

Some Observations of Flow Patterns and Statistical Properties of Three Component Flows

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Vertical air-water flows, solids-water flows and three component air-solids-water flows were investigated in a Three Component Flow Facility. Visual observations of the flow patterns show that three component flows undergo transition and can exhibit strong unsteady vortical motions. Measurements of the fluctuations in cross-sectionally averaged volume fraction measurements were made. The statistical properties of the fluctuations are presented in terms of their amplitude and coherent time scale in the form of the Signal To Noise Ratio (STNR) and the Time Constant (ξ), respectively. Remarkably, the solids-water flows and the dispersed bubbly air-water flows exhibit almost identical values of STNR for the same volume fraction. Equally remarkable in the linear relationship between the Time Constant and the mean bubble or particle velocity; this relationship is found to have the same constant of proportionality for both species in the well behaved disperse regime. In the two-component churn-turbulent and the three-component agitated vortical regimes, the variables ξ and STNR significantly deviate from their dispersed regime values. The onset of large coherent structures characteristic of these regimes is reflected by a rise in the amplitude of the fluctuations and a marked increase in their coherent time scale. The results of this study demonstrate the large information content in the fluctuations of the measured quantity, both as a flow regime indicator and as a measure of flow quantities in two- and three-component flows.

1 Introduction

The discrete nature of multi-component flows is well known to be the cause of fluctuations in measured flow quantities. The statistics of these fluctuations depend on the structure and spatial distribution of the discrete phase. A number of investigators have indeed demonstrated direct relationships between flow properties and the statistics in the measured "noise" that have allowed the extraction of information from the observed fluctuations. For example, the fluctuating component of the pressure drop in a two-phase flow through an orifice was used to derive the flow rates of the components by Ishagai et al. (1965). Jones and Zuber (1975) used the probability density function of X-ray attenuation volume fraction signals as a flow pattern discriminator for vertical bubbly, slug and annular flows. Bernier (1981) used the inherent noise of resistive volume fraction signals in his experimental analysis of kinematic wave propagation in bubbly flows. The significance of the statistical properties of volume fraction measurements depends entirely on the size of the influence volume of the measuring device. For example, hot wire anemometers, optical probes and other devices have been employed to make

point measurements of volume fraction. To obtain useful information, time averaging of the output is necessary. This limits the dynamic resolution of such a device. On the other hand, X-ray and Gamma-ray attenuation techniques inherently carry out line averages along the beam. Capacitive and resistive measuring techniques yield a volume average of concentration. The size and shape of the measuring volume is determined by the geometry of the electrodes. With a large averaging volume, good dynamic response is achieved at the cost of diminished spatial resolution.

In this study we exploit the fluctuation in the measured volume fraction signal to investigate the structure of two- and three-component flows as they undergo transition from a uniform to an agitated regime. We demonstrate that the fluctuations in the signal can be used to measure flow quantities. The flows considered consist of air bubbles (average diameter of 4 mm) and polyester particles (average diameter 3 mm) in a continuous medium of water. Real time volume fraction measurements were made using an Impedance Volume Fraction Meter (IVFM) (Bernier (1981), Kytömaa (1986)).

The fluctuations in the volume fraction signal are characterized by two properties of their auto-correlation function; its amplitude and "width" (coherent time scale). These two quantities are easily measured and are useful characterizations of the flow structure. The visual observations of the transition of two- and three-component flows are related to these statistics. The results suggest a non-intrusive method of

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measuring disperse flow quantities, namely the total volume fraction and velocity, for two- and three-component flows.

In the work presented here, Reynolds numbers of 1000 and 400 were measured for individual bubbles and particles respectively based on relative velocity. These values are significantly higher than the Reynolds numbers in other three-component flow studies by Fessas and Weiland (1981) and Batchelor (1986). Flow regime transitions were nevertheless observed in all these studies.

2 Experimental Facility and Instrumentation

The Three Component Flow Facility (TCFF) shown in Fig. 1 was used to study the statistical properties of volume fraction signals in bubbly, slurry and three component flows. The test section is a vertical clear acrylic pipe .1016 meters (4 in.) in diameter and 2.2 meters in length. The air-water flows are formed by introducing the gas through an injector situated inside the vertical pipe, .5 meters below the test section. The injector consists of an array of twelve 3.2 mm (1/8 in.) diameter brass tubes perforated with .4 mm (1/64 in.) holes. An 8 atm (120 psi) compressed air line supplies the injector through a regulator, an orifice plate flow meter (to monitor air mass flow), valves to control air flow and a manifold to distribute the air flow evenly among the brass tubes. The slurry flows studied consist of water and polyester particles. The polyester particles are of the type used for molding applications (specific gravity = 1.43). They are smooth and have a cylindrical shape with an equal mean height and diameter of 3 mm ($\pm .5$ mm). The most novel aspect of the facility is its ability to handle solids and to control their flow rate independently of the liquid without having to add or remove solids from the system. When at rest prior to an experiment the solids are trapped between a vertical 4 inch control cylinder and the storage hopper (see Fig. 1). As the control cylinder is raised from the reducer on top of which it sits, the gap created allows particles to enter the test section under the action of gravity. The vertical position of the control cylinder can be varied by means of a control rod attached to a worm gear mechanism and this permits the solids flow rate to be controlled by varying the gap between the cylinder and the reducer. To recycle the solids after an experiment the control cylinder is lowered to the closed position and sufficient upward water flow is generated to fluidize the solids in the lower tank and to carry them back to the upper tank where they settle into their original position.

The static pressure gradient in the test section is monitored using an inductive differential pressure transducer. The volume fraction of the dispersed medium is measured using an Impedance Volume Fraction Meter (IVFM). The IVFM was

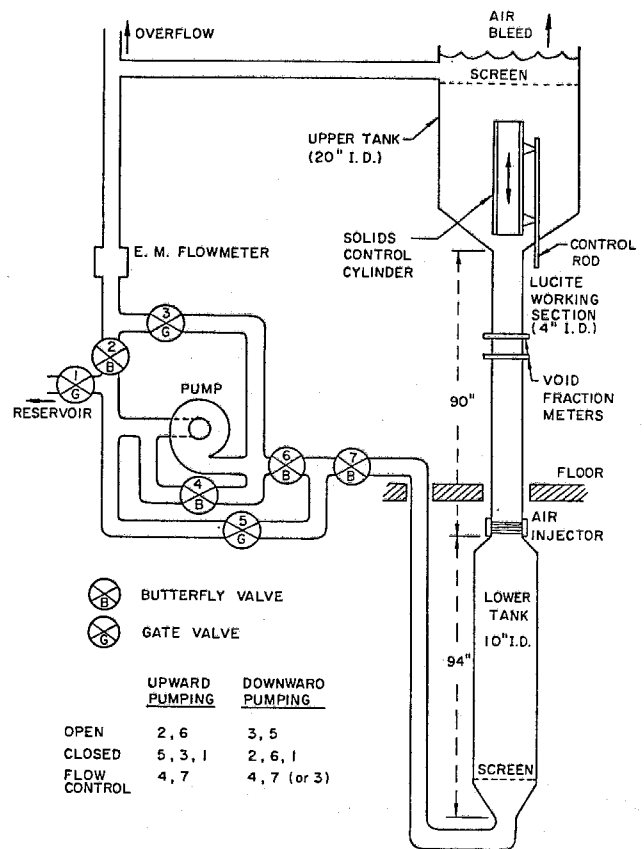


Fig. 1 Schematic of the Three Component Flow Facility

developed by Bernier (1981). It has been modified for temperature compensation and now has a shielded electrode configuration which decreases the axial extent of the influence volume over which the measurement is carried out. The active stainless steel electrodes which are flush mounted into a section of .1016 meter (4 in.) diameter non-conducting acrylic pipe are 6.4 mm in axial length and form diametrically opposed 90 degree arcs on the circumference of the pipe. The active electrodes are each sandwiched between two shielding electrodes. These are 9.5 mm in axial length and also form 90 degree arcs. Figure 2 shows the electrode configuration. The shielding electrodes duplicate the active electrode potential through a high input impedance voltage follower. The IVFM is excited at an amplitude of .3 volts r.m.s. and a frequency of

Nomenclature

ACF = Auto-Correlation Function of the random fluctuations in the volume fraction signal, (V^2)

j = total volume flux, (m/s)
 j_g = gas volume flux, (m/s)
 j_p = solids volume flux, (m/s)
 j_{pj} = solids drift flux, (m/s)
 L = vertical separation between pressure taps, (m)

Δp = hydrostatic pressure difference in a three-component mixture between the pressure taps, relative to that in water, (N/m^2)

$R_{\bar{v}\bar{v}}$ = Auto-correlation Function of the random, fluctuations in the volume fractional signal, (V^2)

STNR = signal to noise ratio of the volume fraction signal, (m/s)

v_g = mean gas velocity, (m/s)
 v_l = mean liquid velocity, (m/s)
 v_p = mean solids velocity, (m/s)
 $v_{g(pl)}$ = mean gas velocity relative to the combined solids and liquid volume flux, (m/s)

\bar{v} = mean value of the volume fraction signal, (V)

\bar{v} = fluctuating component of the volume fraction signal, (V)

α = volume fraction of gas (%)

ν = volume fraction of solids, (%)

ρ_g = gas density, (kg/m^3)

ρ_l = liquid density, (kg/m^3)

ρ_p = solids density, (kg/m^3)

$\tau_{1/2}$ = time at which the ACF has decayed to half of its maximum value, (s)

ξ = time constant of coherence in the random fluctuations of the volume fraction signal

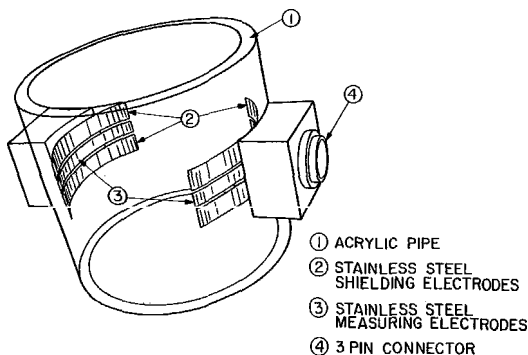


Fig. 2 Isometric view of the shielded Impedance Volume Fraction Meter electrode geometry

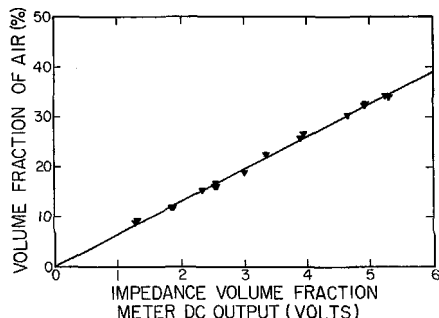


Fig. 3 Steady state calibration of the Impedance Volume Fraction Meter with bubbly flows for zero water volumetric flux. The volume fraction was derived from the hydrostatic pressure gradient measurement.

40 KHz at which the impedance is found to be primarily resistive. The excitation and signal processing equipment is described in more detail by Bernier (1981). The IVFM is calibrated with both bubbly and particulate flows against the volume fraction (α and ν , respectively) obtained from the static pressure gradient measurement. These two plots are shown in Figs. 3 and 4. Equations (1) and (2) are the respective linear regression fits of the shown plots. The corresponding correlation coefficients for these fits are .9992 and .997. The discrepancy between the two fits (up to 4 percent) is attributed to experimental error in the measurement.

$$\alpha(\%) = 6.53 \text{ IVFM(Volts)} - .006 \quad (1)$$

$$\nu(\%) = 6.77 \text{ IVFM(Volts)} - .41 \quad (2)$$

The IVFM is found to have excellent linearity up to the volume fractions of at least 40%. With a sensitivity of .15 Volts per percent of volume fraction, and the passage of individual bubbles (or particles) is readily detectable.

3 Experimental Procedure and Presentation of Results

After initiation of each experiment, data were not taken for 30 seconds in order to permit passage of the initial transient. Then observations of the flow pattern were made. For each run, measurements were made of the air flow rate (using the orifice meter), the liquid flow rate (measured with an electromagnetic flow meter). The total flow rate was constrained by flooding of either the solid or the gas phase and the total flux was restricted to the range of $-.1$ m/s to $.2$ m/s. The IVFM d.c. output and the static pressure transducer output were monitored on a strip chart recorder. In two component flows, ν , the solids volume fraction or α , the air volume fraction is directly obtained from the IVFM. At low flow rates α or ν is also given by the output of the differential pressure transducer since the frictional component of the pressure drop is very small. Indeed this is how the calibration equations (1) and (2) were obtained. In a three-component flow at low flow

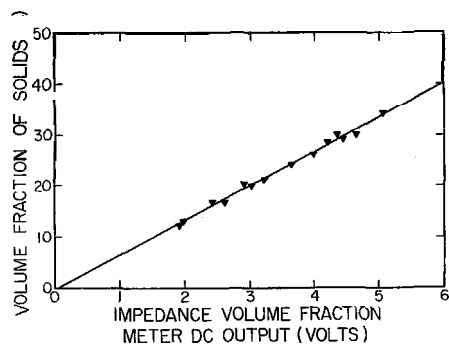


Fig. 4 Steady state calibration of the Impedance Volume Fraction Meter with particulate flows for zero total zero total volumetric flux. The volume fraction was derived from the hydrostatic pressure gradient measurement.

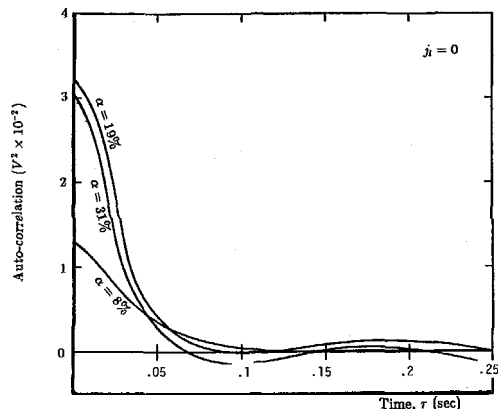


Fig. 5 Typical auto-correlograms of the IVFM output fluctuations in a steady bubbly flow regime obtained from the HP 3562 Digital Signal Processor for a 60 second record

rates, the differential static pressure transducer yields the bulk density which is a function of the individual volume fractions of air and solids. The mean IVFM d.c. output gives the sum of the air and solid volume fractions. Thus we can deduce the concentration of the individual constituents.

The IVFM a.c. component was recorded on magnetic tape through a d.c. blocking amplifier with a 3dB cut off frequency of .032 Hz and a fall off slope at 10 dB per octave. The record length was five minutes whenever possible. The shortest record was of one minute which proved adequate for accurate determination of IVFM output fluctuation statistics.

The size distribution of a multicomponent flowing medium influences the statistical properties of the fluctuating component of volume fraction signals. For example, for two flows of equal volume fraction, the one with large particles will yield less frequent and larger fluctuations in the measurement than the one with very small particles. In this paper we used the properties of the Auto-Correlation Function (ACF) of the IVFM output fluctuations to characterize the flow. Typical ACF records are shown in Fig. 5. The two dominant features of the AFC are a) its amplitude ($R_{\bar{v}\bar{v}}(0)$) which is the mean square magnitude of the fluctuations, and b) the time at which the function has decayed to a certain fraction of its peak value. The latter is interpreted as a measure of the coherent time scale. These two quantities were used to characterize the structure of a variety of two- and three-component flows. The amplitude ($R_{\bar{v}\bar{v}}(0)$) is presented in terms of the dimensionless Signal To Noise Ratio (STNR), and the coherent time scale is presented in terms of the time constant ξ ; these variables are defined below:

$$\text{STNR} = \frac{\bar{V}}{\sqrt{R_{\bar{v}\bar{v}}(0)}}, \quad (3)$$

