REAL TIME MASS FLUX MEASUREMENTS OF GAS-SOLID SUSPENSIONS AT LOW VELOCITIES*

by

J.H. Saunders
Brookhaven National Laboratory
Upton, New York

and

B.T. Chao and S.L. Soo
University of Illinois at Urbana-Champaign
Urbana, Illinois

In previous work, measurement of the particulate mass flux was made based upon a novel electrostatic technique. A small conducting wire sensor was inserted in the flow and as each particle hit the sensor an individual pulse of current was identified. Through suitable electronic circuitry, the number of pulses in a given time were counted. This was a direct measure of the number of particle-probe collisions which was related to local particle mass flow. The technique is currently limited to monodisperse suspensions.

A primary advantage of the impact counter system is that the output does not depend upon the magnitude of the actual charge transfer. As long as the pulses are sufficiently above the noise level, variations in charge transfer will not affect the measurement.

For the current work, the technique was applied to vertical gas-solid flow where the fluid velocity was slightly above the particle terminal velocity. Under these conditions a sufficient signal to noise ratio was not found. The Chao-Soo charge transfer theory indicated that the low particle-sensor impact velocity was responsible. The probe system was then modified by extracting a particulate sample isokinetically and accelerating the particles to a sufficient velocity by an area reduction in the sampling tube. With this technique the signal to noise ratio was about 12 to 1. Mass flux results are shown to compare favorably with filter collection and weighing.

INTRODUCTION

Recently, we have been studying the operation of a novel fluidized bed entrainment suppressing device. In this technique, proposed by Chao(1), particles projected upward at the bed surface entered a particle diverter, which returned them to the bed by utilizing an inertia-gravity mechanism. In our study(2), the device resulted in a significant decrease in the transport disengaging height, a reduction in entrainment by more than 80% at a height of 1 meter above a .33 meter diameter bed and a steadier, less fluctuating flow than an ordinary fluidized bed.

Measurements of the performance and scaling features of the device were obtained by mapping the air velocity and particulate mass flux fields in the region downstream of the particle diverter (Figure 1). Here, the gas flowed vertically upward, with fluid velocities ranging from approximately 1 to 1.4 times the terminal velocities of the particulate bed material. Consequently, the entrained particles moved upward at a relatively low speed, thus complicating the particle measurements.

The electrostatic counter probe, described in our earlier paper(3) was first tried for the particulate mass flux measurement since it offered the advantages of being an in-situ, real time method, thus eliminating isokinetic sampling and filter weighing. However, it was found that further modification of the measurement system was necessary for successful operation under the low speed flow conditions. This modification and its justification are the subjects of this paper.

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ELECTROSTATIC TECHNIQUE

When two uncharged dissimilar materials come into contact, electrons will spill from the material with the lower work function to the material with the higher work function. This results in a charge transfer and an equalization of the Fermi levels at the interface. Thus, the initially uncharged material will acquire a charge upon separation. This process is a function of ambient conditions, including humidity and contamination of the surfaces (4, 5).

Previously, this principle has been used to measure local particle mass flow (6-8). Particles transferred charge to a conducting sphere placed in the flow stream. The sphere was discharged to ground through an electrometer and the resulting current was calibrated against particle mass flux. However, variations in charge transfer due to change of the probe surface condition, such as oxidation, change of ambient condition, speed of impact or particle charge (4, 7, 9) could result in poor reproducibility of data.

Earlier, we reported on a different method of signal processing which to a very large extent, eliminated these problems. As each particle struck a small conducting sensor, an individual pulse of current was identified. Through suitable electronic circuitry, including a Schmitt trigger with variable threshold, the number of pulses in a given time were counted. This was a direct measure of the number of particle-probe collisions which was related to particle mass flux, since the particles were in a narrow size range.

The primary advantage of the impact counter system over the conventional electrostatic probe is that the output does not depend upon the magnitude of the actual charge transfer. As long as the pulses are sufficiently above the noise level, variations in charge transfer will not affect the measurement. In addition, a small sensor size can be used, thereby minimizing the flow disturbance. Further details can be found in (3).

MASS FLUX MEASUREMENT AT LOW VELOCITIES

The probe was first developed and tested for use in systems with particles below 100 μm and a mean air velocity above 5 m/s. When the same probe was tried above the fluidized bed, with air speeds typically less than 1.4 times the particle terminal velocity, pulses of a sufficient magnitude to be counted were not consistently found. This can be explained by the probe theory formulated by Cheng and Soo (7) and will be discussed later in the paper.

To solve the low speed signal problem, a sampling tube was used to extract from the flow system a particulate sample representative of the local flow conditions and accelerate the particles above 1 m/s in a contracting section (refer to Figure 2). A solid-tinned wire of .89 mm diameter by 2.5 mm long was mounted in the sampling tube and connected to the electronic circuitry. When the particles collided with the wire at this speed, a typical signal to noise ratio was 12 to 1. Controlled suction was applied through the sampling tube so that the average velocity in the probe mouth was equal to the local velocity determined by a TSI Model 1610 hot film anemometer.

The difficulties in operating the electrostatic impact probe under low velocity conditions can be seen by examining the probe theory presented in reference (7). In this work, the charge transferred by the impact between two spheres was studied. The current density, \( J_{21} \), from sphere 1 to sphere 2 is given by:

\[
J_{21} = h_{21}(V_2 - V_1)
\]

where, \( h_{21} \), is the charge transfer coefficient:

\[
h_{21} = \sqrt{\frac{\sigma_1 d_2}{\sqrt{\sigma_2 d_1}}} - \sqrt{\frac{\sigma_2 d_1}{\sqrt{\sigma_2 d_1} + \sqrt{\sigma_1 d_2}}}
\]

(1)
In equations (1) and (2) \( V, \sigma \) and \( d \) are respectively, the sphere potential, electrical conductivity, and characteristic length for charge transfer.

The current, \( I \), is simply,

\[
I = J_{21}A_{21} = h_{21}A_{21}(V_2 - V_1)
\]

where \( A_{21} \) is the contact area. This was determined by Hertzian theory as,

\[
A_{21} = \frac{\pi a_1a_2}{a_1 + a_2} \left[ \frac{15}{16} \left( 1 + \frac{r^+}{2} \right) U^2 \cos \theta \left( \frac{a_1 + a_2}{a_1a_2} \right) \right]^{1/2} \left( k_1 + k_2 \right)^{2/5}
\]

where \( m_1, m_2 \) are the sphere masses, \( a_1, a_2 \) are the radii, \( k = (1 - \nu^2)/\pi E \), \( \nu \) is Poisson’s ratio, \( E \) is the modulus of elasticity, \( U \) is the velocity at impact, \( r^+ \) is the ratio of rebound speed to incoming speed.

The theory applies strictly only to metals and semiconductors. For insulators, such as glass, the charge resides on the surface due to the high material resistivity. However, the theory can be used to estimate the effect of velocity, if one assumes that the product \( h_{21}(V_2 - V_1) \) does not depend upon velocity.

Examining equations (3) and (4) shows the height of the current pulse to be proportional to \( U^{4/5} \). This is very important since the extraction system accelerates the flow with an area reduction of 5.36 to 1. Furthermore, the sampling tube is arranged so that the suspension flows downward to the sensor (see Figure 2). Consequently, the particles move faster than the gas phase and the particle-sensor impact velocity is approximately \( 5.36U + U_c \), where \( U \) is the local air velocity and \( U_c \) is the particle terminal velocity. If the same sensor is placed directly in an upward flowing suspension (without extraction), the particle velocity lags the fluid velocity and the impact velocity is at most \( U - U_c \). Therefore, the expected ratio of extraction current peak to in situ current peak is

\[
\frac{I_{\text{extraction}}}{I_{\text{in situ}}} = \left( \frac{U_{\text{extraction}}}{U_{\text{in situ}}} \right)^{4/5} = \left[ \frac{5.36U + U_c}{U - U_c} \right]^{4/5} = 19.2
\]

for \( U = 26 \text{ cm/s}, U_c = 22 \text{ cm/s (typical experimental values)} \). However, the signal to noise ratio of the extraction counter probe is about 12 to 1. Therefore,

\[
\frac{I_{\text{in situ}}}{I_{\text{noise}}} = \frac{I_{\text{extraction}}}{I_{\text{noise}}} = .6
\]

So, according to the theory, the in situ signal is buried in the noise, but can be amplified 19.2 times by the extraction system.

The purpose of the extraction system is to remove and transport a sample from the air stream which is totally representative of the local flow conditions and to raise the particle velocities to a magnitude such that a sufficient signal to noise ratio is insured by their impact with the counter probe.

The sampling and counting system consists of the following items (see Figure 2): 1) an inlet nozzle or probe mouth, 2) a sampling tube, 3) a filter system, 4) a sampling velocity measurement and regulation system, and 5) the sensor and counting circuitry.

Isokinetic sampling from low velocity air streams with significant gravity effects requires care. The following paragraphs will discuss the methods employed to insure that a representative mass flux sample is taken into the probe.

The problem of sampling of dust from high velocity air streams has received extensive study (10-15). In general, the approach of most investigators is to apply controlled suction through
the sampling tube to minimize the difference between the velocity inside the probe mouth and the local (undisturbed) flow velocity.

Sampling at air velocities near the particle terminal velocity requires additional consideration. A primary concern was whether a significant amount of particles would fall out of the probe mouth due to the retarded velocity in the fluid boundary layer developing along the sampling nozzle wall. The approach that was followed to minimize and check measurement error included: controlling the probe suction accurately, designing the sampling tube to minimize flow disturbances and particle fallout, and checking the accuracy of the system with an independent method (particle collection and weighing).

Recent studies of particle sampling have led to design recommendations to minimize flow disturbances. Most investigators now agree that sampling nozzle walls should be as thin as possible to minimize upstream effects. Belyaev and Levin, define thin wall probes as having a ratio of outer diameter to inner diameter of less than 1.1 or if the mouth has a knife edge and a 150 or less bevel. Rouillard and Hicks, in an experimental study, conclude that the bevel should be on the inside diameter. In addition, they recommend the probe stem to be at least 11 diameters from the probe mouth.

The above recommendations were used to design the current sampling nozzle, shown in Figure 3. The outer diameter to inner diameter ratio is 1.08. A contracting section follows the inlet to prevent particles from falling out of the probe. The taper on the inside wall is 15°.

Air velocity through the sampling tube is measured with a Fischer and Porter Lab-Crest Series 10A1460 Rotameter with an accuracy of ± 3% of full scale. Flowmeter pressure is measured by a Wallace and Tiernan absolute pressure gauge. Any flow rate within the desired range could be obtained by adjustment of the two valves located as shown in Figure 2.

PROBE CALIBRATION AND CONSTRUCTION

By calibrating a sensor initially at high velocity, under conditions in which independent measurement of the particulate mass flux could be obtained, the accuracy of the electrostatic technique was assessed in our earlier paper. (3)

A similar sensor arrangement, shown in Figures 2 and 4, was used for the mass flux measurements downstream of the fluidized bed. The sensor shield, 3.24 mm in diameter by 22.9 cm long was connected in series with the sampling tube of the extraction system, as shown in Figure 2. This sensor was a solder-tinned copper wire of .89 mm diameter by 2.5 mm long and was mounted 12.7 mm from the downstream end of the shield. The combination of sensor size and shield diameter gave a sufficient number of particle-probe collisions for an accurate measurement downstream of the fluidized bed system. With a change in sampling tube diameter between the probe mouth and the sensor, the mass flux is given by

\[ \rho_p U_p = \frac{m c}{A_p} \left( \frac{D_2}{D_1} \right)^2 \eta_I \]  

(9)

where, \( m_p \) is the average particle mass, \( c \) is the counts/sec, \( A_p \) is the projected probe area, \( D_2 \) is the sensor shield diameter, \( D_1 \) is the probe mouth diameter and \( \eta_I \) is the fraction impacted (16).

The electronic circuitry is shown in Figure 5. Due to the high resistance to ground of the amplifiers, a current pulse from the probe would flow through the 1 mΩ resistance to ground. Three stages of amplification, all based upon high impedance, low drift, Teledyne Philbrick 1026 operational amplifiers, provided sufficient gain to process the pulse. The first stage used a pair of amplifiers in a low drift configuration to give a gain of 200. A 50 pF feedback capacitor stabilized the circuit. A voltage follower with a gain of 30 was the second stage. Following the second stage was a unity gain, two pole, Bessel filter designed from a Burr Brown UAF41 chip with a bandwidth of 80-1300 Hz. This frequency range was chosen to maximize noise rejection while maintaining high signal quality. It was important to block the d.c. signal component to prevent saturating the third stage amplifier. A final voltage follower with variable gain permitted adjustment of the overall amplification. With a typical system gain of 90450, each amplifier stage had a flat frequency response up to at least 4 kHz.
After amplification and filtering, any pulse over a desired height was converted to a rectangular pulse suitable for counting by a Schmitt trigger. Additional noise rejection was obtained at this stage by the use of a two level discrimination window, as discussed in our earlier paper. The rectangular pulses went to a Hewlett-Packard Model 5300a electronic counter, where the average count per second in a ten second sample was displayed. While the counter could resolve $10^{-7}$ seconds or better between two pulses, the time between actual pulses was of the order of milliseconds. Careful attention was paid to electromagnetic shielding of all leads and circuitry. To avoid ground loops, all ground connections were made to a common ground bus. By carefully following these procedures a noise level of approximately 12-15 µV, referred to input, was obtained.

An independent check on the mass flux measurements was obtained by first determining the total particle mass flow through the flow system exit. This was done by noting the change in mass of the filter thimble located to the model tube outlet (Figure 1) over a measured time interval. By traversing with the counter probe near the tube exit and integrating the resulting mass flux profiles, the total mass flow out of the tube could be obtained by the probe. A comparison of these two measurements is shown in Figure 6 for a variety of flow conditions. It can be seen that the counter probe provides a reliable indication of particulate mass flux, even at air velocities near the particle terminal velocity.

An earlier design of the probe nozzle, with a ratio of outer to inner diameter of 1.28 and a 30° knife edge on the inside surface was used for some of the data as indicated in Figure 6. Little change in accuracy is achieved by use of this nozzle design. It was found that the ratio of sampling tube diameter at the sensor to that at the probe mouth should be selected to obtain counts in the approximate range of 100-500.

Typical results with the extraction probe are shown in Figure 7. The relatively flat mass flux profiles were characteristic of the flow downstream of the diverter.

DISCUSSION

While the extraction and counting system requires careful design and testing, it is nevertheless a reliable instrument. Repeatability, under well controlled flow system conditions, was ± 5%. Sample time was short, typically 10 seconds, enabling data to be taken quickly and repeated often.

The sampling measurements reported here were not made under conditions characteristics of the freeboard region of fluidized beds, since the particle diverter significantly reduced the velocity fluctuations. The accurate application of sampling techniques to ordinary fluidized beds remains to be demonstrated.

Further work on electrostatic probes should aim at improving the signal to noise ratio which will extend the useful range of the in-situ probe.

REFERENCES


Figure 1 - Flow System
Figure 2 - Isokinetic Sampling and Particle Counting System
Figure 3 - Sampling Nozzle

3.18 mm O.D. x 1.6 mm I.D. BRASS TUBE

20.07 mm

3.81 mm

15° BEVEL ON I.D. WITH KNIFE EDGE

15°

7.49 mm

8.13 mm O.D.
Figure 4 - Electrostatic Counter Probe Detail
Figure 5 - Electronic Circuitry
Figure 6 - Comparison of Mass Flow at the Tube Exit: Counter Probe vs. Filter Collection and Weighing.
Figure 7 - Typical mass flux results. Measurements were made 4.6 tube diameters downstream of the particle diverter at a superficial velocity of 25.9 cm/s, using 52 μm glass beads. The mass flux is normalized by the average value.