Adaptive Phase/Doppler Velocimeter and Its Application to In-Situ Measurement of Fine Metallic Particles and Charged Particles

Amir A. Naqwi

TSI Incorporated, P.O. Box 64394, St. Paul, MN 55164, USA

Besides introducing the newly-developed Adaptive Phase/Doppler Velocimetry (APV) hardware, this article discusses in-situ measurement of metallic particles in the size range of 20–300 nm. Sizing of nanometer metallic particles is enabled by a recent advancement in the phase Doppler technique, referred to as *response reversal*. This technique, not only provides an in-situ measurement of particle size, but combines the size measurement with the velocity of the charged particles and thus allows to estimate the absolute charge on individual particles, or at least the power-law relating the charge to the particle diameter.

Theoretical Background

The phase Doppler technique is an extension of laser Doppler velocimetry (LDV), in which a moving particle is illuminated with two laser beams that produce interference fringes, as shown below in Fig. 1. (The LDV technique is described in several books and monographs, such as Adrian [1]). The laser light scattered by the particle is used to generate a signal whose frequency represents the particle velocity. In a phase Doppler system, two or more LDV signals, generated by an individual particle, are measured at different spatial locations. The phase shifts between various oscillating signals are used to determine the particle size. In a conventional phase Doppler setup a *single receiving lens* is used. Scattered light collected by different segments of the lens is sent to different detectors. The receiving lens lies at a certain *off-axis angle* in the plane of symmetry, defined as the plane bisecting the laser beams and oriented perpendicular to the plane of the two laser beams.

The sensitivity of a phase Doppler system is given as the degrees of phase shift between two signals per micron of the particle diameter. It depends almost linearly on the beam angle and the spatial separations between the centroids of the receiving apertures for a given focal length of the receiving lens (see Fig. 2). Hence, for measuring very small particles, one needs a large beam angle and a receiving lens with a large numerical aperture. This leads to the situation of mixed polarization and as discussed by Naqwi & Menon [2], results in a non-monotonic phase-diameter relationship. Furthermore, increasing beam angle leads to an undesirable decrease in the fringe spacing, i.e. an increase in signal frequency that makes signal processing difficult for higher velocities. Also an undesirable upper limit on sensitivity is imposed by the numerical apertures of the available lenses.

As shown by Naqwi & Ziema [3], all the above problems with conventional layout are circumvented by positioning the receivers in the plane of the laser beams. In this *planar layout*, receivers are physically separate and are positioned at large angles on both sides of the beam bisector. This development and several other new advancements [2, 4 & 5] have required *split receiving lenses* (as shown in Fig. 2), as opposed to the single lens used in the conventional hardware.

The split lens arrangement is also useful in implementing the *response reversal* scheme that is shown to be promising for sizing nanometer size metallic particles. A very small particle acts like a dipole that oscillates parallel to the electric vector $\vec{E}$ of the incident electromagnetic field. The light scattered by a dipole is strongest in a plane perpendicular to $\vec{E}$ and vanishes along this vector.

In the optical arrangement of Fig. 1, the electric fields $\vec{E}_1$ and $\vec{E}_2$ of the two beams are in the plane defined by the beams, so that the net field $\vec{E}$ is parallel to the fringes on a dark fringe and perpendicular to them on a bright fringe. Hence, the scattered light of a very small moving particle (dipole), as received by a detector in the side-scatter, is out-of-phase relative to the fringes.

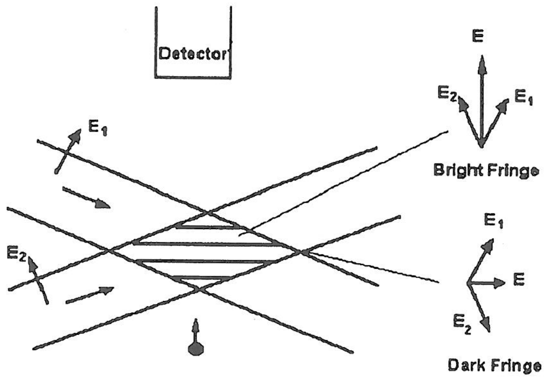

Figure 1: Optical arrangement for response reversal.

Consequently, the phase shift between the signal and the fringes *decreases* from 180° to zero as the particle size increases from a small fraction of wavelength to about the wavelength of light. If the scattered light is collected by two detectors in the side scatter — located on the opposite sides, the phase shift between the two signals decreases from 360° to zero.

In the case a dielectric particle, transition from an out-of-phase to in-phase signal occurs over a range that is too small to be practically useful. However, metallic particles typically allow to cover a size range of 20–300 nm using the above effect.

Hardware Arrangement

The adaptive hardware employs physically separate receivers as shown in Fig. 2. These receivers may be mounted together to constitute a single unit for standard applications or separately for non-conventional applications discussed above. A mask can be used in front of the semi-circular collimating lens, in order to change the size of the receiving aperture, so that it is optimal for the particle size range under investigation.

In the adaptive system, polarization of light may be set either parallel or perpendicular to the plane of the laser beams by adjusting it at the launching end of the transmitting fibers.

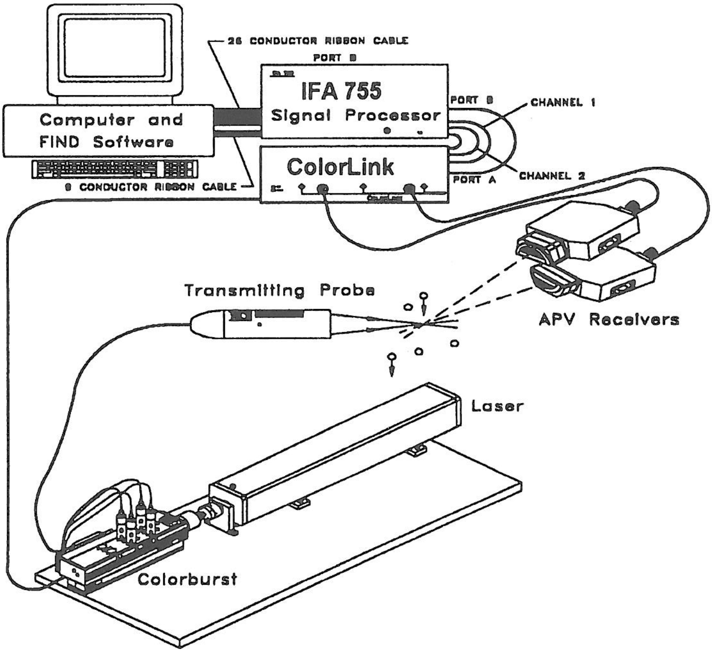

Figure 2: APV system: a typical setup

As shown in Fig. 2, an argon-ion laser beam is transmitted to ColorBurst™ that generates up to three pairs of monochromatic beams. These beams are coupled into optical fibers, connected to the transmitting probe(s) that illuminates the particles crossing the measuring volume. Light scattered by the particles is coupled into the fibers attached to APV receivers and is transported to ColorLink™, where the optical signals are converted into electrical signals using photomultipliers. The electrical signals are further conditioned and routed to a signal processor, which determines the frequency of the individual signals and phase shift between the phase Doppler signals. The IFA755™ processor transfers measured data to a computer via a direct memory access (DMA) link. A Window-based software package FIND-WP™ reduces and displays the results in real-time. The hardware is described in more detail in Ref. 2.

Applications to Metallic Particles and Charged Particles

An example of reversed response for metallic particles is considered in Fig. 3 which is based on Mie theory and pertains to particles of various metals that exhibit similar behavior. According to Fig. 3, particles can be measured with an accuracy of 1–2 nm, as phase shift can be recorded with an accuracy better than 2°. Response reversal is achieved by locating the receivers in almost side-scatter, i.e. at ±80° from the forward direction in a planar configuration. Wavelength of light is 0.5145 μm and laser beams are crossed at an angle of 11.6°. This arrangement is now being proven using silver particles.

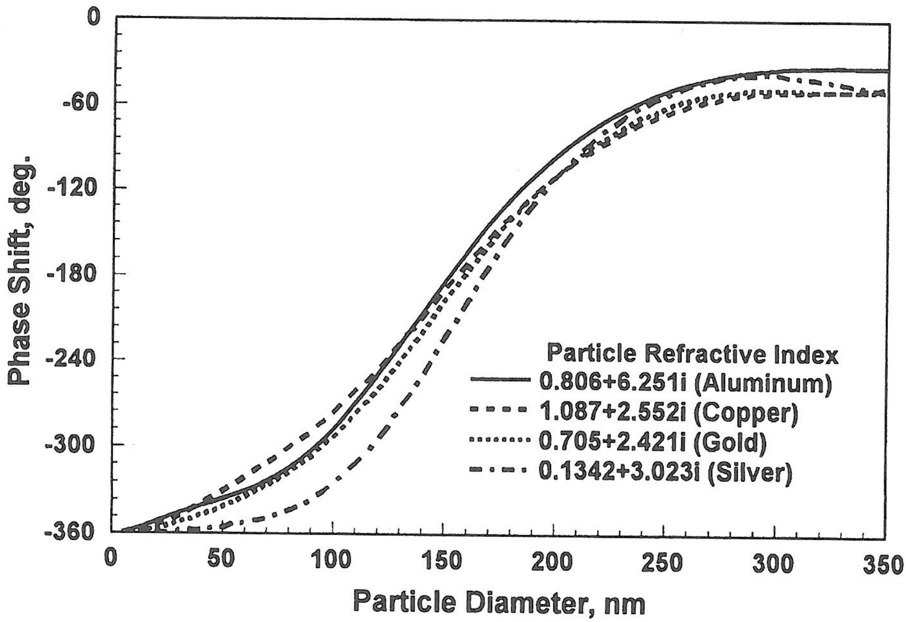

Figure 3: APV response to metallic particles

The in-situ measurement of particle size and velocity may be very useful in understanding the fluid dynamics of a plasma with charged particles. Using measurements at two closely-spaced locations, inertial force can be estimated. However in many practical cases, particle inertia is negligible and the electric force on a particle is primarily balanced by the aerodynamic drag force, so that

$$qE = 3\pi\mu d_p\left(V_p - V_g\right) f(\mathrm{Re}). \tag{1}$$

In the above equation, q and E denote the charge on the particle and the electric field at the measuring location respectively. The right-hand side of Eq. (1) represents the aerodynamic drag that depends upon the slip velocity $\left(V_p - V_g\right)$ of particle relative to the surrounding gas, particle diameter d_p and gas viscosity μ. The factor f is a modifier to the Stokes' drag for Reynolds numbers exceeding 1. The phase Doppler technique provides local values of d_p and V_p. If the gas velocity is negligible, or determined alternatively, then the aerodynamic drag force can be computed. Hence, charge on individual drops can be estimated using Eq. (1), provided that the local electric field is known. If local value of E is unknown but understood to be fairly invariant, the above procedure would unravel the power-law relationship between the particle charge and particle diameter, i.e. if

$$q \propto d_p^n, \tag{2}$$

then measured data would provide the value of n.

The above concepts were applied to a flow of charged alcohol drops, reported by Naqwi et al. [6], whereby the gas (air) velocities were negligible. The drag force based on APV measurements is given in Fig. 4. It was understood that there were enough impurities in the liquid to prevent internal recirculation in the drops, so that a modified Stokes' law could be used for estimating the drag force. The factor f was obtained from Table 5.2 of Clift et al. [7].

In Fig. 4, more than 95% of the drops are larger than 3 μm and their drag force is proportional to the square of the drop diameter; i.e. charge on the drops is proportional to their surface area. These drops were produced by atomization in the presence of a corona, which appears to deposit charges uniformly over the available liquid surface.

A small number of drops are less than 2 μm in diameter and apparently deviate significantly from the square law. Charge on these drops varies almost linearly with the drop diameter; i.e. the surface charge density increases with the decreasing particle size. These drops may have been formed due to secondary atomization that occurs as a result of spontaneous accumulation of charges at certain spots on the surface of a large drop. This causes an ejection of a highly-charged fine liquid jet that breaks up into small drops due to Rayleigh instability.

Conclusions

Adaptive phase/Doppler velocimeter for simultaneous measurement of particle size and velocity is introduced. The new optical system allows to measure metallic particles as small as 20 nm. Measurements with charged droplets are shown to provide power-law relations between particle charge and diameter and hence, unravel the underlying physical mechanisms. Similar results are expected from application of this technique to the studies of plasma-particle interactions.

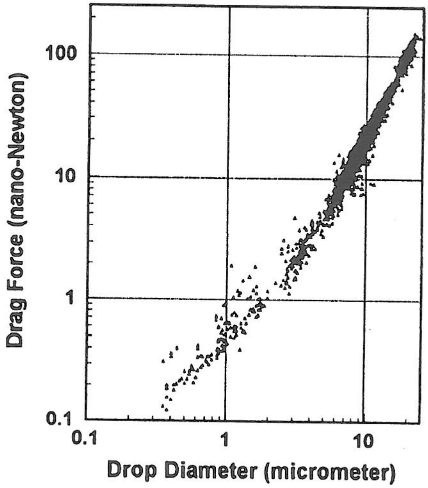

Figure 4: Drag force on particles in an electric field

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