Characteristics of Slugging Regime and Transition to Turbulent Regime for Fluidized Beds of Large Coarse Particles

Slugging characteristics, including slug velocity and frequency and the height of the slugging bed, for a slugging bed of four different types of coarse particles ranging from 1 to 7 mm in size are determined based on pressure fluctuation behavior of the bed. The slugging characteristics of coarse particle slugging beds are found to be much different from those of the particle slugging beds reported in the literature. The pressure fluctuation behavior in a coarse particle turbulent bed and the transition velocity from a slugging bed to a turbulent bed is also examined.

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SCOPE

Fluidized bed combustion is being recognized as one of the most effective means for industrial steam generation. Large coarse particles, defined as particles of diameter above 1 mm, are encountered in combustion processes such as the multisolid fluidized bed combustion process (Nack et al., 1977). For large coarse particle fluidized beds, the slugging regime can be observed over a wide range of gas velocities. Fundamental analysis of slug properties, including slug geometry, velocity, and frequency has been mostly limited to fine particle slugging beds. Little is known regarding the behavior of large coarse particle slugging beds. Furthermore, characteristics of the transition from the slugging regime to the turbulent regime of a bed of large coarse particles are not fully understood.

In this study, the hydrodynamic characteristics of large coarse particle slugging beds are investigated. The statistical properties of the pressure fluctuations in the bed are experimentally determined using pressure transducers. Based on the statistical properties, the slug velocity, frequency, and transition velocity from the slugging regime to the turbulent regime for a slugging bed of large coarse particles are evaluated and analyzed.

CONCLUSIONS AND SIGNIFICANCE

Experiments are conducted to analyze the characteristics of slugging fluidized beds of large coarse particles ranging in size from 1 to 7 mm. The slugging characteristics analyzed include pressure fluctuations in slugging beds, slug velocities, maximum height of slugging beds, and the frequency of slugs. Coarse particle slugging beds are found to behave much differently as compared to fine particle slugging beds. Slug velocity and bed expansion for coarse particle slugging beds is found to be lower than that for fine particle slugging beds. Also the slug velocity is observed to initially increase with increasing air velocity, but beyond an air velocity of approximately (U_{mf} + 1.5) m/s, the slug velocity is found to decrease with increasing air velocity. Slug velocity, height of the slugging bed, and slug frequency for coarse particle beds are semiempirically correlated.

A new method of determining the transition velocity from the slugging regime to the turbulent regime by calculating the probability of zero pressure above the static bed height is described. The transition velocities of the course particles determined by this method are found to match the visually observed transition velocities.

INTRODUCTION

Hydrodynamic information is essential to the successful and optimum design of fluidized bed combustors. For example, hydrodynamic information for a slugging bed of large coarse particles, defined as particles of diameter above 1 mm, in a multisolid pneumatic transport bed (Nack et al., 1977; L.-S. Fan et al., 1983) is of extreme importance in estimating the heat transfer coefficient

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and combustion efficiency and in determining the height of the combustor required to allow disengagement of coarse particles. For fluidized beds of coarse particles the difference between the minimum slugging velocity and the minimum fluidization velocity is small compared to the minimum fluidization velocity, even for a large diameter bed. Therefore, for coarse particle fluidized beds the slugging regime is observed over a wide gas velocity range, from approximately the minimum fluidization velocity to the onset of turbulence velocity.

Most of the data and correlations developed for slugging fluidized beds in the literature are for fine particle beds. Some studies, however, have been reported for the hydrodynamics of slugging beds of coarse particles (Cranfield and Geldart, 1974; Baker and Geldart, 1978; Canada et al., 1978; Canada and McLaughlin, 1978; Miller et al., 1981; Glicksman et al., 1981). Most of these studies utilize particles of size less than 1.5 mm, however some of the hydrodynamic characteristics of slugging beds have been investigated for particles up to 2.6 mm in diameter. One of the major parameters to distinguish a coarse particle slugging bed from a fine particle slugging bed is the ratio of slug velocity to particulate phase gas velocity. For coarse particle slugging beds this ratio is <1 (slow slug condition) and for fine particle slugging beds it is >1 (fast slug condition). This delineation is important due to the fact that the two situations exhibit different gas flow characteristics. At the slow slug condition the gas moves freely from the particulate phase through the slug and back to the particulate phase, whereas at the fast slug condition the gas circulates around the slug and a cloud is formed around the slug.

The two-phase theory originally proposed by Toomey and Johnston (1952) is applicable to fluidized beds where the gas velocity in the particulate phase is equal to the minimum fluidization velocity and there is no through-flow of gas in the bubble or slug phase. The two-phase theory has been questioned by several investigators for fine particle bubbling fluidized beds (Lockett et al., 1967; Grace and Clift, 1974; Rowe et al., 1978), although it appears to be a good approximation for fine particle slugging beds (Grace, 1982). For coarse particle slugging beds operated at the slow slug condition, some through-flow of gas in the slug phase will be present and thus the two-phase theory can not be adequately applied. Davidson and Harrison (1966), Lockett et al. (1967), and Grace and Harrison (1969) have derived expressions for gas flow in the slow bubble regime with through-flow of gas in the bubble phase.

Theil and Potter (1977), Canada et al. (1978), Yerushalmi and Cankurt (1979), and Yang (1982) measured the transition to the turbulent regime velocity for particles of various sizes. The transition from the slugging or bubbling regime to the turbulent regime is not well defined in the literature and contradictory statements have been reported regarding this transition.

In this study, pressure fluctuations and bed expansion are measured for slugging fluidized beds of large coarse particles in the size range from 1 to 7 mm. Measured pressure signals are utilized to obtain the probability density function, slug velocity, and slug frequency. The transition velocity from the slugging regime to the turbulent regime is also determined by the probability density function, amplitude of the pressure fluctuations, visual observations, and bed height data.

EXPERIMENTAL

The experimental apparatus utilized to measure the slugging characteristics of the coarse particle fluidized beds consists of a column of 0.102 m ID and 6.46 m in height. A schematic diagram of the experimental apparatus is shown in Figure 1. Air is sent through an oil filter and an orifice meter before it enters the bottom of the column. The oil filter traps any oil mist contained in the air. The coarse particles are located about 2.0 m from the bottom of the column. Any coarse particles entrained from the bed are separated by two cyclones. These coarse particles are then recovered in the stand pipe, which is 3.81 cm ID and 4.25 m in height.

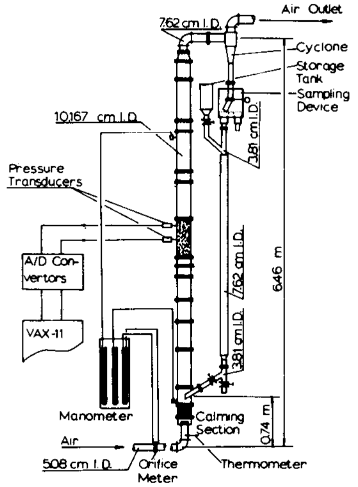

Figure 1. Schematic diagram of the experimental unit.

Two pressure taps are installed vertically along the column. The taps, which are 2.5 cm long, are connected to two differential pressure transducers which are interfaced with a VAX-11/780 minicomputer via A/D converters for real-time data acquisition. The transducers are Sensym model LX 1802DZ®. These transducers are linear in response from 0 to 15 psi (0 to 103.4 kPa) differential pressure. The pressure data acquired from these transducers is utilized to calculate the probability density function, probability distribution function, power spectral density function, autocorrelation function (R_{xx}), and crosscorrelation function (R_{xy}). The equations used for calculating these functions have been described in detail by Bendat (1958) and L. T. Fan et al. (1981).

The pressure taps are located in the upper portion of the bed 15.2 cm and 30.3 cm above the distributor plate. Static bed heights of 15, 20.3, 25.4, 30, and 35.6 cm at minimum fluidization are used in the experiments. A wide range of air velocities, from minimum slugging velocity to beyond the onset of turbulence velocity are tested. A sampling interval of 0.01 seconds is used and 8,192 samples are collected for each run. This sampling interval and number of samples has been verified, by decreasing the sampling interval and increasing the sample size, to adequately represent the inherent system characteristics. Four different types of coarse particles are used including glass beads of 1 mm dia. and aluminum particles of 2.32, 5.50, and 6.96 mm dia. The physical characteristics of the particles are given in Table 1.

RESULTS AND DISCUSSION

The slugging characteristics of coarse particles are measured for four different static bed heights of coarse particles. The slug velocity is found to decrease with an increase in static bed height from 15 cm ($H_{mf}/D = 1.5$) to 20.3 cm ($H_{mf}/D = 2$). However the slug velocity remains constant with the increase of the static bed height beyond 20.3 cm. Similarly, the transition to the turbulent regime velocity is observed to increase with an increase in the static bed

TABLE 1. CHARACTERISTICS OF COARSE PARTICLES

Type of Particle	Particle Avg. Dia. mm	Particle Density g/cm^3	Sphericity Factor
Glass Beads	1.00	2.767	1.000
Aluminum	2.32	3.537	0.838
Aluminum	5.50	3.537	0.990
Aluminum	6.96	3.537	0.920

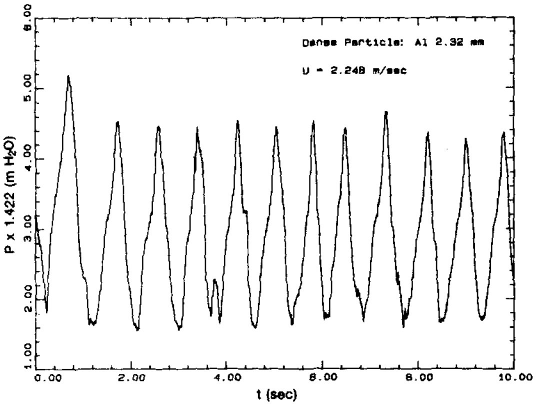

Figure 2. Pressure vs. time signal obtained at 15.2 cm above the distributor plate for 2.32 mm dia. Al particles.

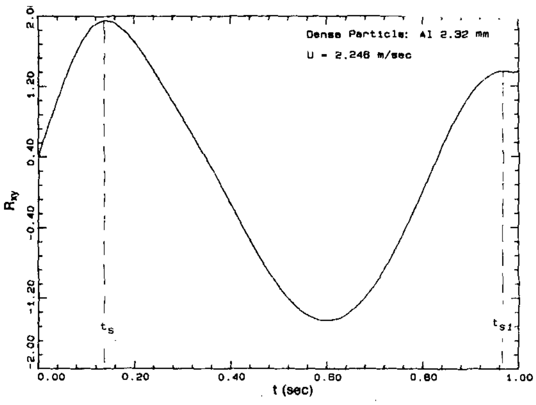

Figure 3. Crosscorrelation function between two signals acquired at 15.2 cm and 30.3 cm above distributor plate for 2.32 mm dia. Al particles.

height up to 20.3 cm and remains constant thereafter. The behavior of coarse particle slugging beds reported in the literature has shown less bed height dependence than for fine particle slugging beds (Canada et al., 1978). Furthermore, the transition from the shallow bed to the deep bed for coarse particle slugging beds was reported to occur at a H_{mf}/D of approximately 2 (Miller et al., 1981). In order to insure independence of slugging characteristics from the bed height, all data reported in this study are for static bed height greater than $2D$, i.e., 20.3 cm.

For all the coarse particles used in this study, square-nosed slugs are observed in the entire gas velocity range considered. Three types of slugs have been noted by other investigators: axisymmetric slugs, asymmetric slugs, and square-nosed slugs. In fine particle slugging beds axisymmetric slugs are the most commonly observed slugs. A large ratio between particle and bed diameters, angular particle shapes, and roughened walls promote the formation of asymmetric slug flows. Square-nosed slugs were observed in tubes up to 0.05 m in diameter only (Kehoe and Davidson, 1970; Hovmand and Davidson, 1971). However, Theil and Potter (1977) observed square-nosed slugs in columns up to 0.22 m in diameter and the tendency to form square-nosed slugs was related to the internal angle of friction of the solid material. In coarse particle slugging beds square-nosed slugs are normally observed.

The slugging characteristics of coarse particles determined from the pressure fluctuation signals and the height of the slugging bed are discussed in the following sections. The pressure fluctuations in turbulent beds of coarse particle and the transition from the slugging to the turbulent regime are also discussed.

Pressure Fluctuations in Slugging Beds

Pressure fluctuations in slugging fluidized beds of particles less than 1.2 mm dia. have been measured and documented in the literature by Kehoe and Davidson (1973), Brodhurst and Becker (1976), Canada et al. (1978), Yerushalmi and Cankurt (1979), L. T. Fan et al. (1983), and Yamazaki et al. (1983). The pressure fluctuations at a point in the slugging bed are caused by the bed height fluctuation and passage of the slug across the point. A typical pressure signal (Y1) measured in a slugging bed of 2.32 mm dia. aluminum particles at a height of 15.2 cm is shown in Figure 2. When a slug is formed at the bottom of the bed, the bed height increases and consequently the pressure at any point above the slug increases. When the roof of the slug reaches a height of 15.2 cm, the level at which the probe is located, the pressure (Y1) begins to decrease. As the base of the slug passes the pressure tap, the pressure is at its lowest. After the base of the slug passes the probe, the pressure begins to rise again. It is noted in the figure that the signal has a definite constant frequency. Similar signals are recorded for all the coarse particles considered in this study operated in the slugging regime.

Slug Rise Velocity

There are several techniques possible for measuring the slug or bubble rise velocity in gas-solid fluidized beds. These techniques include photographing with ordinary cameras as well as with x-ray cameras; sensing with capacitance or electroresistance probes; and computing the crosscorrelation function of the pressure signals obtained from pressure transducers. In this study the slug rise velocities are determined by calculating the crosscorrelation function of two signals obtained from transducers. Figure 3 shows a typical crosscorrelation function obtained for 2.32 mm dia. aluminum particles at a superficial air velocity of 2.246 m/s. The crosscorrelation function shows an absolute maximum at time t_s, and local maxima at times t_{s1}, t_{s2}, t_{s3}, etc. The distance between the two transducers divided by the time t_s yields the slug velocity. The length of time periods are about equal for local maxima. Times t_{s1}, t_{s2}, etc. can be calculated by multiplying the time period by the number of periods and adding t_s.

The variation of the slug rise velocity calculated from the crosscorrelation function with the superficial air velocity is shown in Figures 4 and 5. It is noted in these figures that the slug rise velocity initially increases with an increase in superficial air velocity.

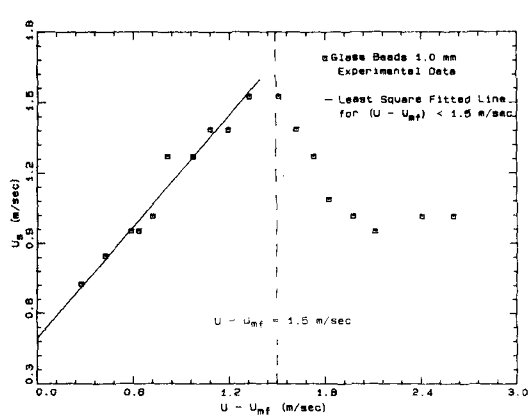

Figure 4. Variation of slug velocity with superficial air velocity for 1.0 mm dia. glass beads.

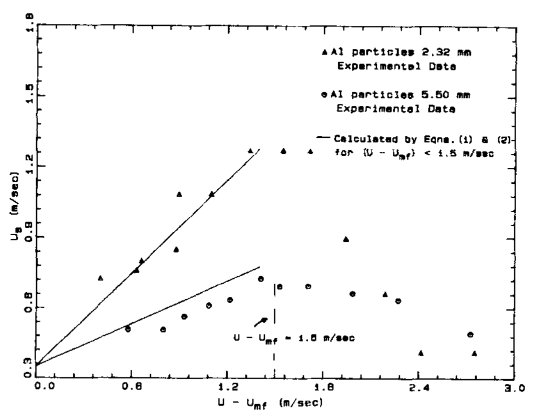

Figure 5. Variation of slug velocity with superficial air velocity for 2.32 mm and 5.50 mm dia. Al particles.

However beyond a certain air velocity the slug velocity decreases with an increase in superficial air velocity. The decrease in slug velocity is observed to occur at approximately $(U_{mf} + 1.5)$ m/s for all the coarse particles used in this study.

Slug rise velocity has been measured and correlated by several investigators including Davidson and Harrison (1963), Ormiston et al. (1965), Matsen et al. (1969), Kehoe and Davidson (1970), Theil and Potter (1977), Baker and Geldart (1978), Geldart et al. (1978), and L. T. Fan et al. (1983). The slug rise velocity has been correlated by an equation of the form

$$U_s = k_2(U - U_{mf}) + k_1\sqrt{gD} \tag{1}$$

where k_1 is found to be equal to 0.35 for axisymmetric slugs and 0.5 for asymmetric slugs. The value of k_1 for square-nosed slugs was observed to be in the same range as for axisymmetric slugs and asymmetric slugs (Baker and Geldart, 1978; Geldart et al., 1978).

The value of k_2 for fine particle slugging beds normally ranges between 0.9 and 2.0 as shown in Table 2. Also shown are the k_2 values for coarse particle slugging beds calculated from the experimental data obtained in this study. These values are significantly less than one and are found to decrease with increasing particle diameter.

The values of k_2 with $k_1 = 0.35$ for coarse particle slugging beds can be correlated by the following equation:

$$k_2 = 1.476\left(\frac{d_s}{D}\right)^{-0.9}\left(\frac{\rho_s}{1{,}000\,\rho_a}\right)^{-4.2} \text{ for } d_s > 2.3 \text{ mm} \tag{2}$$

For the slug velocity of fine particle slugging beds, k_2 was correlated by L. T. Fan et al. (1983) as:

$$k_2 = 2.43\left(\frac{d_s}{D}\right)^{-0.5}\left(\frac{\rho_s}{1{,}000\,\rho_a}\right)^{-4.2} \text{ for } d_s < 1.12 \text{ mm} \tag{3}$$

The k_2 value calculated from Eq. 3 for 1.00 mm dia. glass beads matches reasonably well with the k_2 value experimentally obtained in the present study. The slug velocities calculated from Eqs. 1 and 2 for 2.32 and 5.50 mm dia. aluminum particles are compared with the experimental values, as shown in Figure 5. The agreement between the two values is satisfactory.

The decrease in slug velocity observed beyond superficial air velocities of $(U_{mf} + 1.5)$ m/s can be explained by considering the particle movement. At low superficial air velocities the maximum height of the expanded bed is such that as the slug passes through a plane the solid particles in that plane move up in the bed, reach their maximum height, and come back to their original position before the next slug is formed at the bottom of the bed. At high superficial air velocity the bed expansion is such that the next slug is formed when the particles are falling down. The downward motion of these solid particles encountered by the slug retards the slug and a decrease in the slug velocity is observed. This decrease in slug velocity observed with an increase in air velocity at high air velocities has not been reported by most of the investigators. This may be due to the low range of gas velocities considered by them. L. T. Fan et al. (1983) observed a decrease in the slug velocity for 0.711 mm dia. particles beyond air velocities of 0.76 m/s. The decrease in slug velocity was explained as due to the change in regime of fluidization to the turbulent regime. The transition velocity to the turbulent regime thus determined is, however, low compared to the values obtained in this study and those reported by Canada et al. (1978).

Height of the Slugging Bed

The maximum bed height of the slugging fluidized bed is measured for particles from 1 to 7 mm in diameter. The variations of the ratio of maximum bed height to static bed height with superficial air velocity for all four types of coarse particles are shown in Figure 6. At the same $(U - U_{mf})$, the bed expansion ratio decreases with an increase in particle diameter.

Matsen et al. (1969), Baker and Geldart (1978), Geldart et al. (1978), Babu et al. (1978), Canada et al. (1978) and Miller et al. (1981) have documented bed expansion data for slugging fluidized beds. Most of the data reported are for fine particle slugging beds. Matsen et al. (1969) analyzed over 60 sets of data and correlated the data with the equation

TABLE 2. THE PARAMETERS OF SLUG VELOCITY CORRELATION DESCRIBED BY EQ. 1

Type of Particle	Values Determined by	Values Obtained by Least-Squares Analysis k_1	k_2	k_2 with k_1 = 0.35	k_2 with k_1 = 0.5
GB 1.0 mm	This study	0.512	0.774	0.948	0.787
Al 2.32 mm	This study	0.464	0.555	0.662	0.521
Al 5.50 mm	This study	0.320	0.271	0.243	0.104
Al 6.96 mm	This study	0.320	0.260	0.234	0.095
Particles up to 254 μm	Ormiston et al. (1965)	0.35	0.87-2		
Particles up to 359 μm	Theil and Potter (1977)	0.35–0.5	1.0		
Particles up to 1.12 mm	Fan et al. (1983)	0.35	1–4		

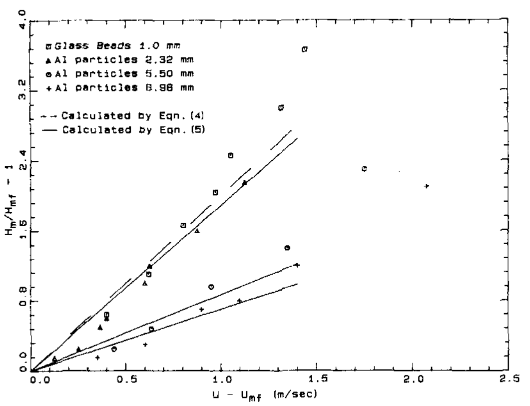

Figure 6. Variation of bed expansion with superficial air velocity.

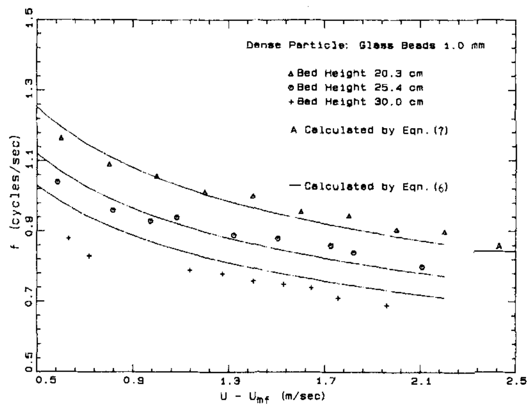

Figure 8. Variation of slug frequency with superficial air velocity as a function of static bed height.

$$\frac{H_m}{H_{mf}} - 1 = \frac{U - U_{mf}}{k_1\sqrt{gD}} \tag{4}$$

where k_1 is 0.35 for axisymmetric slugs and 0.50 for asymmetric slugs. Equation 4 is the most widely accepted correlation for bed expansion of slugging fluidized beds. As shown in Figure 6, the bed expansion data for 1.0 mm dia. glass beads correlates well with Eq. 4 for $k_1 = 0.5$. For 2.32 mm dia. aluminum particles, Eq. 4 overpredicts the bed expansion slightly whereas, for aluminum particles with diameters of 5.50 and 6.96 mm, Eq. 4 overpredicts the bed expansion data considerably. Similarly the correlation of Babu et al. (1978) overpredicts the bed height data for particles larger than 1.0 mm in diameter.

The maximum bed height of the slugging bed can be better correlated by an equation of the form

$$\frac{H_m}{H_{mf}} - 1 = \frac{k_2(U - U_{mf})}{0.35\sqrt{gD}} \tag{5}$$

where k_2 is given by Eq. 2. The maximum bed height calculated from Eqs. 2 and 5 for Al particles 2.32, 5.50, and 6.96 mm in diameter are compared with the experimental values as shown in Figure 6. The comparison is found to be satisfactory.

Slug Frequency

The frequency of the pressure signals acquired from fluidized beds can be determined by calculating the power spectral density function. Figure 7 shows the power spectral density function of the pressure signal acquired at 15.2 cm above the distributor plate for 2.32 mm dia. aluminum particles at a superficial air velocity of 2.246 m/s. At this air velocity, the bed is in the slugging regime. It is noted that the power spectral density function has a sharp peak at a frequency of 1.23 cycles/s (Hz), which is the dominant frequency of the signal. The dominant frequency of the signal thus calculated is defined as the slug frequency in this study.

The variation of the slug frequency determined in this study for 1.0 mm dia. glass beads with the superficial air velocity as a function of the static bed height is shown in Figure 8. The slug frequency is found to decrease with an increase in air velocity and bed height. The slug frequency appears to be only a weak function of superficial air velocity and it appears to approach a limiting value. Figure 9 shows the variation of the frequency with air velocity for aluminum particles with diameters of 2.32, 5.50, and 6.96 mm. The frequency is found to be affected by the particle diameter, i.e., at the same $(U - U_{mf})$, particles with large diameters show higher frequencies as compared to particles of small diameter. Also, the frequency is found to decrease sharply with an increase of air velocity. This decrease of slug frequency continues up to a $(U - U_{mf})$ of 4.5 m/s.

Slug frequency for fine particle slugging beds has been investigated by several investigators including Verloop and Hertjees (1974), Baeyens and Geldart (1974), Brodhurst and Becker (1976), Theil and Potter (1977), Baker and Geldart (1978), Canada et al. (1978), and Sadasivan et al. (1980) at room temperature, and by Yamazaki et al. (1983) at high temperatures. Baker and Geldart (1978) found the dominant frequency to decrease with an increase in bed height and superficial gas velocity. The tendency for the

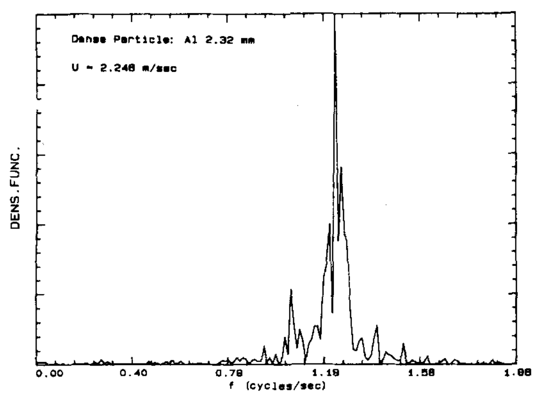

Figure 7. Power spectral density function for 2.32 mm dia. Al particles at a superficial air velocity of 2.246 m/s.

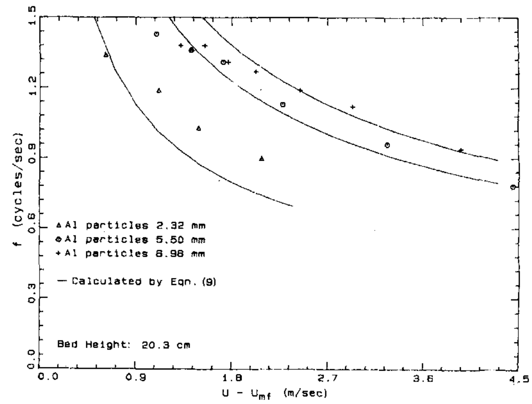

Figure 9. Variation of slug velocity with superficial air velocity for 2.32 mm, 5.50 mm, and 6.96 mm dia. Al particles.

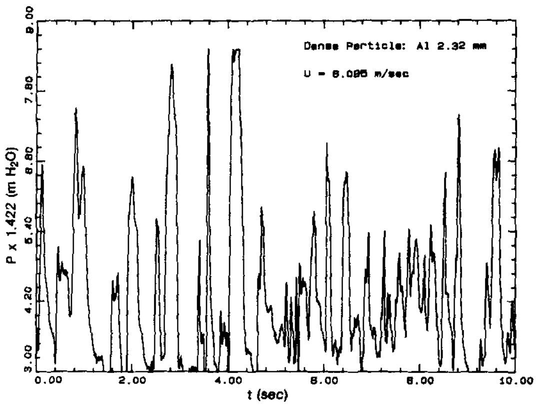

Figure 10. Pressure vs. time signal obtained at 15.2 cm above distributor plate for 2.32 mm dia. Al particles at a superficial air velocity of 6.095 m/s.

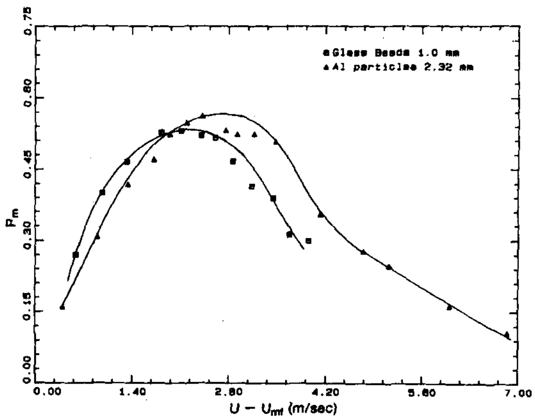

Figure 12. Variation of mean pressure fluctuation with superficial air velocity for 1.0 mm dia. glass beads and 2.32 mm dia. Al particles.

frequency to approach a limiting value at high $(U - U_{mf})$ was also observed. Baeyens and Geldart (1974) also found the slugging frequency to decrease with an increase in bed height. But beyond a certain bed height the frequency was found to reach a limiting value. The slug frequency was found by Baeyens and Geldart (1974) to be independent of the particle's physical properties, which is in contrast to the observations made in this study for large coarse particles.

Due to the different behavior of the slug frequency observed for 1.00 mm dia. glass beads and for aluminum particles greater than 2.32 mm dia., a single correlation for all the coarse particles is not justifiable. The slug frequency for 1.00 mm dia. glass beads before its limiting value is attained, i.e., $(U - U_{mf}) < 2$ m/s, can be correlated by the equation

$$f = 4.75 \left(\frac{1}{(U - U_{mf})^{0.5} H_{mf}} \right)^{0.5} \qquad (6)$$

where H_{mf} is in m and U and U_{mf} are in m/s. The limiting value of slug frequency can be calculated from the equations of Baeyens and Geldart (1974) described by Eq. 7 and Brodhurst and Becker (1976) described by Eq. 8:

$$f = 0.607\, D^{-0.143} \qquad (7)$$

$$f = 0.34\, (g/D)^{-0.5} (H_{mf}/D)^{-0.85} \qquad (8)$$

where D is in m.

The correlation of Baeyens and Geldart (1974) was obtained for spherical particles up to 1.85 mm in diameter and that of Brodhurst and Becker (1976) for particles less than 0.35 mm in diameter. The slug frequencies calculated from Eq. 6 are compared with the experimental values for 1.0 mm glass beads at $(U - U_{mf})$ less than 2 m/s in Figure 8. The comparison is found to be satisfactory. It is also seen that the limiting value of the slug frequency can be estimated by Eq. 7. Equation 8 considerably overpredicts the slug frequency and cannot be used for particles as large as 1.0 mm in diameter.

For particles greater than 2.32 mm in diameter, the slug frequency can be correlated by an equation of the form

$$f = 100 \left(\frac{d_s}{(U - U_{mf}) H_{mf}} \right)^{0.5} \qquad (9)$$

where d_s is in m. The comparison of the slug frequency values calculated by Eq. 9 with the experimental values for three types of coarse particles, as shown in Figure 9, is found to be satisfactory.

Pressure Fluctuations in Turbulent Beds

The pressure signal observed in a turbulent fluidized bed is more random in nature as compared to that in the slugging fluidized bed. Also the amplitude of the pressure signal in a turbulent bed is much

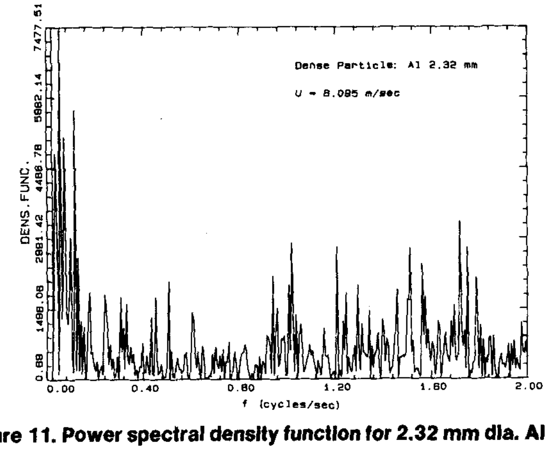

Figure 11. Power spectral density function for 2.32 mm dia. Al particles at a superficial air velocity of 6.095 m/s.

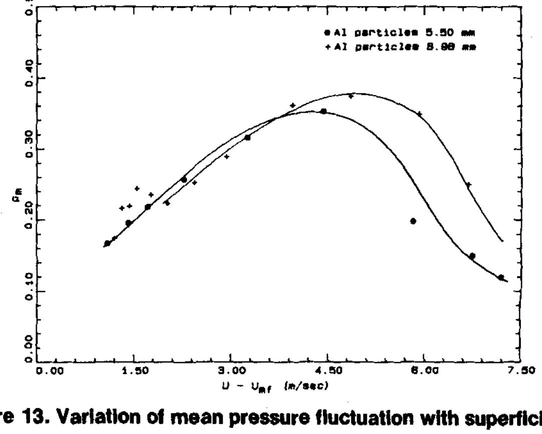

Figure 13. Variation of mean pressure fluctuation with superficial air velocity for 5.50 mm and 6.96 mm dia. Al particles.

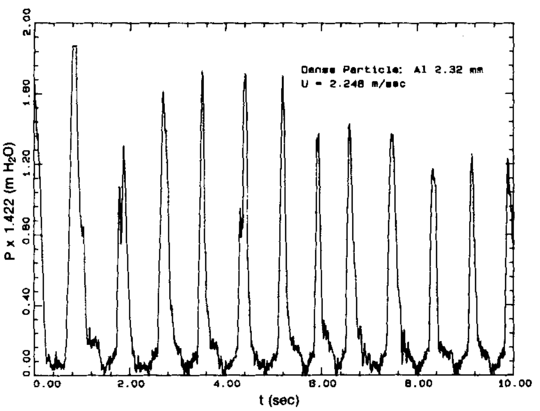

Figure 14. Pressure vs. time signal obtained at 30.3 cm above distributor plate for 2.32 mm dia. Al particles at a superficial air velocity of 2.246 m/s.

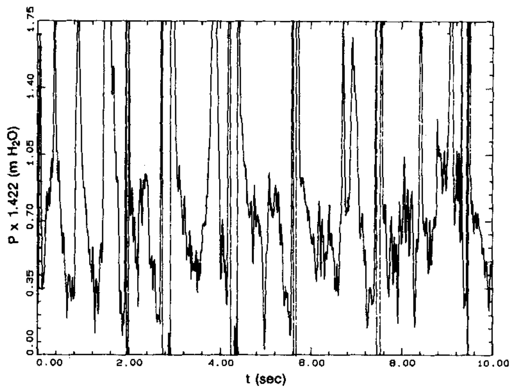

Figure 16. Pressure vs. time signal acquired 30.3 cm above distributor plate for 2.32 mm dia. Al particles at a superficial air velocity of 5.476 m/s.

smaller than that in a slugging bed. Figure 10 shows a typical pressure signal acquired 15.2 cm above the distributor plate for aluminum particles 2.32 mm in diameter when the bed is operated in the turbulent flow regime. Pressure fluctuations in a turbulent bed have been documented in the literature by Canada et al. (1978) and Yerushalmi and Cankurt (1979).

The power spectral density function of the pressure signal acquired at 15.2 cm above the distributor plate at an air velocity of 6.095 m/s for a bed operated in the turbulent regime is shown in Figure 11. 32,768 sample points are used for this figure. It is found that by increasing the sample size from 8,192 to 32,768 points the power spectral density function remains practically the same. It is noted that no well-defined dominant frequency exists for turbulent beds.

Transition to the Turbulent Regime

As the air velocity through a slugging bed is increased, the fluctuations grow in amplitude and bed expansion increases. However, beyond a certain air velocity, denoted as U_c by Yerushalmi and Cankurt (1979), the pressure fluctuations begin to decrease and the randomness of the fluctuations increases. As air velocity is further increased, Yerushalmi and Cankurt found the fluctuations to level off beyond a certain air velocity denoted as U_k. They characterized this air velocity as the onset of the turbulent regime velocity. They measured the transition velocity for particles up to 268 μm in diameter and found that both U_c and U_k decrease with particle diameter. Also, the ratios U_c/U_t and U_k/U_t were found to be in excess of 10 for beds of fine particles.

Values of transition velocity ratios U_c/U_t and U_k/V_t greater than 1 are observed due to the formation of fine particle clusters. The ratio of carryover velocity to terminal velocity has been reported in the literature to be in excess of 20 (Yerushalmi and Cankurt, 1979), whereas this ratio should be equal to 1 if particle clusters are not formed.

Theil and Potter (1977) conducted experiments with cracking catalyst in three beds of diameters 5.1, 10.2, and 21.6 cm. They indicated that the transition velocity to the turbulent regime decreases sharply with increasing bed diameter. It should be noted that the results of Theil and Potter are indicated as a single transition velocity without any specification of how it was determined. Staub and Canada (1978) also marked the transition to the turbulent regime by a single velocity which was determined by several keys including visual observation, bed height data, pressure trace chart recordings, and bed pressure drop. They estimated the onset to turbulent regime velocity (U_{tr}) to be marginally higher than U_c. Transition velocity ratios, U_{tr}/U_t, of 0.65 for 650 μm glass beads and 0.35 for 2.6 mm beads were determined by Staub and Canada (1978) in a bed 0.305 m × 0.305 m. Yang (1982), based on the pressure fluctuation data of Li and Kwauk (1980), reported that the gas velocity U_k at which the fluctuations begin to level off may represent the end of the turbulent regime instead of the onset to the turbulent regime velocity as defined by Yerushalmi and Cankurt (1979).

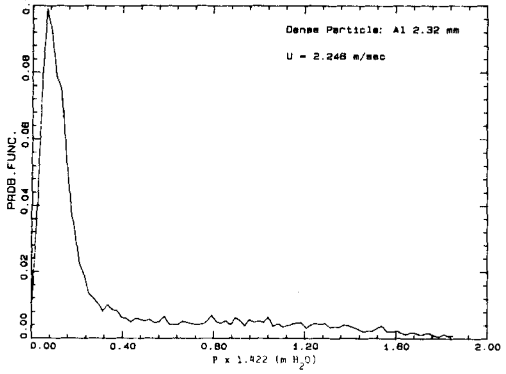

Figure 15. Probability density function for the signal acquired at 30.3 cm above distributor plate at superficial air velocity of 2.246 m/s.

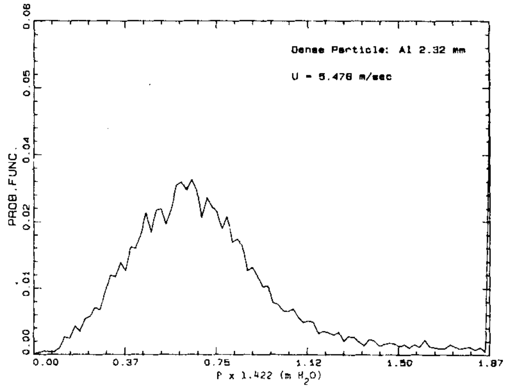

Figure 17. Probability density function for the signal acquired 30.3 cm above distributor plate at a superficial air velocity of 5.476 m/s.

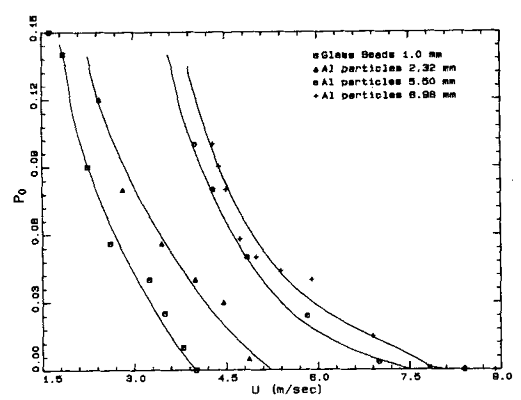

Figure 18. Variation of p_0 with superficial air velocity.

In this study, the pressure signals recorded at various superficial air velocities are utilized in calculating the mean fluctuation, P_m, at a point in the bed. The mean fluctuation is defined as

$$P_m = \left[\frac{\Sigma(P_i - \bar{P})^2}{N}\right] \Big/ \bar{P} \tag{10}$$

where N is the total number of data points and $\bar{P}$ is the average pressure.

The variation of the mean pressure fluctuation with the superficial air velocity for the four particles studied is shown in Figures 12 and 13. It is noted in the figures that for 1.0 mm dia. glass beads the fluctuations appear to level off beyond a certain air velocity, whereas for the other particles the fluctuations continue to decrease even at high air velocities where the bed is visually observed to be in the turbulent regime. Evidently it is difficult to define U_k for some particles directly from the amplitude of pressure fluctuation.

The transition to the turbulent regime can be alternatively defined by considering the probability density function of the pressure signal acquired at a height which is greater than the minimum fluidization height, as discussed below. The pressure is recorded at two positions in the fluidized bed at locations 15.2 and 30.3 cm above the distributor plate. For the static bed height of 20.3 cm, the minimum pressure at 30.3 cm from the distributor plate (denoted as Y2) is around zero. As the slug rises through the bed, Y2 increases; as the bed collapses to about the minimum fluidization height, Y2 approaches zero. Figure 14 shows a typical Y2 profile obtained with the bed of 2.32 mm dia. aluminum particles and at a superficial air velocity of 2.246 m/s. The probability density plot obtained from this data is shown in Figure 15. Clearly the Y2 pressure is around zero about 10% of the time. As the flow regime of the bed changes to the turbulent regime, the fluctuations in bed height decrease, and if the bed height is higher than 30 cm, pressure Y2 remains above zero. Figure 16 shows the pressure profile obtained for 2.32 mm dia. aluminum particles at a superficial air velocity of 5.476 m/s. The variation of the probability density function with pressure is shown in Figure 17. It is noted that the probability of Y2 being zero is almost negligible. Thus the onset to turbulence can be defined as the air velocity at which the probability of Y2 = 0, denoted as p_0, is zero. Figure 18 shows the variation of p_0 with superficial air velocity for all four coarse particles utilized in this study. The onset to turbulence velocities calculated from this figure are shown in Table 3. It is noted that these velocities match closely the visually observed ones. It is seen in Table 3 that the onset to turbulence velocities obtained in this study are comparable to the values of Canada et al. (1978).

To apply the method described above for determining the transition velocity to the turbulent regime, probe location below the height of the turbulent bed at transition and operation of the bed at atmospheric pressure are required. The void fraction of the bed at the transition to the turbulent regime has been observed to be approximately 0.75 (Canada et al., 1978). Thus if the pressure transducer is located between the heights H_{mf} and $3H_{mf}/2$, the bed height of the turbulent bed will be higher than the level of the pressure transducer and p_0 will be zero. In the event that the transducer is located above the surface of the turbulent bed, p_0 will be approximately 1 in the turbulent bed and a sharp jump in p_0 in the p_0 vs. $(U - U_{mf})$ plot at the transition will be noticed, in contrast to the smooth drop in p_0 observed in the alternative situation. If the bed is operated at high pressure, this method of determining the transition to the turbulent regime can be utilized by considering the probability density function at pressures approximately equal to the outlet pressure instead of zero pressure.

TABLE 3. TRANSITION VELOCITY TO THE TURBULENT REGIME

Type of Particle	Determined by	U_{tr}/U_t
GB 0.65 mm	Canada et al. (1978)	0.50
GB 1.00 mm	This study	0.459
Al 2.32 mm	This study	0.368
GB 2.60 mm	Canada et al (1978)	0.35
Al 5.50 mm	This study	0.343
Al 6.96 mm	This study	0.338

NOTATION

- d_s = diameter of coarse particles, L
- D = diameter of the bed, L
- f = slug frequency, $1/\theta$
- g = gravitational acceleration, L/θ^2
- H_m = maximum height of the slugging bed, L
- H_{mf} = height of the bed at minimum fluidization, L
- k_1, k_2 = parameters defined by Eq. 1
- N = number of data points used in calculating average pressure
- P_m = mean pressure fluctuation, $M/L\theta^2$
- P_i = pressure at any instant i, $M/L\theta^2$
- $\bar{P}$ = average pressure, $M/L\theta^2$
- P = pressure, $M/L\theta^2$
- p_0 = probability of Y2 being equal to zero
- R_{xx} = autocorrelation function
- R_{xy} = crosscorrelation function
- t = time, θ
- t_s = global maximum of the crosscorrelation function, θ
- t_{s1}, t_{s2} = local maxima of the crosscorrelation function, θ
- U = superficial air velocity, L/θ
- U_{mf} = minimum fluidization velocity, L/θ
- U_c = air velocity at which pressure fluctuations begin to decrease, L/θ
- U_k = air velocity at which pressure fluctuations begin to level off, L/θ
- U_s = slug velocity, L/θ
- U_{tr} = onset velocity to turbulent regime, L/θ
- U_t = terminal velocity of coarse particles, L/θ

Greek Letters

- ρ_s = density of coarse particles, M/L^3
- ρ_a = density of air, M/L^3

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