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# THE MEASUREMENTS OF VELOCITY IN HOT MEDIA

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ABSTRACT

In this paper we shall attempt to review some of the methods used to measure velocities in hot conducting media such as those found in arc discharges and furnaces at atmospheric or higher pressures.

In such media the temperatures, and pressures are often known and the velocity is the crucial quantity required to establish a meaningfull energy or momentum balance.

The range of methods available is very wide it includes methods based on an application of all three of the conservation equations, for mass, momentum or energy; methods based on electromagnetic interactions, spectroscopic and scattering measurements.

Each of these headings may be further divided according to whether or not an active measurement or whether or not the original flow field has been modified.

A survey of some of these possibilities underlines the necessity of choosing the most appropriate method not only in terms of the prevailing experimental situation but also according to the body of measurements already accumulated.

## 1. INTRODUCTION

In the measurement of velocity we may distinguish two different kinds of methods.

In the first group are those methods which do not interfere with the flow pattern being probed, we may in this group include spectroscopic, scattering, correlation techniques, tracer and magnetic field methods.

In the second group are methods which rely on a deliberate modification of the flow pattern, among these we may include mass flux, energy flux and momentum measurements.

In this paper we shall look at some of these methods with the object of determining their relevance in hot gas, cold plasma experimental situations for which the velocity is less than $10^4$ m/s.

Since all the conservation equations contain velocity terms a correct knowledge of this quantity is necessary if one wishes to test these equations.

It is however commonly found that velocity is derived from the necessary balance of these equations and is thus obtained almost by default.

An experimental measurement can often, together with the balance equations hint at or allow an evaluation of some otherwise neglected or elusive quantity such as turbulence or radiation.

## 2. SPECTROSCOPIC METHODS

These rely on the Doppler sifting of some emitted radiation. The principle of such measurements is evident: to a fixed observer the wavelength of the light emitted by a moving emitter is

Doppler shifted by an amount $\frac{\lambda V \cos\theta}{C}$.

For this to be detectable the broadening of the emitted line radiation caused by natural, thermal, collision .... etc (ref. 1) must not be too great. If stark and pressure broadening are not too important thermal broadening caused by the thermal motion of the emitters will usually limit the accuracy of the measurement.

Since this motion is typically at sound velocity there is clearly, in mixtures an advantage in using line radiation issued from the heavier components.

In any event it will prove difficult to measure velocities less than one tenth of the sound velocity of the heavier component.

Another difficulty is that the measured line profile is integrated along the line of sight. In cylindrical geometry it will therefore be necessary to perform an Abel inversion (ref. 2,3) on the data.

Furthermore, if axial flow is being probed then measurements will have to be taken along lines inclined to the flow axis; any axial variations of the emitted profile will then invalidate the Abel unfolding.

Under such conditions a two dimensional unfolding technique of the type proposed in (réf. 4.5) is needed with unfortunately the requirement to take many more readings.

Whilst these measurements are usually made in emission an identical effect is found in absorbtion and can be used if a suitable illuminating source is available.

The incoherent nature of the process calls for high resolution spectral analysis; the required resolution being of the order of $\frac{V}{C}$.

Fabry Perot systems are easily ablt to attain the required finess, even in the scanning mode and the major difficulty remains that of unfolding the data both spectrally and temporally (ref. 6).

## 3. L.D.V. METHOD

In this method the light scattered by small particles or droplet (ref. 7) convected with the flow is analysed to obtain the Doppler shift.

Two cases have to be considered according to whether coherent or incoherent scatter takes place.

Coherent scatter is found in cases where only single particles cross the scattering volume. Phase information is then preserved and the Doppler frequency shift can be obtained directly by beating the scattered light with a fraction of the illuminating beam. Suitable optics must be used to ensure equal curvature of the scattered and illuminating wavefronts at the detector station. For visible radiation the maximum Doppler shift is from 2 to 3 MHz per m/s flow rate. Since it is inconvenient to have to deal with frequencies much above 30 MHz it is necessary in high speed flows to choose illuminating and scattering observation directions which are nearly perpendicular to the flow direction.

Under such conditions the system becomes very sensitive to small angular errors:

$$V = \frac{\lambda f}{n(\cos\theta_s - \cos\theta_i)}$$ because of the difference between the two cosine terms.

This problem may be obviated by diffential scattering using two coherent illuminating beams which intersect at a small angle within the scattering volume. The difference between the two Doppler shifts is then directly encoded on the scattering radiation and no further beating is required at the detector.

In that case $$V = \frac{\lambda f}{2n \sin\frac{\theta_{i2} - \theta_{i1}}{2} \sin\frac{\theta_{i2} + \theta_{i1}}{2}}$$

and f is independent of the scattering angle.

The intensity of the scattered light is distributed according to the ratio of scatterer size to wavelength. For most applications the particles will have dimensions greater than $\lambda$ and preferential scattering will take place in the forward direction (ref. 7).

An important limitation comes about because of the weakness of the scattered light from a sigle particle but recent work has shown that good signals can be obtained even against the background of high current arc discharges (ref. 8). In the case of incoherent scatter the phase information is lost and the velocity must be obtained from a direct measurement of the frequency shift.

In hot flows a further limitation arises because of the evaporation of the particles which is more rapid the smaller the particles. This is in direct conflict with Stoke's law which demands that small particles be used to minimize the velocity difference between particles and fluid (ref. 9).

There is thus a domain of flow which remains inaccessible to L.D.V. measurements because particles large enough to survive residence in the flow will be too large to accelerate to the true flow velocity.

This limit has not yet been clearly defined and poses challenging problems as to drag and energy transfer in a strongly ablative situation.

The L.D.V. method also poses challenging problems in the data acquisition field. The derived signal is usually in the form of a short burst of high frequency oscillation which must be rapidly analysed in terms of amplitude and spectral terms as described in (ref. 10).

Whilst only one component of velocity is obtained, with the systems we have outlined extension to the three directions is easily achieved through the use of multiple beams of differing wavelength all convergent on the same scatter volume.

As described the velocity measurements are insensitive to the direction of flow. To provide directionnality a bias must be introduced in the system by offseting the frequency of one of the laser beams or using polarization coding (ref. 11).

Even a stationary particle will now return in the offset case modulated scattered radiation and the Doppler frequency shift will be added or substracted from the standing bias according to the direction of travel.

Of course under steady flow conditions a cheaper solution night simply be to realign the system.

A final difficulty which ought to be mentionned is the distorsion of the wave front induced by the shape of observation windows in pressurized systems.

Such windows introduce lens like abberations which must be corrected (ref. 12) large refractive index gradients can also prove troublesome and distort or smear out the required signal.

The L.D.V. method is very usefull for finding the velocity at a point but does not provide a picture of the whole flow field. This can be obtained, when the luminosity of the fluid is sufficiently small by particle track photography (ref. 13).

Yet another method using very large particles (ref. 14) exploits the small velocity of the particle to calculate the flow drag and hence the fluid velocity.

## 4. ELECTRON SCATTERING

Instead of relying on particle scattering one may use the much smaller incoherent scattering from electrons in the fluid.

This phenomena is usually divided into Rayleith, Thomson and resonance scattering. Rayleith scattering is related to molecule polarizibility, Thomson scattering to the movement of free electrons and resonance scattering to the presence of energy level differences close to the exciting photon energy (ref. 15).

Because the scattering centers move with the fluid the scattered radiation will be Doppler shifted in exactly the same way as with the L.D.V. method. The smallness of the scatter cross section will however impose the incoherent domain and require the same type of spectral analysis as for the spectroscopic method.

A major advantage of the scattering technique is the good spatial resolution which can be achieved through large angle crossing of the illuminating and detecting axis.

As with the spectroscopic method however velocity resolution will be limited by the scatter line width which will also set the signal to noise ratio of the system. Ideally the heaviest possible scatterer should be chosen to minimize the thermal Doppler effect.

As a consequence when Thomson scattering dominates it is essential to choose the scattering angles such that the parameter $\alpha = \dfrac{\lambda}{\lambda_D \quad 4\pi \sin \theta/_2}$ is larger than one, in this way the line width will be governed not by the electron but by the ion thermal velocity, obviously a much smaller quantity.

Recent results (ref. 16) indicate the usefullness of Thomson scattering as a tool for measuring fluid velocities. The general availability of dye lasers will allow widespread use of resonant scattering and fluorescent lines. This will improve the precision of the measurements.

It should be noted that the scattering techniques we have outlined rely on the detection of a signal which is very small compared with that given by a solid or liquid particle scatterer, accordingly it is a technique which is only applicable to clean fluids and not to the fluids for which the L.D.V. method is operational.

## 5. CORRELATION TECHNIQUES

Correlation techniques rely on the detection of one or several disturbances which are assumed to be convected with the flow.

There may for example be differences in the light emission or refractive index from different parts of the flowing gas. A comparison of the spatial distribution of these differences at two separate instants of time will reveal a displacement for which there is a best correlation.

A convective velocity may then be derived which may or may not be the fluid velocity.

The actual measurement may be photographic, spectroscopic or interferometric but the two problems of determining the region from which and the meaning of the derived velocity remain essentially the same.

Fine disordered structure as found in turbulence is convected with the flow and therefore provides a reliable marker, if it can be detected. There remains however the problem of spatial resolution which may be, to a certain extend, diminished by using naturally occuring spatial variations in spectral emission (ref. 17).

The development of correlation techniques is closely linked with the ability to rapidly perform the necessary mathematical correlation with a minimum of data storage. The availability of scanning solid state optical sensors now offers the possibility of completely eliminating auxiliary data storage (ref. 18).

An alternative to the observation of natural irregularities is the injection of tracers substances which can subsequently be followed spectroscopically (ref. 19). The main difficulty here is the determination of the centre of gravity of the emitted tracer radiation which is rapidly spreading through diffusion and turbulence.

## 6. INTERFEROMETRIC MEASUREMENTS

A great many interferometers have been designed to probe the refractive index distribution of hot media. These may be used in conjunction with a correlation technique to measure the movement of turbulent refractive elements. It should be noted however that a direct measurement of the fluid velocity is in principle possible using the Fizeau effect. This effect is quite small since the apparent velocity of propagation in a moving media is

$C = C_o + v\,(1 - \frac{1}{n^2})$, where n is the refractive index. Writing $n = 1 + \Sigma$, the phase shift over a path length L is: $\phi = \frac{2\pi}{\lambda}\ L\ \frac{v}{C}\ 2\Sigma$.

Because $\Sigma$ is typically less than $10^{-4}$ v.L must reach values of the order of $10^4$ for $\phi$ to become easily measurable.

Clearly since the precise value of n is unknown $2\phi$ would have to be obtained by a double pass with and against the flow through the same volume. Whilst this $\phi$ appears very small in most experimental situations, it is not unconceivable that a resonant Fizeau measurement could be made on a practical plasma by illuminating the system with a dye laser carefully tuned so as to increase n (ref. 20). To date however no measurements seem to have been made using this scheme.

## 7. MAGNETOELECTRIC METHOD

A conductor moving across a magnetic field generates an electromotive force proportional to both its velocity and the magnetic field density.

It is thus not surprising that a whole range of measurement techniques based on this phenomena have been developed (ref. 21).

The phenomenological domain in which these measurements are conducted may be defined by evaluating three non dimensional numbers: $R_m = \mu_o \sigma V L$, $S = R_m \frac{B^2}{\mu_o \rho V^2}$, $\beta = \frac{\sigma B}{n_e e}$, where

L = scale length, V = flow velocity, $n_e$ = electron density. The magnetic Reynold's number $R_m$ indicates the degree of disturbance of the magnetic field by the flow. The interaction number S shows whether or not the flow is changed by the interaction. Finally $\beta$ the Hall parameter indicates whether or not the Hall effect is important.

Where a small magnetic field has been introduced to measure velocities, both S and $\beta$ will be much less than one and the interaction specified by $\underline{\nabla}.\underline{J} = 0, \underline{\nabla x E} = 0$ & $\underline{J} = \sigma(\underline{E}+\underline{V}x\underline{B})$ where $\underline{J}$ and $\underline{E}$ are governed by the boundary and geometrical conditions and $\underline{V}$ & $\underline{B}$ are given.

The coil or magnet structure generating the magnetic field may either be within the flow, in cases where some local velocity is being measured or outside the flow when average values are required.

Two types of limitations arise in these measurements. Firstly if an externally generated field is established and potentials measured with electrodes (ref. 22), it is found that the unavoidable sheath and boundary layers developed at the electrode surfaces yield unaccountable potentials and fluctuating voltage drops.

These effects may completely mask the desired voltage unless the field and or velocity is very large.

It is possible to reduce the effects of electrode potentials by using an A.C. magnetic field. In this case the velocity induced potential will also be A.C.and can be distinguished from the inductive potential by its phase.

Secondly if the field is generated internally, with small coils imbedded in the flow the major interaction takes place in close proximity to the coils, in those regions where the flow is most disturbed.

This latter situation is also found with R.F. conductivity probes (ref. 23) and cannot easily be avoided.

## 8. GAS DYNAMIC MEASUREMENTS, PITOT TUBE

This is one of the oldests ways of finding the flow velocity. The method relies on the measurement of the stagnation pressure at the front of a small body. The ratio between this and the static pressure at the same point in the flow field is:

$$\frac{p_o}{p} = (1 + \frac{\gamma - 1}{2} M^2)^{\gamma/\gamma-1}$$

and the flow velocity is then:

$$(\frac{u}{C_o})^2 = \frac{2}{2/M^2 + \gamma - 1} .$$

Note that in the case of supersonic flow the stagnation pressure must be modified by the factor:

$$\frac{\left[\frac{2\gamma}{\gamma+1}M^2 - \frac{\gamma-1}{\gamma+1}\right]^{1/\gamma-1}}{\left[\frac{\gamma+1}{2}M^2\right]^{\gamma/\gamma-1}}$$

to account for the existence of a stand off shock.

Technical difficulties arise because of heat flux loading to the probe surface (ref. 24) or resonances in the tube joining the probe to the pressure transducer (ref. 25).

Reliable measurements have been obtained for steady flows in arc discharges (ref. 26) but the technique seems incapable of resolving fast changes under the same conditions.

This is clearly a fundamental limitation brought about by the cold dead volume situated between the stagnation point and the pressure transducer.

## 9. DISCUSSION

The present situation in relation to velocity measurements is highly fragmented, no one technique is ablte to probide accurate measurements over the complete range of hot gas, cold plasma flow. There even exist domains for which, at present no satisfactory methods exist. This is especially so for opaque media in fast transient flow fields. Because of the importance of obtaining a detailled local description of the velocity field in for instance turbulent flow heavy stress has been laid on methods which provide good spatial resolution.

This accounts for the popularity of L.D.V. methods which offer additionally the ability to deal with a range of velocities extending from m/s to many km/s. Problems of seeding and of particle acceleration will however set a limit to the development of this technique and it may be anticipated that other optical methods will now be developed.

The availability of stable tunable dye lasers has already opened the way to a number of new diagnostic approaches to temperature and density measurements (ref. 27,28,29,30).

There is little doubt that some of these methods will be developed to provide velocity data allowing a compromise to be made between the very good spatial resolution of the L.D.V. method and the good acceleration and high speed characteristics of electron scattering measurements.

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