Recent developments in non intrusive measuring techniques for particle velocity and size measurements

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ABSTRACT

Laser techniques for local particle velocity and size measurements in flows are presented and discussed. The Laser Doppler Anemometer utilising the Doppler shift of light scattered on small particles in a flow for velocity measurements is the basis of the presented techniques. Furthermore Phase Doppler Anemometry based on the spatial properties of the Doppler shift and Shadow Doppler Velocimetry utilising the shadow image of a particle for size measurements are briefly discussed. Experimental results illustrating the use of the techniques are presented. These comprise particle velocity measurements in a sudden expansion liquid solid flow as well as in a model of a beater wheel mill. PDA measurements of the size distribution of droplets produced by a nebulizer are also presented.

Keywords: LDA, PDA, Shadow Doppler Velocimetry, Turbulence, Two Phase Flow , Particulate Flow

1. INTRODUCTION

Optical, non-intrusive measurement techniques find now-a-days wide application in the measurement of flow quantities such as velocity, particle size, and concentration, mass flow rates, temperatures etc. since they offer the advantage of not-disturbing the flow. With regard to the spatial resolution one may identify three different measuring approaches:

- local measurement techniques like laser Doppler anemometry (LDA), phase Doppler anemometry (PDA) or shadow Doppler velocimetry (SDV).1,2,3,4
- particle tracking velocimetry (Particle Image Velocimetry,-PIV) and axial viewing techniques
- whole field flow visualisation (laser light sheet, diffuse light illumination) techniques.

In this work optically-based measurement techniques for the measurement of particle velocity and size of the dispersed phase in two phase flows are presented. An important class of techniques sharing common optical components includes laser Doppler anemometry (LDA), phase Doppler anemometry (PDA) and shadow Doppler velocimetry (SDV). The fact that they provide accurate local measurements with a high frequency response give them significant advantage in fluid flow research. Moreover the reliability, ease of use and ruggedness developed in the modern instruments make them suitable for demanding industrial situations.

2. BASIC PRINCIPLES

2.1 Laser Doppler Anemometry (LDA)

Laser Doppler anemometry is based on the Doppler shift of light elastically scattered on small moving particles in a flow. Using small tracer particles which follow the flow, the velocity of the fluid can be determined. Moreover in two phase flows the velocity of both the continuous and the dispersed phase particles can be monitored simultaneously.

The complete analysis of LDA and PDA techniques and the most efficient selection of a measuring configuration require the detailed study of the light scattering on the particles moving in the flow (with methodologies varying from Geometrical Optics to Generalised Lorenz-Mie theory5) and the evaluation of the interference resulting on the collection aperture. In this short presentation though of the basic principles of the method we will restrict ourselves to the more illustrative "fringe" model suitable for the most common "dual beam" configuration. In this configuration (Fig. 1,2) the original Laser beam is split into two beams which are focused to the measuring point. Fringe planes parallel to the beams' bisector and normal to their plane are formed at the beam intersection due to interference. The fringe spacing is:

\[ d_f = \frac{\lambda}{2\sin(\theta/2)} \]  (1)

in the direction normal to the fringe planes, where, \( \lambda \) is the light wavelength and \( \theta \) is the beam angle.

The light scattered by particles in the beam intersection is collected by a receiving lens on a photodetector (PD) (photomultiplier or avalanche photo diode). As a particle crosses the fringe planes, the PD receives intensity modulations of frequency:

\[ f_D = \frac{u_x}{d_f} \]  (2)
where, \( u_x \) is the particle velocity component normal to the fringe plane. The envelop amplitude modulation due to the Gaussian nature of the beams produces a characteristic Doppler burst for each particle crossing the control volume (fig. 1). The x component velocity is measured through the evaluation of the frequency \( f_D \).

Equations (1) and (2) reveal two important advantages of LDA, first that it has a linear response with no calibration requirements and second that the frequency-velocity relation is indifferent of the receiving optics location in the dual beam system. The optics location is dictated by the optical paths available to the measuring point and the laser power requirements. Scattering efficiency in the forward direction (i.e. the direction of the incident beams) is for most particles much higher (as much as 200 times) than in all other directions and forward scatter systems have minimum requirements of Laser power. Especially in optically dense or illuminating flows forward scatter may be the only feasible solution. On the other hand backscatter systems require only one window in the test section and once aligned are easily positioned.

A difference in the frequency of the incident beams (usually passing one or both of them through an acousto-optic modulator) adds a directional bias to the Doppler frequency (the fringes are moving normal to their planes) thus allowing the determination of the direction of the motion.

In modern LDA systems the use of fiber optics allows the separation of the laser source and heavy optical units from the transmitting-receiving optics assembly. In this way the rugged and compact end sensors allow very easy and accurate positioning while being able to operate in heavy duty environments. Signal processing is accomplished with several methods such as frequency counting, correlation or FFT techniques. High data rates can be achieved even for poor signals. Multibeam systems can be used to monitor all the three components of the velocity vector. The foreseen use of diode Lasers will lead to much more compact and lighter systems vastly enhancing the applications of the technique.

### 2.2 Phase Doppler Anemometry (PDA)

Phase Doppler anemometry extends the capabilities of LDA to simultaneous measurements of velocity and size of spherical scattering particles. The basic setup is the same as that shown in Fig. 1, sharing the same transmitting optics with the dual beam LDA and the velocity measurement is accomplished as in LDA. The receiving optics though, must be located in a direction in which a specific mode of transmission, i.e. either reflection or refraction through a transparent particle, is dominant. Following the same line of presentation we define for a specific particle size, PD location and mode of transmission the Loci of Fringes (LoF). When a particle centre is in a LoF the two reflected (or refracted) rays of the two beams arrive at the PD with a phase difference of 180°. The LoF are geometrically similar to the beam intersection fringe planes but displaced in space. For the same transmitting optics, particle size and mode of transmission the displacement of the LoF is a function of the PD location. Thus using two PDs the corresponding LoF will be relatively displaced as seen in figure 3, showing the cross sections of the two LoF control volumes (with continuous and dashed lines respectively) with the xy plane. A particle whose centre is passing through these LoF will produce on both detectors the conventional Doppler burst planes but displaced in space. For the same transmitting optics, the diameter, \( d \), of a particle can be evaluated from the \( \Delta \phi \) measurement by:

\[
d = \frac{\lambda \Delta \phi}{2 \pi n \beta}
\]
where \( \beta = \sqrt{\frac{1}{2}} \left[ 1 + \sin(\theta / 2) \sin \psi - \cos(\theta / 2) \cos \psi \cos \phi - \sqrt{1 - \sin(\theta / 2) \sin \psi - \cos(\theta / 2) \cos \psi \cos \phi} \right] \) (4)

for reflection and

\[
\beta = 2 \sqrt{1 + n_{rel}^2 - n_{rel}^2} \left[ 2 \left( 1 + \sin \frac{\theta}{2} \sin \psi + \cos \frac{\theta}{2} \cos \psi \cos \phi \right) \right]
\]

(5)

for refraction and \( n_1, n_2 \) are the refractive indices of the fluid and the particle respectively with \( n_{rel} = n_2 / n_1 \).

Advances in PDA instrumentation are closely related to those of the LDA technique. Commercial systems are now reliable, compact and friendly to the user. Current research indicates that new capabilities are on the way extending the field of applications for example to non-spherical particles as well as to other physical quantities such as particle refractive index.

2.3 Shadow Doppler Velocimetry (SDV)

Information on the flux and concentration of the dispersed phase is of great importance but hard to obtain in two phase flow experiments. Besides the size and velocity of the dispersed phase particles it demands accurate evaluation of the effective measuring volume which is not easily defined in PDA configurations since it is a function of the particle size. Moreover the inability of the PDA technique to handle particles of arbitrary shape, has led several investigators to search for alternative techniques.

Shadow Doppler velocimetry is such an effort trying to provide size, shape and flux-concentration information for non-transparent particles of arbitrary shape. It is using the transmitting optics of a dual beam LDV which operates at the same time. The laser beams are refocused after the control volume projecting the probe volume and the moving shadows of passing particles onto a linear diode array. The temporal output of the array elements is recorded and the shadow of a particle’s passage is used to derive information about the size and the shape of the particle. The position of the particle in the control volume is determined by the type of shadow recorded (Fig. 5). Particles passing through the central plane of the probe volume give only a dark shadow. Particles at a distance from that plane produce light and dark shadows due to the two superimposed shadows of each incident beam. Particles with non overlapping shadows are considered as being out of the control volume. The projected equivalent diameter is calculated from the average area of the two types of shadow as:

\[
d_a = \frac{4}{\pi} S_p, \quad \text{where} \quad S_p = \frac{2 S_L + S_U}{2}
\]

(6)

SDV is a promising, recently introduced technique capable to provide size information for particles of arbitrary shape.

3. EXPERIMENTAL MEASUREMENTS USING LDA AND PDA

3.1 Particle-particle interactions in a vertical, sudden expansion liquid-solid flow

The effects of particle to particle collisions at 3% and 5% volumetric loading were examined with respect to the reattaching length and the characteristics of particle dispersion in an axisymmetric, descending sudden expansion in a liquid-solid (diesel oil-glass beads) flow.

Fig. 6. Variation of axial particle mean slip velocities with particle loading
The laser-Doppler anemometer used for the velocity measurements comprises a 50 mW He-Ne laser, a TSI optical module with double Bragg-cells (freq. shift used 2-5 MHz), and a 150 mm focusing lens (incident beam spacing 50 mm) resulting to a control volume of 0.918 mm length ($l_m$) and 0.15 mm diameter ($d_m$). A 350 mm collection lens and an avalanche photodiode were used for the collection of scattered light.

The signal from the PD was band pass filtered and the Doppler burst segments were digitised with a transient recorder (Le Croy-9400A) at 12.5 MHz. A IEEE-488 interface (National Instruments) was used to connect the transient recorder to a 386-SX PC. The frequency evaluation was accomplished with FFT of the bursts by a Digital Signal Processing (DSP) board mounted in the PC. The phases were discriminated by signal amplitude control since the large solid particles gave higher amplitudes than the small seeding particles following the liquid flow.

Mean and rms velocities were calculated from 10,000 samples. The sample size was selected according to Yanta so that errors due to collected sample size were less than 1% in the mean velocities for 40% turbulence intensity and 95% confidence level and less than 2% in the turbulence quantities for 99% confidence level.

The experimental results (Fig. 6,7) demonstrate that the particles move with higher negative velocities than the carrier fluid inside the recirculation zone. Increasing loading increases particle fluctuations in the recirculation zone and in particular close to the pipe walls, where turbulent quantities tend to attain their single phase values. Particle dispersion is affected by increases in the particle loading in the main "core" flow, close to the entrance plane and downstream the mean reattachment point. Increasing the loading induced a recovery of the mean reattachment point towards the single phase flow value.

### 3.2 Particle motion in a model of a beater wheel mill

A mill-model has been constructed with the aim to retain the same particle motion characteristics as in the mills used by the Greek Public Power Corporation (P.P.C.) for the pulverisation and drying of lignite. The objective was to study the particle motion inside the mill and to locate areas, where particles tend to accumulate and where erosion-wear is expected to be high.

The laser Doppler anemometer used for the velocity measurements is the Dantec/Invent "FlowLite" system consisting of an integrated laser-optical unit for back scattering measurements, a signal processor (Flow Velocity Analyzer-FVA) and oriented software (FLOware/graphics). The FlowLite integrated 1D laser-optical unit comprises a 10mW He-Ne laser and a 40 MHz Bragg cell. The unit is connected to a 60mm diameter probe by a fiber optic cable. A 160mm focal length lens is used in the probe resulting to a measuring volume size $75\mu m \times 630\mu m$. Beam separation was 38.4mm and the beam diameter 1.7mm.

The FVA covariance signal processor employs special detection and validation techniques. The FVA can analyze low signal-to-noise ratio signals, and provides higher data rates than processors based on the counter principle. Velocities ranging from -16 to +80m/s can be measured. The system has a burst validation based on signal-to-noise ratio and the number of fringes in the measuring control volume and it uses a threshold down to -6dB.
The detected data rate can be up to 150,000 samples/s with continuous trigger (800Hz or 26KHz). The arrival time resolution is 1ms and the dead time varies from 500ns (typical) to 800ns (maximum).

The FLOware software provides on-line monitoring of data acquisition and processing. Mean and rms velocities, turbulence intensity, flatness and skewness, histograms of velocity, transit time, arrival time, and the energy spectrum have been measured at different locations in the model of the lignite mill. For the measurements presented here glass particles ($\rho_p=2500\text{Kg/m}^3$) have been used of 45µm average diameter (size distribution 0-60µm). Mean and rms quantities and particle arrival rates have been measured at each location based on 10000 collected samples per measuring location.

Velocity profiles and particle data rates have been measured in the convergent intermediate duct connecting the spiral mill volute to the classifier section (Fig. 8). The results indicated that this part of the mill redirects the flow from the outer mill casing walls to the inner walls towards the classifier section. The measured velocity vectors and measurement of the particle mean impact angles indicated that erosion wear is expected to be high at the inclined wall connecting the convergent duct to the mill spiral section and at the duct outlet, at the connection with the mill classifier. Erosion wear in these two parts can be reduced by design modifications that alter the angle of impact of particles on the walls.

3.3 Size distribution of droplets produced by a medical nebulizer

Fine water mist has a wide field of applications in modern technology. The size distribution of droplets produced by a medical nebulizer has been studied to investigate if it was suitable as a water mist generator for seeding air flows and for experiments in fire extinguishment.

A 15mW He-Ne Laser was used as light source. The TSI transmitting optics incorporated a single Bragg cell (freq. shift 40 MHz) and a 610mm focusing lens. Beam separation was 50mm and the length and width of the control volume were 2.4mm and 0.1mm respectively. The classic PDA Dantec receiving optics with a 310mm lens and three avalanche photodiodes completed the optical setup. The Dantec PDA signal processor controlled by a Pentium PC and SIZEware software were used for the data acquisition.

The distribution for 30000 samples of droplet sizes and the corresponding log normal fit is shown in Fig. 9.

4. REFERENCES

3. M. Founti, Recent Developments in Laser Doppler Anemometry, National Technical University of Athens, 1995