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Measurement of Gas Velocities in the Presence of Solids in the Riser of a Cold Flow Circulating Fluidized Bed

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MEASUREMENT OF GAS VELOCITIES IN THE RISER OF A COLD FLOW CIRCULATING FLUIDIZED BED

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ABSTRACT

The local gas velocity and the intensity of the gas turbulence in a gas/solid flow are a required measurement in validating the gas and solids flow structure predicted by computational fluid dynamic (CFD) models in fluid bed and transport reactors. The high concentration and velocities of solids, however, make the use of traditional gas velocity measurement devices such as pitot tubes, hot wire anemometers and other such devices difficult. A method of determining these velocities has been devised at the National Energy Technology Laboratory employing tracer gas. The technique developed measures the time average local axial velocity gas component of a gas/solid flow using an injected tracer gas which induces changes in the heat transfer characteristics of the gas mixture. A small amount of helium is injected upstream a known distance from a self-heated thermistor. The thermistor, protected from the solids by means of a filter, is exposed to gases that are continuously extracted from the flow. Changes in the convective heat transfer characteristics of the gas are indicated by voltage variations across a Wheatstone bridge. When pulsed injections of helium are introduced to the riser flow the change in convective heat transfer coefficient of the gas can be rapidly and accurately determined with this instrument. By knowing the separation distance between the helium injection point and the thermistor extraction location as well as the time delay between injection and detection, the gas velocity can easily be calculated. Variations in the measured gas velocities also allow the turbulence intensity of the gas to be estimated.

INTRODUCTION

The independent determination of local gas and particle velocities in circulating fluidized beds (CFBs) and transport reactors is crucial for validating predictions from today's complex computational fluid dynamic codes. These velocities, however, are difficult to measure. Laser based optical methods designed to measure gas velocities require the gas to be seeded with small reflective particles capable of following the gas streamlines between the larger bed particles (1). Also, the presence of the larger bed particles restricts the laser mean free path making it difficult to make measurements deep in the bed. A solids concentration of 0.5% with 200 µm particles allows a mean free path of less than 2.5 cm (2).

Other researchers have used a variety of methods to measure gas velocities in the presence of solids. Moran and Glicksman (2) used a hot wire anemometer surrounded by 37 μm mesh screen to determine mean gas velocities and turbulence. Great care was necessary to assure no particles were smaller than the mesh size. Yang (3) used pitot tubes to determine the velocity profile of a jet in a fluidized bed but encountered problems such as plugging and the difficulty in separating momentum contributions of gas and solids.

Another way to measure gas velocities is to use a tracer gas and measure the time of flight between the injection point and the detection point. A key aspect of this technique is to detect the tracer gas within the riser with little time delay associated with the sampling. Such a detector might be based those used to measure gas dispersion. Many dispersion researchers such as Kimura *et al* (4) Liu *et al* (5) and Namkung and Kim (6) use a thermal conductivity detector (TCD) to measure concentrations of a helium tracer. Such a detector has the potential of being very small, having a quick response time, and can be placed directly within the flow to give time of flight, ie. gas velocity.

In a TCD, a Wheatstone bridge is formed between a reference element and balancing potentiometer on one side and a sample element and balancing potentiometer on the other side. The sensing reference and sample elements are usually either electrically heated wires or thermistors. The bridge is balanced while a known gas flows over the reference and sample elements. Changes in the gas composition and hence its heat transfer characteristics flowing past the sample element causes a change element's steady state temperature. This temperature change is electronically detected as an imbalance in the Wheatstone bridge. In this study, a similar bridge with a self-heated thermistor as the sample element is used. The bridge contains a fixed resistance instead of the reference element, however, since only the time at which the gas composition change is of interest and not an absolute indication of composition as in a GC.

EXPERIMENTAL APPARATUS

Thermistor bridge and helium injection

The device employed in this research con`sists of a Whetstone bridge containing a thermistor as the active element and a solenoid valve that allows pulsed injections of helium into the flow at a point upstream of the thermistor detector. The sampling frequency and duty cycle of the injections are computer controlled using LabVIEW data acquisition programming and a NI6036E data acquisition PC board. With the distance between the helium injection point and the thermistor detector known, the delay between helium injection and thermistor response indicates the time of flight for the gas between the two points. The gas velocity can then be calculated by simply dividing the separation distance by the time of flight. If the flow direction is unknown then a second helium injection can be performed on the other side of the thermistor.

The Wheatstone bridge employed (Figure 1) contains two variable resistors, one fixed resistor and a thermistor. The thermistor (Sensor Scientific S14A10225) is nominally 400 microns in diameter, has a time constant of 1 second and a dissipation constant of 0.1 mW/K. A DC source supplies 5.5 volts to the bridge. The solenoid valve used to control the helium flow is manufactured by Peter/Paul (PN 52N8DGB) with a response time of 4 – 16 ms. Solenoid operation is controlled using a Crydom DO061A relay with a 60 µs response time which is driven by a computer generated square wave.

The thermistor and helium injection probes are inserted into the flow via 0.95 cm nominal diameter, 0.3 m long, stainless steel tubes tipped with 6.4 mm dia., 25.4 mm long, 20 µm pore size sintered metal filters (Figure 2). A 9.5 mm diameter stainless steel sheath surrounds each sintered metal filter. The sheath is required because the impact of the 200 um solid glass spheres used as bed particles tended to "hammer" the filter pores closed. Additionally, a 20 µm screen was placed on the tip of the thermistor probe to minimize the accumulation of particles between the filter and sheath. The filter on the helium injection probe helps to disperse the gas upon injection. Care was taken to not impart a substantial to the helium in the direction of measurement and the filter was thought to aid in this goal.

The steady-state temperature of the self-heated thermistor depends upon general system properties, the voltage across and the current through the thermistor, the temperature difference between the thermistor and the gas, the velocity of the gas past the thermistor, and the composition of the gas. The time scale of each cycle of the helium injection is sufficiently short that the temperature of the system can be assumed to be constant. To insure the velocity of the gas past the warm thermistor is constant, a vacuum pump maintains a critical pressure ratio across the filter thus insuring the gas flow through the filter is relatively constant. Such a technique also tends to minimize the effect of pressure fluctuations within the riser on the measured signal. With temperature and velocity fluctuations minimized, the thermistor's response is then largely a function of changes in gas composition.

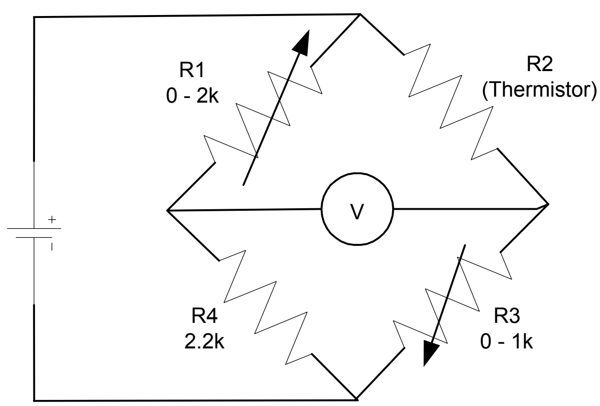

Figure 1 Thermistor bridge

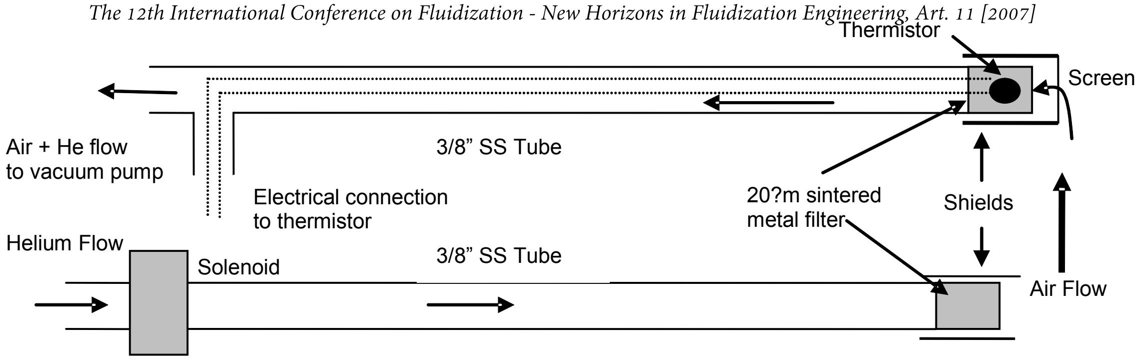

Figure 2 Thermistor and helium injection probes

Gas velocity tests are typically conducted for 30 seconds during which 15 pulses of helium are introduced with a duty cycle of 5 percent. The bridge voltage sampling frequency is 1 kHz. Two pulses of a fifteen-pulse chain are shown in Figure 3 for a superficial gas flow of 4.6 m/s and probe separation of 15.3 cm.

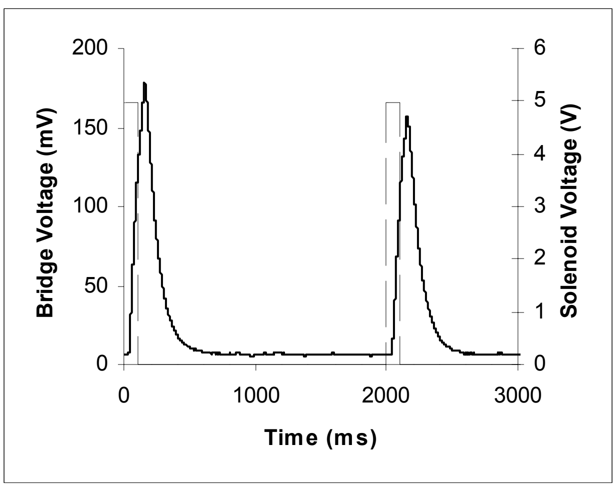

Figure 3 Typical helium pulse and thermistor reaction to air flow without solids.

Cold flow circulating fluidized bed

Velocity experiments are conducted in the cold flow circulating fluidized bed (CFCFB) and located at NETL, Morgantown, WV shown in Figure 4. The riser (located on the left of the diagram) is nominally 15.4 m high with an inside diameter of 0.30 m. A detailed description of the test unit can be found in Monazam et al (7). The riser is constructed of sections of either flanged steel or acrylic. Gas velocity measurements were made via ports in the flanged steel sections. Solids enter the riser from a side port 0.23 m diameter and 0.27 m above the gas distributor. Solids exit the riser through a 0.2 m port in line with the entrance and 15.4 m above the solids entry location. Riser gas flows and pressures are managed using flow control and backpressure control valves. Solids circulation rates are adjusted using standpipe aeration and monitored using a twisted spiral vane located in the packed region of the standpipe bed (8).

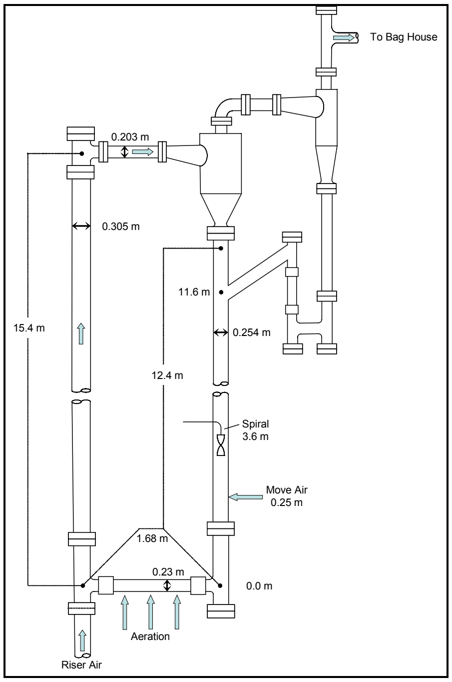

Figure 4 Schematic Diagram of CFB Test Unit

EXPERIMENTAL RESULTS

Without solids

Because the assembled gas velocity measurement system is made up of mechanical and electronic elements each with characteristic time constants, experiments were conducted to characterize the intrinsic time delay between the initiation of the signal to inject helium and the detection of the gas. A series of test were conducted with a superficial air flow of 4.6 m/s and the thermistor located at seven evenly spaced radial positions. No solids were present during these experiments. By knowing the superficial gas velocity and assuming a one seventh power law turbulent velocity profile, the intrinsic time delay was determined by minimizing the difference between the theoretical and measured gas velocities. Using this technique, the time delay was found to be 14.6 ms. Figure 5 shows the comparison between the experimental and theoretical gas velocities. The error bars represent 95 percent confidence intervals.

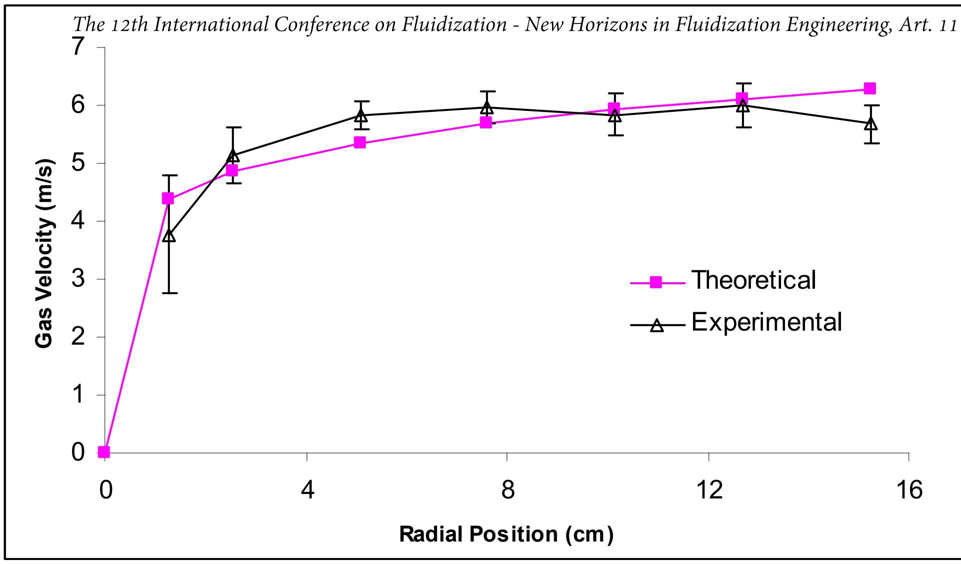

Figure 5 Probe Calibration

With solids

A 2x2 factorial experiment with a center point was conducted on the riser of the CFB. Superficial gas velocities (Ug) of 5.5, 6.6 and 7.7 m/s and mass circulation rates (Ms) of 6.3, 14.2 and 22.1 kg/s were employed using 200 μm glass beads (ρ = 2.426 g/cc). The injection and sampling probes were vertically aligned and separated by 10.0 cm. Multiple replicates of gas velocity measurements were obtained at the riser centerline, 7.6 cm and 2.5 cm from the wall at an axial position of 4 m above the centerline of riser solids inlet. A typical thermistor output is shown in Figure 6 for the center point of the factorial experiment. As can be seen, the magnitude of the bridge's response varies from pulse to pulse. Such a variation is expected as a result of the turbulent solids mixing which occurs within the riser. This mixing causes the concentration of helium to change as it travels to the thermistor probe. Sometimes this mixing is so intense that the helium is not readily detectable above the background noise, for example see pulses that occur between 10,000 and 15,000 ms. This phenomenon occurs with greater frequency with increased solids loadings.

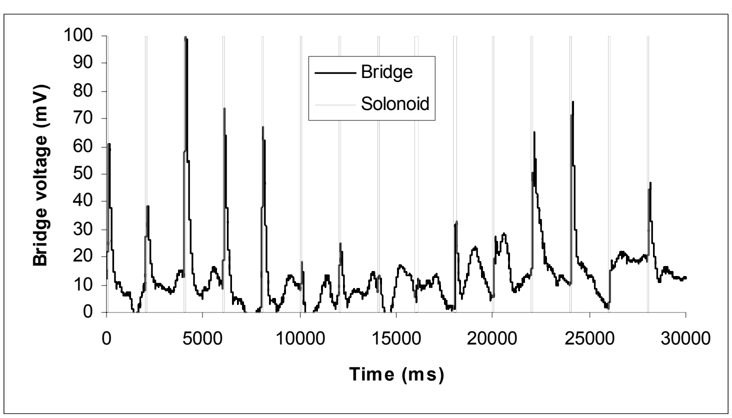

Figure 6 Typical thermistor response to helium injections

Table 1 displays the results obtained in the described factorial experiments. As expected for a given superficial gas velocity, as the solids circulation rate increases, so does measured interstitial gas velocities and their standard deviations. This trend suggests that for constant gas velocity the turbulence intensity is increasing with increasing solid circulation. Turbulence intensity was calculated as a the standard deviation of the gas velocities divided by the average. For a constant solids circulation rate, an increasing superficial gas velocity decreases the turbulence intensity. The turbulence intensity for all conditions tested increases from the center to wall.

Table 1 Gas velocity data from riser experiments

Set Conditions		Centerline (15.2 cm)			Midpoint (7.6 cm)			Near wall (2.5 cm)		
U_g	M_s	Avg Vel	St dev	Turb. Intensity	Avg Vel	St dev	Turb. Intensity	Avg Vel	St dev	Turb. Intensity
m/s	kg/s	m/s	m/s		m/s	m/s		m/s	m/s	
5.5	6.3	7.26	2.75	0.38	4.86	2.29	0.47	2.96	1.54	0.52
5.5	22.1	8.14	3.90	0.48	6.19	3.64	0.59	3.21	3.68	1.15
6.6	14.2	8.21	3.53	0.43	6.61	3.15	0.48	3.71	1.83	0.49
7.6	6.3	9.26	3.02	0.33	6.20	1.97	0.32	3.53	2.19	0.62
7.6	22.1	12.25	5.04	0.41	7.83	3.87	0.49	4.12	2.56	0.62

CONCLUSIONS

The methodology employed allows the determination of interstitial gas velocities between two points in gas-solids flows. From these measurements various trends were noted. The interstitial gas velocity and the standard deviation increase as the solids circulation rate increases for a given superficial gas velocity. The standard deviation increases faster than the gas velocity indicating increasing turbulence intensity. For a constant solids circulation rate, an increasing superficial gas velocity decreases the turbulence intensity. The turbulence intensity for all conditions tested increases from the center to wall.

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