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A LASER–FLUORESCENCE TECHNIQUE FOR TURBULENT TWO-PHASE FLOW MEASUREMENTS

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Abstract—A non-intrusive measurement technique has been developed for accurate determination of gas and particle velocities in a turbulent two-phase flow field. The principle of the technique is based on the discrimination between the scattered light from particles and the fluorescence emission from particles coated with a fluorescent dye. A high-powered, argon-ion based, single-channel, on-axis backscatter laser–Doppler velocimetry system was used. The fluorescent dye was Rhodamine 6G. A study of the gas–solid two-phase flow behaviour in the freeboard of a cold gas-fluidized bed was undertaken. The solid phase contained two particle groups: bed material (sand) and fuel particles (wood). Measurements of the axial velocity and turbulence intensity distributions of the gas phase and both particle groups within the solid phase were made along the column centre and across the freeboard. Excellent discrimination of velocities from the two phases and from the two particle groups within the solid phase was achieved.

1. INTRODUCTION

Considerable interest has been directed towards the measurement of gas and particle velocity fields within the freeboard of a gas-fluidized bed. The freeboard is defined as the space between the bubbling bed surface and the gas exit. Particles ejected into the freeboard by the bursting action of gas bubbles are responsible for additional combustion reactions as well as carryover of fuel, sorbent and bed material. Information on the velocity distribution of the two phases is essential to gain a thorough understanding of the two-phase behaviour above the bubbling bed surface and in the freeboard. To obtain reliable and accurate information on this flow behaviour, a non-intrusive measurement technique is required. The technique should also be capable of responding to high-frequency velocity fluctuations caused by the bubble-induced turbulence.

Laser–Doppler velocimetry (LDV) is now a well-established, non-intrusive, flow measurement technique. Solid phase velocities can be measured directly by LDV; however, it is not possible to distinguish the velocity distribution of different particle groups within the solid phase. In our experiments the solid phase contained two particle groups: inert bed metarial (sand) and fuel particles (wood). To measure gas-phase velocities seed particles, which are small enough to faithfully follow the flow, must be injected into the fluidizing air stream. This further complicates the measurements, as now there are three distinct particle groups present: each group of particles acts as light scatterers and yields velocity information. Unless one can simultaneously measure both velocity and particle size it is not possible to distinguish accurately from which phase or particle group the velocity information is being derived from. Whilst LDV-based methods are available for simultaneous measurement of velocity and size information they are expensive, complex and may lead to ambiguous results, particularly if the size distribution of different particle groups overlap.

In this work a phase-discrimination technique based on LDV–fluorescence emission has been developed. Measurements of gas- and solid-phase (both sand and wood particles) velocities and their r.m.s. fluctuations within the freeboard have been made.

2. PREVIOUS EXPERIMENTAL WORKS

Due to the complexity of freeboard two-phase flow, most previous experimental works have been concerned with the measurement of global freeboard properties (such as the elutriation rate constant), rather than the flow structure of the individual phases. Some workers, however, measured particle and/or gas velocities within the freeboard. Table 1 summarizes the experimental techniques used by previous investigators.

Table 1. Summary of previous velocity measurement techniques

Investigators	Experimental technique	Category
Do *et al.* (1972)	Fast photography	Non-intrusive
Levy & Lockwood (1983)	LDV	
Fournol *et al.* (1973)	Hot-wire anemometry (HWA)	
Horio *et al.* (1980)	HWA and fibre optics	Intrusive
Morooka *et al.* (1983)	Fibre optics	
Pemberton & Davidson (1984)	HWA	

With the exception of Levy & Lockwood (1983), all other investigators used a hot-wire anemometer to measure the gas-phase velocity and its r.m.s. fluctuations. Hot-wire anemometry (HWA) is an intrusive technique and the resulting disturbance to the flow field may lead to inaccuracies, particularly at low flow rates. Impingement of solid particles upon the hot wire creates another serious problem—it causes additional output voltages which are not generated by the air flow. Furthermore, insensitivity to the direction of velocity limits its use to turbulence intensities of $\leqslant 30\%$.

Horio *et al.* (1980) and Morooka *et al.* (1983) used a fibre optic probe to measure the particle velocities; this is also an intrusive technique which can result in disturbances to the flow field. Do *et al.* (1972) used a high-speed camera to measure the particle velocities and, although this was a non-intrusive technique, no measurements of gas-phase velocity were made.

Levy & Lockwood (1983) were the first investigators to use a non-intrusive technique for the simultaneous measurement of gas and particle velocity fields within the freeboard. They used an LDV system with a pedestal amplitude detection facility to discriminate between the gas and particle velocities. However, they did not seed the air flow but relied upon attrition of the bed material to produce fine enough particles to act as seed material; thus, they make the assumption that the finer material faithfully follows the gas flow, which may not necessarily be valid.

3. EXPERIMENTAL APPARATUS

A schematic of the experimental apparatus is shown in figure 1. The experimental setup consisted of an air delivery and exhaust system, a cold fluidized bed unit, a seeding generator and an LDV system.

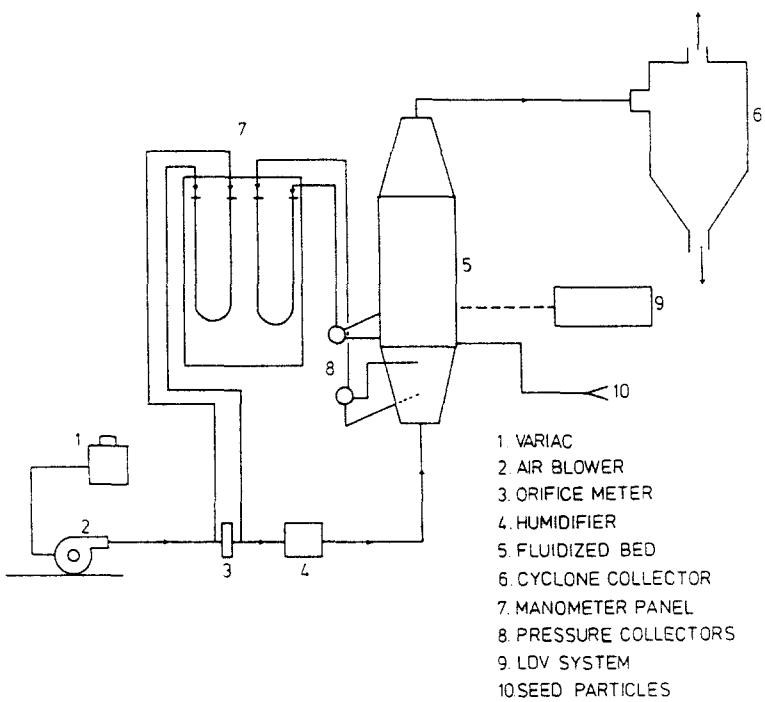

Figure 1. Schematic of the experimental apparatus.

The fluidized bed was of modular construction with the column being made up of units of rectangular cross-section (319 × 176 mm). Each unit was made of Plexiglas sheets (7 mm thick). Two of the column sections were 0.5 m high and the other two sections were 1.0 and 2.0 m high, respectively. The sections were flanged such that the column height could be varied up to a maximum of 4.0 m. A pair of first-quality crown glass plates were mounted on each side of one of the 0.5 m high sections to ensure good optical access. This section was interchanged with other sections when making measurements at different freeboard height locations. The entire fluidized bed unit was mounted on a traversing mechanism to enable measurements at various locations with the freeboard.

Fluidizing air was supplied by a variable-speed blower. A perforated-plate-type distributor (2.9 mm hole dia) was used to distribute the air uniformly in the bed. A humidifier was placed between the blower and entrance section to the bed to minimize the effect of static electricity; in addition the interior walls were sprayed with antistatic agent and the distributor plate was grounded.

Sand particles, mean dia 300 μm, were used as the bed material. Wood particles, with an initial size distribution of 40–85 μm, were loaded into the bed at a concentration of 4% by wt.

A fluidized-bed-type seeding generator was built to supply a continuous and uniform feed of seed particles. Aluminium oxide (Al_2O_3) particles were used as the seed material. The seeding generator produced no particles $\gtrsim 1$ μm. Particles elutriated from the cold fluidized bed (wood or seed) were collected by a 75 mm cyclone separator.

A high-powered (2 W), argon-ion based, single-channel, on-axis backscatter LDV system (TSI 9100-6) was used to make the velocity measurements. A counter-type signal processor (TSI 1980A) was used. The digital output from the counter processor was interfaced to an IBM-PC microcomputer for subsequent data handling.

4. THE PRINCIPLE OF THE LASER-FLUORESCENCE TECHNIQUE

In a conventional LDV as a particle passes through the probe volume it scatters light at the incident laser wavelength. In our experiments the argon-ion laser was operated at 514.5 nm (green). However, if a particle coated with a fluorescent dye (Rhodamine 6G) passes through the probe volume, in addition to weekly scattering light at the incident laser wavelengths (514.5 nm) it also emits strongly at longer wavelengths in the range 520–660 nm, as shown in figure 2.

4.1. Velocity discrimination between the two phases

The Al_2O_3 seed particles were impregnated with Rhodamine 6G dye solution and fed to the bed via the seeding generator. When all particle groups (seed, sand and wool) were present in the freeboard, the particulate-phase material scattered light at the laser wavelength (514.5 nm), whereas the dyed seed material emitted strongly in the range 520–560 nm. The scattered light at the laser wavelength was eliminated by placing an optical narrow bandpass filter (Optikon FS 10-25) with a central wavelength of 560 nm (orange) between the receiving assembly and the photodetector

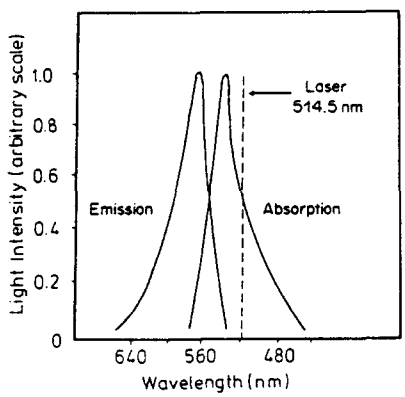

Figure 2. Absorption and emission spectrum of Rhodamine 6G (dos Santos & Stevenson 1977).

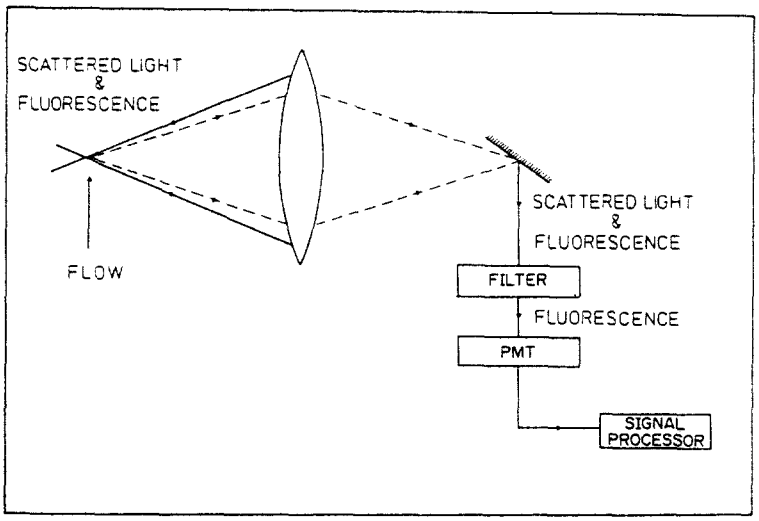

Figure 3. Schematic representation of signal discrimination.

pinhole, as shown in figure 3. This filter blocked the scattered light but allowed the longer-wavelength signals from the fluorescent seed particles to enter the photomultiplier tube. Thus, the gas-phase velocity was measured even though the particulate-phase particles were present in the flow.

4.2. Velocity discrimination between the particulate-phase particles

For these measurements no seed was used. The wood particles were coated with dye solution. To measure the velocity of the wood particles the same procedure was followed as for the gas-phase velocity measurements. Thus, only the emitted light from the dyed wood particles was allowed to enter the photomultiplier and all scattered light at the laser wavelength was blocked.

The velocity of the sand particles was measured by placing an optical narrow bandpass filter (TSI 9158), centred at the laser wavelength (514.5 nm), between the receiving assembly and the photodetector pinhole. In this case only the scattered light from the sand particles (which is very much stronger than the scattered light from the dyed wood particles) was allowed to enter the photomultiplier, whilst the fluorescent emission from the dyed wood particles at the longer wavelengths was blocked.

By use of these two filters velocity information was obtained from one group of particles at a time, even though both groups were present in the freeboard.

5. DYE PREPARATION AND PRETESTS

The dye concentration and attainable quantum yield are strongly dependent on the solvent. A 50:50 (% by vol) mixture of benzyl alcohol and ethylene glycol gives the highest possible signal level, 0.956 at 514.5 nm (dos Santos & Stevenson 1977). A number of tests were made to determine the optimum dye concentration. The seed particles were impregnated with dye solutions of different concentrations. These particles were charged to the seeding generator and fed to a simple laminar air flow test rig consisting of a 50 mm dia glass tube. The fluorescence-induced signals from the dyed particles were observed through a microscope eyepiece (TSI 10096) clamped on the photodetector pinhole. In addition, with the photomultiplier in place, it was found that in most cases the fluorescence emission was too weak to give signals with an acceptable signal-to-noise ratio when observed on an oscilloscope. After a number of tests the optimum dye solution was obtained by dissolving 13.4 g of 98% purity Rhodamine 6G in 1 dm^3 of a 50:50 (% by vol) mixture of benzyl alcohol and ethylene glycol.

No significant scattering at the laser wavelength from the dyed particles was observed when the narrow bandpass filter (TSI 9158) was placed in front of the photodetector pinhole. Further tests

showed that all scattered light at the laser wavelength was blocked when the other optical narrow bandpass filter (Optikon FS 10–25) was placed in front of the photodetector pinhole.

The particles to be dyed (seed or wood) were soaked in the solution and placed on a shaker for 2 h. They were then put in a drying oven for 4 h at a temperature of 80°C and then stored in a dessicator for 3 days before use. Samples of dyed seed particles were collected from the outlet of the seeding generator and examined under a microscope: no particles $>1.0\,\mu$m were observed.

6. RESULTS AND DISCUSSION

A series of experiments were made to investigate the two-phase flow behaviour in the freeboard of a fluidized bed. The following measurements were made:

(1) mean and r.m.s. velocity distributions of the gas phase;

and

(2) mean and r.m.s. velocity distributions of the solid phase—both particles of sand and wood.

Six different superficial gas velocities ($\bar{U}$) were used, as shown in table 2. At each value of $\bar{U}$ the freeboard region was traversed in three directions (x, y and z). The centre of the column was taken as the zero position ($x = 0$, $y = 0$). The slumped bed height was taken as $z = 0$. Measurements in the immediate vicinity of the bed surface were not possible because of very high particle concentrations. As the superficial gas velocity was increased, so measurements had to be made further from the bed surface. The minimum height at which measurements could be made at different values of $\bar{U}$ is given in table 2. Gas-phase velocity measurements could be made up to the column exit because seed particles were always present. However, solid-phase velocity measurements could not be made above a certain height because too few solid-phase particulates were present, which made sampling times prohibitively long. As the superficial gas velocity was increased, so solid-phase velocity measurements could be made at greater heights from the bed surface, as shown in table 2.

At each measurement location between 1000 and 3000 data points were collected. The local mean and r.m.s. velocities were calculated from a velocity histogram like the one shown in figure 4. Many

Table 2. Summary of the test conditions

Superficial gas velocity, U (m s^{-1})	Gas flow rate, Q (dm^3 s^{-1})	Limits of measurement, z (mm)	
		Minimum	Maximum
0.12	6.74	50	400
0.20	11.23	70	400
0.28	15.72	70	600
0.40	22.46	80	700
0.45	25.27	80	760
0.60	33.67	100	850

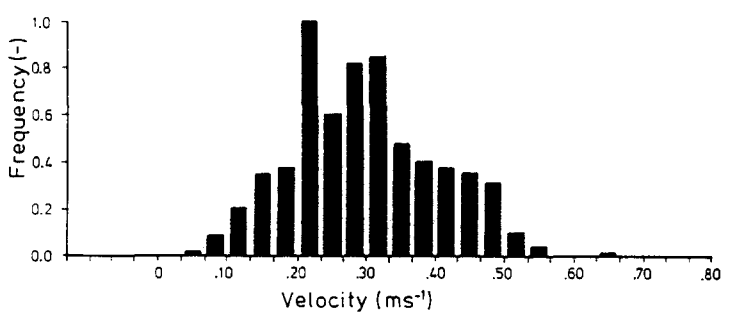

Figure 4. A typical velocity histogram. Gas phase: $\bar{U} = 0.28$ m s^{-1}, mean velocity = 0.33 m s^{-1}, SD = 0.111.

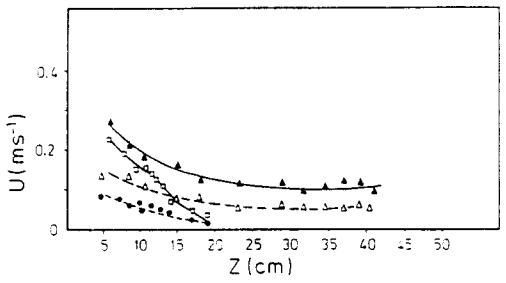

Figure 5. Variation of local mean and r.m.s. velocities of the gas phase and sand particles as a function of the freeboard height. $\bar{U} = 0.12\ \mathrm{m\ s^{-1}}$, $x = 0$, $y = 0$; ▲, U_{gas}; △, $(\overline{U'^2})^{\frac{1}{2}}_{gas}$; □, U_{sand}; ●, $(\overline{U'^2})^{\frac{1}{2}}_{sand}$.

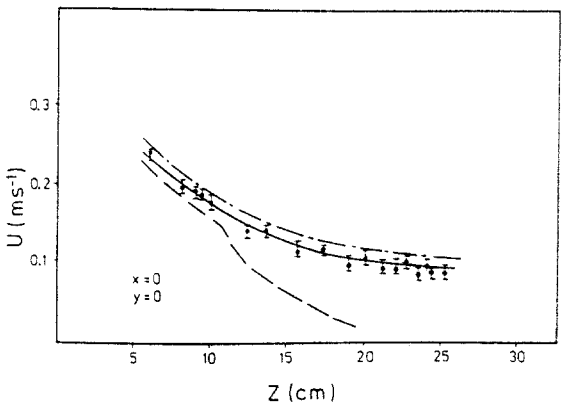

Figure 6. Comparison of the local mean gas-phase velocity (—·—) with the local mean sand (---) and wood (——) particle velocities across the freeboard. $\bar{U} = 0.12\ \mathrm{m\ s^{-1}}$, $x = 0$, $y = 0$.

duplicate experiments were performed to check the reproducibility of the data. In order to measure negative (falling) velocities of the particulate-phase material a frequency shift unit (TSI 9182 optical module) was included in the laser optics train. An electronics package (TSI 9186) supplied a 40 MHz power source for the Bragg cell and a downmixer which provided a selectable "effective" frequency shift from 2 kHz to 10 MHz; in these experiments "effective" frequency-shift values of 0.5–1.0 MHz were used.

Figure 5 shows the variation of local mean and r.m.s. velocities of the gas phase and the sand particles within the solid phase, as a function of freeboard height along the column centreline ($x = 0$, $y = 0$) at $\bar{U} = 0.12\ \mathrm{m\ s^{-1}}$. The gas-phase velocity decays with height and becomes constant around $0.12\ \mathrm{m\ s^{-1}}$. The r.m.s. fluctuation velocity, $(\overline{U'^2})^{1/2}$, follows a similar decaying pattern and reaches a constant value at about the same freeboard height as the gas velocity. The local mean velocity distribution of the sand exhibits a different kind of variation with freeboard height: about 120 mm above the bubbling bed surface the sand velocity is greater than the superficial gas velocity. At this point the shape of the velocity distribution changes abruptly with the velocity decaying more rapidly.

A clear distinction among the velocity distributions of the three particle groups (seed, sand and wood) is shown in figure 6. The velocity distribution of the wood particles shows a different pattern than the velocity distribution of the sand particles. This is because the density of wood is less than the density of sand, also the particle size of the wood is smaller than that of the sand. The difference between the gas velocity and the wood particle velocity is $0.03\ \mathrm{m\ s^{-1}}$, which is the terminal velocity of a wood particle (Kunii & Levenspiel 1979).

7. CONCLUDING REMARKS

The detailed results of all the freeboard measurements are discussed elsewhere (Hamdullahpur 1985; Hamdullahpur & MacKay 1986).

The results presented in this paper demonstrate the ability of the technique to discriminate clearly between gas- and solid-phase velocity distributions. In addition, it has been shown that the technique can also be used to measure particle velocity distributions of different particulate groups within the solid phase. There was no evidence of dyed material adhering to undyed particles. With the LDV system used in this work it was not possible to simultaneously obtain velocity information from more than one particle group at a time. However, by addition of another receiving assembly, photomultiplier and signal processor, simultaneous velocity measurements from two particle groups would be possible. If other suitable fluorescent dyes were available the measurement system could be further expanded. Caution is advised when handling Rhodamine 6G.

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