fundamental fluctuation frequency is related to the emergence of gas bubbles at the surface of the bed and derived a formula to determine the fundamental frequency of pressure fluctuations in a bubbling bed. His fundamental frequency formula is independent of fluidization velocity (or void fraction in the bed).

Statistical approach has been widely used by various investigators in analyzing the random pressure fluctuation signals in fluidized beds. Fan, et al. (1981) proposed an on-line statistical study of the pressure fluctuations in fluidized beds. They indicated that the motion of bubbles appears to be the major cause of the pressure fluctuation in the upper portion of a fluidized bed. In the lower portion, the combined effects of the formation of larger bubbles in the middle portion of the bed, the formation of small bubbles near the distributor, and the jet flow immediately above the distributor appear to be the major causes of pressure fluctuations. So far, the pressure fluctuation study has not been directly correlated to the kinetic performance

of solid particles in fluidized beds. In this study, the pressure fluctuation signals were evaluated and correlated to the transient forces of fluidized particles based on the root-mean-square deviation method and the transient pressure fluctuation method.

2.2.0 PRESSURE FLUCTUATION METHOD

As mentioned earlier, the cause of pressure fluctuations can be the motion of bubbles, bubble coalescence, the formation of small bubbles near the distributor, and the jet flow immediately above the distributor. No matter what is the reason, the change of the pressure indicates the change of potential energy in the gas phase. The instant drop of gas pressure corresponds to the release of potential energy from the gas phase. Therefore the peak of transient gas pressure fluctuation was defined in this chapter Maximum Energy Release of gas phase, causing the transient motion of solid particles. The successive increase in gas pressure corresponds to the recharge of potential energy to the gas phase by the pressure wave. The released energy, partly consumed by gas-solid interaction and partly transferred to the solid phase, affects the kinetic performance of fluidized particles. Assuming a certain energy transfer efficiency from the gas phase to the solid phase at a specific fluidization condition, the degree of energy release is proportional to the change of kinetic energy of fluidized particles.

The root-mean-square deviation of pressure fluctuations represents the stability of the fluidized bed. Higher values of root-mean-square deviations indicate more energy is transferred from the gas phase to the solid phase and the fluidized bed is less stable. To some extent, the root-mean-square deviation of pressure fluctuations can be used to predict the kinetic performance of solid particle in fluidized beds. However, at the higher superficial gas velocities the root-mean-square deviation can only approximately represent the maximum forces of fluidized particles, since the distribution of the energy release spreads wider as the superficial gas velocity increases. Accordingly, a direct measurement of maximum energy release is necessary for the more precise prediction of the kinetic performance of fluidized particles. The largest energy release taking place more than once is defined as the maximum energy release.

A schematic diagram of the experimental facilities is shown in Figure 2.1. The fluidized bed assembly included a bed column, a distributor and a plenum column. The diameter of bed column is 0.108m, 0.203m, and 0.292m respectively. The gas distributor was made of #100 mesh sintering plate. Pressure taps

Figure 2.1. Schematic Diagram of the Pressure Fluctuation Measurement

were installed vertically along the columns. The distance between two adjacent taps was about 0.10m. The inside opening of each tap was packed with fiber glass wool to prevent the fluidized media from entering the tap. The outside opening of a tap was connected to a differential pressure transducer (Validyne P305D), which had two input channels and produced an output voltage proportional to the pressure difference between the two input channels. In measuring the pressure fluctuations at a specific location (tap), the tap was connected to the positive input channel while the other channel was left exposed to the atmosphere. The transducer has a diaphragm capacity of +17.24kPa (+2.5psi). The calculating and recording assembly included IBM PC data acquisition and custom programs. The data acquisition system has the capability of storing up to 20,000 data points at any sampling rate between 10 and 28,000 Hz, saving the data to the floppy disk, plotting the data to the screen or paper and calculating the energy release in the gas phase during fluidization and the root-mean-square deviation of pressure fluctuations.

In the past, the pressure fluctuations in fluidized beds were measured at various sampling rates and sampling times. This study started with the determination of the optimal data taking conditions. The maximum response frequency of the transducer used in this study is 200 Hz. Accordingly, pressure fluctuations in fluidized beds were measured at various sampling

rates (10, 30, 100, and 200 Hz, respectively) and various sampling times (6, 10, 30, 60 and 90 seconds, respectively) in the 0.108m I.D. fluidized bed with $d_p = 1.0\text{mm}$, $H/D_t = 1.0$, $U_o = 0.755\text{m/s}$. PC data-acquisition system was employed to trace the pressure fluctuations. The root-mean-square deviation(s) and maximum transient pressure fluctuations ($\Delta\Delta P$) were investigated. The root-mean-square deviation was calculated by the equations:

$$S' = \left[\frac{\sum_{i=1}^N (X_i - \bar{X})^2}{N} \right]^{1/2} \quad (1)$$

and

$$\bar{X} = \frac{\sum_{i=1}^N X_i}{N} \quad (2)$$

where

X_i : pressure in the fluidized bed sampled by data acquisition system

N : total number of data sampled in a period of time

The maximum of gas pressure fluctuation, which is named maximum energy release of pressure fluctuations, is the intensity of pressure fluctuations and can be expressed as follows:

$$- \frac{\Delta(\Delta P)}{\Delta t} \cdot \Delta t = (\Delta P)_1 - (\Delta P)_2$$

where

ΔP : gas pressure at the measuring point

$(\Delta P)_1$: transient highest gas pressure at some instants at a certain point

$(\Delta P)_2$: transient lowest gas pressure following the previous highest pressure at the same point.

t : time

The maximum of gas pressure fluctuation in a time interval shown in the above equation named briefly as the maximum energy release. Accordingly the maxima of energy release taking place more than once, were obtained directly from the distribution of energy releases. The energy release distribution curve (in Figure 2.2) was constructed. The results are shown in Tables 2.1 and 2.2.

Figure 2.2. The Distribution of Energy Release at Various Sampling Times

Table 2.1. The Root-Mean-Square Deviation of Pressure Fluctuations at Various Sampling Times and Sampling Rates

S' (KPa)	Sampling Rate (Hz)			
	10	30	100	200
Sampling Time (s)				
6			0.083	
10	0.076	0.092	0.086	0.086
30	0.090	0.086	0.087	0.081
60	0.083	0.086	0.088	0.088
90			0.085	

Table 2.2. The Maximum Energy Release at Various Sampling Times and Sampling Rates

Max. ΔAP (KPa)	Sampling Rate (Hz)			
	10	30	100	200
Sampling Time (s)				
6			0.1516	
10		0.0792	0.2543	0.3099
30	0.2813	0.3200	0.3941	0.3265
60	0.3116	0.4227	0.3907	0.4177
90			0.4261	

Table 2.1 shows that the root-mean-square deviation remains constant at various sampling rates and sampling times. It seems not critical to choose an appropriate sampling rate and sampling time. However, Table 2.2 shows that the sampling time is very important in determining maximum energy release of the gas phase. Besides, Figure 2.2 also shows that a substantial sampling time is necessary to collect sufficient data for a better representation of the energy release distribution. As a result, the sampling rate of 100 Hz and the sampling time of 60 seconds are chosen as the optimal data taking conditions for the current study.

A very systematic data taking of the transient forces of solid particles was accomplished under the experimental conditions shown in Table 2.3 by using gas pressure fluctuation ($\Delta\Delta P$) measurement method and fracture sensitive sensor method.

2.3.0 RESULTS AND DISCUSSION

The pressure fluctuations were measured along the bed height at various fluidization conditions. When the superficial gas velocity was fixed, the root-mean-square deviation of pressure fluctuations tended to increase and then decrease along the column height from the bottom to the top. The height, where the maximum root-mean-square deviation occurred, decreased with an increase in

Table 2.3. Experimental Conditions for Measurement of Transient Forces of Solid Particles in Fluidized Beds

Bed Diameter D_t (m)	0.108, 0.203, 0.292
Bed Aspect Ratio H/D_t	0.5, 1, 2,
Gas Velocity U_0/U_{mf}	1, 2, 3, 4, 5, 6
Particle Size D_p (mm) (glass beads)	0.5, 1.0, 2.18

the superficial gas velocity. A typical example is shown in Figure 2.3. This is in agreement with Fan's (1981) observation. It seems that the cause of the root-mean-square deviation is the formation of large bubbles in the bed which are determined by the bed height and bed diameter. In general, the maximum occurred at the bottom of the bed for fluidized beds with large bed diameters and small bed heights. The root-mean-square deviation of pressure fluctuations changed with the flow regime in the fluidized bed. As shown in Figure 2.4 the root-mean-square deviation(s) increased with the increase of superficial gas velocity from the bubbling to the slugging flow regimes. As the fluidized bed became turbulent, the root-mean-square deviation(s) decreased.

A relationship between the root-mean-square deviations and the maximum transient forces of fluidized particles measured by the fracture sensitive sensor particle method can be developed by using the experimental data from various fluidization conditions (including various bed heights, bed diameters, fluidized particle sizes, and superficial gas velocities in the experimental range of this study). The results are plotted in Figure 2.5. A reasonable good correlation can be obtained between dimensionless group Sdp^2/Mg and F/Mg . Mg is the weight of solid particles in a fluidized bed. However, the results also showed that the root-mean-square deviation is in a sense an average and may not be enough to predict a corresponding maximum transient force of fluidized particles at higher superficial gas velocities. As a result of this, the maximum of transient forces of solid particles named as the maximum energy release of the gas phase was proposed and evaluated in relation to the force of fluidized particles.

Typical results of energy release measurement are shown in Figure 2.6. A slightly skewed distribution of energy release is observed at a low superficial gas velocity. As the superficial gas velocity increases, the distribution spreads wider and the maximum energy release becomes larger; however, the distribution becomes narrow and the maximum energy release decreases when the fluidization regime turns into turbulent as seen in Figure 2.6(g). At a constant superficial gas velocity, a wider energy distribution and a larger maximum energy release can be obtained at the location ($Z=23cm$) where higher root-mean-square deviation is observed (in Figure 2.7. But the shape of distribution does not depend on the location in the turbulent flow regime. (See Figure 2.8) Higher frequencies of small energy releases can also be observed when fluidization is in the turbulent flow regime or the location of data sampling is close to the surface of a fluidized bed. This frequent, small energy release indicates small and rapid pressure fluctuations and homogeneous fluidization.

The maximum energy release in fluidized beds was also correlated to the peaks of transient forces of solid particles in fluidized beds measured by the fracture sensitive sensor particle

Figure 2.3. The Root-Mean-Square Deviations of Pressure Fluctuations at Various Locations above the Gas Distributor

Figure 2.4. The Root-Mean-Square Deviations of Pressure Fluctuations at Various Superficial Gas Velocities

Figure 2.5. The Correlation Between the Root-Mean-Square Deviations of Pressure Fluctuations and the Kinetic Forces of Solid Particles in Fluidized Beds

Figure 2.6. Energy Release Distribution at Various Superficial Gas Velocities in a 0.108m I.D. Fluidized Bed With $d_p = 1.0\text{mm}$ and $H/D_t = 1.0$

Figure 2.7. Energy Release Distribution at Various Distances Above the Gas Distributor in a 0.108m I.D. Fluidized Bed With $d_p = 1.0\text{mm}$, $H/D_t = 3.0$, and $U_o = 0.76\text{m/s}$

Figure 2.8. Energy Release Distribution at Various Distances Above the Gas Distributor in a 0.108m I.D. Fluidized Bed With $d_p = 1.0\text{mm}$, $H/D_t = 3.0$, and $U_o = 4.5\text{m/s}$

method. The result is plotted in Figure 2.9. Figure 2.10 compares two correlations. The first correlation is maximum energy release as a function of transient forces (correlation coefficient 0.98). It can be seen that the maximum energy release sensitively responds the change of kinetic forces of fluidized particles. The maximum energy release is a better parameter to evaluate the transient forces of fluidized particles. Replotting data in Figure 2.9 on the logarithmic scale, a correlation is obtained as follows:

$$\frac{F_t}{M_g} = 1.2842 \left[\frac{\Delta P d_p^2}{M_g} \right]^{0.7088} \quad (4)$$

The maximum energy release of the gas phase in fluidized beds can directly be related to the maximum force of fluidized particles with an average error of 4.5%. By estimating the maximum energy release at any location in fluidized beds, the corresponding maximum transient force of fluidized particles can be predicted.

A systematic data taking for the transient solid particles was accomplished by using the gas phase pressure fluctuation method and fracture sensitive sensor method. The experimental condition of fluidization was already shown in Table 1.3 in the preceding chapter. We changed such parameters as bed diameter (D_t), bed aspect ratio (H/D_t), gas velocity (U_0/U_{mf}) and glass beads diameter (D_p).

The experimental data were shown in Figure 2.11 to Figure 2.18 systematically. It should be noted that the peaks of the gas phase transient pressure fluctuation (ΔP) and the peaks of transient forces of solid particles changed almost in the same way as the fluidization parameters were varied. For example, as shown in Figures 2.11 and 2.12, the peaks (exactly, the second maximum) of transient forces of solid particles (F_t) do behave very similarly as ΔP by changing particle size (d_p), bed aspect ratio (H/D_t), and gas velocity (U_0/U_{mf}) in a fluidized bed (I.D. 10.8 cm). The same kinds of comparisons were made by using fluidized beds of large sizes (I.D. 20.3 and 20.9 cm) as illustrated in Figures 2.13, 2.14, 2.15 and 2.16. Although these results were already summarized in Figure 2.9, a very reliable correlation can be verified by comparing the original experimental results. The significant point is that the peaks of transient solid particle force (responsible for erosion and attrition) can be indirectly estimated by measuring the peaks of transient gas pressure fluctuations, which can pretty easily be measured even at elevated temperatures and pressures. This advantage is very important in view of application.

The Scale-up effects on ΔP and F_t were systematically shown in Figures 2.17 and 2.18. In the past there have been many discussions on the scale-up effect on the erosion and attrition in fluidized beds. Figure 18 really shows, as an example, the transient maximum

Figure 2.9. Correlation Between the Maximum Energy Release and the Kinetic Forces of Solid Particles in Fluidized Beds

Figure 2.10. The Comparison of Maximum Energy Release and Root-Mean-Square Deviation of Pressure Fluctuations With Respect to the Kinetic Forces of Solid Particles in Fluidized Beds

Figure 2.11. $U_o/U_{mf}(-)$ versus $\Delta P(\text{Pa})$ Particles: Glass beads
 $d_p = 0.5, 1.0, 2.18\text{mm}$; $Dt = 0.108m$; $H/Dt = 1, 2, 3$.

Figure 2.12. $U_o/U_{mf}(-)$ versus $F_t(\text{N})$ Particles: Glass beads
 $d_p = 0.5, 1.0, 2.18\text{mm}$; $Dt = 0.108m$; $H/Dt = 1, 2, 3$.

Figure 2.13. $U_o/U_{mf}(-)$ versus $\Delta\Delta P(\text{Pa})$ Particles: Glass beads
 $d_p = 0.5, 1.0, 2.18\text{mm}$; $D_t = 0.203\text{m}$; $H/D_t = 0.5, 1, 1.5$

Figure 2.14. $U_o/U_{mf}(-)$ versus $F_t(\text{N})$ Particles: Glass beads
 $d_p = 0.5, 1.0, 2.18\text{mm}$; $D_t = 0.203\text{m}$; $H/D_t = 0.5, 1, 1.5$

Figure 2.15. U_o/U_{mf} (-) versus $\Delta\Delta p$ (Pa) Particles: Glass beads
 $d_p = 0.5, 1.0mm$; $D_t = 0.292m$; $H/D_t = 0.7, 1$

Figure 2.16. U_o/U_{mf} (-) versus F_t (N) Particles: Glass beads
 $d_p = 0.5, 1.0mm$; $D_t = 0.292m$; $H/D_t = 0.7, 1$

Figure 2.17. $U_o/U_{mf}(-)$ versus $\Delta P(\text{Pa})$ Particles: Glass beads
 $d_p = 1.0\text{mm}$; $D_t = 0.108, 0.203, 0.292\text{m}$; $H/D_t = 1$

Figure 2.18. $U_o/U_{mf}(-)$ versus $F_t(\text{N})$ Particles: Glass beads
 $d_p = 1.0\text{mm}$; $D_t = 0.108, 0.203, 0.292\text{m}$; $H/D_t = 1$

forces increases by increasing the bed diameter from 10.8 cm to 29.2 cm While maintaining the other fluidization condition the same.

2.4.0 CONCLUSION

The pressure fluctuations of fluidized beds were found to be not only an index of the quality of fluidization but also an effective tool to study the hydrodynamic phenomena of gas-solid two phase flow in fluidized beds. Pressure fluctuation can predict the maximum transient forces of solid particles, which should be responsible for the erosion and attrition in fluidized beds. This study further explored the application of pressure fluctuation measurement on the prediction of solid-particle forces in fluidized beds. The root-mean-square deviation of pressure fluctuations was shown to be reasonably correlated to the kinetic forces of fluidized particles. With the understanding that the local transient pressure fluctuations can result in transient solid-particle forces which cause erosion and attrition, the transient gas pressure fluctuation distribution (energy release distribution from gas phase) was proposed. The maximum energy release was experimentally found more sensitive in predicting maximum transient solid-particle forces. A correlation was also developed, so the transient forces of solid particles in fluidized beds can be predicted by measuring pressure fluctuations and maximum energy release.

In order to verify a good correlation between the peaks of transient pressure fluctuation (ΔP) and transient solid particle force (F_t) the original experimental data were shown in a wide range of fluidized bed condition. This is significant not only to show the good correlation between ΔP and F_t , but also to provide the effect of fluidization parameters on ΔP and F_t .

The scale up effect of bed diameter on peaks of transient forces of solid particles were also shown by changing the bed diameters.

2.5.0 NOMENCLATURE

d_p	Diameter of fluidized particle
D_t	Diameter of fluidized bed
E	Durable impact energy of fracture-sensitive tracer particle
F	Transient force of solid particles prevailing in a fluidized bed
F_p	Force measured by piezoelectric sensor method
F_t	Force measured by fracture sensitive sensor method
g	Gravitational constant
h	Probe height
H	Loosely packed bed height

M	Mass of solid particles in a fluidized bed
(ΔP) ₁	Transient highest gas pressure at some instants at a certain point
(ΔP) ₂	Transient lowest gas pressure following the previous highest pressure at the same point.
$\Delta \Delta P$	Maximum of transient gas pressure fluctuation named as maximum energy release from gas phase
S'	Root-mean-square deviation of pressure fluctuations
t	Time
U _{mf}	Minimum fluidization velocity
U _o	Superficial gas velocity
X	Mean of force distribution
X _i	Gas pressure sampled by data acquisition system
$\bar{X}$	Mean of data sampled in a period of time
Z	Distance above the gas distributor
ρ_p	Particle density

2.6.0 REFERENCES

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CHAPTER 3
MEASUREMENT OF TRANSIENT FORCES OF SOLID PARTICLES
IN FLUIDIZED BEDS BY PIEZOELECTRIC SENSOR METHOD
AND COMPARISON OF EROSION AND ATTRITION RATES
WITH TRANSIENT FORCES OF SOLID PARTICLES MEASURED

CHAPTER 3 SUMMARY

First in this chapter the piezoelectric sensor, PC data acquisition, and data analysis programs were developed and used to evaluate the transient particle impact forces of solid particles on bed column. Through the experimental verification, the transient force signals occur apparently at a low frequency with various magnitudes. To obtain a representative force distribution, it is better to have a long sampling time. Thus, a sampling rate of 200 Hz with the sampling time of 90 seconds were chosen to take data. In the tests, the forces imposed on the probe by gas flow were found negligible and the transient force of solid particles plays a decisive role. Also, the noise signals could be controlled under a very small level by using appropriate noise protection plates. Transient forces of solid particles were measured at wide fluidization conditions including various particle sizes, bed diameters, bed aspect ratios, and superficial gas velocities. The experimental results were compared with the kinetic forces of solid particles measured by fracture sensitive sensor method and pressure fluctuation method. At a fluidization condition, the maxima of transient particle forces measured by the above two methods were in the same order of magnitude. This verifies the reliability of the above two force measurement methods. The maxima of transient forces of solid particles were further correlated to the maxima of transient gas pressure fluctuations measured at the same fluidization conditions and at the same measurement locations. Within the range of experiments, the maxima of transient forces of solid particles can be predicted by measuring pressure fluctuations, which is a very important conclusion.

Secondly, the attrition and erosion problems in fluidized beds were experimentally verified that they are mainly affected by the maxima of transient forces of solid particles and physical properties of particles and metals used in fluidized bed. The purposes of this chapter are to show the effect of transient solid particle forces on the particle attrition and in-bed tube erosion. The particle attrition in terms of the weight loss of fluidized particles was found to increase with increasing particle size and superficial gas velocity. The maxima of transient pressure fluctuations of fluidized beds were also measured at the conditions where attrition tests were made.

A relationship between the particle attrition rate and maxima of transient pressure fluctuation of the gas phase ($\Delta\Delta P$) in the fluidized bed (which was defined as the maximum energy release of gas phase) was observed. This result shows that the attrition of fluidized particles can be predicted by measuring maxima of transient pressure fluctuations. The erosion of in-bed tubes was investigated by observing the weight loss and the diameter reduction of in-bed tubes at various fluidization conditions. Tubes were eroded faster at higher superficial gas velocities and by using larger fluidized particle sizes. This is consistent with the understanding that transient forces of solid particles increase with an increase in superficial gas velocity and particle size. The erosion of tubes was also found to be about symmetric with respect to the tube center, and higher erosion was observed at the tube center, especially in the direction right against the air flow. These results indicate a rigorous bubble motion and coalescence at the center region of the bed.

The bed vibration was measured by using piezoelectric sensor method. At a constant holdup, larger bed particles ($d_p = 2.18\text{mm}$) could give higher bed vibration forces, although there were no differences between 0.5 and 1.0mm particles. The bed vibration forces were also found to be about one order of magnitude higher than the particle forces measured previously in this project. This provides an additional support to the reliability of transient forces of solid particles measurement by piezoelectric sensor method. A direct evidence of the effect of transient forces of solid particles on the attrition and erosion problem in fluidized beds are shown in this chapter.

Thirdly, the effect of the motion of bubbles on the maximum transient force of solid particle in fluidized beds was investigated to understand the occurrence mechanism of the maximum forces. The fact that the bubble wake induces the maximum transient forces was proven in the two-dimensional bed by using pressure probe and piezoelectric sensor simultaneously. This result is in agreement with the video observation of the destruction of fracture sensitive sensor particles in fluidized beds in chapter 1. To mathematically predict solid-particle forces, a transient model will be necessary to describe the bubble wake phenomenon as a function of fluidization conditions.

A correlation between the average bubble diameter and the maximum energy release was made in the two-dimensional fluidized bed. The average bubble diameter increases with increasing the maximum energy release.

These experimental results provide information for the cause of transient solid-particle forces. Also, the peak of transient forces of solid particles can be used to predict the local solid-particle forces, the transition of flow regimes, and the average bubble diameter in fluidized beds. This study assists in the prediction of

solid-particle forces prevailing in fluidized beds.

3.1.0 INTRODUCTION

3.1.1 General Remarks

The objectives of this study are to develop the techniques to measure solid-particle forces in fluidized beds, and to predict the solid-particle forces by data analysis and mathematical modeling.

The fracture sensitive sensor method was developed and used to measure the maxima of transient forces of solid particles in various fluidized beds. That fracture sensitive sensor method was correlated with the transient gas phase pressure fluctuation measurement. Tests of piezoelectric sensor measurement were used to measure the maxima of transient forces of solid particles in fluidized beds under various fluidized bed conditions.

The transient forces of solid particles measured by the developed technique are in good agreement with the forces measured by the fracture sensitive sensor method and also by the maxima of gas phase pressure fluctuation method.

The attrition of fluidized particle and the erosion of in-bed tubes were measured and correlated to the transient forces of solid particles. Very good agreement was found between the above mentioned forces and the attrition and erosion.

This discovery is very significant, since the attrition and erosion were found to be possible to predict by measuring gas pressure fluctuation and further assessing the transient forces of solid particle. The relation between the motion of bubbles and the peaks of transient forces of solid particles was investigated by synchronizing both measurements in two dimensional, transparent fluidized beds.

This approach is significant to understand the mechanism causing the maxima of transient forces.

3.1.2 Background of Piezoelectric Sensor Method for Measurement of Transient Forces of Solid Particles

Forces on objects immersed in fluidized beds were studied by several investigators. Bordet and Co-workers (1968) measured the kinetic energy of particles and the collision frequency against a wall by a small piezoelectric crystal microphone immersed in the liquid fluidized bed. Their experimental results were used to explain some wall mass transfer properties in fluidized beds. However, this method was reported to have some technical difficulties as applied in gas-solid fluidized beds. Nguyen and Grace (1978) reported that the net buoyancy force imposed on an immersed object in the fluidized bed can be estimated by taking the

particulate phase density as equal to the bed density at minimum fluidization. By synchronizing the photographic films and pressure fluctuations on the surface of submerged tubes, they also concluded that bubbles passing immersed objects cause transient forces leading to tube vibrations. Kennedy, Donovan, and Trigas (1981) used strain-gauge load cell to measure the external forces imparted by the bed material on tubes in a fluidized bed pertinent to the structural design of heat-exchanger tube systems. They reported that the load cell data support the view that the force pulses on the tubes are produced by the passage of bubbles. They also suggested that the forces on the tubes are the result of an impulse caused by the transfer of the momentum of a body of solids in the wake of a bubble striking the tube. Grace and Hosny (1985) measured vertical and horizontal forces using externally-mounted strain-gauge force transducers for three bare tubes and one finned tube in fluidized beds. They concluded that static forces dominated at low gas flow rates, while bubble-induced pulses became dominant at high flow rates. Vertical forces tend to be much larger than horizontal forces. They also proposed a simple mechanistic model for the prediction of the root-mean-square forces and of the variation of these forces with superficial gas velocity, tube size, and particle properties. Meijer and Co-workers (1986) used a scaled-up liquid fluidized bed to study particle impact against bed column. They reported that the Maxwell-Boltzmann velocity distribution appeared not to be valid when the values of comparatively low velocity impacts were included. They also reported that the mean perpendicular velocity at impact was about a factor of 10 times lower than the superficial fluid velocity at a porosity of 0.8.

The study of particle impact in fluidized beds has been done so far mostly in liquid fluidized beds or with immersed tubes in the bed. Also, there is no systematic approach to determine the reliability of the measurement techniques. Our approach intends to correlate the measurement results measured by three different methods, namely the maxima of the transient forces of solid particles measured by the piezoelectric sensor, by maxima of gas phase pressure fluctuation, and by the fracture sensitive sensor. The transient forces of solid particles against bed column are systematically evaluated in conjunction with the pressure fluctuation measurements. The force measurement technique using piezoelectric sensor is also investigated in detail.

3.1.3 Background of Attrition, Erosion, and Vibration in and of Fluidized Beds

In fluidized bed systems, particles are normally required to remain in the bed for considerable periods. Any attrition to smaller sizes may affect the fluidizing properties or the process operating conditions as well as causing loss of fine material by

elutriation. To insure a stable operation of fluidized beds, it is important to maintain a constant holdup and a definite size distribution of solid particles. Therefore, the attrition rate of solid particles must be considered. In addition, fluidized beds commonly contain heat transfer tubes, diplegs, probes, etc., which are immersed in the bed for cooling, heating, addition of solids or fluids, or measurement purposes. These immersed objects are exposed to forces of irregular magnitude and suffered by the erosion. The above attrition and erosion problems are mainly affected by the transient forces of solid particles and physical properties of particles and metals used in fluidized beds. The objectives of this project are to show the effect of transient forces of solid particle forces on the particle attrition and in-bed tube erosion. Also, the vibration of fluidized beds caused by the solid-particle forces was evaluated.

3.1.4 Background of Bubble Motion and Solid Particle Forces in Fluidized Beds

The objectives of this study are to develop techniques to measure the peaks of transient solid-particle forces in fluidized beds, and to predict the transient forces by data analysis and mathematical modeling. The fracture sensitive sensor method was developed and used to measure the peaks of transient forces of solid particle in various fluidized beds as shown in chapter 1. In the meantime, the pressure fluctuation method and piezoelectric sensor method were also developed to evaluate the pressure fluctuations forces in fluidized beds as shown in chapter 2. These measurement results were correlated to the maxima of transient forces of fluidized particles measured by the fracture sensitive sensor method. As a result, the transient forces of fluidized particles can be predicted by measuring the pressure fluctuations of the gas phase. The pressure probe and piezoelectric sensor method were applied simultaneously to trace the passage of bubbles in a two-dimensional fluidized bed. The relationship between the bubble diameter and the gas pressure fluctuation at various fluidizing air velocities and fluidized particle sizes were observed in the two-dimensional fluidized bed. These experimental results provide quantitative data to elucidate the solid-particle forces which induce the attrition and erosion problem in fluidized beds.

3.2.0 METHODOLOGY

3.2.1 Piezoelectric Sensor Force Measurement Method

The measurement of transient forces of solid particles against our sensor was accomplished by using a Kistler Piezotron (Figure

3.1; 9712A5 low-impedance piezoelectric sensor force transducer) with a threshold of approximately 0.0009N and a compressive measuring range up to 22.2N. The sensor consists of a crystalline quartz load washer housed within a stainless steel casing. Force is determined by exploiting the piezoelectric sensor effect as follows. The imposition of a force on a piezoelectric sensor crystal generates an electrostatic voltage across the crystal which is proportional to the force. The amplifier senses this change in voltage and responds by giving a calibrated signal proportional to the force imposed on the crystal. Because the sensor is quite rigid, there is virtually no deformation and the sensor as a whole can be considered a stationary non-deformable body.

The Kistler Piezotron fitted at one end with a 3.43mm x 4.30mm brass probe was set in a rubber cork. The rubber cork was then plug onto the bed column with the surface of probe flushing to the internal surface of the column. The schematic diagram of measurement device is shown in Figure 3.2.

The Piezotron probe is connected to its own amplifier (Kistler 5004), the resulting analog signal fed to an A/D converter (IMI ADALAB w/Fast AD and multiplexing amplifier), and the digital output stored in the memory of a personal computer (IBM PC w/512K Bytes RAM). The raw data is then stored on floppy disks for later analysis. The system is also equipped with a dot matrix graphics printer (IBM Proprinter I).

The custom software has been designed to minimize the effects of vibration and amplifier drift on force data. The construction of the probe itself is such that it can only be stimulated to give a negative force in two ways. The first one is vibration and characterized by repeating positive and negative peaks of decreasing amplitude (damped) and constant (system resonant) frequency. To correct for this, the computer program only recognizes peaks whose amplitude is not steadily decreasing (i.e. there must be outside interaction to increase the signal amplitude; presumably particle impact).

The physical meaning of the second type of negative peak is difficult to understand without some insight into the operation of the amplifier itself. It has been observed that for static loads the amplifier signal tends to zero exponentially with time. Set for a long or medium time constant (high-pass filter), the exponential decay is easily observable. Since it is desired to sample a dynamic phenomenon (particle impact), the time constant or high-pass filter of the amplifier is set at "short" (highest value of high-pass filter). In order to evaluate the behavior of the measuring system (transducer and amplifier) under these circumstances, a high frequency recording was made of discrete impulses on the piezoelectric sensor. The raw signal was recorded and plotted in Figure 3.3(a). Since, this trace was produced by a five discrete impulses only the first peak in each set has physical significance.

Figure 3.1. Schematic Diagram of Piezoelectric Force Transducer

Figure 3.2. Schematic Diagram of Force Measurement Devices

Figure 3.3. Time Trace of Delta Function from Piezoelectric Sensor

Note that the signal does not return immediately to the baseline after the impulse, but initially falls below, then oscillates about it. The program designed to interpret this signal should be able to discern between the imposition of a force on the probe and the afterimage vibration. Since the subsequent vibration can be characterized by regular oscillation of decreasing amplitude, the program identifies and ignores signals of this type.

Because time zero is defined only as the beginning of recording in an operating fluidized bed, the initial voltage reading may have any value. Also, individual interactions may overlap in which case the signal may not return to the baseline. For these reasons, the absolute voltage cannot be used to reflect the force exerted by particles on the probe. Rather, the change in the amount of force exerted on the probe should be reflected by the change in the voltage caused by a single interaction. Consequently, the program interprets the voltage difference between successive peaks (determined by the program and not due to vibration) as the change in voltage caused by particle interaction. The results of this is to put all interactions at the same reference baseline eliminating the negative portion of the raw signal.

Figure 3.3(b) is the resulting trace after the interpretation program has attempted to eliminate the spurious signals. Note that not only have the original peaks survived at their correct magnitudes, but nearly all of the remaining signals have been filtered out. Figure 3.3(c) is the same as Figure 3.3(b) except that a threshold of 0.69% full scale prevents the program from recognizing very small peaks. Such peaks are a result of random noise and can "fool" the program when followed by a larger peak resulting from vibration. The peak due to vibration will be smaller in magnitude than that of the previous vibration wave due to damping, but almost certainly larger than a noise peak. This treatment completely eliminates all but the peaks corresponding to the imposed impulses. It is intended that the logic of this filtering scheme will discard questionable data rather than analyze misleading data when used for the measurement of particle impact forces in fluidized beds. A probability and force distribution diagram can further be constructed from the filtered signals.

In order to anticipate the relative signal resulting from gas flow alone in the column, a measurement was taken at a high gas flow in the absence of particles (raw data and force distribution presented as Figures 3.4(a) and 3.4(b) respectively), it could be seen that the proportion of the force exerted by the gas flow could be considered negligible.

We believe that the solid-particle forces can be estimated with the measurement of pressure fluctuations. This study attempts to correlate the maximum energy release ($\Delta\Delta P$) measured by pressure fluctuation method and the peaks of transient forces of solid particles measured by piezoelectric sensor method. In this case,

Figure 3.4. Raw Force Data and Force Distribution from a Gas Flow Without Solid Particles in a Fluidized Bed

sampling rate and sampling time are rather critical. Therefore, preliminary experiments were done to determine the optimal sampling time and sampling rate. Tables 3.1, 3.2, and 3.3 show the experimental results of various sampling times and sampling rates using the Piezotron sensor attached on a 0.108m I.D. bed column with $d_p = 1.0\text{mm}$, $H/D_t = 2.0$, and $U_0 = 1.09\text{m/s}$. Three repeated experiments were done for each case. The peaks of transient force (being defined as the maximum force taking place more than once), mean, and root-mean-square deviation of the measured force distribution were separately listed in the tables. It can be seen that sampling time and sampling rate were not important in terms of mean and root-mean-square deviation, although with higher sampling rate it samples more high-frequency, low-amplitude signals, and causes the mean and root-mean-square deviation to slightly decrease. To evaluate the maximum particle impact force, the selection of sampling time and sampling rate becomes critical. Experimental results also proved the maximum force to be transient and occurred at a relatively low frequency. Figure 3.5 shows Fourier spectral analysis sampled at 2000 Hz. As a result, the sampling rate of 200 Hz with a sampling time of 90 seconds was chosen for all experiments.

Particle impact forces and pressure fluctuations in fluidized beds were measured at the same locations on bed column under various fluidization conditions. The experimental results are correlated

Table 3.1. The Maximum of Transient Forces of Solid Particles
Obtained From Piezoelectric Sensor Measurement at Various
Sampling Times and Sampling Rates

Maximum Force (N)		Sampling Time (s)					
Sampling Rates (Hz)	10	20	30	40	60	90	
50					run		
					a	0.068	0.053
					b	0.057	0.055
100					c	0.060	0.057
						0.053	0.068
						0.047	0.062
200						0.053	0.060
500							
1000							
2000							

Table 3.2. The Force Mean Obtained From Piezoelectric Sensor
Measurement at Various Sampling Times and Sampling Rates

Force Mean (N)		Sampling Time (s)					
Sampling Rates (Hz)	10	20	30	40	60	90	
50					run		
					a	0.026	0.025
					b	0.026	0.026
100					c	0.028	0.026
						0.017	0.017
						0.018	0.019
200						0.017	0.018
500							
1000							
2000							

Table 3.3 The Root-Mean-Square Deviation of Force Distribution
Obtained From Piezoelectric Sensor Measurements at Various
Sampling Times and Sampling Rates

Root-Mean-Square Deviation of Force Distribution (N)			Sampling Time (s)					
Sampling Rates (Hz)			10	20	30	40	60	90
50	run a b c						0.017	0.017
							0.016	0.017
							0.017	0.017
100							0.016	0.016
							0.017	0.017
							0.016	0.015
200				0.014	0.011	0.012	0.011	
				0.011	0.012	0.011	0.012	
				0.013	0.013	0.013	0.013	
500				0.008	0.010			
				0.009	0.010			
				0.008	0.009			
1000			0.009					
			0.008					
			0.008					
2000		0.008						
		0.008						
		0.010

Figure 3.5. Fourier Spectral Representative of Force Data From
Piezoelectric Sensor

and compared to solid-particle forces measured by fracture sensitive sensor method at the same fluidization conditions.

3.2.2 Attrition, Erosion and Vibration in and of Fluidized Beds

Spherical silica-alumina (Mullite) particles were employed as a model solid particle material. The chemical and physical properties of Mullite particles are shown in Table 3.4. Two different particle sizes were used. As can be seen in Table 3.4, these particles have a high mechanical strength (19.6 MN/m^2) and are difficult to break. To evaluate the experimental results, it is important that breakage does not take place, because the attrition mechanism of particles would become complex as a result of the existence of nonspherical fragile fragments.

Throughout the experiments the attrition rate data and pressure fluctuations were measured as functions of superficial gas velocity and particle size. The attrition rate of solid particles was obtained by measuring the decreasing rate of solid holdup weight in a 0.108m I.D. ordinary fluidized bed. Initial holdup weight is 2.1 kg ($H/D_t = 1.5$) for all experiments. The loss of weight in a certain period of fluidization was calculated and taken to indicate an attrition amount caused by fluidization. The carry-over fine powder was collected by the bag filter. Each test run took 8 to 12 hours, and every half-hour the holdup weight was measured. The size

Table 3.4. Chemical and Physical Properties of Solid Particles

Particle diameter	U _{mf}
2.00 - 2.83mm	1.27 m/s
2.83 - 3.36mm	1.50 m/s
Particle density	2380 kg/m ³
Sphericity factor	0.60
Compressive strength	19.6 MN/m ²
Void fraction	0.473
Chemical Composition	
SiO ₂	29 wt. %
Al ₂ O ₃	67 wt. %
other	4 wt. %

of this attrition powder was also checked to confirm that attrition only (not breakage) was taking place in the fluidized bed. Within our experimental range, the breakage of solid particles did not take place because the collected powder in the bag filter was under 88μ in size.

It was found that the attrition rate of solid particles in a fluidized bed was approximately constant in this study. The attrition rate can be expressed as Equation 1.

$$M = \frac{-1}{W} \cdot \frac{dW}{dt} \cdot 100 \quad (1)$$

During the attrition experiment, the pressure fluctuations of the fluidized bed were also measured. The Maxima of transient forces of solid particles named as maximum energy release were calculated and correlated to the attrition rate of particles.

The erosion rate of in-bed tubes was obtained by measuring the decreasing rate of both tube weight and diameter in a 0.203m I.D. ordinary fluidized bed with $H/D_t = 1.0$. Three sizes of glass beads ($d_p = 0.5, 1.0, \text{ and } 2.18\text{mm}$) were used as fluidized media. The in-bed tube is a cylindrical rod made by plaster. The mechanical strength of the tube is 1.18 MN/m^2 which allows us to observe the tube erosion in a relatively short time. The tube was inserted horizontally in the bed and 0.1m above the gas distributor. Each test run took 4 to 6 hours. Every half-hour the tube diameter at various locations and the total tube weight were measured. The measured points of the tube are shown in Figure 3.6, including 3 angles and 7 positions along a $203 \times 23\text{mm}$ cylindrical rod.

The erosion rate of the in-bed tubes is also found approximately constant within the range of our experiments. The erosion rate in terms of tube weight reduction can be expressed as Equation 2.

$$M_T = \frac{-1}{W_T} \cdot \frac{dW_T}{dt} \cdot 100 \quad (2)$$

The erosion rate in terms of tube diameter reduction can be expressed as Equation 3.

$$L = \frac{-1}{D_T} \cdot \frac{dD_T}{dt} \cdot 100 \quad (3)$$

In the measurement of bed vibration, the piezoelectric sensor (Kono and Huang, 1988) was supported by a stationary stand, and the sensor probe touched the surface of a 0.203m I.D. bed column. The vibration forces of the bed were evaluated as functions of particle size and superficial gas velocity.

Figure 3.6. Schematic Diagram of Measured Points Along the In-Bed Tube

3.2.3 Bubble Motion and Force in Fluidized Beds

For the investigation of bubble motion in relation to the pressure fluctuations, a two-dimensional fluidized bed was constructed. Its dimensions are shown in Figure 3.7. To synchronize the bubble motion and transient forces of solid particles, a pressure sensor and a piezoelectric were installed on the bed wall facing each other at the height of 0.3m above the gas distributor, and bubble sizes were video taped. Glass beads of 1.0mm in diameter were used as fluidized media. The two-dimensional fluidized bed was operated at $U_0 = 0.722$ m/s and $H = 0.5$ m. For the investigation of bubble size in relation to the pressure fluctuations, a video was taken with a high speed camera simultaneously as the pressure fluctuations of the bed were measured. Three particle sizes ($d_p = 0.5, 1.0, \text{ and } 2.18$ mm) at various fluidizing air velocities and $H = 0.324$ m were evaluated. Maximum energy release was calculated from the transient pressure fluctuation data. Bubble diameter was determined by the average of bubble length and width observed in the playback of video tapes at 0.2m above the gas distributor.

DIMENSION: mm

Figure 3.7. The Schematic Diagram of Two-Dimensional Fluidized Bed

3.3.0 RESULTS AND DISCUSSION

3.3.1 Solid Particle Force Measured by Piezoelectric Sensor

To maintain consistency and accuracy throughout the study of transient forces of solid particles on sensors, computer programs were developed for data analysis according to the methodology discussed earlier. Figure 3.8 shows a typical force distribution obtained by the piezoelectric sensor. The force distribution is skewed toward the origin. This agrees with Meijer and Coworkers' (1986) conclusion for the particle velocity distribution in fluidized beds.

To evaluate the effect of noise signals on the force measurement, experiments were done with/without a mask covered on the surface of the probe. It is presumed that the measurements obtained by the probe when it is covered by the mask are noise signals. Figure 3.9 shows the results of this experiment when $D_t = 0.203\text{m}$, $d_p = 2.18\text{mm}$, and $H/D_t = 1.0$. It can be seen that noise signals are far below the forces detected by the particle impact on the probe. Thus, the developed piezoelectric sensor was used to evaluate the transient forces of solid particles on sensor at various fluidization conditions.

The maxima of transient forces of solid particles measured by piezoelectric sensor (F_p) were measured by using fluidized beds of

Figure 3.8. A Typical Force Distribution Obtained by Piezoelectric Sensor

Figure 3.9. The Effect of Noise Signals on Force Measurements

0.108, 0.203 and 0.292m I.D. under various fluidization conditions. The operating parameters, i.e., particle size ($d_p = 0.5, 1.0$ and 2.18mm), bed aspect ratio ($H/D_t = 0.7, 1.0, 1.5, 2.0$ and 3.0) and dimensionless gas velocity ($U_o/U_{mf} = 1 \sim 6$) were changed in the experiments. The results are shown in Figure 3.10, 3.11 and 3.12. These results are found to be very similar to those obtained in chapter 2 by using fracture sensitive sensor particles (Figure 2.11 to 2.18 in chapter 2). Both results obtained from two different measurement methods were surprisingly in good agreement. As seen in Figure 3.13, the maxima of transient forces (F_p) measured by the piezoelectric sensor probe on bed column are in the same order of magnitude as the transient forces of solid particles (F_t) measured by the fracture sensitive sensor method. A correlation can be obtained as follows:

$$F_p[N] = 0.018822 + 1.4317 F_t[N] \quad (4)$$

The forces measured by the piezoelectric sensor on bed column are greater than those measured by fracture sensitive sensor method. This may be because the strain gauge is fixed on bed columns and records absolute particle impact forces. On the other hand, fracture sensitive sensor particles move around in the fluidized bed. The forces of solid particles measured by this method could be smaller due to the relative motion between fluidized media and fracture sensitive sensor particles.

The maxima of transient forces of solid particles were also correlated to the maximum energy release of pressure fluctuations ($\Delta\Delta P$). Figure 3.14 shows the results of this correlation. The correlation equation is as follows:

$$\frac{F_p}{M_g} = 1.6336 \left[\frac{\Delta\Delta P d_p^2}{M_g} \right]^{0.75663} \quad (5)$$

The above correlation is derived from our experimental data in the range of

$$\begin{aligned} 0.5\text{mm} &\leq d_p \leq 2.18\text{mm}, \\ 1.1 &\leq U_o/U_{mf} \leq 5.5, \\ 0.108\text{m} &\leq D_t \leq 0.292\text{m}, \\ \text{and } 0.7 &\leq H/D_t \leq 3.0. \end{aligned}$$

The correlation coefficient of the linear regression is 0.87. Within the range of experiments, the maxima of transient forces of solid particles in fluidized beds can be predicted by measuring the maxima of $\Delta\Delta P$ named as maximum energy release of pressure fluctuations.

Figure 3.10. Transient Particle Force Measured by Piezoelectric Sensors (F_p) in Fluidized Beds ($D_t = 0.108\text{m}$)

Figure 3.11. Transient Particle Force Measured by Piezoelectric Sensors (F_p) in Fluidized Beds ($D_t = 0.203\text{m}$)

Figure 3.12. Transient Particle Force Measured by Piezoelectric Sensors (F_p) in Fluidized Beds ($D_t = 0.292m$)

Figure 3.13. The Comparison Between the Maximum Particle Impact Forces and the Kinetic Forces of Solid Particles Prevailing in Fluidized Beds

Figure 3.14. The Relationship Between the Maximum Transient Forces of Solid Particles and the Maximum Energy Release of Pressure Fluctuations

3.3.2 Attrition, Erosion and Vibration

Experimental results showed that the attrition rate of fluidized particles depends on the fluidizing air velocity and fluidized particle size. As seen in Figure 3.15, the attrition rate increases with an increase in superficial gas velocity and fluidized particle size. The maximum energy release defined in our previous report, also has the same dependence as attrition rate on the gas velocity and particle size, shown in Figure 3.16.

The transient solid-particle forces prevailing in fluidized beds were found to increase with increasing superficial gas velocity and fluidized particle size in our previous reports (Kono and Huang, 1987). The results of attrition test indicate a direct relation between solid-particle forces and the attrition rate of fluidized particles.

The maximum energy release in terms of pressure fluctuations has been shown to be a good indication of maximum solid-particle forces prevailing in fluidized beds (Kono and Huang, 1988). By measuring the pressure fluctuations of fluidized beds, the attrition rate of fluidized particles can be estimated. Figure 3.17 shows that the attrition rate of fluidized particles can be correlated to the maximum energy release (ΔP). The maximum energy release (ΔP), which can easily be converted to the maxima of transient forces of solid particles (F_p or F_t), can predict the attrition rate (M) by

Figure 3.15. Attrition Rate as a Function of Fluidizing Air Velocity and Fluidized Particle Size

Figure 3.16. Maximum Energy Release as a Function of Fluidizing Air Velocity and Fluidized Particle Size

Figure 3.17. The Relationship Between Particle Attrition Rates and Maximum Energy Releases

using Figure 3.17.

The erosion of in-bed tubes was investigated by measuring the decreases of total tube weight and tube diameter at various locations. Figure 3.18 shows the erosion rate of in-bed tubes in a weight basis. It can be seen that the weight loss increases with an increase in superficial gas velocity. Also, a larger size of fluidized particles causes a higher erosion of tubes. These are consistent with the results of transient solid-particle force measurement (Kono and Huang, 1987 and 1988).

The erosion rates of model in-bed tubes are shown in Figure 3.19, which indicates the relationship between the erosion rate (M_T) and the maxima of transient forces of solid particles in fluidized beds.

Figure 3.20 shows a typical example of tube diameter reduction at 0° angle as a result of erosion in fluidized beds. The erosion of in-bed tube increases with time and is rather symmetric with respect to the tube center at point 4 as marked in Figure 3.6. The higher erosion at the center of the tube indicates a rigorous bubble motion and coalescence around there. Figure 3.21 shows the erosion rate of tube diameter at various orientations as described in Figure 3.6. It can be seen that the direction against the air flow (0° angle) experiences higher tube erosion.

Figures 3.22, 3.23, and 3.24 show the erosion rate of in-bed tube as a function of fluidized particle size and superficial gas

Figure 3.18. Tube Erosion Rate in a Weight Basis as a Function of Fluidizing Air Velocity and Fluidized Particle Size

Figure 3.19. Erosion Rate of Model In-Bed Tube (M) Versus Maxima of Transient Forces of Solid Particles in Fluidized Beds (F_p)

Figure 3.20. Tube Diameter Reduction as a Function of Fluidizing Time

Figure 3.21. Erosion Rate of Tube Diameter at Various Orientations

Figure 3.22. Erosion Rate of Tube Diameter as a Function of Fluidizing Air Velocity for $d_p = 0.5\text{mm}$

Figure 3.23. Erosion Rate of Tube Diameter as a Function and Fluidizing Air Velocity for $d_p = 1.0\text{mm}$

Figure 3.24. Erosion Rate of Tube Diameter as a Function of Fluidizing Air Velocity for $d_p = 2.18\text{mm}$

velocity in the direction against the air flow at 0 angle. The same erosion pattern can be found for all three fluidized particle sizes. Apparently, the erosion rate of in-bed tubes is increasing with an increase in superficial gas velocity, and the center of tube is eroded faster than its side. Also, at constant U_o/U_{mf} , the larger size fluidized particles caused higher erosion of the tube than the smaller ones. Again, these results are in agreement with particle force data measured previously in this project (Kono and Huang 1988).

Photographs 3.1, 3.2, and 3.3 show the actual in-bed tubes used in the erosion experiments. Air flows upward in these pictures. It can be seen that an obvious erosion on the top of the tube took place for larger size fluidized particles ($d_p = 2.18\text{mm}$). This may be because the gravitational forces of fluidized particles become important as particle size increases.

The above attrition and erosion tests clearly showed that the maximum transient forces prevailing in fluidized beds are responsible for the attrition of fluidized particles and the erosion of in-bed tubes. To ease the attrition and erosion problem, the transient forces of solid particles have to be evaluated and controlled.

As for the measurement of bed vibration forces, the results are shown in Figure 3.25. At a constant holdup, larger particles ($d_p = 2.18\text{mm}$) gave higher bed vibration forces, although there were no

$D_t = 0.203m$
 $H/D_t = 1.0$
 $dp = 0.5mm$

No.	$U_o/U_{mf} (-)$	$t (h)$
1	0.0	0
2	2.92	6
3	3.71	5
4	6.30	5

Photograph 3.1. Tube Erosion Occurred for Fluidized Particle Size
 $dp = 0.5mm$

$D_t = 0.203m$
 $H/D_t = 1.0$
 $dp = 1.0mm$

No.	$U_o/U_{mf} (-)$	$t (h)$
1	0.0	0
2	2.13	6
3	2.46	5
4	3.13	4

Photograph 3.2. Tube Erosion Occurred for Fluidized Particle Size
 $dp = 1.0mm$

$$D_t = 0.203\text{m}$$

$$H/D_t = 1.0$$

$$d_p = 2.18\text{mm}$$

No.	$U_o/U_{mf} (-)$	$t \text{ (h)}$
1	0.0	0
2	1.14	6
3	1.19	5
4	1.42	5

Photograph 3.3. Tube Erosion Occurred for Fluidized Particle Size $d_p = 2.18\text{mm}$

Figure 3.25. Bed Vibration Forces as Functions of Fluidizing Air Velocity and Fluidized Particle Size

differences in smaller particles ($dp = 0.5$ and 1.0mm). The bed vibration forces were found to be about one order of magnitude higher than the particle forces measured previously (Kono and Huang 1988). This provides an additional support to the reliability of transient force measurement by the piezoelectric sensor method.

3.3.3 Bubble Motion and Force in Fluidized Beds

In the two-dimensional bed experiment, the bubble passage was monitored by the pressure sensor. In the meantime, the piezoelectric sensor could measure the transient forces of solid particles during the bubble passage. Figure 3.26 shows digital signals obtained simultaneously by the pressure sensor (smooth curve) and the piezoelectric sensor (zigzag lines). Because the two-dimensional bed limits the motion of fluidized particles, the digital signals from particle impact are different from those observed in conventional fluidized beds. In the two-dimensional bed, a group of particles impacts the strain gauge so that the duration time of contact is much longer than that in conventional fluidized beds. In Figure 3.26, the up-going curve indicates the approach of a single bubble, and the curve goes down to the bottom as the bubble leaves. It can be seen that significant particle impact forces were recorded by the sensor right after the bubble passed through. This is because the wake of bubbles is in a turbulent state. The existence of eddies in the wake results in larger solid-particle impact forces. This phenomenon explains the fact that the fracture sensitive sensors are destroyed in the bubble wake.

Figure 3.27 shows consecutive bubbles passing the sensors. The same phenomenon as that of a single bubble can be seen. This concludes that maximum particle forces in fluidized beds are caused by the bubble wakes. To mathematically predict solid-particle forces, a model to describe the bubble wake as a function of fluidization conditions will be necessary. At the present state of arts, no transient mathematical model can predict the bubble wake motion. Thus, the prediction of solid particle forces practically depends on empirical correlations.

Figure 3.28 shows the maxima of transient gas pressure fluctuation (maximum energy release) as a function of fluidization conditions in the two-dimensional fluidized bed. In the range of experiments, the maximum energy release increases with an increase in fluidized particle size and superficial gas velocity. A similar tendency can also be observed for the average bubble diameter as a function of fluidization conditions. (See Figure 3.29). Correlating the average bubble diameter to the maximum energy release as seen in Figure 3.30, the larger the maximum energy release the larger the average bubble diameter in the bed. As to the sensitivity between the above two parameters, dimensionless

Figure 3.26. The Traces of Individual Bubbles in a Two-Dimensional Fluidized Bed

Figure 3.27. The Traces of Consecutive Bubbles in a Two-Dimensional Fluidized Bed

Figure 3.28. The Maximum Energy Release as a Function of Fluidizing Air Velocity and Fluidized Particle Size in a Two-Dimensional Fluidized Bed

Figure 3.29. The Average Bubble Diameter as a Function of Fluidizing Air Velocity and Fluidized Particle Size in a Two-Dimensional Fluidized Bed

Figure 3.30. The Relationship Between the Maximum Energy Release and the Average Bubble Diameter

group D_b/d_p was plotted against $\Delta\Delta P d_p^2/Mg$. In Figure 3.31 the sensitivity between the maximum energy release and the average bubble size increases with a decrease in the fluidized particle size. This is because the bubble size is larger and soon reaches its maximum for a fluidized bed with coarser fluidized particles.

3.4.0 CONCLUSION

The transient force measurement technique for the transient motion of solid particles was developed by using a piezoelectric sensor. The reliability of this measurement technique was experimentally verified. An optimal sampling condition was also experimentally determined. The maxima of transient forces of solid particles measured by the piezoelectric sensor method and the fracture sensitive sensor method were found in the same order of magnitude. This verifies the reliability of the above two force measurement methods. The maxima of transient forces of solid particles were further correlated to the maxima of $\Delta\Delta P$ (maximum energy release of pressure fluctuations). Within the range of experiments, the maxima of transient forces of solid particles can be predicted by measuring pressure fluctuations.

The attrition of fluidized particles and the erosion of in-bed tubes were investigated in relation to the solid-particle forces

Figure 3.31. The Sensitivity Between the Maximum Energy Release and the Average Bubble Diameter at Various Fluidized Particle Sizes

prevailing in fluidized beds. The particle attrition in terms of the weight loss of fluidized particles was found to increase with increasing particle size and superficial gas velocity. The transient pressure fluctuations of fluidized beds were also measured at the conditions where attrition tests were made. A relationship between the particle attrition rate and the peak of ΔP (maximum energy release of the gas phase) in a fluidized bed was observed. This result shows that the attrition of fluidized particles can be predicted by measuring pressure fluctuations. The pressure fluctuations have been proven to indicate the solid-particle forces prevailing in fluidized beds in our previous report. Apparently, the attrition of fluidized particles is caused by the solid-particle forces.

The erosion of in-bed tubes was investigated by observing the weight loss and diameter reduction of the tubes at various fluidization conditions. Tubes were eroded faster at higher superficial gas velocities and larger fluidized particle sizes. This is consistent with the experimental results that solid-particle forces increase with an increase in superficial gas velocity and particle size. The erosion of tubes was also found to be about symmetric with respect to the tube center, and higher erosion was observed at the tube center, especially in the direction right against the air flow. These results indicate a rigorous bubble motion and coalescence at the center region of the bed.

The bed vibration was measured by using piezoelectric sensor method. At a constant holdup, larger bed particles ($d_p = 2.18\text{mm}$) could give higher bed vibration forces, although there were no differences between 0.5 and 1.0mm particles. The bed vibration forces were found about one order of magnitude higher than the particle forces measured previously in this project. This provides an additional support to the reliability of solid-particle force measurement by piezoelectric sensor method.

The two-dimensional bed experiments indicated that the bubble wake induces the maximum of transient forces of solid particles. To mathematically predict solid-particle forces, a transient model will be necessary to describe the bubble wake as a function of fluidization conditions. At the present state of arts, no transient mathematical model is available to predict the bubble wake motion. Thus, the prediction of solid-particle forces practically depends on empirical correlations.

A correlation between the average bubble diameter and the maxima of ΔP (maximum energy release) was investigated in the two-dimensional fluidized bed. The average bubble diameter increases with the increase of the maximum energy release.

These experimental results provide more insights for the cause of transient solid-particle forces. This study assists in the prediction of solid-particle forces prevailing in fluidized beds.

3.5.0 NOMENCLATURE

d_p	Diameter of fluidized particle
D_b	Average bubble diameter
D_t	Diameter of in-bed tubes
F	Kinetic force prevailing in a fluidized bed
F_p	Maximum force measured by piezoelectric sensor method
F_t	Maximum force measured by fracture sensitive sensor method
g	Gravitational constant
H	Loosely packed bed height
L	Erosion rate of the in-bed tube in weight
M	Mass of solid particle in a fluidized bed
M_p	Attrition rate of fluidized particles
M_t	Erosion rate of the in-bed tube in weight
r	Radial distance
R	Radius of the fluidized bed
ΔP	Maximum energy release from gas phase in terms of pressure fluctuations
U_{mf}	Minimum fluidization velocity
U_o	Superficial gas velocity
V	Bed Vibration forces
W	Mass of fluidized particles in the bed
W_t	Mass of in-bed tube in the bed

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FINAL CONCLUSION

The significant achievements of this project can be summarized as follows:

(1) Three measurement methods, (piezoelectric sensor, fracture sensor particle, and gas pressure fluctuation methods) were developed to measure the transient forces of solid particles in fluidized beds.

(2) The maxima of transient forces of solid particles were found to be the determining major factor which controls the erosion rates of in-bed tubes in fluidized bed.

(3) The maxima of the above transient forces were measured under various fluidization conditions and in various fluidized beds with three different scales.

(4) Based upon these accomplishments, the erosion rate of in-bed tubes seems to be predicted by the above transient forces of solid particles.

(5) Finally, it seems that the development of a diagnostic approach can be accomplished in the near future to assess the erosion rate of in-bed tube by using the technical accomplishments made in this contract.

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