LASER-DOPPLER SYSTEMS FOR PLASMAS DIAGNOSTICS : A REVIEW AND PROSPECTIVE PAPER.

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ABSTRACT

Since the first experiments by Y.Yeh and H.Z. Cummins, then J.W. Foreman, interest in laser-doppler velocimetry (LDV) for measuring mean and fluctuating velocities in fluids rapidly increased with applications to turbulence, environment, combustion... Plasmas investigations started more lately because of the expected difficulties, but the time has nevertheless come to present an overview of experiments carried out in such hot flows. It will be the review part of this paper.

LDV-measurements need the presence of scatter centers suspended in the flow to be studied. It can be of a tremendous importance to know the diameters of these particles as well as their velocities. Such simultaneous velocimetry and particle sizing measurements have been carried out in combustion systems (and are currently further developed) but never in plasmas flows as far as we are aware of. So, the prospective part of this paper will present a review of laser-Doppler and similar systems for simultaneous velocities and sizes measurements with emphasis on possible plasmas applications.

I. INTRODUCTION

Since the first experiments by Y.Yeh and H.Z. Cummins in water (1), then by J.W. Foreman in gases (2), interest in laser-Doppler velocimetry (LDV) for measuring mean and fluctuating velocities in fluids rapidly increased because of the tremendous versatility of the method, with applications to turbulence, environment, etc... and more lately combustion (3, 4).

Plasmas applications started only very recently because of the expected difficulties : high temperatures giving rise to noise problems due to plasma and seeding particles radiations ; electromagnetic saturation of the electronic devices (r.f. torches) or electrical interference from the large current supplied to arcs ; fast evaporation of the scatter centers, enhancing the difficulty to be sure that they are small enough to follow the fluid ; thermophoresis phenomenon (5, 6) producing possibly errors in fluid velocity measurements and sometimes very slow rates of data acquisition ; sensitivity of the plasma state to the presence of possible artificial seeding particles (7), etc...

There was indeed a lot of methods available for plasmas velocities measurements including the modulation technique where a modulation of the plasma jet is detected at two points separated by a known distance (8), the modulation or perturbation being possibly produced by artificial means like a laser pulse (9) ; the Gold's plasmascope (10) ; electron temperature measurements associated with an ETL assumption (or the determination of the difference between electron and atom temperatures), then utilization of an equation linking temperatures and velocities (11) ; measurements of the force acting on a plate in the plasma jet (12) ; Doppler shift of an emitted line (13, 14, 15) ; examination of particles trajectories using cinematography (16, 17, 18)...

But all these techniques are rather cumbersome, or suffer of inaccuracies, or integrate the data along lines of view, or are not versatile enough to provide a wide range of applications.

On the other hand, LDV can be achieved through various optical set-up and processing systems, giving to this technique the versatility which is necessary to handle a wide range of situations. It can provide accurate, local data using an optical probe which does not disturb the fluid. Even crude systems (that means not costful) can produce valuable informations. Furthermore, sophisticated systems (but costful) can be built, producing accurate data with a high speed of acquisition. So the authors think that LDV will have a tremendous success for plasmas applications, notwithstanding the disadvantage of the cost and the necessity to be well aware of a lot of details in order to get correct data.

It will produce new knowledge from a fundamental as well as from a practical point of view. From a practical point of view, let us mention the plasma spraying processes (19) for fabrication of coatings and thin-walled components. From the fundamental point of view, let us mention a more basic knowledge of the heat and mass transfer processes between a plasma flow and particles embedded in it, new investigations of the departures from the translation equilibrium (20), more generally a wide range of plasmas flows and boundary layers new understanding (21, 22, 23).

Nevertheless, until now experiments have been rather scarce. So the authors tried to be exhaustive as far as the review part of this paper is concerned. They hope having pretty well reached their aim. Nevertheless, claiming to be exhaustive is always a bit delicate and we must apologize if we have forgotten some people. In this case, we should be pleased to be contacted in order to improve our own knowledge of the matter.

A few years ago, people began to be interested in simultaneous velocities and particle sizing measurements by means of laser-Doppler systems. It could be quite straightforward to adapt these methods for plasma diagnostics. The only thing to do is to do it. The authors insist that it should be done since it represents a new tool of tremendous potential for, let us say, plasma chemistry. Let us only mention two examples.

One of the specific difficulties for plasmas velocities measurements is to be sure that the scatter centers (of which in fact the velocities are measured) are small enough to follow the fluid. But, if they are small enough at the beginning of the jet, it is likely that they will vaporize before reaching the optical probe. On the other hand, if they are large enough for not completely vaporize before the control volume, it could be difficult to be sure that their velocities are equal to the fluid velocity. The only way to properly solve this problem whatever the situation is to achieve simultaneous velocities and particle sizing measurements.

Let us now come back to the heat and mass transfer between a plasma and an embedded solid phase. The theoretical analysis shows notable difficulties (24, 25). A complete experimental study could require knowledge of particles and plasmas velocities, diameters of the particles and how they evolve when they move downstream. Simultaneous velocities and particles sizes measurements could provide new valuable informations on such problems.

So the prospective part of this paper will give an overview of simultaneous velocimetry and particle sizing measurements carried out in the past. It is nevertheless a prospective part since these methods are now to be used in plasmas flows.

II. LASER-DOPPLER VELOCIMETRY

II.1. Generalities

The reader is assumed to be well aware of the general theory and main applications of the laser-Doppler velocimetry. Basic books are available (26, 27, 28). A fairly simple overview can be found in the reference 29.

Let us nevertheless introduce a rough classification. The basic idea in LDV is to focus a laser beam into the flow to study and to measure the Doppler shift of the light scattered by small particles embedded into the flow and traversing the focus. The most popular systems detect beat signals produced by heterodyning using quadratic photodetectors.

In the referential set-up, a single laser beam is focused into the flow and there is heterodyning between the scattered light and a reference beam.

In the Doppler mode, again a single laser beam is focused into the flow and beat signals are obtained from two beams scattered in two different directions.

In the interferential-(or differential-, dual-,real fringe-) systems, a laser beam is splitted in two laser beams which are made converging to the same focus. Heterodyning is achieved using the light scattered in one solid angle from the two incident beams. The beat frequency f can be computed from Doppler discussion or by noting that the incident beams give birth to a 3D real fringe system. The following expression is found : $f = 2u_z \sin(\alpha/2)/\lambda$, where u_z is the scatter center

velocity in the direction perpendicular to the fringes and α the angle between the incident beams of wavelenght λ.
The only heterodyning system which has been used for plasmas works is the interferential one. It allows to collect the scattered light in a large solid angle and thus to process individual realizations. Furthermore, it is easier to adjust, less sensitive to vibrations.
Other systems proceed without heterodyning, by directly detecting the Doppler shift of the scattered light. Although these are strictly speaking laser-Doppler systems,the authors think that these are rather spectroscopic measurements than 'classical LDV'.

II.2. The review

S.A. Self started experiments in a MHD boundary layer (30, 31, 32) in order to provide an understanding of the characteristics of the gas dynamic boundary layers and their modification by electromagnetic effects, more specially empirical constants for modelling of performance of MHD generators. He managed with additional problems due to restricted optical access, high velocities (> 500m/s), high spatial resolution requirements, refractive index inhomogeneity, scatter from the wall... Seeding was achieved through ∿1μm - refractory particles, without drastic vaporization problems owing to the rather low temperatures (∿ 2700K). A single beam system was used, without heterodyning detection. The Doppler shift of backward scattered light was measured by means of a Fabry-Perot. A laserline filter (10Å bandwidth) was used to remove thermal radiation and ambient light. Mean and fluctuating flow velocities were measured through the velocity probability density functions. Experiments have been then carried out with a differential-forward scatter method for sidewall measurements (33, 34).
But the angle α was small in order to get low frequencies in spite of high velocities, giving birth to a fairly bad spatial resolution. Processing was achieved through a high-speed counter linked to a HP-2100 computer. The principal source of parasitic radiation was found to arise from laser light scattered incidentally from the optics, windows and channel walls. All optical mounts and the support framework was made of non-magnetic materials, and the laser and photomultiplier was located some ten feet away from the measurement point, because of the stray field from the magnet. Also, there was noise and vibration levels from the MHD system, compelling to mount the optics on substantial support framework. Mean velocities, turbulence intensities and spectrum of velocity fluctuations have been measured.
M.R. Barrault et al reported about heterodyning LDV-experiments in a transient (12ms) arc circuit breaker (35). Specific problems arose plus the extra problems of transient nature of the arc, and high velocities (up to 3000ms^{-1}), thus corresponding to drastic seeding problems. Parasitic radiation was removed with a 10Å interference filter and associated polariser, plus a Fabry-Perot filter of 0.5Å bandwidth.

Signal processing was achieved through an oscillographic raster display. Measurements showed that the problem of equality between fluid and particles velocities was not solved. Thus improvements were then made in order to cover the entire arcing period (36), with attempt to solve the above mentioned problem of particles slip. But problems of interpretation remained due to the unknown size of scatter centers which did not always follow the fluid. The flow velocities were studied within and surrounding a 10kA peak current, free-burning arc with copper electrodes giving birth to 'natural' seeding. Artificial seeding using carborundum powder has also been tested. An approximate correlation has been found and used between signal frequencies (particles velocities) and signal amplitudes (particles sizes) in order to deduce the plasma velocities from the particle ones. But such a crude correlation is not very reliable since for instance big particles passing through the edges of the control volume give rise to the same signal amplitudes than small ones passing through its center. Effectively, Todorovic and al consider that the accuracy is not better than about 40%.
Then, Irie and Barrault carried out measurements without foreign elements and without heterodyning using the Doppler shift of a Q-switched ruby laser (37). Processing was achieved by means of a Fabry-Perot system. So, again, it is more spectroscopic measurements than 'classical' LDV.
Gouesbet reported LDV-mean velocities measurements in a 4MHz, radio-frequency torch,by means of a 5mW He-Ne forward real fringe system with oscillographic display of the signals (38, 39). But the exact fluid velocity was not measured due to the too large sizes of the used particles, although the disagreement were further found to be less than typically 20%.
Further experiments were carried out with a more powerful laser, a Krypton one giving 800mW on the 6471Å - line, and an automatic data acquisition and processing system using a single counter system (40, 41, 42, 29). The parasitic emitted light was removed by means of a 2Å - bandwidth monochromator. Seeding was achieved using a counter-current system supplying the flow with Al_2O_3- particles, small enough to follow the fluid, at a rate sufficiently low for not disturbing it. Laser beams were expanded before focusing to improve signal/ noise ratios and spatial resolution. The spatial resolution was also increased by off-axis light collection. The influence of the parasitic radio-frequency radiation was decreased by means of a shielding cage and electronic rejectors. Mean velocities and 'fluctuations' measurements have been successfully carried out.
Mme Thi Hien Ho attempted measurements in a 4MHz radio-frequency torch with a 5mW He-Ne laser, using a real fringe mode set-up (43). Seeding was made using Al_2O_3- particles of about 1μm- diameter. The parasitic light was removed with a ±10Å interference filter. Processing was attempted by means of a frequency tracker and a frequency analyser. Measurements were not really successful. The frequency tracker was

probably not working properly owing to the small particles arrival rate. The frequency analyser probably picked up the radio frequency radiation. A shielding copper enclosure improved the situation but not enough to make the measurements really feasible. With such low laser powers, a photon correlation technique could be successful.
Moreover, such a technique has been recently successful used in Limoges (44). The fringe spacing was about 100µm, requiring a 90° - observation to obtain a good spatial resolution. Consequently the S/N ratios were probably bad due to the inefficiency of the scattering process, but the very sensitive photon correlation technique enabled measurements of mean velocities of particles.
LDV-measurements are also reported from the Imperial College of Science and Technology (London) in a DC transferred arc heater at the National Physical Laboratory (45, 46). Real fringe systems were tested in forward and backward scatterings. A spectrum analyser, a frequency tracker, and a frequency counter, have been tested. Particles were nickel (∿ 50µm) and alumina ones (∿ 1µm). Velocity histograms were recorded. Alumina particles exhibit much higher velocities than nickel ones, as it could be expected from drag arguments. Let us finish by mentionning the Tiller's paper (47), the Bentley and Bomar report (48), and the LDV work which is planned at the ONERA (Châtillon/Bagneux).

III. PARTICLE SIZING

We shall distinguish III.1) The visibility approach, III.2) The calibration approach III.3) Some miscellaneous methods and III.4) we shall report on the work carried out in Rouen. No attempt is made in this section to be completely exhaustive.

III.1. The visibility approach

According to Farmer (49) analysis of Doppler signals in real fringe systems enables to simultaneously measure particle size, number density and velocity of the scatter centers. The figure shows the shape of a Doppler signal corresponding to a scattering particle having a trajectory near the center domain of the fringe system (the low-frequency part of the signal, the so-called pedestal, is not filtered out). The visibility v of the signal can be defined by the following relation :

$$v = (V_{max} + V_{min})/(V_{max} - V_{min}) .$$

Farmer shows that there is a relation between the visibility v and the diameter of the scatter center. The following assumptions are made : (A1) the wavefronts are planar (A2) the dielectric constant and magnetic permeability of the medium surrounding the particle are approximately 1, (A3) the scattered light is observed in the far field (A4) the angle α is small enough to get $\sin \alpha \simeq \alpha$ and $\cos \alpha \simeq 1$, (A5) the polarization vectors of the illuminating waves are perpendicular to the plane of the incident beams (A6) only paraxial front or back scatter from the incident light is considered (A7) the center line intensities in each incident beam are identical (A8) the relative phase difference in the beams due to differences in pathlength in arriving at the probe volume is zero (A9) the scattered intensity is calculated by assuming that the scatter center receives a mean illuminating intensity equal to a simple average on the cross-sectional area of the scatter center of the illuminating intensity (A10) the fringe spacing is smaller than the radius b_o of the focused laser beams in the control volume (A11) the particles are spheres or cylinders (but only spheres will be considered in the present paper) (A12) the diameter of the spherical particle is smaller than b_o (A13) only location at the geometric center of the probe volume is considered. The visibility then reads :

$$v \simeq 2J_1(\pi d/i)/(\pi d/i),$$

where J_1 is the first-order Bessel function and i the fringe spacing. Notwithstanding the fact that the visibility thus is not an uniform function versus (d/i), the measurement of v and the knowledge of i allow to measure d. Now, taking into account for the non-uniform character of v(d/i), it is shown that the size cannot be unambiguously determined unless $v \gtrsim 0.15$.

The assumptions A2, A3, A5, A7, A8 are trivial or can be made easily true. The assumption A1 is false (50), but it is certainly not an important point. The assumption A4 is often at least fairly obeyed. The assumption A6 is critical since a lot of LD-systems use off-axis collections. The importance of A9 seems to be difficult to appreciate. A11 shows that some information about shapes is needed before performing size measurement. Not taking into account A13, the expression for the visibility is much more complicated and not given here. It shows that, generally speaking, knowledge of the particles trajectories could be needed, a difficult point in the present state of art.

Let us finally consider the assumptions A10 and A12. We must then have $i \ll b_o$ and $d \ll b_o$, and also, to avoid ambiguity problems, we need, let us say, $d<i$. It could be difficult to simultaneously obey $d<i$ and $i \ll b_o$, especially when large particles (let us say 100μm) need to be measured. Furthermore, a small angle α is needed to obey $d<i$ giving birth to signal/noise ratios and spatial resolution problems.

Farmer then reported experimental observations carried out in order to check the previous theoretical analysis (51). He pointed out that the solid angle of collection of the scattered light must be introduced in the analysis. The observation angle appeared also as an important parameter. Moreover non paraxial observation of large particles relative to the fringe period can lead to ever ambiguous values of size. But reasonable agreement between theory and experiments is obtained when the assumption of (49) are obeyed. The need for an electronic instrumentation to be developed before the visibility technique being viable is emphasized.

Robinson and Chu performed a similar analysis but using scalar diffraction theory (52). They found that the rather simple Farmer's expression previously given is only valid for collecting the total forward scattered signal. For an on-axis finite receiving aperture, a much more complicated expression is given.

Hong and Jones showed that the visibility was not sensitive to complex refractive index at small finite apertures and for paraxial observations, but it is to be taken into account for more general cases (53). Adrian and Orloff emphasized differences between forward and backward observations (54). Chu and Robinson reported new improvements of their previous diffraction analysis (55) and Roberds rather makes a review of previous works (56), while Owen and Bachalo reported about measurements in spray flames (57) using off-axis collection.

III.2. The calibration methods

Owing to mathematical difficulties (requiring a lot of assumptions, to simplify the analysis), and also to the difficulties of automatic analysis, other people attempted another approach.

More particularly, Yule, Chigier, Atakan and Ungut showed that 'one-to-one' relationships between the mean amplitudes $\bar{V}$ of the Doppler signals and the diameters of spherical particles can be found (58, for instance). Particles larger than the fringe spacing are considered. Calibration experiments were carried out using droplets of water and kerosene, various opaque particles and glass cylinders or spheres. Theoretical analysis has been achieved using geometrical optics and good agreement with experiments has been found. It is pointed out that the change of visibility versus diameter is much less sensitive that the change of the mean amplitude. So, the calibration method should be preferred.

But the peak mean signal is also sensitive to the particle trajectory. Two approaches have been developed to solve this problem. The first one is to use a gate photomultiplier introduced at right angles of the control volume in order to select only those particles passing through the central region of it (59). So the dependence of the measurements on position of the particle along the length of the control volume is eliminated, but dependences in the transverse directions remain requiring corrections to take into account for them. The second approach is thus preferred, that is to compute actual distributions of sizes from measured distributions using a mathematical inversion based on the assumption that each particle has the same probability of presence in the control volume, whatever its location (60).

These methods have been successfully used in combustion systems and adaptation to plasma experiments seems straightforward.

III.3. Miscellaneous methods

In this section, we shall give a fast review of miscellaneous methods which could be attempted for plasmas measurements but which are not always laser-Doppler systems although having more or less strong connections with them.

Lee and Srinivasan showed that it is possible to obtain the statistics on the size number density distribution and, for each size range, velocity distribution of the particles and of the fluid phase by using a scheme of discrimination on the amplitude, residence time, and frequency of the laser-Doppler bursts (61). Durst and Umhauer used a separate white light source to measure the particle size whereas a LDA system was used to measure the velocity (62). Chou and Waterson used the ratio between the forward and backward scattered light to measure diameters of small particles (63). Wu used dual parallel laser beams crossed by particles embedded in the flow, to simultaneously measure their size and velocity (64). Chabay and Bright used only one laser beam, the size being measured through the amplitude of signals detected from particles crossing the beam (65). Gravatt (66), and Boron and Waldie (67) carried out size measurements by a forward lobe scattered intensity-ratio technique. G.Wigley determined sizes of large particles crossing a LD-control volume from observations of the glancing angle reflections (68). Hirleman suggested to use parallel laser beams to specify completely the particle trajectory, and simultaneously measure particle size and velocity (69). Levy used the double peak signals produced by an opaque particle much larger than the width of the control volume and crossing it (70). Others used the diffraction pattern at infinity of a coherent beam passed through a sample (71, 72). Finally, it is not possible to end this section without mentionning holography, cinematography (regularly used for plasmas works), and double-spark high speed photography. A review of these techniques can be found elsewhere (73).

III.4. Investigations carried out in Rouen

Let us come back to the calibration methods. Because of the need for corrections due to trajectories in the control volume, calibration methods do not really simultaneously measure the velocity of one particle passing through the control volume and its size, but rather simultaneous distributions of velocities and sizes.

A research programme is carried out in Rouen to overcome this defect. A code has been built - the SUPERMIDI one - to achieve Mie calculations for particles as large as 100μm, and even more, having possibly imaginary parts of the refractive index as high as 10^5 (74). This code was used to prepare extensions of Chigier's calibration method (75), and to design new systems allowing really simultaneous measurements of size and velocity of individual particles, but it is not possible to report about them because of patent procedures.

CONCLUSION

A review of LDV - applications to plasmas has been given. The feasibility of plasmas measurements by means of such methods is now proven. Furthermore, it is pointed out that particle sizing or simultaneous velocimetry and particle sizing can be achieved by means of laser-Doppler or similar systems. There is no doubt that these rather new methods will allow new developments of plasmas investigations.

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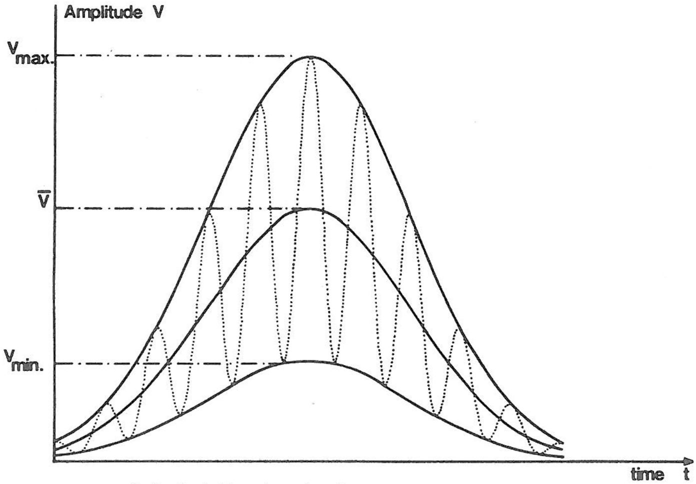

A typical Doppler signal