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Velocity Measurement Techniques for Large-Scale Explosions

Prepared by

Imperial College Consultants Ltd

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SUMMARY

This report provides a review of a wide range of different velocity measurement techniques which may be suitable for explosion applications. A range of "mechanical devices," such as pitot tubes and hot wire probes, are considered along with optical techniques such as Laser Doppler Anemometry. All techniques are assessed with respect to their range of operation, sensitivity and feasibility of use in a hostile large-scale explosion environment. Practical aspects related to the ease of operation such as calibration, drift and seeding of flow are also discussed. Indicative cost estimates of the equipment both in terms of the initial investment and its maintenance are also provided.

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1. INTRODUCTION

Vapour cloud explosions due to accidental spillage of explosive substances remain one of the unresolved hazards affecting industrial plant and their surroundings. Detailed and comprehensive accounts of such explosions have been presented by Strehlow [1], Gugan [2] and Bangash [3] among others. Lenoir and Davenport [4] presented the results of a survey which included only those incidents believed to be caused by vapour cloud explosions. Table 1 identifies a few of the most devastating of the explosions recorded in the literature. Out of over 100 cases reported by Strehlow [1], more than 55 % of these events have resulted in explosions producing blast effects of varying degrees of magnitude. It is also evident that the frequency of such incidents has increased significantly during the period from 1970 to 1980 [5–6]. It has also been noted that number of vapour cloud incidents for the period from 1980 to 1990 is lower than for the previous decade, although the recent past there has been a number of very large losses [4]. Following the major explosion at Flixborough in 1974, substantial amount of effort and large sum of money have been spent on research to establish the necessary conditions to initiate such a large explosion in a gaseous fuel–air cloud. At the same time, the industrial safety standards have been tightened through the introduction of new measures to control and prevent major accidents, and to improve the emergency procedures (eg [7]). Risk assessment in practical situations does, however, necessitate a clear understanding of the factors involved in flame acceleration and the resulting overpressures. Hence a considerable effort has been diverted into research in this area, especially over the last decade.

Accidental leakage of a flammable substance causes it to disperse into the surrounding air to form a thick explosive cloud, often covering a large area as can be seen from Table 1. The extent of the damage produced by the ignition of this explosive mixture depends on the amount of substance escaped, the degree of confinement (including obstacles in the form of pipe works etc), degree of turbulence, cloud configuration, reactivity of fuel, strength of ignition source, degree of cloud mixing (the equivalence ratio of the mixture) and the time between the release of the substance and the ignition [4]. The last two factors are undoubtedly interdependent while the time factor also determines the extent over which the explosion occurs. Although detonation, a phenomenon in which a flame front propagates into a reactant mixture at a supersonic velocity, is the most devastating, its occurrence has been suspected in only a few events [1]. The estimates of well-documented disasters like the one at Flixborough show that the flame speeds are in the range 200–300 ms^{-1} which correspond to burning velocities two orders of magnitude higher than the related laminar burning velocities. One of the difficulties in realistic hazard analyses of accidental gaseous explosions is accounting for the influence of turbulence-producing obstacles on the severity of the explosions. The underlying mechanisms of turbulent flame deflagrations do, therefore, form an important part in explosion hazard analyses and safety modelling. Although considerable advances have been reported in theoretical predictions in the recent past, the modelling of turbulent flame propagation is still inadequate for use in many practical applications. To establish fully the conditions responsible for gas explosions through the use of field scale experiments is excessively expensive in terms of both money and effort. It is therefore imperative to establish effective measurement techniques which can provide reliable and accurate data within the short period of a gaseous explosion for subsequent use in model development.

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Table 1
A list of major industrial explosions [1–4]

Date	Place	Flammable material	Source of leakage	Time to ignition	Remarks
1968	Pernis Holland	Mixed hydrocarbons	Storage tank	8 min	A huge cloud was formed with the breaking of water-oil emulsion in slop-oil tank
1970	Port Hudson Missouri USA	Propane	Pipeline rupture	24 min	Fuel spillage produced a cloud of 460 m long and 3–6 m high. The explosion resulted in detonation
1972	East St. Louis Illinois USA	Propylene (94%) & propane	Rail tanker	1 min	Two explosion centres were identified and detonation was suspected
1974	Flixborough UK	Cyclohexane	Chemical reactor	25–35 s	A 500 cm temporary pipe failed due to poor installation and the subsequent explosion caused large overpressures
1975	Beek Holland	Propylene	Reactor	2 min	The ignition of the vapour cloud was deposited about 46 m away
1975	Antwerp Belgium	Ethylene	Compressor Pipe	4 min	Explosion produced overpressures of 34–48 kPa at 60 m in one direction and 3.4–6.9 kPa at 60 m in the opposite direction
1988	The Piper Alpha Platform Aberdeen UK	Natural Gas	Gas Riser		A major explosion occurred in the Piper Alpha platform due to the rupture of a gas riser. Further explosions led to the structural collapse of the platform resulting in loss of 164 lives.

There thus exists a vital role for velocity and turbulence measurements in large-scale explosions. Although this fact has been recognised over the years, the lack of proper measurement techniques as applied to the hostile environment prevalent in an explosion has led to a dearth of associated flow field information. Indeed, it is disappointing that there is very little activity in this area at present given that highly advanced velocity measurement techniques have been developed which may possibly be adopted to for this area. Clearly, the capability to make velocity measurements which are both precise and consistently accurate would constitute a huge advantage from a model development perspective. Sadly, only a few velocity measurement results have been reported thus far in transient flame propagation, even at laboratory scale. Lindstedt and Sakthitharan [8] have successfully measured flow velocities and turbulence characteristics in laboratory scale explosions through the use of a laser Doppler anemometer in forward scattering mode. At large-scale Catlin *et al.* [9] have measured particle size and velocity of water droplets used for explosion mitigation in offshore modules. Their approach consisted of a phase Doppler anemometer with three photomultipliers.

It is clear from the above discussion that with the exception of one laboratory scale study [8], there have not been detailed velocity measurements under any explosion conditions. Laboratory scale data is most helpful in evaluating the physics of gas explosions and more data covering a wide range of geometries is urgently required. However, the complex scaling behaviour of gas explosions makes it a distinct advantage to have such information, albeit in much less detail, also available from large scale explosions. The present report is, thus, an attempt to review possible velocity measurement techniques for the application to large-scale explosions. This report is divided into four parts. The first part describes velocity measurement techniques applicable to combustion, followed by a detailed description of intrusive and optical techniques. Finally, recommendations are given with consideration of the approximate costs involved.

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2. VELOCITY MEASUREMENT TECHNIQUES

2.1 INTRODUCTION

There are numerous velocity measurement techniques designed to be used under various conditions. Their suitability evidently depends heavily upon the particular problem in hand. The methods vary from simple differential pressure measurement techniques to highly sophisticated optical measurement techniques. Depending on their nature, the techniques can be broadly divided into two categories: intrusive and non-intrusive (optical) techniques. A vast majority of the techniques provide means to measure the mean velocity, although optical and some intrusive techniques allow the characterisation of flow turbulence. Most of the techniques were initially developed for isothermal flows and then modified and extended to be used in combusting flows. Additional difficulties arise when measurements are made in hostile, short-time scale, combustion environments. The severity of such difficulties is reaching a peak for the problem of velocity measurements in explosions. Large-scale explosions pose additional problems thus compounding the issue further. Since there are many coupled physical phenomena involved in explosions, velocity measurements should ideally be provided at large scale to supplement data sets produced at laboratory scale and aimed at evaluation of the physics of explosion models.

Attempts to measure velocities in combustion systems have been made over a long period of time with varying degrees of success. Pitot tubes and other pressure impact probes, which require water cooling to withstand the high temperatures in flames, feature in early velocity measurements. Special probes constructed using platinum require no cooling, while those constructed using high temperature steels need partial cooling and allow the probe end to be heated. Such probes necessitate the measurement of temperature and, if possible, local concentration (to find the local density), in order to determine the velocity. Since it is not usually possible to measure temperature and concentration at the same time as pressure measurement, the resulting measurements only provide mean velocities.

In isothermal systems the hot-wire anemometer has become a principal velocity measurement technique. The method can provide turbulence characteristics since it is capable of a high frequency response. Transfer of such a valuable device to combustion conditions is not trivial. A number of attempts have been made to adapt the hot-wire anemometer for combustion and it was found that iridium wires could be used in non-oxidising circumstances. However, the technique does not work under excessive temperature levels or with particles in the system. Another shortcoming of the technique is the requirement that the temperature must be known, as the hot-wire is sensitive to both velocity and temperature changes.

Optical or non-intrusive techniques have gained in popularity, in particular, in combustion systems with the advent of the laser and laser diagnostics have led to a revolution in the approach to experimentation in combustion. As optical techniques are fundamentally non-intrusive, they eliminate many of the concerns, such as flame holding and flow alternation, associated with intrusive probes like Pitot probes and hot-wire anemometers. There are a number of optical systems which are used in combustion flows: Laser Doppler Anemometry (LDA) [10], Particle Image Velocimetry (PIV) [11], Laser Speckle Velocimetry (LSV) [12], Particle Tracking Velocimetry (PTV) [13].

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Laser Doppler anemometry, in particular, is now well established for measuring fluid velocities in combustion. This is particularly evident in research work at a laboratory scale. Its use in large-scale experiments is still more limited and it is part of the objective of this report to uncover the difficulties associated with such applications.

The following sections examine the velocity measurement techniques which possess a realistic prospect of being used in large-scale explosion experiments. The advantages and disadvantages of both intrusive and non-intrusive techniques are outlined along with a brief description of each method. Particular importance is given to techniques which have been successfully used to obtain velocity and turbulence characteristics in explosions at laboratory scale, eg LDA [8].

2.2 INTRUSIVE TECHNIQUES

One of the most fruitful techniques for studying steady combustion processes has been the use of measuring probes. Their reliability and availability mean that they are still preferred in development test-rigs and full-scale furnaces. Probe techniques are inherently simple and easy to use and certainly less expensive than advanced optical techniques. However, they are intrusive and therefore can disturb the flow field and the combustion patterns so that measurements are not being made of the combustion system it set out to investigate. The disturbances can be largely fluid dynamic, thermal or chemical in nature but in general all three will be present. In combusting flows these probes suffer from additional shortcomings, namely mechanical resistance of probes to very high temperatures, the blockage of instruments by particles carried in suspension, the measurement of very small differential pressures and, notably, response related difficulties.

2.2.1 Pitot Tubes

The pitot tube method of measuring velocity is fundamental in aerodynamics. If a tube connected to a pressure-measuring device is directed against a fluid flow, it will register a pressure which is proportional to the square root of the velocity. This provides one of the most robust means of measuring the velocity of a fluid. For a gas flow, Pitot tubes indicate the stagnation pressure and therefore the static pressure should be measured separately.

In Pitot static tubes (designed by Prandtl), the tubes recording the static pressure and stagnation pressure are combined into one instrument (Figure 1a). A central tube measures the total pressure and is surrounded by another tube to measure the static pressure. Two or more holes are drilled radially through the outer wall into the annular space. These holes must be positioned correctly, since the flow is accelerated past the nose of the instrument, resulting in a reduction of static pressure. Also, around the supporting stem the velocity is reduced with an increase in pressure. The holes must therefore be placed at a position where these tow effects cancel each other out. The sizes of these probes have been standardised to obtain very accurate results. A further requirement of the Pitot static tube is that the tube must be aligned with the flow of fluid. Any such misalignment may result in error in the measurement. However, it has been found the error due to instrument misalignment is less than 1% for yaw angles up to 15°.

The use of a Pitot static tube in an incompressible (constant-density) flow only requires the measurement of the difference between the stagnation pressure and static pressure. It is not

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necessary to measure them separately. However, in a compressible flow, the fluid may undergo a considerable change of density when it is brought to rest at the front of the Pitot static tube. It means that stagnation and static pressures must be measured separately.

In flames the pressure differences obtained using Pitot static tubes are small but measurable. However, the measurements are difficult to interpret because the probe must be small compared with the flame front thickness and boundary layer corrections become important. The measured pressure depends not only on velocity, but also on Reynolds number which in turn is a complex function of temperature and probe diameter. The usual practice is therefore to restrict its application to very low Mach numbers [14]. This in itself eliminates its use in an explosion.

Attempts have been made to use Pitot tubes to obtain turbulence information. Becker and Brown [15] studied comprehensively the response of pitot tube in turbulent streams and it was shown that a measure of turbulence could be obtained using Pitot tubes. Nevertheless, their study was performed in an axisymmetric two-dimensional jet flow which was assumed to be homogeneous and isotropic. For measurements in turbulent flows, the flow over the instrument should be quasi-steady. In other words, the velocity should not change appreciably over a distance of the order of the tube diameter or a time of order diameter divided by the velocity. In other words, temporal and velocity gradients must not be too strong.

Five-hole pressure probes can be used to measure in swirl flows or recirculating flows where it is necessary to measure both the magnitude and direction of the velocity. The five-hole probe is ideally a ball-head probe with five pressure taps (Figure 1b). One of these pressure taps is located on the probe axis in the normal Pitot configuration and the other four at 90° intervals around the axis. The latter four holes are drilled at an angle back from the axial tap and this angle is typically around 40°. Water-cooled versions are available for use in combustion applications, although these are not important in explosions where the time evolution of temperature is fast enough not to cause difficulties.

Another design based on the Darcy's modification to the Pitot tube is a bi-directional low-velocity probe which is robust enough to be used in flames and fires [16, 17]. The probe (see Figure 2) has a section of a circular tube with two chambers separated by a central diaphragm located between the end points. For axial flows, the upstream chamber measures a pressure closer to the stagnation pressure of the flow. The downstream chamber measures a pressure slightly lower than the static pressure of the flow. The pressure differential is thus slightly higher than that expected in a Pitot static tube. These two pressures are tapped closer to the central barrier and connected to an electronic sensing instrument. The flow direction is indicated by the sign of the pressure differential. Furthermore, the device is insensitive to the angle of flow up to about 50°. The tube is made of stainless steel allowing its use in more hostile environment such as explosions. Because of its angular insensitivity it provides a possible means to measure mean velocities accurately in explosions where flow angles cannot be known before hand. The bi-directional feature due to its symmetricity permits the probes to be positioned without prior knowledge of flow direction. However, the high velocities of gaseous explosions are likely to cause similar difficulties with respect to the accuracy as encountered with other Pitot tube based designs.

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2.2.2 Hot-wire Anemometry

The hot-wire anemometer operates on the principle of the rate of heat loss from a wire whose temperature is deduced from its resistance. Hot-wire anemometry is now a well-known and well-understood technique for fluid flow measurement eg [18]. The sensing element of the hot-wire anemometer is a small diameter wire (about 5 μm or less) made of tungsten, platinum, or platinum alloy and is usually between 0.5 and 3 mm long. The sensing elements are thus mechanically quite delicate and have excellent frequency response, providing an excellent measure of rms velocities. A typical design of a hot-wire anemometer is schematically shown in Figure 3. A hot wire placed perpendicular to a constant pressure gas stream will be sensitive to the mean velocity and the streamwise component of the turbulent fluctuations. The hot wire is also sensitive to temperature, density and composition fluctuations of the gas stream. The directional ambiguity can be removed by using a pulsed-wire technique, in which two fine platinum wires are mounted on hot-wire probes and placed parallel to each other. This parallel wire arrangement is very sensitive to flow direction.

Hot-wire anemometer has been used in internal combustion engines under non-combusting conditions, but the problems of interpretation of the measurements are complex, raising interpretation difficulties. Although this method is still being developed as a useful tool in combustion, given the delicate nature of its element, it is unlikely to be beneficial in explosions. However, the exception is that useful information may possibly be obtained using hot-wire anemometers up to the point of arrival of the flame.

2.3 OPTICAL TECHNIQUES

Optical techniques are invaluable in experimental combustion research because of their non-intrusive nature and their ability to produce instantaneous records of transient processes. They range from simple systems for flow visualisation to highly sophisticated techniques producing remarkably accurate measurements. Fundamentally simple optical systems such as shadowgraphy, deflection mapping and interferometry record refractive index variations and have over the years attained a wide range of applications, especially in premixed combustion studies. Further, refractive index distributions have been used to quantify properties of combusting flames eg [19-21]. The advent of the laser and the recent advances in electronics have broadened the scope of optical techniques, extending their measurement capabilities to properties such as velocity, temperature and concentration with good accuracy. Laser Doppler Anemometry (LDA), Particle Image Velocimetry (PIV), Laser Speckle Velocimetry (LSV), Particle Tracking Velocimetry (PTV) are all techniques which have received attention in the past. Unlike probe techniques, optical techniques do not disturb the flow. Moreover, it is easier to resolve the directional ambiguity and the techniques may offer excellent resolution and signal quality.

Due to its high frequency response LDA provides both mean and rms velocities. With the recent advances in both electronic and optical systems, the errors involved in the measurement are readily quantifiable. However, the use of LDA depends on optical access to the point of measurement and on the use of scattering particles. A further significant factor is the high cost of many optical measurement systems.

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2.3.1 Laser Doppler Anemometry

Laser Doppler anemometry takes advantage of the fact that the crossing of two coherent light beams give rise to an interference pattern. In general, the interference patterns are formed in three ways which are referred to as the dual-beam, reference-beam and two-scattered beam modes. Laser Doppler anemometry obtains the flow velocity since the associated physical processes can be described by displacements of the interference patterns by movements of scattering particles. Photodetectors are employed to detect these intensity variations and result in electrical signals with the frequency related to the velocity of the particles. A laser Doppler anemometer thus comprises a light source (laser), optical arrangements to transmit and collect light, a photodetector and signal processing arrangement.

In the reference-beam mode, the laser beam is split into an intense scattering beam and a weak reference beam. The reference beam is directed on to a photodetector where it beats with light scattered from the strong beam by particles moving with the flow. The frequency of the scattered light has been altered by the Doppler effect and the interference with the reference beam provides a frequency difference which is proportional to the particle velocity.

In the dual-beam mode, two intersecting light beams of equal intensity are used to produce a pattern within their volume of intersection. As each particle crosses the fringes, the intensity of light scattered onto the photodetector rises and falls at a rate directly proportional to the particle velocity. A typical dual-beam LDA system in forward scattering mode is schematically shown in Figure 4.

In the two-scattered beam mode, a single focused laser beam is directed into the flow and light scattered by a particle in two directions is collected symmetrically about the system axis. When the scattered lights are combined, the relative phase of their wave fronts depends on the distances of the particle from each light collecting aperture. Hence, as the particle moves across the beam the scattered light beams interfere constructively and destructively leading to a light intensity at the photodetector which fluctuates at the Doppler frequency.

In a recent development, LDA fibreoptic probes in backscattering mode have been introduced as a means to measure velocities in applications where access is difficult or the environment is hostile. Use of fibreoptic components enhance the application of LDA by expensive components, eg lasers, optics and signal processors, to be located remotely from the measurement point. A schematic of a one-component LDA system with a fibreoptic probe is shown in Figure 5. A fibreoptic probe consists of a compact head which has the necessary optics to collimate the transmitted beams from the fibreoptic cable, focus the beams to produce the measuring volume, and collect the scattered light onto a built-in receiving fibre. A photomultiplier finally receives the signal from the fibreoptic cable and sends for signal processing.

Signal processing system can be a spectrum analyser, a frequency tracker, frequency counter or a frequency processor. In a spectrum analyser a distribution proportional to the probability density distribution of the Doppler signal at a given point in the flow can be recorded. In order to obtain such a probability density function, a large number of particles must be observed which means that a long time will be required to acquire data at each point. Frequency trackers, on the other hand, are more convenient and faster to operate. Here, instantaneous frequency-to-voltage conversion is provided giving a real-time demodulation of the Doppler signal. They provide a continuous output signal even though the corresponding input signal is usually

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discontinuous. Care is needed in processing their data since low particle concentrations can preclude continuous signals. In a frequency counter, the period of the Doppler signal is measured by means of timing. A delayed trigger is employed to initiate the timing process once a signal burst has been detected and some form of logic circuitry is incorporated to reject false counts. Although this technique is excellent at high turbulence intensities in low particle situations, this requires a good signal-to-noise ratio. A frequency processor performs a fast Fourier transformation (FFT) of a digitised burst from which the frequency of the Doppler signal is determined. Doppler bursts are detected by exceeding a preset threshold amplitude of either the high- or low-passed output of the photodetector and the associated circuitry also provides the time occurrence of the signal and its residence time.

Selection of scattering particles plays an important role as the relative magnitude of the modulated and unmodulated components of the light scattered from a particle depends on the size of the particle and the ratio of this size to the fringe spacing. It is also important to find out the extent to which the particles of different diameter and density will follow the flow. Different seeding materials are used, eg water droplets, silicone oil droplets, TiO_2, Al_2O_3, MgO, which result in different particle diameters depending on the method of atomisation. Their suitability to the application depends on the particle diameters, material density and the index of refraction, since these parameters affect the amount light scattered onto the photodetector.

Laser Doppler anemometry has been successfully applied to measure the turbulence characteristics of flow fields developing during a gaseous explosion at laboratory scale [8]. The measured quantities include mean and fluctuating velocities and Reynolds shear stress. The main difficulty found was associated with the introduction of seeding particles. However, such problems were overcome by adopting appropriate experimental procedures for different types of particles. Another potential source of difficulty is related to the number of data acquired during any single experiment which may be too low to permit the accurate time-resolved determination of turbulence quantities.

2.3.2 Particle Image Velocimetry (PIV)

PIV is a technique in which particles and their images are used to determine the velocity field and its characteristics. The generic technique includes laser speckle velocimetry and particle tracking velocimetry. A typical PIV system is schematically shown in Figure 6. Particles in the fluid are illuminated by a sheet of light which is pulsed at regular intervals. The light scattered by the particles is focused by a photographic lens located at 90° to the sheet onto a photographic film or a video array detector. The images are subsequently transferred to a computer for analysis. This stage of analysing the recorded image field is the important step in this measurement technique. The coupling between the method of analysis and the acquisition process of the images determines the accuracy, reliability and spatial resolution of the measurements.

One of the advantages of the techniques is that structure and characteristics of complicated flow fields can be investigated at a particular instant in time as long as scattering particles are present. This contrasts with LDA, for example, where only a point-to-point analysis is feasible. However, this technique suffers from the fact that a large number of images need to be collected and analysed further which imply a large number of repeated experiments and in the case of turbulence measurements a high reproducibility. There is also the practical limitation imposed by the size of the sheet and the actual image area recorded. This is of particular

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importance in large scale experiments where the area covered by the present day PIV technique is negligibly small compared to the geometry scales. Thus the differences with between PIV and LDA (point-to-point) techniques become less apparent. Depending upon the mean concentration of scattering particles, its effects on the image field and the scales of the fluid field being measured, particle image velocimetry is divided into three different operating modes: *Laser Speckle Velocimetry, Particle Tracking Velocimetry and High Image Density Particle Image Velocimetry.*

In Laser Speckle Velocimetry, the concentration of scattering particles in the fluid is so large that the recorded images of the particles overlap. There are random phase differences between the images of the individual particles which are randomly located within the record. This results in the random interference patterns which are also called laser speckle. The determination of the velocity relies on the fact that the local speckle pattern is the superposition of images from a local group of scattering particles, and therefore it translates with the group of particles. The velocity is then measured through the measurement of the speckle displacement. Laser speckle velocimetry is a natural extension of similar techniques used in solid mechanics. In such techniques, coherent light scattered from solid surfaces, for example, naturally forms speckle patterns. The development of the Young's fringe method made it possible to analyse a double-exposed specklegram which consists of superposed speckle fields. In the Young's fringe method, an analysis spot on a double-exposed specklegram is illuminated by a laser beam. The speckle field from each exposure diffracts a light wave from the coherent interrogation beam which interferes with the other wave to form a Young's fringe pattern. The orientation of the fringes is perpendicular to the direction of the displacement and the spacing between the fringes is inversely proportional to the magnitude of the displacement.

Particle tracking velocimetric technique has its origins in flow visualisation techniques such as particle streak photography. In particle tracking velocimetry, the concentration of the scattering particles is so low that there is no possibility of obtaining overlapping images of the particles. Consequently, the images of the scattering particles are sparse and multiple exposures of the particles render tracks of the particles which are shorter than the mean spacing between the particles. The images of the individual particles are easily identified and displacements of these individual images can be measured to provide the velocity. In other words, the image of each individual particle is tracked as the particles move along with the flow. Directional ambiguity is usually eliminated by adopting an asymmetric time pattern (eg short-long-long-long) of the pulsing light source [22].

In practice, scattering particles in fluid flows are often not dense enough to create speckle patterns which may be used in laser speckle velocimetry. In high image density PIV, the concentrations of the scattering particles are usually between those required for LSV and PTV described above. Here the particle concentrations are large enough to ensure that every spot of analysis in the image field contains a number of images. However, the images do not overlap to produce laser speckle. It is tedious and time consuming to perform tracking of individual particles due to the abundance of images. Instead, displacements of small groups of particles are measured to determine the mean velocities.

A notable difficulty with PIV at present is the dynamic range of velocity measurements. The technique has so far been applied mainly to low-speed laboratory scale experiments where flow velocities do not often exceed 50 ms^{-1}. This means that the duration of each pulse of illumination and the duration between them can be longer without the risk of particles moving out of the field of view. The higher the velocity, however, the shorter should be the duration of the each pulse of illumination and shorter the duration between two successive pulses. This

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introduces practical difficulties associated with image acquisition (or recording) and processing when PIV is applied to high velocity measurements such as in gaseous explosions.

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3. VELOCITY MEASUREMENTS IN EXPLOSIONS

3.1 INTRODUCTION

The preceding sections highlighted the main velocity measurement techniques which have been successfully used in isothermal and steady combustion flows. In this section, a description of the velocity measurement techniques which have been used in gaseous explosions is presented. The review includes the details, as much as possible, of the instruments used and the experimental procedure adopted. It is hoped that this will indicate the possibility of extending their application to large scale explosions.

3.2 PROBE TECHNIQUES

Considering the difficulties outlined in Section 2.1, it is not surprising that virtually no velocity measurements have been performed in gaseous explosions using velocity probes. Only one instance can be found where the principle of pressure loss has been applied in estimating the unburnt gas velocity ahead of the flame front in vented explosions. Alexiou et al. [23] applied the pressure loss expression given for a 90° bend to that at the side vent to find the unburnt gas velocities prior to the flame exit from the tube. The experiments were performed in a cylindrical vessel of 162 mm diameter with a total length of 2.5 m. They used the pressure measured using a series of KELLER pressure transducers mounted on the wall of the explosion vessel. The accuracy of such a procedure is likely to be very low, as it, for example, ignores transient and compressiblity effects.

3.3 OPTICAL TECHNIQUES

3.3.1 Laser Doppler Anemometer

Laser Doppler anemometry (LDA) has been used to measure the velocities of gas flow induced by the flame propagation at laboratory scale [6, 24]. The experimental set-up consisted of a 10 m long tube with rectangular cross-section of 72 mm × 34 mm. Premixed stoichiometric methane–air mixture was used at ambient conditions. A baffle-type obstacle providing 50% blockage was placed in the path of the flame propagation and the flow field behind the obstacle was obtained through the velocity measurement.

The velocity measurement system is a standard dual-beam forward scatter laser Doppler anemometer. The key to velocity measurement in transient flow, particularly in one induced by flame propagation, lies in obtaining as many velocity realisations as possible within a very short period of time. The time involved in explosions is often in the region of 30–100 ms for premixed gaseous mixtures. Any measurement technique used under these conditions should include the following features:

- A frequency shift sufficient to measure negative velocities;
- Sufficient intensity of scattered light to produce a detectable signal;

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- A photomultiplier responsive to reasonably high frequencies;
- A signal processor whose time requirement for processing a Doppler burst is short enough to ensure its capacity to measure high frequencies;
- Fast data transfer to microcomputer without any loss of data.

The frequency shift, which is the difference in frequency between the two beams which make up the anemometer, is necessary for two reasons: one to provide directional sensitivity and the other to increase the frequency separation between the pedestal frequency and the frequency of the Doppler signal. The former refers to the reciprocal of the residence time of a light-scattering particle within the probe volume. By increasing the separation between this and the Doppler-shift frequency the pedestal frequency can be removed without the risk of losing the Doppler signal. The choice of frequency shift was, however, complicated by the nature of the problem being studied. The flow velocities at most of the points of measurement would be high in magnitude in both positive and negative directions and required a large frequency shift which could only be provided by a Bragg cell (acousto-optic cell). Thus, a fixed frequency shift of 40 MHz was applied to one of the beams via a Bragg cell. The rest of the transmitting optics consisted of a beam splitter with a lens of 600 mm focal length. The high focal length was chosen in order to increase the fringe spacing and hence the maximum velocity that could be measured.

The velocities in the kind of flow characterised by the present study are usually so high that the amplitude of the photomultiplier signals produced by the light scattered by the fast moving particles is small. Consequently, the signal-to-noise ratio (SNR) is usually low. This problem can be dealt with in two ways: one by using a high power laser and the other by increasing the gain of the photomultiplier and the signal processor. The first requirement was met by using a 1.5 W argon-ion laser operating in single-line mode at 514.5 nm wavelength. To satisfy the second condition, the photomultiplier tube was equipped with a pre-amplifier which was composed of fast responsive electronic components. The arrangement thus permitted the measurement of positive velocities up to 300 ms^{-1} and negative velocities up to 150 ms^{-1}.

The receiving optics consisted of collecting lenses which focused the scattered light from the probe volume onto a photomultiplier placed at an angle, through a pinhole of 0.1 mm diameter to control the amount of scattered light received. The photomultiplier signals were processed by a frequency counter (TSI 1990c; TSI Inc.). The experimental procedure and precautions taken to ensure correct operation of the counter and proper data acquisition are discussed in this section.

As mentioned earlier the frequency processor should provide fast processing of the Doppler burst to avoid loss of data. The TSI counter meets this requirement through two main features: namely, the maximum frequency measurable and the clock speed. The maximum frequency of the signals that TSI counter can process is of order 120 MHz and the clock frequency is 1 GHz. Since the frequency shift applied and hence the maximum frequency measured are high, the clock frequency is a decisive factor determining the accuracy of measurement.

The counter was digitally interfaced to the microcomputer via a purpose-built interface card. The 16-bit output of the counter contained the exponent and mantissa of the frequency of the validated Doppler burst. The time at which the Doppler burst occurred was also recorded. The interface card had an FIFO (First-In-First-Out) memory of 8 kilobytes to store the validated 16-bit digital frequency signals and 24-bit counter values generated by its 1 MHz timer. The data was transferred to the computer using DMA (Direct Memory Access) co-ordinated by the

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software. The transfer of three 16-bit words per measurement coupled with the 16-bit DMA transfer and sufficiently large FIFO memory ensured the high data transfer rate essential in high velocity measurement.

Two types of particles were used as seeding particles: silicone oil droplets and aluminium oxide particles. Silicone oil aerosol of 1 mm nominal size generated by an atomiser. The introduction of correct amount of particles needed some experimentation with the duration and the way of introducing the particles. It was found that the best location for the atomiser was the circulation loop of the flame tube. The duration of seeding was determined such that an optimum number of data could be accumulated during the explosion prior to the arrival of the flame at the point of measurement. Hence, the gas mixture was allowed to pass through the atomiser for the last sixty seconds of the gas circulation.

Aluminium oxide (Al_2O_3) particle seeding was used to measure velocities throughout the flame propagation process — including behind the flame front. The particles were introduced using a cyclone-generator based on the design of Glass and Kennedy [25]. The metal bellows pump used to circulate the gas mixture (to obtain homogeneity) can be damaged by the solid particles which can get between the welded joints of the stainless steel bellows and ultimately wear out the welding. Hence, the aluminium oxide particles were not introduced in the circulation loop in the same manner as for silicone oil droplets. The gas mixture was, therefore, prepared separately in the mixing chamber at 200 kPa. The flame tube was then evacuated to levels below 5 kPa and filled with the gas mixture from the mixing chamber. During filling the gas mixture was sent through the cyclone-generator so that the entire gas mixture was seeded.

As explained earlier, the data rate should be maximised for velocity measurement in transient flow. The data rate is directly proportional to the number of seeding particles available for measurement within the gas mixture. However, there is a compromise between maximising the number of data and saturating the probe volume with multiple particles at any one instant of measurement, since multiple particles within the probe volume result in erroneous measurements. Assuming that an optimum number of particles have been introduced into the gas mixture, the data rate is then controlled by the laser power which determines the amount of light scattered, and by the signal gain introduced on the receiving end. Hence, there are three variables which can be manipulated to increase the data rate: (a) the laser power, (b) the voltage applied to photomultiplier tube and (c) the gain selected on TSI counter. Maximising all these parameters together results in a noisy signal and hence a lower data validation and data rate. It was, therefore, necessary to optimise all three parameters such that a maximum data rate could be achieved. A large number of experiments were carried out systematically to determine the optimum settings of the parameters.

3.3.2 Particle Image Velocimetry

Particle Image Velocimetry (PIV) has been applied to obtain a two-dimensional imaging of the flow field occurring ahead of the flame propagating inside a small scale vented duct containing arrays of cylindrical obstacles [26]. The experiments were performed in a 2 m long 0.1 m high and 0.2 m deep, partially vented flame tube with near-stoichiometric methane-air mixtures.

In PIV, the flow is seeded and two short pulses of light sheet is generated which are separated by a known duration. The light scattered by the particles is recorded onto a suitable two-dimensional detector. From the recording the particle velocities could be determined. The field

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of view was approximately 25 mm × 25 mm. It was found difficult to use a three-pulse PIV technique, which would have eliminated directional ambiguity, due to great difficulty associated with the analysis code. Therefore, measurements could not be made within the recirculation zone. The duct contained an obstacle in the form of a rod in its middle section and the flow could be reversed. In view of the difficulties in relation to the measurements within the recirculation zone behind the obstacle, the measurement region was chosen to be about 6 mm downstream of the obstacle. The flow could be reversed and therefore the upstream conditions could be measured through the same window without having to relocate the PIV set-up.

About 100 repeated experiments were performed and the generated images were used for analysis. This raises the issue of reproducibility of the experiments. It is notoriously difficult to produce highly repeatable transient experiments, especially gaseous explosions. However, high reproducibility has recently been reported with laboratory scale gas explosions. When turbulence quantities are extracted from the measurements in flows associated with gas explosions, it is imperative that the shot-to-shot variations are quantified [8]. The data analysis must exclude such variations from turbulence quantities. Although turbulent velocity components were extracted from the measurements using PIV [26], the contributions from shot-to-shot variations were not quantified.

3.3.3 Phase Doppler Velocimetry

Phase Doppler Velocimeter (PDV) has been applied to measure particle velocities and their sizes simultaneously in water spray characterisation experiments by Catlin et al. [9] as part of their explosion mitigation experiments. The experiments were performed in a cubical compartment of 27 m^3 which housed a nozzle and water catchment area. This rig geometry was representative of off-shore modules. The cubical vessel contained a window to provide optical access required for the PDV system. The nozzle was mounted on a traversing bar so that the measurement position could be changed without having to move the laser. This is quite useful in PDV systems as the optical alignment is critical. The PDV system consisted of 5W (all lines) Ar-ion laser generating green light at 514 nm with 1.2 W power. A Dantec 58N10 signal processor was connected to three photomultipliers of the receiving optics, from which the diameter and the velocity of the water droplets could be determined. Catlin et al. [9] also report that the PDV measurements were sufficiently reproducible. However, they could not apply the technique for the explosion tests.

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4. RECOMMENDATIONS

4.1 INTRODUCTION

The present report has reviewed a number of velocity measurement techniques, ranging from simple mechanical probes to highly advanced state-of-the-art optical techniques. Main features of the techniques and their potential applicability to large scale explosions have been highlighted. The present section provides a summary of the velocity measurement techniques which are potentially useful in gas explosions and identifies those which warrant further consideration. An indication of the likely cost involved in their application to large scale explosions is provided. Final recommendations are given to indicate the directions in which further investigations are desirable in order to achieve the objective of mean and turbulence velocity measurements in explosion driven flows.

4.2 EXPERIMENTAL CONDITIONS

The experimental conditions assumed for the purposes of the present report are those corresponding to the full scale explosions performed under the Offshore Gas Explosions Phase 3A programme.

4.3 PROBE TECHNIQUES

Although velocity probes are still preferred for use in many development test-rigs and full-scale furnaces, their use in gas explosions is likely to be limited due to response related difficulties. Moreover, such probes are likely to have significant shortcomings with respect to the accuracy in measuring the high velocities involved in gaseous explosions. However, it is possible that velocity probes can be useful in measuring mean velocities during the early development of large-scale explosion driven flows. It is therefore recommended that consideration is given to the evaluation of velocity probes under relevant conditions by careful comparisons with existing velocity data obtained in gaseous explosions [8].

4.4 LASER TECHNIQUES

Among the non-intrusive techniques reviewed in this report it would appear evident that PIV does not offer advantages over LDA for measurements in large scale explosions. The dynamic range of PIV velocity measurements is at present limited and there are practical difficulties associated with image acquisition and processing. The technique is still being developed for much more benign experimental conditions and may eventually be fruitful in the context of gas explosions. However, the main disadvantage is the necessity for repeated experiments in order to deduce turbulence quantities and the time-history of velocity profiles. The latter quantities are determined naturally through the use of LDA. Finally, the field of view is most likely to be insignificant compared to the scale of the experiments.

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Laser Doppler Anemometry and, potentially Phase Doppler Anemometry can, with some difficulty, be applied to large scale explosions. The required laser power is an important consideration and arguably forms the single most important factor in determining the number of data acquired per single experiment. Naturally, a large number of data leading to a full time-history of mean and turbulence velocities at a point may be viewed as vital in expensive large scale explosions. The selection of scattering particles is another topic which merits attention and there must be an effective means of introducing such particles within the gas mixture at the beginning of an experiment. Silicone oil droplets provide an easy solution for the measurement of unburnt gas velocities. However, solid particles should be used if a complete characterisation of the velocity field is required. Alumina particles are an excellent choice as titanium oxide particles have been reported to produce a reduction in the data rate after the arrival of the flame. Water sprays which produce droplets of a sufficiently small size to follow the flow properly may also be used to provide appropriate seeding.

LDA can be operated in forward or back scattering modes. Forward scattering is normally preferred as it yields better signal quality. However, the back scattering technique is very attractive in the sense that the complete instrument can be placed at a single secure location. Furthermore, the use of fibre-optic cables offer the advantage that the risk of damage to expensive laser equipment can be minimised. In this context, the use of a compact back-scattering LDA system combined with fibre-optics provides a potentially ideal solution to the problems associated with the application of LDA to large-scale explosions. Expensive laser and optical components can be securely located and the fibre-optic probe placed in a shielded manner within the actual rig. Fibre-optic cables from the probe leading to the optics can be hidden within the obstacles and other parts of the experimental rig.

4.5 COST INVOLVED

The costs discussed below are only to be interpreted as indicative and may be the subject of significant change.

4.5.1 Velocity Probes

Pricing for velocity probes has been requested but has not been obtained at the time of writing of the present report.

4.5.2 Laser Doppler Anemometer

The "list price" cost of buying a new one-component LDA system with sufficient laser power, fibre-optics, fibre-optic probe and associated electronics is expected to be about £ 100,000. The price includes the cost of a 5 W water-cooled Argon ion laser, one component optical system with Bragg cell and fibre optic couplers, photo-multiplier, one channel signal processor and a fibre optic probe. The laser is capable of delivering 1.5 W power at a wavelength of 514.5 nm for which the fibre-optic probe has been designed. The fibre optic connections can handle up to 1 W and it means that at 514.5 nm this arrangement can (after beam splitting) cope with the maximum power the laser can deliver. The fibre-optic probe costs about £ 15,000 and

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may be considered to be the only component vulnerable during measurements in full-scale explosions. However, unlike mechanical probes there is naturally no need for physical contact with the flow field. The only additional consumable cost is associated with seeding particles. The main maintenance cost is related to the servicing of the laser.

4.6 FINAL RECOMMENDATIONS

In view of the above discussion, it is clear that despite the simplicity and cost-effectiveness associated with velocity probes, such probes have not been tested for use under transient high velocity conditions. The accuracy and temporal response of such probes should be clearly established before their application to large scale gaseous explosions. Failure to do so may result in the dissemination of erroneous or misleading information. Thus, it is recommended that as a starting point tests are carried out using (commercially) available mechanical probes in laboratory scale gas explosion experiments for which reliable (LDA based) velocity measurements exist [8]. Such an investigation would enable an informed decision to be made as regards to the accuracy of such probes under the high-velocity compressible flow conditions typical of gaseous explosions. Pending the outcome of such an investigation the implementation of such probes in full scale experiments is not recommended.

Given the difficulties associated with many optical techniques, including LDA, as applied to gas explosions, the potential promised by back-scattering LDA fibre-optic probes should be explored further. The option combines simplicity and safety with all the advantages offered by Laser Doppler Anemometry. Most of the expensive equipment components can be located remotely from the measurement point. In order to assess the technique, it is recommended that tests are initially carried out in laboratory scale gas explosion experiments to establish its feasibility and to identify any related difficulties. Nevertheless, the achievable laser intensities are similar to those used by Lindstedt and Sakthitharan [8] in their laboratory scale measurements and the prospects of success must be viewed as good. Thus this technique would at present appear the only viable option for the measurement of mean and turbulence velocities in full scale explosions. However, it must be noted that the costs of this state-of-the art technique are considerable.

Given the complex scaling behaviour of gas explosions a knowledge of flow field characteristics for large scale explosions are at a premium. However, the cost of such experiments is significant to the point of being prohibitive for more than comparatively isolated measurement points. Thus further consideration should be given to complementary small (laboratory) scale measurements aimed at producing data suitable for the development and proper evaluation of the physics of explosion models. Such data sets should ideally be produced after appropriate consultation and within an industry-wide framework to facilitate their dissemination.

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REFERENCES

1. Strehlow, R A
Unconfined Vapour-Cloud Explosions — An Overview
Proc. 14th Symp. (Intl) on Combustion, The Combustion Institute, Pittsburgh, pp 1189 – 1200, 1973

2. Gugan, K
Unconfined Vapour Cloud Explosions
The Institution of Chemical Engineers, London, 1979

3. Bangash, M Y H
Impact and Explosion: Analysis and Design
Blackwell Scientific Publications, Oxford, pp 46 – 49, 1993

4. Lenoir, E M and Davenport, J A
A Survey of Vapour Cloud Explosions: Second Update
Process Safety Progress, Vol. 12, No. 1, pp 12 – 33, 1993

5. Health and Safety, Commission
Advisory Committee on Major Hazards
HMSO, London, First Report, 1976

6. Health and Safety Commission
Advisory Committee on Major Hazards
HMSO, London, Second Report, 1979

7. Health and Safety, Executive
A Guide to the Control of Industrial Major Accident Hazards Regulations 1984
HMSO, London, HS(R) 21 Series, 1990

8. Lindstedt, R P and Sakthitharan, V
Time-resolved Velocity and Turbulence Measurements in Transient Flame Driven Flows
To appear in Combustion and Flame

9. Catlin, C A, Gregory, C A J, Johnson, D M and Walker, D G
Explosion Mitigation in Offshore Modules by General Area Deluge
Transactions of Institution of Chemical Engineers, Volume 71, Part B, pp 101–111, 1993

10. Durst, F, Melling, A and Whitelaw, J H
Principles and Practice of Laser-Doppler Anemometry
Academic Press, London, 1981

11. Adrian, R J
Particle-Imaging Techniques for Experimental Fluid Mechanics
Annual Review of Fluid Mechanics, Volume 23, pp 261–304, 1991

Contents

12. Meynart, R
Equal Velocity Fringes in a Rayleigh-Benard Flow by a Speckle Method
Applied Optics, Volume 19, pp 1385–1385, 1980

13. Adamczyk, A A and Rimai, L
2-Dimensional Particle Tracking Velocimetry (PTV): Technique and Image Processing Algorithms
Experiments in Fluids, Volume 6, pp 373–380, 1988

14. Young, A D
Note on the Effect of Compressibility on Jone's Momentum Method of Measuring Profile Drag
Aeronautical Research Council Reports and Memoranda, Volume 1881, 1939

15. Becker, H A and Brown, A P G
12th Symp. (Intl) on Combustion, The Combustion Institute, Pittsburgh, pp 1059–1068, 1968

16. Heskestad, G
Bi-directional Flow Tube for Fire Induced Vent Flows
Appendix K in Crose, P A and Emmons, H W *The Large-scale Bed-room Fire Tests* July 11, 1973 Factory Mutual Research, FMRC S/N 21011.4. July 1975

17. McCaffrey, B J and Heskestad, G
A Robust Bidirectional Low-velocity Probe for Flame and Fire Application
Combustion and Flame, Volume 26, pp 125–127, 1976

18. Bradshaw, P
An Introduction to Turbulence and Its Measurement
Pergamon Press, Oxford, 1971

19. Weinberg, F J
Geometric-Optical Techniques in Combustion Research
Progress in Combustion Science and Technology, Volume 1, pp 111–144, 1961

20. Weinberg, F J
Optics of Flames,
Butterworths, London, 1963

21. Merzkirch, W.
Flow Visualization
Academic Press, London, 1987

22. Marco, K A and Rimai, L
Video Recording and Quantitative Analysis of Seed Particle Track Images in Unsteady Flow
Applied Optics, Volume 24, pp 3666–3672, 1985

23. Alexiou, A, Andrews, G E and Phylaktou, H
Side-vented Gas Explosions in Long Vessel: The Effect of Vent Position
Journal of Loss Prevention in Process Industries, Volume 9, pp 351–356, 1996

Contents

24. Sakthitharan, V
Time-Resolved Measurements of Flame Propagation over Baffle-type Obstacles
PhD Thesis, University of London, 1995

25. Glass, M and Kennedy, I M
An Improved Seeding Method for High Temperature Laser Doppler Velocimetry
Combustion and Flame, Volume 29, pp 333–335, 1977

26. Lindstedt, R P, McCann, H, Sakthitharan, V, Puttock, J S, Snowdon, P, Yardley, M and Chynoweth, S
Detailed Experimental Measurements of the Effects of Obstacles and Pre-ignition Turbulence of Explosions
Final Summary Report for EMERGE. EC Contract EV5V-CT93-0274, pp 94–110, 1996

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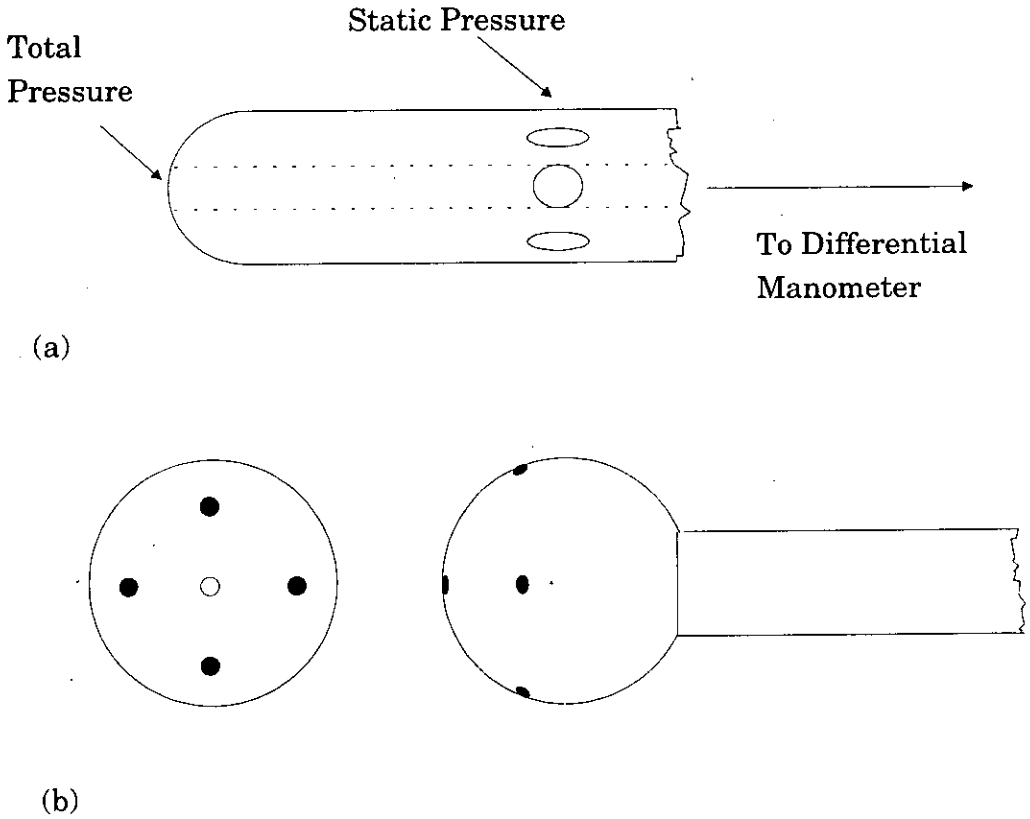

Figure 1
Schematic of (a) the conventional Pitot-static probe combining Pitot tube with a Prandtl static pressure probe, and (b) a five-hole ball-head probe

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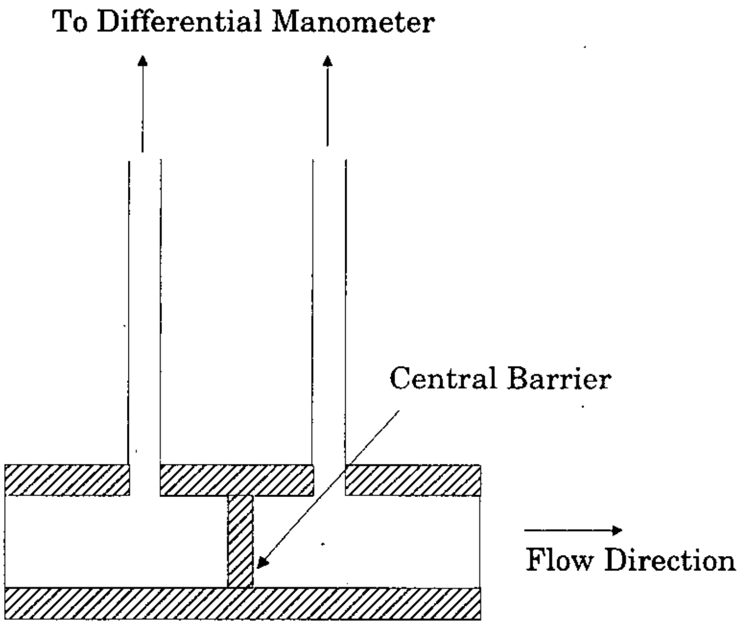

Figure 2
A bi-directional low-velocity robust probe based on the Darcy's modification to the conventional Pitot tube

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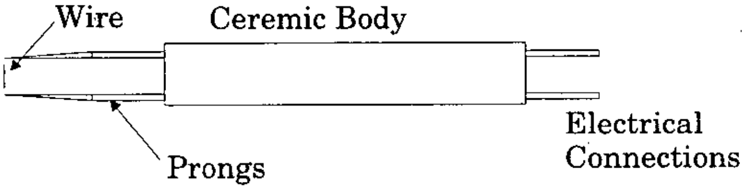

Figure 3
Typical design of a hot-wire anemometer

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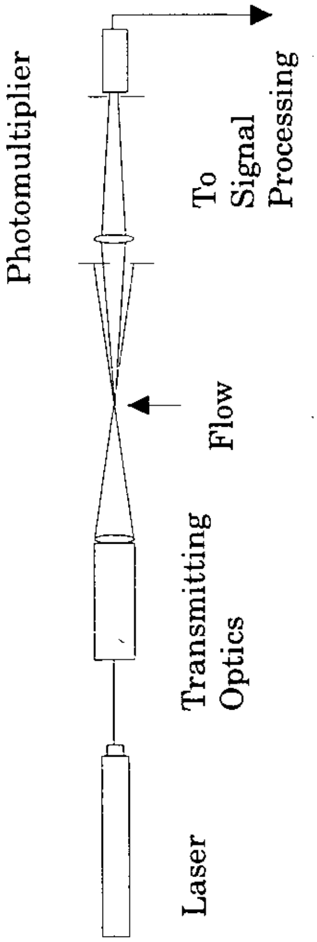

Figure 4
Schematic of a typical dual-beam forward scattering Laser Doppler Anemometer

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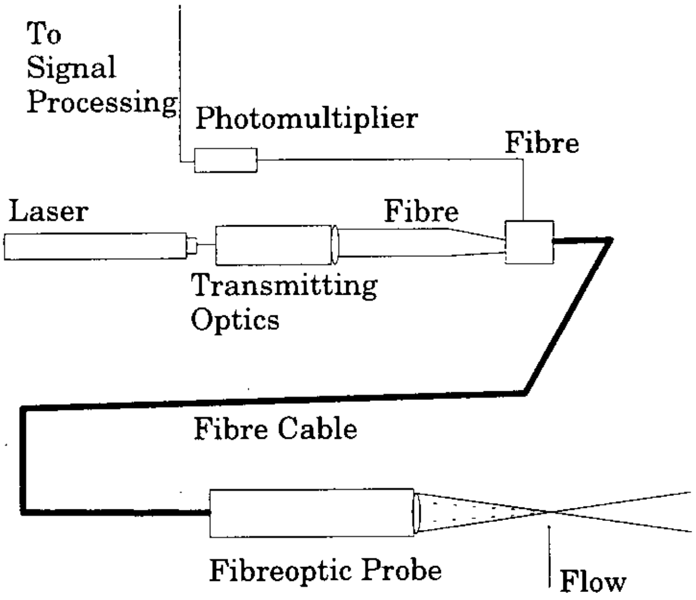

Figure 5
Schematic of a typical dual-beam back scattering LDA fibreoptic probe

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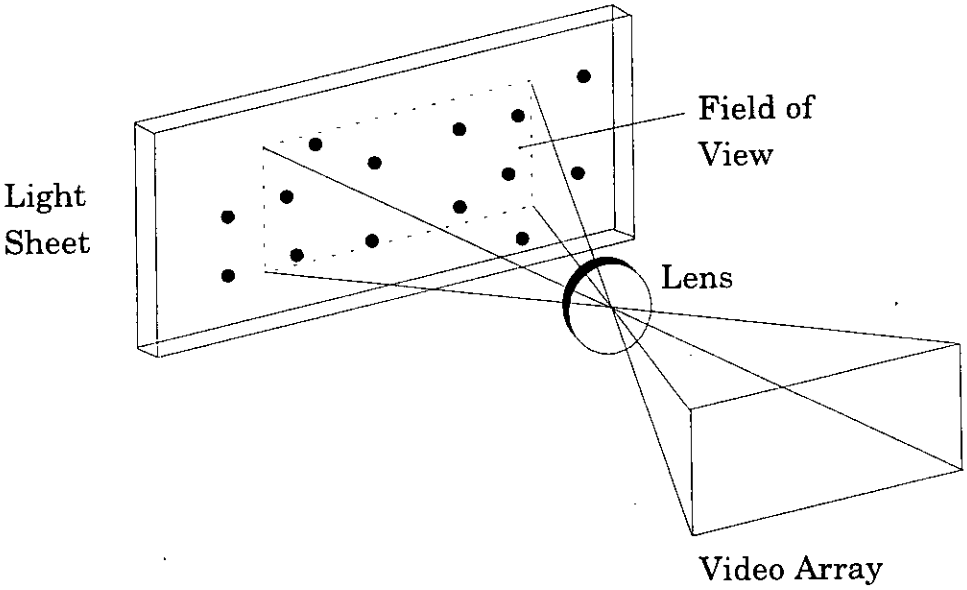

Figure 6
Optical arrangement of a planar particle image velocimeter

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