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LDV measurements and analysis of gas and particulate phase velocity profiles in a vertical jet plume in a 2D bubbling fluidized bed Part I: A two-phase LDV measurement technique

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ABSTRACT

A laser Doppler Velocimetry (LDV) technique has been developed to simultaneously measure the gas and particulate phase velocities in a high-speed jet plume in a 2D bubbling fluidized bed. The laser, optics, and signal processing filters were configured to eliminate problematic laser-beam intensity fluctuations, which can contaminate Doppler signals in optically dense flows. In order to avoid damaging the optical access windows, the high-speed gas jet was seeded with small ice crystals. LDV bursts from the bed particles and gas tracer ice crystals were simultaneously recorded. The Doppler signals from the tracer crystals and bed particles were differentiated based on their burst intensity and coincidence to yield the particulate and gas phase velocities at a given location within the jet plume. Example gas and particulate phase velocity profiles and the associated measurement uncertainties are presented.

1. Introduction

Fluidized beds are commonly used as chemical reactors and solid fuel combustors due to the vigorous mixing of the reacting constituents. In many configurations, high-speed gas jets are employed to introduce reactants into a bubbling particulate emulsion. For example, jets of steam and air are sprayed into fluidized bed reactors during the gasification of coal or biomass. The mass and momentum transport of the jet is the key to predicting and optimizing the efficiency of a reactor.

When a gas jet is injected into a bubbling bed, particles and interstitial gas in the emulsion are entrained into the jet plume. The nature of the mass entrainment and subsequent momentum transfer are still not completely understood due, in part, to the paucity of published experimental data. The high solids fraction gas–particle flow is often opaque, and the high-speed jet flow can be extremely harsh and abrasive. This makes experimental measurements challenging.

In order to quantify the mixing and transport, the velocity profiles of both phases at various locations from the jet exit must be known. An overview of transverse and axial profile measurements of jet plumes into emulsions is provided by Massimilla [1]. Typically, gas velocities are obtained with pitot tubes, and high-speed video is used to determine the particle velocities. Pitot tubes are intrusive, and their pressure measurements can only be correlated to the gas phase velocity if the gas and solids momentum contributions can be distinguished from one another. In order to measure the relatively high particle velocities in a jet plume (~10 m/s), significant illumination is needed for video techniques, and this is often difficult in bubbling beds due to their limited optical access; therefore, these measurements tend to be limited to particles near the wall. Other optical techniques, such as optical fiber probes [2] and Laser Doppler Velocimetry (LDV) [3,4] have been successfully applied to measure the particle phase velocities of dilute, circulating fluidized beds. The present work describes the development and implementation of an LDV technique to obtain simultaneous gas and particulate phase velocity measurements in a high-speed jet plume in two-dimensional (2D) bubbling fluidized bed, extending this technique.

2. Method

2.1. Experimental facility

Experiments were conducted in a two-dimensional bubbling fluidized bed, which is shown in Fig. 1. The bed dimensions are 457 mm wide by 1 m tall with a 12.7 mm gap. The walls are transparent acrylic with 102 mm by 153 mm by 5 mm thick quartz viewing windows inserted 50 mm above the vertical jet inlet orifice, which is 9.2 mm in diameter. The vertical jet is located midway across the porous polyethylene fluidization distributor and is set flush with the surface.

The particles used in the emulsion are 838 μm Sauter mean diameter high-density polyethylene (HDPE) micropellets, which have a density of 900 kg/m^3. The minimum fluidization velocity for these particles was experimentally determined to be 29 cm/s. The velocity

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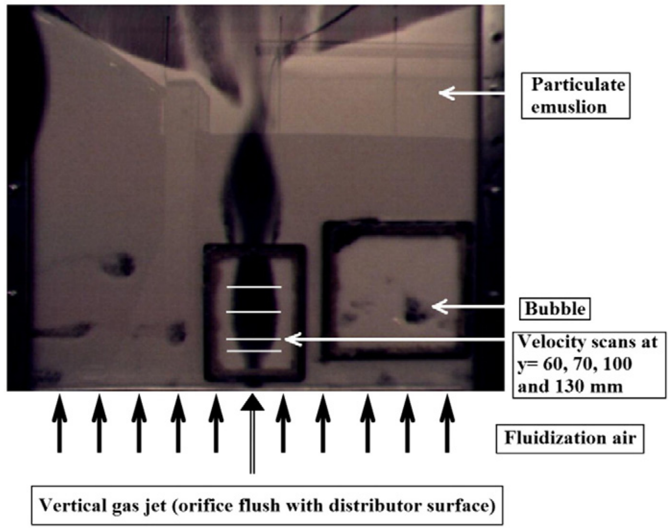

Fig. 1. Vertical gas jet in the laboratory 2D bubbling fluidized bed. The bed dimensions are 457 mm wide by 1 m tall with a 12.7 mm gap. The walls are transparent acrylic with 102 mm by 153 mm by 5 mm thick quartz viewing windows inserted 50 mm above the vertical jet inlet orifice, which is 9.2 mm in diameter. The square quartz windows may be used for horizontal jet experiments in the future. The vertical jet is located midway across the porous polyethylene fluidization distributor. The particle emulsion is white and the jet plume is black.

profiles presented in this paper are obtained with a jet inlet velocity of 92 m/s and a distributor fluidization velocity of 33.4 cm/s. The distributor gas velocity is defined as the volumetric flow rate of air used for fluidizing the bed divided by the area of cross-section of the column. The static bed height is 38 cm.

2.2. LDV configuration

Bed particle and gas phase velocities were obtained with a two-component LDV system employing a 5 W argon-ion laser. The axial velocities were recorded on channel 1 using the green beam (514.5 nm) and the transverse velocities were recorded on channel 2 using the blue (488 nm) beam. The LDV parameters and settings are listed in Table 1.

In order to simultaneously measure the gas and particulate phase velocities, high power laser beams are needed to form the LDV measurement volume. It should be noted that increasing the beam power can sacrifice the beam quality for an ionized gas laser [5]. Therefore a compromise must be reached in order to efficiently launch the laser beams into single mode optical fibers, which is necessary in many LDV systems.

LDV is an established measurement technique and detailed explanations of the fundamentals are available in the literature [6,7]. The basic operating principle is that an LDV signal is recorded when a particle scatters light as it traverses the interference fringe pattern established by intersecting monochromatic laser beams. Therefore the particle velocity is measured as the product of the frequency of the scattered light and the fringe spacing.

Table 1
LDV parameters. The system was optimized for maximum laser-beam power and minimal laser-beam intensity fluctuation complications. The large dynamic velocity range enables simultaneous gas and particulate phase velocity measurements.

	Ch1	Ch2
Laser power per beam (mW)	90	55
Beam diameter (microns)	90	85
PMT gain (mV)	450	450
Burst threshold (mV)	250	150
Frequency downmixing (MHz)	0	0
Band pass filter (MHz)	5–50	20–65
Bragg shift frequency (MHz)	40	40
Fringe spacing (microns)	3.74	3.55
Velocity range (m/s)	131 to −37	71 to −89
Coincidence interval (μs)	10	10

In order to remove the directional ambiguity of the velocity associated with a specific Doppler frequency (f), one of the intersecting laser beams is frequency shifted by an acousto-optic element, usually a Bragg Cell operating at $f_B=40$ MHz. This slight optical frequency shift causes the fringe pattern to propagate in space at a velocity of δf_B within the measurement volume. Therefore, a stationary particle would produce a Doppler signal at f_B, a particle moving in the direction of the fringe motion would produce a Doppler signal less than f_B, and a particle moving in the opposite direction of the fringe motion would produce a Doppler signal greater than f_B. Typically, the beams are oriented so that the fringe pattern moves counter to the bulk particle motion.

Another feature of the Bragg Cell is that it can also modulate the intensity of the frequency shifted beam, creating an intensity fluctuation that occurs at twice the Bragg frequency [8]. This intensity fluctuation will mix with the Doppler burst signal according to trigonometric relationship expressed in Eq. (1), where t is time.

$$cos(2\pi 2f_B t)cos(2\pi f t) = \frac{1}{2}cos[2\pi(2f_B+f)t] + \frac{1}{2}cos[2\pi(2f_B-f)t] \quad (1)$$

The FFT shown in Fig. 2 reveals that the Bragg shifted beam intensity fluctuation at 80 MHz mixes with a Doppler burst signal at 47 MHz to create spurious peaks at 33 MHz and 127 MHz. The false peak at $2f_B-f$ can be problematic due to its proximity to the Doppler burst frequency.

In addition to the Bragg Cell intensity modulation, all beams emerging from ionized gas lasers experience intensity fluctuations due to mode hopping, which occurs at a frequency of $C/2\,L$, where C is the speed of light and L is the cavity length. For a 1.2 m laser, the mode hopping frequency will occur at 125 MHz. When mixed with the Bragg cell intensity fluctuation, this produces a peak at 45 MHz, as shown in Fig. 3. Note that for this figure the Doppler burst frequency occurs at 36 MHz and thus a Bragg–Doppler mixed signal occurs at 44 MHz, which is very near the $C/2\,L\text{-}2f_B$ mixed peak. Also note that the laser used to obtain the data in Fig. 2 was smaller with a cavity length of approximately 300 cm, and therefore had a mode hopping frequency around 500 MHz.

These intensity fluctuation frequency mixings are an optical phenomena and are only noticeable when a significant portion of the

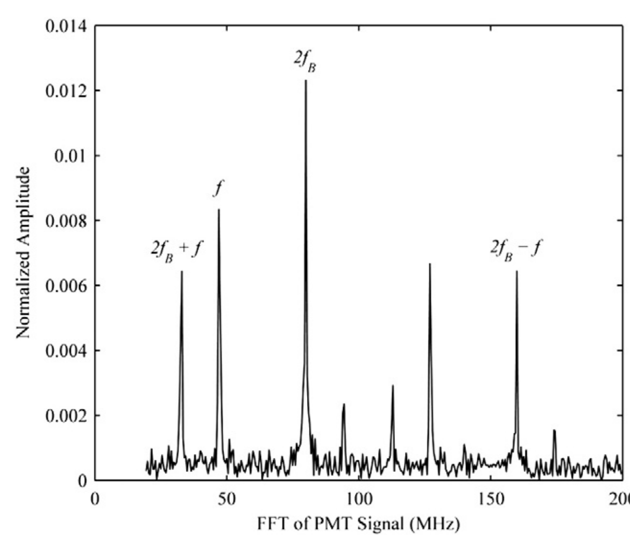

Fig. 2. Frequency mixing of the Doppler burst signal with the Bragg shifted beam intensity fluctuation.