(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
25 January 2001 (25.01.2001)

PCT

(10) International Publication Number
WO 01/06216 A1

(51) International Patent Classification[7]: G01F 1/708

(21) International Application Number: PCT/GB00/02742

(22) International Filing Date: 17 July 2000 (17.07.2000)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
9916932.8 16 July 1999 (16.07.1999) GB

(71) Applicant and
(72) Inventor: FUNES-GALLANZI, M [GB/GB]; Photon Imaging, 21 Crescent Gardens, London, Greater London SW19 8AJ (GB).

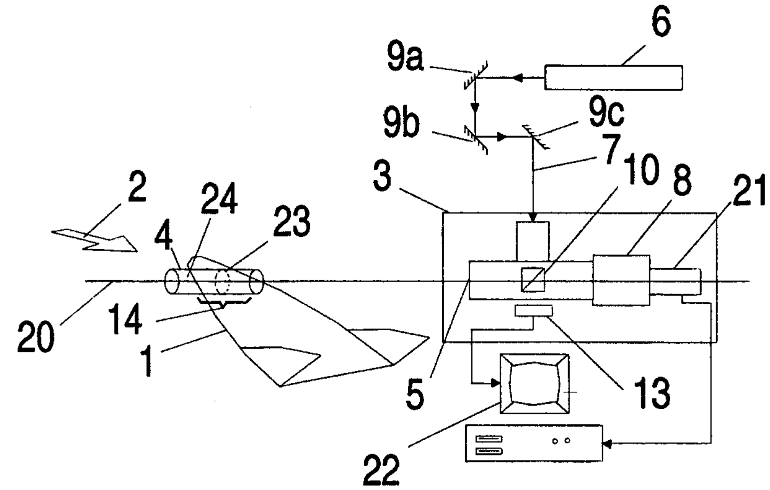
(81) Designated States *(national)*: CA, JP, MX, US.

(84) Designated States *(regional)*: European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published:
— *With international search report.*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: METHOD AND APPARATUS FOR INVESTIGATING FLUID FLOW VARIABLES, ELEMENT CHARACTERISTICS AND NEARSURFACE TEMPERATURE AND FORCES



(57) Abstract: A flow field seeded with elements is illuminated by a shaped light beam (5) introduced into the optical axis (20) of a video detector (21) by a polarising beam-splitter (10). The laser is pulsed and (21) records multiple element scattering images, after going through a lens (8). Images are then processed to extract the velocity field and/or aerosol characteristics. To measure of viscosity, pressure, density, and velocity, three seeding populations of varying size are used to derive a set of simultaneous equations, together with the perfect-gas law. Furthermore, the remaining portion of the light beam not striking any seeding can be used, in conjunction with parameter-sensing paints, to record back-surface temperature/pressure, or PSP/TSP data can be recorded of luminescence created by an external excitation source. This apparatus is capable of providing real-time, 3D aerodynamic together with back-surface heat transfer/pressure information, simultaneously through a single integrated modular measurement means.

WO 01/06216 A1

Title: METHOD AND APPARATUS FOR INVESTIGATING FLUID FLOW VARIABLES, ELEMENT CHARACTERISTICS AND NEAR SURFACE TEMPERATURE AND FORCES

Description of Invention

This invention relates to an apparatus and method of investigating fluid flow containing elements from which energy directed onto the elements may be reflected or from which energy is emitted as a result of energy being directed onto the elements. The elements may be elements of the fluid, or elements seeded into the flowing fluid to aid investigation and may be simple reflecting elements or elements emitting energy, and may also be the object of investigation where their characteristics are unknown. The invention also relates to the apparatus herein described also being capable of separating the information from each population of elements, where more than a single population of elements having a common set of characteristics are used, and the method to derive fluid velocity, density, viscosity, temperature and pressure in three dimensions. The invention also relates to the apparatus herein described also being capable of separating energy coming from a surface, coated with a parameter-sensitive coating, as a result of energy being directed onto the surface, either by the said apparatus or an external source, and the method to combine fluid flow information with surface parameter data.

An explanation in fluid mechanics to describe the realities of unsteady flow implies the capacity to make non-intrusive, instantaneous and simultaneous flow measurements of the four fluid variables: velocity, temperature, density and pressure, in all three dimensions, along with body surface pressure/temperature distributions, in some cases.

Methods are known for investigating surface parameters, such as pressure/temperature. In particular, Pressure/Temperature Sensitive Paints (PSP/TSP) offer a unique and inexpensive means of determining body surface pressure and temperature distributions. These distributions are impossible to obtain using conventional measurement techniques at a comparable measurement density, are critical for understanding complex flow mechanisms, and allow direct comparisons with results from computational fluid dynamic (CFD) calculations. The cost of the PSP/TSP technique is competitive in comparison to the cost of pressure/temperature transducers. Not only is the cost of installing these conventional probes an issue as well as their size, but the aerodynamics and structural dynamics of the component can be seriously altered by modifications to accommodate such transducers. Data rates for PSP/TSP are also faster than for conventional techniques.

In turbomachinery for instance, prediction of the heat transfer to blade and endwalls is particularly important for an accurate assessment of turbine component life. On the endwalls, there are complex 3D flows present, which make predictions of heat transfer difficult. In order to increase thrust-to-weight ratios and achieve maximum cycle efficiencies with gas turbine engines it is necessary to raise the cycle temperatures to the maximum, within constraints of structural integrity. Thus, the need to understand in detail and predict accurately the heat transfer distributions for high-pressure turbines becomes an important factor. The presence of complex highly three-dimensional secondary flows within the turbine passage makes the turbine designer's task very difficult and requires accompanying detailed aerodynamic information. Moreover, in turbulent flow conditions, where free-stream turbulence is high, heat flux on the blades is largely controlled by free stream eddies of large size and energy reaching deep into the blade's boundary layer. Furthermore, flutter is an aeroelastic interaction between a fluid and objects, which induces vibrations. These vibrations can cause blade failure, and hence endanger turbomachines and aircraft.

Aerodynamic structures such as aircraft and aircraft components are commonly tested in a wind tunnel to gather data for use in verification of characteristics and in design improvements. Various quantities are measured in wind tunnel testing including, for example, the pressure distribution at the surface of the structure. The pressure information is used to calculate air flows and force/pressure distributions over the structure. Thus, the aerodynamic structure is effectively "instrumented" for wind tunnel testing by painting it with a PSP, illuminating the structure with the required wavelength of radiation, and measuring the luminescence and light output intensities over the surface of the model using an optical imaging system. However, these measurements are often made over the entire structure and, if corresponding fluid flow information is required, it can be difficult to achieve registration between PSP data and aerodynamic information. Dual-purpose coatings for simultaneous TSP/PSP measurements are possible, and currently under development and refinement by a number of research groups. A variation of this is used to produce surface-shear-stress-sensitive coatings. Liquid crystal coatings contain molecules that scatter incident white light as a spectrum of colours. For a fixed/oblique-view observer, the colour-change response is dependent on both the magnitude of the shear force and the relative in-plane view angle between the shear-vector and the observer. These methods, however, generally use multiple light-sources and multiple-camera detection assemblies, and therefore require ample optical access to the region under test, whereas a small region (such as transition, stagnation, wakes, etc.) are often of interest. They are also not used in an integrated apparatus to measure surface parameters together with fluid parameters.

A variety of techniques have evolved through time to attempt to achieve the goal of fluid variable measurement. The most relevant published material is included at the end of this description in a bibliography. Some are able to measure intrusively by point measurements like pressure probes. Others are non-intrusive but integrate in one of the three dimensions, like interferometry, which can be used to measure density, temperature and pressure. In the last few years, a lot of successful development effort has been oriented towards measuring the fourth variable: velocity.

Existing methods of measuring flow velocity in wind tunnels, for instance, are mainly based on single-point Laser Doppler Velocimetry (LDV) and Laser-2-Focus (L2F) velocimeters, in their various versions. These techniques, including those which measure particle size and velocity, require scanning over the region of interest to obtain a whole-field velocity measurement and are therefore time-consuming and primarily effective for steady flows.

For unsteady turbulent flows several methods of whole-field measurement have been proposed, such as Doppler Global velocimetry and variants thereof, Laser Induced Fluorescence, and Particle Image Velocimetry. The last technique normally referred to by its acronym: PIV has been shown to work in hostile industrial environments.

The technique of PIV is a whole-field method of measuring fluid velocity almost instantaneously. This approach combines the accuracy of single-point methods such as LDV with the multi-point nature of flow visualisation techniques. Typically (see Figure 1), a double exposure of the light scattered by elements **24** introduced into the flow **2** as seeding, when lit by a pulsed light source forming a thin light-sheet **27**, is recorded by a detector **21** such as a film camera with a lens **8** during a sampling period. The viewing position lies orthogonal to the light-sheet plane, and so the scattered energy received is due to side-scatter from the seeding elements. So, the recording contains pairs of element images, where the displacement between the element images encodes the velocity field. Methods making use of element displacement between light pulses for the measurement of velocity are also known as Particle Tracking Velocimetry (PTV), where multiple particle tracks are used to reconstruct the velocity field. A variation of these methods is known as laser-speckle velocimetry (LSV). In LSV, the concentration is so large that element images overlap in the image plane, and it is to be understood as a special case, though it is not normally found in experimental fluid mechanics due to the high seeding concentrations required.

An analysis system is then employed which measures velocity from the motion information, given knowledge of the pulse separation between the first and second light pulse.

PIV and related variations thereof suffers from several major disadvantages as a technique.

Firstly, the need for orthogonal viewing of the light sheet places severe restrictions on the applicability of the technique, as many flow fields of interest do not allow the required optical access. Secondly, the technique is intrinsically a 2D technique since a thin light sheet in normally used. Thirdly, the separation between the light-sheet generation optics and the viewing optics means that the viewing optics need to focus and align on to the light-sheet plane and this process is therefore a source of experimental constraint and errors. Fourthly, seeding side-scattering efficiency is very low compared to back scatter and forward scatter. Finally, it cannot cope with arbitrary magnitudes for the velocity components in all three dimensions, for a given viewing position, the largest velocity component needs to lie in-plane as otherwise the element transit time through the light sheet severely limits the technique's accuracy.

Alternative techniques for the three-dimensional investigation of fluid flow have been proposed, at the cost of increased complexity. These techniques involve scanning light sheets, multiple light-sheets, graded intensity light-sheets, multi-focus arrangements on light sheets, stereoscopic views, holographic recording, or mixtures thereof.

However, these methods mostly still look at a light sheet orthogonally, and consist of essentially two modules: one the light delivery module and a stereo camera arrangement, which have to be correctly placed in relation to each other and calibrated. Moreover, for practical applications, restricted optical access eliminates stereoscopic approaches. Robustness, the need for measurement of the absolute energy level emitted by the elements, speckle noise limitations, and the need for real-time results make holography an unattractive option. Finally, scanning/multiple light sheets are difficult to operate with restricted optical access and high-speeds. Therefore, in industrial applications, film and Charge-Coupled-Devices (CCD) single-camera arrangements have predominated, with stereoscopic arrangements being used where optical access allows. In general, errors reported in practical experiments for all these methods are unacceptably high.

Another recent development in this area, Forward Scattering PIV, is a microscopic technique, which uses forward-scattering information to yield 3D element position information, though only within the instrument itself. However, it has a very limited field-of-view, alignment and optical access problems.

An even more recent development is that of Three-State Anemometry (3SA), a derivative of PIV, which uses a combination of three monodisperse sizes of seeding to yield velocity, viscosity and density, by the differential paths of each seeding population. From the viscosity information, temperature can be derived in air and water, and by using the perfect-gas law thermodynamic pressure too can be inferred. Here, for the first time, a technique was proposed which aims to make non-intrusive, instantaneous and simultaneous measurement of all four variables in a fluid flow. However, this technique also suffers from the same experimental deficiencies as PIV.

There is a need therefore, to provide an apparatus for investigating an arbitrary velocity field which minimises alignment/experimental errors, can be operated in real-time mode, is intrinsically 3D, and with single optical-access requirements. Also desirable is the capacity to measure temperature/forces of near-surfaces, using a single apparatus able to derive fluid flow and surface data. The present invention is based on the task of providing a method to solve the disadvantages of conventional PIV, 3SA, and parameter-sensitive coatings. The method and apparatus herein described is capable of making 3D fluid variables and near-surface parameter measurements simultaneously in a non-intrusive optical method. It is also desirable to provide a method by which light, when hitting a surface near and/or beyond an investigation volume can be blocked from coming back along the direction of the optical axis and mix with the elements' scattered light, thereby reducing the visibility of such elements.

According to a first aspect of the invention I provide a method of investigating fluid flow containing elements which reflect or emit energy in response to energy being directed onto the elements, the method including directing a first pulse and subsequently a second or more pulses of radiant energy along a path, each to intersect a volume of the fluid flow, means being provided to regulate said radiant energy intersecting said volume, from almost all of the energy emitted by the energy source down to a negligible amount, positioning energy detecting means in a region outside of the fluid flow, detecting with the detecting means energy scattered or emitted from the elements for each pulse whereby an image of the elements of the intersected volume is detected for each pulse, including providing means to maximise the amount of energy reflected or emitted from the elements falling on the detecting means, and investigating the images to determine displacements of the elements occurring between energy pulses, and wherein the method includes positioning the detecting means to detect energy scattered or emitted from the elements in a direction coincident with the path along which the radiant energy is directed to intersect with the volume of the fluid flow.

Thus, using a method in accordance with the invention a single access point for both the directed and detected energy only is required, and intrinsically, the detecting means can receive energy scattered or emitted from elements moving within the volume rather than only from a plane, as is the case with a conventional PIV apparatus, and by the nature of the arrangement alignment problems are also resolved. By maximising the radiant energy intersecting a volume of the fluid flow and also maximising the energy falling on the detecting means, the method can be applied to unsteady high-speed flows that require small element diameters. The method of the invention may be made relatively simple compared with existing proposals which require apparatus with multiple detecting means and/or multiple energy directing means, or complex multiple optical access holographic capability.

By determining motion of the energy emitting or reflecting elements from analysis of the images, and by knowing the duration between pulses, a measure of the velocity of the elements in the volume of the fluid flow into which the radiant energy is directed may be determined.

Preferably the radiant energy is coherent polarised light, such as laser light which is reflected from the elements in the volume of the fluid flow under investigation.

Preferably the method used to regulate the radiant energy intersecting a volume of fluid flow and to maximise the amount of energy falling on the detecting means uses manipulating polarisation through the use of retarding plates and a beam deflecting means sensitive to energy polarisation. Preferably prior to the energy impinging upon the deflecting means, the polarised energy is passed through a half-wave plate, the method including adjusting the half wave plate to vary the magnitude of the energy directed to the investigated volume of the fluid flow e.g. to a level such that the level of energy reflected or emitted from the elements in the fluid flow, is appropriate for the detecting means or provide a reference beam for holographic recording. Preferably the method further includes circularising the polarised radiant energy which is directed to the investigated volume e.g. using a quarter wave plate located to receive the polarised energy from the deflecting means. By positioning the quarter wave plate in such a position, the quarter wave plate will also effect a further phase rotation on the energy reflected from the reflecting or emitting elements, thereby maximising energy transmission through the deflection means to the detection means, where said beam deflecting means transmits or reflects light according to polarisation, thus allowing for light to be directed towards said volume or to the detecting means depending on beam direction and polarisation.

Preferably the method uses a collimated beam of radiant energy to intersect the volume of the fluid flow under investigation. However, other beam shapes might be more desirable where high sensitivity is required such as a spherical beam.

The method may include shifting the phase of the radiant energy so that energy transmission through the deflecting means to the detecting means beyond is enhanced. This can be accomplished for instance by the use of a tilted full-wave retarder plate. This may be specially important to compensate for the slight tilting of wave plates and other components required to ensure that secondary reflections are not directed to the detecting means.

Whether the energy received by the detecting means is reflected or emitted from the elements in or of the fluid flow, the detecting means may also include an imaging means to enable multiple images of the elements in the investigated volume to be recorded for investigation, one image for each pulse and/or one image for selected frequencies ranges of energy. Most conveniently, the detecting means includes a charge-coupled device, such as a video camera, but could comprise a film/hologram or other chemical based means, and the detecting means may include a filter means so that primarily energy in a selected frequency range is received. Thus, for example the detecting means may discriminate between energy reflected from the elements in the fluid flow, and energy emitted from near surfaces.

Preferably the radiant energy is generated by a source located away from the path along which the energy is directed to the investigated volume of the fluid flow, and the radiant energy thus produced is deflected along the path e.g. by a deflecting means being a polarising beam splitter for example only, to the volume of the fluid flow to be investigated.

In a preferred arrangement, in order to produce the at least two pulses, a shutter in the path of the directed energy is opened and closed twice, although in another arrangement, a source of the radiant energy may be of the kind able to produce the pulses.

Where a shutter is provided, the method may include positioning and operating the shutter in a position prior to the energy being deflected along the path to intersect the volume of the fluid flow, and preferably before any shaping or other beam manipulation.

It will be appreciated that upon analysing an image for each of two pulses of energy directed to the investigated volume, whereas spatial movement may be determined, it may not readily be apparent which way the element moved, i.e. there is an 180° degree ambiguity in velocity. Accordingly, to determine unambiguously element and hence fluid velocity, a means of resolving such directional ambiguity is required.

Thus, the method may include artificially displacing the image for the first or second pulse, a predetermined amount, and subsequently during image analysis accounting for the artificial displacement thereby enabling directional ambiguity to be resolved.

Such artificial displacement of the image may be achieved by inserting between the deflecting means and the detecting means, a switchable image shifting device, such as a Ferro-electric liquid crystal cell or Pockels cell, and a calcite plate, and switching the device between the first and second pulse to displace the second image relative to the first image by an amount depending on the thickness of the calcite plate.

Depending on the position of the fluid flow relative to a wall of a fluid flow containment vessel, during the method, directed energy which passes the elements in the fluid flow without impinging upon the elements, may be reflected back from the wall of the containment vessel or other near surface.

Thus the method may include treating and/or configuring near-surfaces to prevent or at least reduce energy reflections or emissions from said surfaces to the detecting means. For example, surfaces may be coated with an energy absorbing coating, a fluorescent coating which re-emits energy whose frequency can be separated from that reflected or emitted from the elements, or have energy absorbing cavities therein.

The method also may include, where energy is required to be absorbed by a near-surface, providing an energy absorbing cavity consisting of a filtering angle-dependent means to allow into the cavity the frequency to be absorbed, energy deflecting and reflecting means, positioned so the reflected energy impinges on the filtering means at an angle which no longer allows for its transmission and is therefore repeatedly reflected within this cavity.

In another arrangement the method may include providing beyond the fluid flow, a surface which is treated to reflect or emit energy as a result of the directed radiant energy impinging thereon, in a known frequency range, and providing a filter to filter out such energy in the known frequency range, to negate any deleterious effect such energy may have on the investigation of the fluid flow.

However if desired the detection means may be tuned to receive reflected or emitted energy from the surface, so that images of the elements in the fluid flow may be recorded for analysis using such so-called forward scattered energy. If the back surface is a specular surface, for example only, energy can be reflected by the surface and strike the elements on their path back along the optical axis, yielding a forward-scatter image of each element as well as a back-scatter image. However, since forward scattering is normally much larger than back scattering, the detector sensitivity can be adjusted so that only forward scattering is recorded.

The method may include investigating the element images recorded by the detecting means to derive any unknown element characteristics, such as element size element refractive index or fluid refractive index, by using a model such as Lorenz-Mie theory, for example only, to solve by comparison to said element image for position as well as said unknown element characteristics. In the case of fluid refractive index, where the fluid is air for instance, and by knowing the element refractive index, it is possible to calculate from the element image the fluid refractive index as said image is dependent on the ratio of the fluid to element refractive indexes. For air, the refractive index is related to temperature. Therefore, it is possible to derive air temperature from element images if the element refractive index is known.

In another arrangement the method may include means for stereo viewing, which may be required in cases where two regions of fluid flow need to be recorded simultaneously or where element density is such that high energy illumination of a volume of interest only within the fluid flow is required. Such viewing arrangement may be accomplished by providing means to direct energy being redirected away from a primary path along which radiant energy is directed to intersect with the volume of the fluid flow by a first beam deflecting means as an input to a second beam deflecting means coupled to a second detecting means, capable of being oriented in any desired direction, such that a secondary path is created, along which the secondary detecting means can record element reflected or emitted energy.

The method may include providing a means to separate part of the radiant energy with a regulating means into an object beams to intersect volume of the fluid flow and a reference beam, recombining said beams to travel along a common path, replacing the detecting means with a holographic recording means, and thus obtaining a holographic recording by the interference of the object and reference beams.

Thus, where holographic recording is used, the method may also include providing a means to direct the reference beam to impinge on the holographic recording means at an angle relative to the object beam, thus obtaining an off-axis holographic recording.

According to a second aspect of the invention the method may be adapted to investigate surface parameters such as temperature and/or pressure either alone or in combination with fluid velocity. This may be achieved by providing surfaces in or beyond the fluid flow, with a coating, such as a suitable temperature and/or pressure sensitive paint, whose energy reflecting or emission characteristic changes with temperature and/or pressure, the detecting means being adapted to recognise the energy reflecting or emission characteristic thus to determine surface parameters such as temperature or pressure. Energy from an external source to the apparatus or energy directed onto the volume of fluid flow not scattered by the seeding can be used to illuminate said surface. This can be achieved by placing a colour-sensitive deflecting means, such a dichroic beam deflecting means, along the optical path so that the apparatus is able to direct PSP/TSP energy to one detector and element energy to a separate detector(s). If an alternative source of energy is used to excite the PSP/TSP coating, the apparatus can still be used to detect the energy emitted by the said surface. The advantage of such an arrangement is that conventional whole-body, multiple-camera PSP/TSP data, obtained over the entire body of an aircraft model for instance, can be matched to the information this apparatus yields. By obtaining real-world co-ordinates of the near-surface being investigated together with apparatus position, the PSP/TSP data obtained from using the apparatus herein described can be related to those obtained from whole-body PSP/TSP data as well as to the fluid flow variables also obtained from using the apparatus herein described. Thus, in cases where transition, boundary-layer/shock or vortex/surface interactions, stagnation points, etc. are being investigated, whole-body pressure/temperature data can be matched and complemented by aerodynamic data obtained by this apparatus, through the common surface region PSP/TSP measurement which would appear in both data sets.

In another arrangement the method may include the use of conventional thermal imaging techniques applied to near surfaces to complement the fluid velocity information using an infrared camera, instead of the PSP/TSP coating on a near surface.

According to a third aspect of the invention the method may also include providing in the fluid flow first reflecting/emitting elements which reflect/emit energy at a given frequency range, and further sets of elements which reflect/emit energy of other frequencies. The method may include detecting each set of elements' energy in a detection means separate from detection means for detecting other elements' energy.

Alternatively, each set of elements may be separated according to their image as recorded onto the detector means, i.e. the scattering field. Moreover, since detectors such as CCDs, have a frequency dependent sensitivity, each element population will have image characteristics on the detector's plane depending on emitting/reflecting element energies at different frequencies.

The method may be used to investigate the density and/or viscosity and/or pressure of the fluid of the fluid flow by seeding the fluid flow with at least first energy reflecting or energy emitting element population, second energy reflecting or energy emitting element population, and third energy reflecting or energy emitting element population, the first elements having a lower Stokes number than the second and third elements, the first element population being adapted to follow the fluid flow whilst movements of the second and third element populations between energy pulses will vary relative to the fluid flow depending on fluid density and viscosity, and providing means to discriminate between energy reflected from or emitted from the first, second and the third element populations. The elements' differing velocity fields can be used to derive fluid density, temperature and pressure, by solving a particle motion simultaneous equation over the whole field to provide both density and viscosity data. Viscosity can be used to derive fluid temperature by an approximation such as Sutherland's law. The perfect gas law can be used to derive fluid pressure from the temperature and density data or a fourth set of elements can be introduced into the flow to derive pressure directly. Of course, further element populations can be used to derive temperature and pressure directly rather than using the perfect gas law and Sutherland's law.

According to a fourth aspect of the invention I provide an apparatus for use in investigating fluid flow and near surfaces according to the method of the first, second or third aspect of the invention.

The apparatus of the fifth aspect of the invention may have any of the features of the apparatus mentioned in relation to performance of the method of the first, second or third aspect of the invention.

The essential features of the invention can be considered to include an intrinsically volumetric method of investigating fluid flow variables, single optical access position requirements, maximising the energy falling on the detecting means to allow low element diameters, capability to make real-time measurements, the technique further allows the simultaneous measurement of back surface temperature/forces using TSP/PSP, full fluid variable measurement, and finally it is a versatile and modular technique; as it includes variations such as off-axis and in-line holography, stereo-viewing, image-shifting, all using a single apparatus and complementary modules, as described hereinafter.

For a better understanding of the invention, as well as further features and objects thereof, reference is made to the following description, which is to be read in conjunction with the accompanying drawings wherein:

Brief Description of the Drawings

For a further appreciation of the above and other features and advantages, reference is made to the following detailed description and to the drawings, in which:

FIG. 1 schematically shows a typical PIV measurement set-up.

FIG. 2 Schematically shows an overall experimental set-up for flow measurement using the method described in this patent.

FIG. 3 Schematically shows a preferred embodiment of an apparatus performing the method for determining the whole-field velocity of a flow.

FIG. 4 shows a preferred embodiment of an apparatus further incorporating the facility of element image-shifting in order to resolve directional ambiguity.

FIG. 5 Shows a preferred embodiment of an apparatus further incorporating the facility of placing a second beam splitter to be able to record two light frequencies one on each detector so that a two-colour system may be implemented. Alternatively, this arrangement can be used to record the first and second pulse images on two separate CCDs.

FIG. 6 Shows a preferred embodiment of an apparatus further incorporating the facility of viewing a volume(s) of interest with the aid of two cameras mounted on the same instrument so that either two views of the same region may be obtained or two different regions may be investigated simultaneously.

FIG. 7 shows a preferred embodiment of an apparatus further incorporating the facility of recording an in-line holographic recording using the apparatus.

FIG. 8 shows a preferred embodiment of an apparatus further incorporating the facility of recording an off-axis holographic recording using the apparatus.

FIG. 9 shows a preferred embodiment of an accessory to the apparatus, used to absorb and trap incoming light so it does not return along the optical path.

Detailed Description of the Invention

Depending on the characteristics of the flow field under investigation, the speed with which results are desired (i.e. whether the system needs to be real-time or not), laser available, size of the region of interest, etc., different configurations of the apparatus are possible. Some of these can be used in conjunction with each other or separately. These will now be described in detail.

Turning now to the basic configuration of the apparatus, as shown in an overall diagram in FIG. 2, it describes a three-dimensional flow field velocimeter system in accordance with the teachings of the present invention (now to be known as a Tunnelling Velocimeter: TV). A flow (gas or liquid) streams along a profile **1**, in the direction of arrow **2**. The flow is seeded with elements **24**, such as polystyrene spheres. Instrument **3** determines the velocity of the flow within a light cylinder **4** in the investigation volume **14** (the size of which is determined by the characteristics of the viewing lens **8** as well as those of the detector) centred on the focal plane of the viewing lens **8**. The light cylinder **4** is a three-dimensional section of the shaped collimated light beam generated by **6**, and it can also have an expanding or contracting shape. For a spherical beam shape, the sensitivity to movement is enhanced. The intensity profile of the light cylinder **4** is normally Gaussian but this can be changed to any desired profile by using the well-known methods of beam shaping filtering or using a liquid crystal active lens without altering the basic teaching of the method described in this patent. In the light cylinder **4** the elements **24** are illuminated with radiant energy **5** such as light. **5** comes from a source **6**, such as an Argon Ion (in single-line or multi-line mode) or frequency-doubled Nd:YAG laser lasing at 532nm, whose laser beam **7** is reflected on mirrors **9(a,b,c)** to input into instrument **3** where it is shaped, and output along the primary optical axis **20**.

For determining the velocity of the flow in a part **14** of the light cylinder **4**, there is provided a return path substantially along the direction of the primary optical axis **20**, to the video detector **21**. With regard to the invention, the particular method of determining image recording is not important. It is sufficient to record images of the elements in the light cylinder. This can be accomplished using for instance a K2 Infinity long distance microscope lens **8** and record it in a video detector **21** such as a CCD camera. The physical mechanism is that light impinges on the moving element two or more times, at least some of the light being scattered/emitted by the element in the direction of the detector **21**, thereby creating multiple images of itself. Knowing the pulse separation, element image profile recorded on the detector, and displacement encodes each element's velocity, and the combination of all the element pairs found yield the desired almost instantaneous whole-field velocity information. The element image profile is needed because although the X-Y component of displacement (this plane being orthogonal to the optical axis) between the first and second pulse can be derived from the centre of the element images, the out-of-plane displacement (along the optical axis) requires investigation of the shape of the element image using, for example, a Lorenz-Mie scattering calculation (including lens characteristics, aberrations and the effect of digitalisation) or a simplified treatment such as a Fresnel or Fraunhofer diffraction model. The more accurate the model, the more accurate the 3D displacement estimate. A particle will exhibit scattering/diffraction images varying with position along the direction of the optical axis. If other information, such as element size is unknown, this can also be derived from the element image recorded by the detector, along with the element position. An accurate model of the particle image at the image plane will enable calculation of 3D position. Such a model is also dependent on the ratio of refraction index of the fluid divided by the refraction index of the element. Therefore, if there is a varying temperature field in air for instance only, then this can also be deduced from each element image and therefore for the whole investigation volume. At least some of the light also falls on a photodiode sensor **13** to provide diagnostics/triggering information for the controlling computer **22** which also contains the frame grabbing card to digitise the element image field. Similar parts to those appearing in subsequent figures are indicated with the same reference numerals and letters in all figures.

Referring now to FIG. 3, instrument **3** contains a deflecting means (such as a polarising beam splitter **10**) at its heart. This must be made bearing in mind the need to minimise secondary reflections along the optical axis. This can be achieved for instance by using a polarizer plate together with two rotating wedge prisms to fine tune the optimum beam angles. The laser beam **7** enters instrument **3** and to create pulses it is modulated by a shutter 25 (if a continuos laser is used rather than a pulsed laser) which can be placed at a number of locations in this system (the most obvious alternative location being in front of the detector **21**), it then passes through a spatial filter **15** and collimating lens **16** followed by a beam expander **11** to obtain the desired beam diameter, a half-wave plate **12** can be optionally included (which controls the proportion of light to be reflected/transmitted by **10** thus controlling beam strength along the primary axis **20** by varying the proportion of the energy which is horizontally and vertically polarised) and the output is then shaped by a beam shaping filter **26** before going into the polarising beam splitter **10**. The half-wave plate **12** serves to vary the intensity of light going out along the primary optical axis **20**, the surplus energy going into the photodiode **13**, for power level estimation purposes and regulation of power desired at the measurement volume and/or it can be used to trigger image capture. If a half-wave plate is not included, then an energy level broadly equal to the energy delivered by the radiant energy source will be delivered into the measurement volume. Once the laser beam is propagating along the optical axis **20**, it can be made to pass through a quarter-wave plate **17** to circularise the polarisation. This is ideally slightly tilted off-axis so that secondary reflections are not returned along the optical axis, though this distorts the beam, which can be corrected by a full-wave plate as described subsequently. Optical systems/mirrors can be placed between the apparatus and the measurement volume, though the effect of the beam on its way out and return path need to be considered. This is particularly important where it is required to launch the beam and collect the reflected or emitted light from each element into a remote imaging means (such as an endoscope, periscope, optical fiber or gradient varying index lens system) with the purpose of achieving remote viewing in constrained geometries. In these cases, optics can be placed between the beam deflecting means and the measurement volume and these must be matched to a further set of optics placed between the beam deflecting means and the detector **21** such that the net effect for the detector is that of an optical relay while achieving the objective, for instance, of expanding the beam into a spherical shape on its way towards the measurement volume.

Once the light is emitted or reflected from the elements, it can pass again through the quarter-wave plate **17** making it horizontally polarised, the beam splitter **10** therefore transmits the light, and then through a polarizer to filter the horizontal component only and/or an interferometric filter **18**, before being focussed onto the detector **21** by an imaging lens **8**, which has a focussing ring **19** which determines its focus plane **23**. Hence the name of the technique, it is as if the camera was viewing the particles, from whose displacement velocity is derived, inside a lit tunnel. In fact, a refinement of this approach involves using a full-wave plate, tilted about its fast/slow axis as required, to transmit light on its outward and return paths in such a way as to compensate for any elliptical distortion of the scattered field produced by the seeding. The seeding elements are assumed to be of a suitable material and spherical and therefore to maintain the polarisation they are illuminated with. However, if they differ from a spherical shape it will have an elliptical polarisation, rather than linear, upon passing **17**, and so some of the scattered light will be reflected back towards the light source. Furthermore, in some cases, elements may not maintain polarisation. Typically, a polarising beam-splitter acts a 50/50 beam-splitting prism for un-polarised incoming light. So, in this case, half the energy will not be received by the detecting means. Therefore, there will be an element image recorded on the image plane even if the quarter-wave plate is not included. Moreover, in high concentrations, a full colloidal suspension calculation needs to be performed according to the teachings of Mie theory.

The observed image can be translated into a quantitative velocity component image by a programmable processing device, or computer, **22** for processing the image information received from device **21**. This information processing involves assignment of a velocity value in each of three directions, as a function of element displacement, position, laser intensity (which is measured by **13**), and a prior calibration procedure. The calibration procedure involves determining parameters such as beam intensity profile in the region of interest, focus distance, lens **8** (focal length, F/#, magnification, etc.) characteristics, ratio of the refractive index of element and medium, element diameter(s), focus distance, image distance, detector's frequency sensitivity and in the case of a CCD for instance, pixel calibration and transfer function. This assignment is executed for each element image pair recorded. The filter **18** can have a pass frequency the same as the laser so that all other frequencies including background frequencies are excluded from the video detector, thereby increasing the signal-to-noise ratio.

Surfaces behind the measurement volume, cause a danger that the element reflected or emitted light will be overcome by the light reflected back from such a surface. To avoid this effect, five options are envisaged in this first implementation: firstly the surface is covered with a fluorescent paint which will emit light of a lower frequency and thus will be blocked by the filter **18** if it only passes the laser frequency, and so only the scattered light from the elements will be seen. Secondly, fluorescent elements can be used and the filter set to pass only the frequencies at which these elements will fluoresce, thereby also blocking harmful background glare. Thirdly, the light beam can be directed towards a light dump, i.e. a receptacle where it can undergo multiple internal reflections and the light be absorbed (see subsequent description of such a light absorbing disk which is also included as a claim under this patent application). Fourthly, if the surface is a specular surface, then, since this apparatus has no preferred orientation of the measurement volume relative to the flow direction, the apparatus can be aimed at a slight angle relative to the surface so the reflecting light does not enter the primary optical axis but is reflected away from it, for instance towards the plenum of a wind tunnel. Finally, if the back surface can be made specular, the beam can be aimed so that it reflects back along the optical axis, hitting the elements on its return path, thereby generating a forward scattering field. Since this is very much larger than back scatter, the detector can be tuned to record forward element scattering, for cases where the elements are too small and require the higher scattering efficiency of forward scattering to be recorded. The imaging lens **8** also serves to define the volume of interest. Its characteristics, such as focal length and f/#, will define the in-focus region, defocus region, and the areas which are filtered out. Initially, it is envisaged that a long-distance microscope such as the Infinity K2, is adequate by being able to provide suitable magnification, depth-of-field and spatial filtering characteristics.

The first option mentioned in the preceding paragraph for suppressing light reflected by a surface behind the flow measurement volume, i.e. that of using a fluorescent coating, provides two benefits: it allows element reflected or emitted energy discrimination, and also provides a means by which surface temperature/pressure measurement can be accomplished. If the fluorescent/phosphorescent coating used is parameter-sensitive, then near-surface temperature/pressure, for instance, can be calculated. See the description of FIG. 5 where details of the apparatus used to make these investigations is described.

An additional practice of this invention uses a pulsed visible laser such as a Nd:YAG. These lasers emit pulses of approximately 15 ns duration at high intensity and with variable pulse separation and a coherence length of the order of 5 cm. Therefore, near instantaneous measurements of unsteady fields can be made of high speed flows by using sub-micron-sized elements, which can only be imaged, by using high powers. This is an improvement over the shuttered continuously illuminating laser sources, such as Argon Ion lasers. It is readily apparent that a video signal can be used, with an appropriate delay to trigger the pulsed laser to capture element images in each frame of a real-time system. Recently, more advanced versions of the conventional frame-transfer CCD technology has appeared with built-in functions so the frame containing the first pulse element images and the second pulse element images can be separately recorded (e.g. TSI PIVCAM cameras or PCO cameras).

FIG. 4 shows an alternative realisation of the apparatus for complex flows where the directional ambiguity of conventional two-image particle velocimetry needs to be overcome. This method displaces the element image field by an appropriate uniform, known distance between the first and second pulses. As a result, the second image of each element image pairs shifted by a displacement such that the most negative fluid velocity still produces a positive displacement of the second element image with respect to the first. After analysis, the artificial shift is subtracted mathematically to obtain the actual fluid velocity. In this case, two items a Ferro-electric liquid crystal cell **28** (which can be replaced by a Pockels cell for fast switching or other Electro-optical device) and calcite plate **29** are placed between the beam splitter **10** and the lens **8**. Between the first and second pulse, the polarisation of the FLC is rotated so the element images are shifted by an amount dependent on the calcite plate's thickness. Currently, there are three calcite plates in use having thicknesses of 2mm, 6mm and 10mm, which may be mounted separately or combined to provide image shifts magnitudes of 0.2-1.8mm. In this way, the directional ambiguity is resolved.

FIG. 5 shows an implementation of the apparatus where a second dichroic (i.e. it transmits or reflects light depending on its frequency) beam splitter is placed behind/ahead of the primary beam deflecting means to direct the energy coming from the elements or a near surface into one of two detectors **21a** and **21b,** with a band-pass filter **18** between the two beam-splitters, to allow only the range of frequencies of interest onto the detectors. This configuration can be used in a number of different ways.

Firstly, where a two-colour laser system is used, such as Nd:YAG and a YAG-pumped dye laser, this dichroic beam splitter **10b** serves to direct the scattered light due to the first pulse into one detector and the second pulse which is a different colour, into the other detector. To separate first and second pulse images has two advantages. Firstly, it eases the analysis procedure, and secondly denser seeding, leading to a higher measurement rate, can be used as the probability of overlapping images is reduced.

Secondly, if two populations of fluorescent elements with different diameters are inserted into the flow, then the cut-off frequency of this beam splitter **10b** can be set mid-way between the two fluorescing frequencies so as to capture the element images of each population in each camera. Clearly, this can be extended to three or more frequencies/cameras.

Thirdly, as previously mentioned, if a pressure/temperature sensitive paint is applied to the surface behind the flow measurement volume, this surface's temperature/pressure can be measured by a detector and element velocities in the measurement volume by the other detector. For instance, a blue Argon Ion laser line at 488nm could be used (alone or in conjunction with a 532nm Nd/YAG) as the light source. A dichroic beam splitter **10b** centred at 550nm would redirect the scattered light to one detector (light at 488nm or 532nm) and the PSP/TSP intensity field (light at 600-650nm) to the other detector. With no elements but the flow on, the detector receiving the high frequency (i.e. low wavelength) illumination can be used as a reference frame, and the detector receiving the PSP/TSP illumination can be used as the signal frame, to ratio the two frames and enable an accurate derivation of the surface temperature/pressure. Once the reference frame has been saved, the higher light frequency detector can be used to record element scattering information, thereby providing the capacity to make simultaneous velocity and PSP/TSP measurements. An alternative embodiment of this apparatus consists of placing beam splitter **10b** in front of the polarising beam splitter **10a** to maximise the fluorescent signal intensity.

Fourthly, it is also possible to synchronise the laser with the detectors by using asynchronous trigger CCD cameras for instance, so that one camera captures the first pulse and the other one the second pulse, by placing a conventional 50/50 beam-splitter in the place of **10b.** However, in this case half the light is lost. So, a more effective technique which redirects the light in the direction of the desired detector is to place an FLC cell between the two beam splitters **10a** and **10b** and make **10b** also a polarising beam splitter. This method works by letting the element image field through **10b** at the first pulse and on to **21a**, since it comes horizontally polarised after going through **10a**, and then alter the polarisation of the FLC **28** so the element images due to the second light pulse are now vertically polarised, reflected by **10b** and so fall on to **21b**.

Fifth, in yet another arrangement the method may include the use of conventional thermal imaging techniques applied to near surfaces to complement the fluid velocity information using an infrared camera as a detector for the infrared range of energy, instead of the PSP/TSP coating on a near surface.

Finally, polychromatic light can be used (such as that emitted by a shuttered multi-line Argon Ion lasing in the 457, 465, 476, 488 & 514nm wavelengths) to generate both pulses and record the reflected or emitted energy fields at a number of frequencies. The element images at each wavelength can be recorded on separate detectors (or a single colour detector) and then combined in a colour frame and from this information the diameter and displacement of each element can be derived, for instance, to determine element diameter and position with even higher accuracy.

FIG. 6 shows a stereoscopic implementation for applications where two regions of flow need to be simultaneously investigated or if seeding is too dense in the flow field for instance. By splitting the beam strength into two and projecting these along two optical axes, only elements in the overlapping volume are made visible as those along the optical axes but outside this region can be made to receive too little light to be visible by the detectors **21a** & **21b**. In this implementation, half-wave plate **12a** controls the amount of light that is transmitted and so it is rotated until the desired proportion of light is transmitted though **10a**. The secondary beam is then made vertically polarised again by half-wave plate **12b** (this plate again controls which proportion will travel along **20b** and how much light will fall on **13**), before proceeding by way of mirrors **9a** & **9b**, onto an identical set-up to that implemented along the principal optical axis **20a**, creating a secondary optical axis **20b**, which can be oriented in any direction desired, for instance by a goniometer/rotary stage arrangement **33**. The photodiode **13** on the transmission path of **10b** is used for power level monitoring and dumping any excess light power if required.

FIG. 7 shows a modified in-line holography implementation of the apparatus, for cases requiring high resolution recording, large recording area, and large depth of field where the transmitted portion of the beam **7** in **10** is used as the reference beam and the scattered light from the elements is used as the object beam. After passing beam-splitter **10**, the beam is made circularly polarised by **17c**, goes through a compensating plate **31** if required (normally now used in conjunction with a piezoelectric linear stage mount for the mirror **9d** to achieve the exact path length desired, and combined with the length between the beam-splitter and the mirror **9d**), attenuated as required by a variable attenuator **32**, unlike the case for conventional in-line holography where there is no control of the reference beam strength, before being reflected by a mirror **9d** . On its return path, its polarisation is changed to vertical polarisation by the quarter wave plate **17c**. Therefore, it is reflected by **10** along the primary optical path, together with the object beam (which is horizontally polarised) towards the filter **18** and quarter wave plate **17b**. This plate **17b** serves to enable the useful interference of the two beams, which now have a component in phase and one cancelling out at the holographic plate (e.g. AGFA-GAVAERT 8E56 HD) plane **30**. Of course, polarizational holographic recording on photoanisotropic materials, taking advantage of the Weigert effect, can also be used to record the two orthogonal beams directly, though efficiency is typically low. The viewing and digitising stage can be accomplished by in-line viewing though this is quite noisy, or by off-axis viewing as described for the case of conventional in-line recording of HPIV data (see for instance Meng & Hussain, 1995).

FIG. 8 shows an off-axis implementation of the apparatus which is a revised version of that appearing in FIG. 7 In this case, once the two orthogonally polarised object and reference beams are travelling along **20** towards the holographic plate **30** (e.g. a AGFA-GAVAERT 10E75) a Wollaston prism is inserted so that the orthogonally polarised reference and object beam diverge by 20°. A wedge **34** is inserted directly behind this prism **10b** to direct the object beam along the optical axis **20** and the reference beam in the direction of the mirror **9e**. Between 34 and **9e** lies a half wave plate **12b** to make the polarisation of both beams equal and an FLC cell **28a** to rotate the polarisation of the reference beam by 90° when activated. The reference beam then proceeds to the holographic plate **30** where both beams interfere. The object beam also traverses an FLC cell **28b**, which can rotate its polarisation 90° when activated. This configuration has basically two modes of operation: if the FLC cells are omitted, then the element images due to the first and second light pulse are recorded together on the holographic plate; on the other hand, if the FLC cells are activated between the first and second pulse to rotate the polarisation of both the reference and object beams, then the second pulse images will be recorded with an orthogonal polarisation to the first and they can be reconstructed separately thereby resolving the directional ambiguity inherent in recording them together. Typically, Nd:YAG lasers used for high speed flows have a coherence length of about 5 cm, and if the light cylinder was of the order of 1" in diameter which is a common optics size, then the resulting hologram would have a size of 1 In.^{3} which is a good size for investigating complex flows of interest such as those found in turbomachinery and aircraft design/testing.

An example of a light absorbing disk designed specially for this application is shown in FIG. 9. This accessory is made up of an interference filter layer, a prism, and a mirror, all mounted on a single disk frame **35**. This accessory works on the principle that interference filters are highly angle sensitive. Transmission efficiency is 90%< orthogonally but drops to 10% only 5° away from this angle. Therefore, if a filter(s) **18** is matched to the light source emission frequency, then the light will pass through it freely if the beam hits the filter surface orthogonally. The beam is then redirected by the prism **34** and reflected by the mirror **9**, but on its return path, due to the angle subtended between the beam and the filter, the light is reflected back into the cavity and is unable to return along the optical path.

Finally, the configurations described in FIG.5, FIG 3 and FIG. 6 can be combined to investigate fluid density, viscosity and pressure as well as velocity. Thus, there is a stereo arrangement (as in FIG. 6), in order to minimise stray scattering from elements outside the measurement volume, with one detector on the secondary optical axis (as in FIG. 3) and two detectors on the primary axis (as in FIG. 5). The method involves using the 3 detectors (ideally TSI PIVCAM cameras so as to be able to separate the first from the second pulse element images) to look at 3 element populations of varying element diameters, simultaneously injected/present into the flow. Each element population possesses differing scattering characteristics and generates a different velocity field due to their differing aerodynamic characteristics. For instance, an Argon Ion laser lasing at 488 to generate the laser beam **7** can be used. The smallest polystyrene element population can be recorded using the 488nm line on the secondary optical axis with a 488nm filter, and the two other element image fields can be recorded by using fluorescent polystyrene elements dyed with Fluorescein (peak fluorescence: 514.5nm) and Rhodamin-B (peak fluorescence: 575nm), and recorded along the primary optical axis using a dichroic beam splitter set at 550nm, with a band-pass filter **18** ahead going from 500-600nm, to increase the signal-to-noise ratio. By combining the velocity fields due to each element population, it is possible to derive a set of simultaneous equations which yield fluid density, viscosity (from which temperature can be derived) and pressure by applying the perfect-gas law, thereby describing a fluid flow completely and almost instantaneously in a non-intrusive manner. The perfect gas law is in fact an approximation. Clearly, four or more element populations could be used to solve the set of simultaneous equations and derive thermodynamic pressure directly.

Thus, the use of the invention, either in conjunction to its various modular forms or as a basic system with associated data processing and recording instrumentation extends to various velocity measurements: air flow around objects in a wind tunnel, such as aircraft wings and body; jet engine intake and exhaust flow patterns, turbine and compressor flow studies, stator/rotor interactions, engine combustion diagnostics; propeller and rotor flow fields on helicopters; pipe flow analysis; and wind flow studies near man-made and natural structures.

While the invention has been described with reference to its preferred embodiment, it would be understood by those skilled in the art that various changes and permutations may be made, and equivalents may be substituted for elements thereof without departing from the true spirit and scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teaching of the invention without departing from its essential teachings.

The features disclosed in the foregoing description, or the claims, or the accompanying drawings, expressed in their specific forms or in terms of a means for performing the disclosed function, or a method or process for attaining the disclosed result, as appropriate, may, separately, or in any combination of such features, be utilised for realising the invention in diverse forms thereof.

Bibliography

U.S. Patent Documents

Pat. No.	Date	Inventor	Class
4,919,536	4/1990	Komine	356/28.5
4,988,191	1/1991	Adrian et al.	073/861.06
5,002,389	3/1991	Benser	356-28
5,333,044	7/1994	Shaffer	356/28
5,440,144	8/1995	Raffel et al.	250/574
5,491,642	2/1996	Wormell et al.	356/28
5,532,814	7/1996	Cha	356/337
5,548,419	8/1996	Adrian et al.	359/024
5,561,515	10/1996	Hairston et al.	356/28
5,610,703	3/1997	Raffel et al.	364/510
5,612,492	3/1997	Schwab et al.	73/147
5,684,572	11/1997	Bütefisch	356/28.5
5,731,995	3/1998	Benne et al.	364/558
5,751,410	5/1998	Rohle et al.	356/28.5
5,812,248	9/1998	Ruck et al.	356/28
5,883,707	3/1999	Arndt et al.	356/028

Other Publications

Adrian, R.J., "Particle-Tracking Techniques for Experimental Fluid Mechanics", Annu. Rev. Fluid Mech., 23, 261-304, 1991.

Barker, L.M., Hollenbach, R.E., J. Appl. Phys., Vol. 41, 4208, 1970.

Bertuccioli, L., Gopalan, S., Katz, J., "Image Shifting for PIV Using Birefringent and Ferroelectric Liquid Crystals", ASME-FED, Vol. 229, Laser Anemometry, 307-312, 1995

Brüker, Ch., "Whole-volume PIV by the concept of a scanning light sheet: technique and application to 3D unsteady bluff body wakes", ASME FED-229, pp. 115-121, 1995.

Coupland, J.M., Halliwell, N.A., "Holographic Particle Image Velocimetry: three-dimensional Fluid Velocity Measurements Using holographic recording and Optical Correlation", Applied Optics, Vol. 31, 1005-1007, 1992.

Erskine, D.J., Holmes, N.C., "White-light Velocimetry", Nature, Vol. 377, 317-320, 1995.

Fabry, E.P., "3D holographic PIV with forward-scattering laser sheet and stereoscopic analysis", Exp. In Fluids, vol. 24, pp. 39-46, 1998.

Funes-Gallanzi, M., Bryanston-Cross, P.J., Chana, K.S., "Wake Region Measurement of a highly three-dimensional nozzle guide vane tested at DRA Pyestock using Particle Image Velocimetry", ASME, 94-GT-349, The Hague, June 13-16, 1994.

Funes-Gallanzi, M., "A Numerical Investigation of Flow Past a Bluff Body Using Three-State-Anemometry (3SA)", Int. J. for Numer. Meth. in Fluids, vol. 26, pp. 1023-1038, 1998.

Grant, I., Pan, X., Romano, F., Wang, X., "Neural-network method applied to the stereo image correspondance problem in three-component particle image velocimetry", Applied Optics, Vol. 37, No. 17, 3656-3663, June 1998.

Gogineni, S.P., Trump, D.D., Goss, L.P., "PIV Measurement of a Jet in a Cross Flow", ASME FED, Vol. 218, Experimental and Flow Visualisation, 71-75, 1995.

Holmberg, D.G. & Pestian, D.J., "Wall-Jet Turbulent boundary layer heat flux, velocity, and temperature spectra and time scales", ASME 96-GT-529, June 10-13, 1996.

Kautsky, H., "Quenching of Luminescence by Oxygen", Trans. Faraday Soc., 35, pp.216, 1939.

Lwin, M.J., *et al.*, "A velocity interferometer system for any reflector utilising a short coherence length laser", Rev. Sci. Instr., Vol. 69, No. 9, 3103-3105, 1998.

Meng, H., Hussain, F., "In-line recording and off-axis viewing technique for holographic particle velocimetry", Applied Optics, Vol. 34, No. 11, 1827-1840, 1995.

McBride, R., Harvey, D., Barton, J.S., Jones, J.D.C., "Velocity Measurement Using a Fiber Optic Sagnac Interferometer", Fifth Int. Symp. Appl. Laser Tech. to Fluid Mech., Lisbon, 1991.

McDaniel, J.C., "Investigation of Laser-Induced Iodine Fluorescence for the measurement of density in compressible Flows", Stanford University, SUDAAR No. 532, 1982.

Mosharov, V., Orlov, A., Petunin, A., Radchenko, V., Rozanov, N., Talykov, V., Fonov, S., Chikin, I., "Luminescent Coating for Pressure Distribution Investigation on the Models Surface in Wind Tunnels", CIAM Proceedings, N1232, 1988 (in Russian).

Ovryn, B., Wright,T., Khaydarov, J.D., "Measurement of three-dimensional velocity profiles using forward scattering particle image velocimetry (FSPIV) and neural net pattern recognition", SPIE vol. 2546, pp. 112-123, 1995.

Roberts, N.C., "Beam Shaping by Holographic filters", Applied Optics, Vol. 26, No. 1, 1989.

Santiago, J.G., Werely, S.T., Meinhart, C.D., Beebe, D.J., Adrian, R.J., "A Particle Image Velocimetry System for Microfuids", Exp. in Fluids, vol. 25, no. 4, 316-319, 1998.

TSI Inc., PIVCAM camera description & Powerview Stereo PIV System description, 1998.

Woodruff, S.D., Cha, D.J., Richards, G.A., "Single Port Access Holographic Particle Image Velocimetry", ASME FED, Vol. 229, Laser Anemometry, 65-70, 1995.

List of Reference Signs

1 - Profile
2 - Arrow
3 - Instrument
4 - Light cylinder
5 - Shaped light beam
6 - Laser
7 - Laser beam
8 - Lens
9 - Mirror
10 - Polarising beam Splitter
11 - Beam expander
12 - Half-wave plate
13 - Light power sensor/photodiode
14 - Part
15 - Spatial filter
16 - Collimating lens
17 - Quarter-wave plate
18 - Filter
19 - Focus ring
20 - Optical Axis
21 - Video Detector
22 - Computer
23 - Focus plane
24 - Particle
25 – Shutter/Acousto-Optic modulator
26 – Beam Shaping Filter
27 – Light Sheet
28 – Electro-optical device (e.g.: Ferro-electric Liquid Crystal Cell - FLC)
29 – Calcite Plate
30 – Holographic recording plate
31 – Compensating Plate
32 – Variable attenuator
33 – Goniometer/Rotary stage arrangement
34 – Wedge prism
35 – Disk frame

Claims

1. A method of investigating fluid flow containing elements which reflect or emit energy in response to energy being directed onto the elements, where the level of the energy directed onto the elements is broadly equal to that delivered by the radiant energy source, the method including directing a first pulse and subsequently further pulses of radiant energy along a path, each to intersect a volume of the fluid flow, positioning energy detecting means in a region outside of the fluid flow, detecting with the detecting means energy scattered or emitted from the elements for each pulse whereby an image of the elements of the intersected volume is detected for each pulse, and investigating the images to determine displacements of the elements occurring between energy pulses, and wherein the method includes positioning the detecting means to detect energy scattered or emitted from the elements in a direction substantially coincident with the path along which the radiant energy is directed to intersect with the volume of the fluid flow.

2. A method according to claim 1 wherein the energy level can be adjusted from broadly equal to that delivered by the radiant energy source down to a negligible level.

3. A method according to claim 2 wherein energy level adjustment is achieved by manipulating polarisation states of the radiant energy.

4. A method according to claim 1 wherein a measure of the velocity of the elements in the volume of the fluid flow into which the radiant energy is directed, is determined by determining displacements of the energy emitting or reflecting elements from analysing the images , and by knowing the duration between pulses.

5. A method according to any one of the preceding claims wherein the radiant energy is coherent light which is detected from the elements in the volume of the fluid flow under investigation.

6. A method according to claim 5 wherein the directed energy is polarised and the magnitude of the directed energy and/or of the energy received in the detecting means, is controlled using a polarising filter, to a level appropriate to the detecting means.

7. A method according to claim 5 or claim 6 wherein the detecting means is focused on a plane in the investigated volume of the fluid flow, and energy from a reflecting element moving other than in the plane of the fluid flow is received by the detecting means, the detecting means being adapted to determine, using such received energy, a measure of the displacement of the reflecting elements in the investigated volume, out of a plane of focus of the detecting means between pulses.

8. A method according to claim 7 wherein the detecting means includes optics to focus the detecting means primarily on the centre plane of the investigated volume of the fluid flow.

9. A method according to claim 1 wherein the energy received by the detecting means is primarily energy emitted from the elements in or of the fluid flow.

10. A method according to any one of the preceding claims wherein the detecting means includes an imaging means to enable multiple images of the elements in the investigated volume to be recorded for investigation.

11. A method according to claim 10 wherein the imaging means includes an electro-optical device such as a charge coupled device.

12. A method according to any one of the preceding claims wherein the detecting means includes a filter means so that primarily energy in a selected frequency range is received by the detecting means.

13. A method according to any one of the preceding claims wherein the radiant energy is generated by a source located away from the path along which the energy is directed to the investigated volume of the fluid flow, and the radiant energy thus produced is deflected along the path to the volume of the fluid flow to be investigated.

14. A method according to claim 13 wherein the radiant energy is deflected by a deflection means being a polarising beam splitter arrangement.

15. A method according to claim 14 wherein prior to the energy impinging upon the deflecting means, the energy is passed through a half wave plate, the method including adjusting the half wave plate to vary the magnitude of the energy directed to the investigated volume of the fluid flow to a level such that the level of energy reflected or emitted from the elements in the fluid flow, is appropriate for the detecting means.

16. A method according to claim 15 wherein the phase of the polarised energy reflected from the reflecting elements is shifted so that the transmission of the reflected or emitted energy through the deflecting means to the detecting means beyond, is enhanced.

17. A method according to claim 16 wherein the method further includes circularising the polarised radiant energy which is directed to the investigated volume.

18. A method according to claim 17 wherein the polarised radiant light is circularised using a quarter wave plate located to receive the polarised directed energy from the deflecting means, and the method includes causing the energy reflected or emitted from the reflecting elements to pass back through the quarter wave plate and through the deflecting means to the detecting means to effect a further phase rotation on the energy reflected from the reflecting elements.

19. A method according to any one of the preceding claims wherein in order to produce the at

least two pulses, a shutter in the path of the directed energy is opened and closed twice.

20. A method according to claim 19 wherein the method includes positioning and operating the shutter in a position prior to the energy being deflected along the path to intersect the volume of the fluid flow.

21. A method according to any one of the preceding claims wherein the method includes artificially displacing the image for the first or second pulse, a predetermined amount, and subsequently during image analysis accounting for the artificial displacement thereby enabling directional ambiguity to be resolved.

22. A method according to claim 21 wherein such artificial displacement of the image is achieved by inserting between the deflecting means and the detecting means, a switchable imaging shifting device, and switching the device between the first and second pulse to displace the second image relative to the first image

23. A method according to any one of the preceding claims wherein the method includes treating and/or configuring a wall of a body containing and/or within the fluid flow to prevent or at least reduce energy reflections or emissions from the body wall to the detecting means.

24. A method according to claim 23 wherein the body wall is coated with an energy absorbing coating.

25. A method according to any one of claims 1 to 22 which includes providing beyond the fluid flow, a surface which is treated to reflect or emit energy as a result of the directed radiant energy impinging thereon, in a known frequency range, and providing a filter to filter out such energy in the known frequency range, to negate any deleterious effect such energy may have on the investigation of the fluid flow.

26. A method according to any one of the preceding claims wherein the method of the invention is adapted to investigate near surface temperature and forces such as pressure either alone or in combination with fluid velocity.

27 A method according to claim 26 wherein elements in the fluid flow, or on a surface in or beyond the fluid flow, are provided with a coating whose energy reflecting or emission characteristic changes with temperature and/or pressure, the detecting means being adapted to recognise the energy reflecting or emission characteristic thus to determine fluid temperature and/or pressure.

28. A method according to any one of the preceding claims wherein the method includes seeding the fluid flow with at least first energy reflecting or energy emitting element population and second or more energy reflecting or energy emitting element populations, the first element population having a a lower Stokes number than other element populations, the first element

population being adapted to follow the fluid flow whilst movements of the second or more element populations between energy pulses are adapted to vary relative to the fluid flow depending on fluid density, pressure, temperature and viscosity, and providing means to discriminate between energy reflected from or emitted from each element population.

29. A method according to claim 28 wherein the method includes means to derive fluid variables using the velocity fields produced by each element population.

30. A method of investigating fluid flow containing elements, the method including directing a first pulse and subsequently a second pulse of radiant energy along a path, each to intersect a volume of the fluid flow, positioning energy detecting means in a region outside of the fluid flow, detecting with the detecting means energy returning from the fluid flow for each pulse whereby an image of the elements of the intersected volume is detected for each pulse, and analysing the images to determine displacements of the elements occurring between energy pulses, and wherein the method includes positioning the detecting means to detect energy scattered or emitted from a surface near and/or beyond the fluid flow in a direction substantially coincident with the path along which the radiant energy is directed to intersect with the volume of the fluid flow.

31. A method according to claim 30 wherein the method also includes means to detect surface temperature using thermal imaging techniques.

32. A method according to any one of the preceding claims wherein the method also includes means to estimate fluid temperature from the ratio of the fluid and element refractive indexes, where the fluid refractive index is a function of temperature.

33. A method according to any one of the preceding claims wherein the method also includes means to launch and detect radiant energy into a remote imaging means to achieve remote viewing in constrained geometries.

34. A method according to any one of the preceding claims wherein the method also includes means for absorbing and trapping radiant energy, consisting of a filter with an angle dependent transmissivity, followed by a beam redirecting means, and a radiant energy reflecting means.

35. A method according to any one of the preceding claims wherein the method further includes means to add a reference beam in-line to the detecting means so as to be able to record holographically the energy reflected or emitted by the elements in the measurement volume.

36. A method according to claim 35 wherein the method also includes means to separate two orthogonally polarised beams, redirect and rotate the polarisation of one of them to produce an off-axis holographic recording.

37. A method according to any one of the preceding claims wherein the method includes

means to redirect part of the radiant energy to a secondary optical axis, thereby achieving stereoscopic recording of one or more measurement volumes.

38. A method of investigating fluid flow substantially as herein before described with reference to the accompanying drawings.

39. An apparatus for use in investigating fluid flow according to the method of any one of the preceding claims.

40. An apparatus according to claim 39 having any of the features of the apparatus specified in any one of claims 1 to 38.

41. An apparatus for investigating fluid flow substantially as herein before described with reference to and as shown in the accompanying drawings.

42. Any novel feature or novel combination of features described herein and/or in the accompanying drawings.

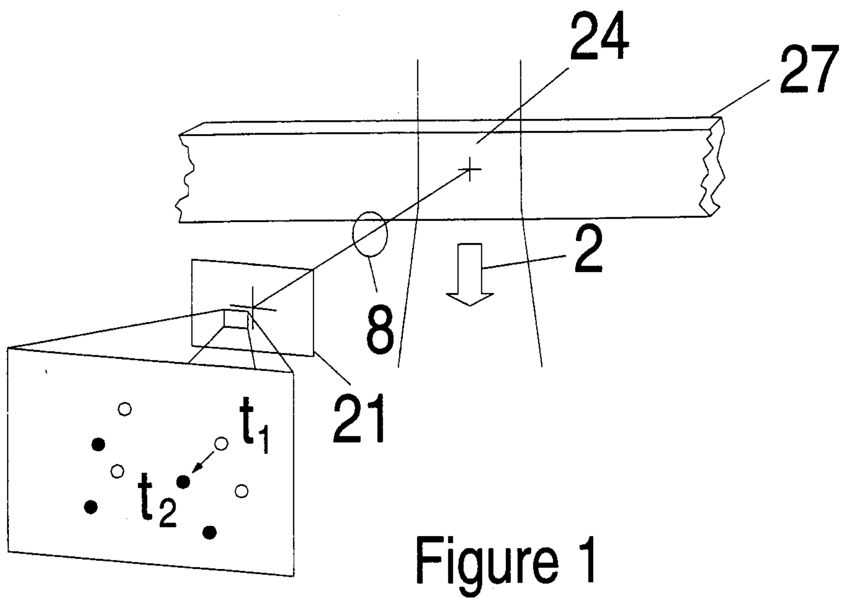


Figure 1

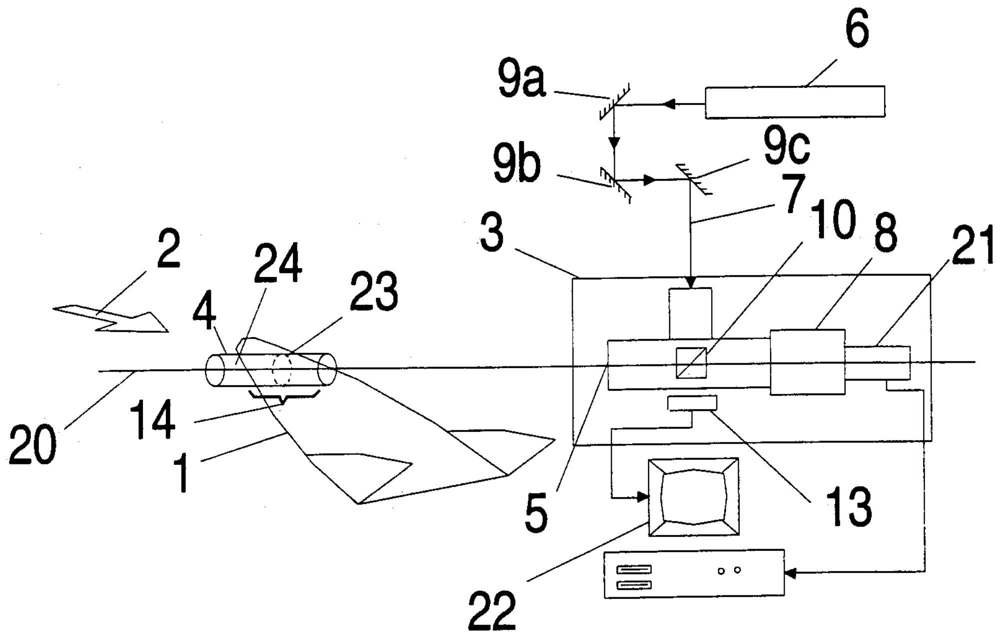


Figure 2

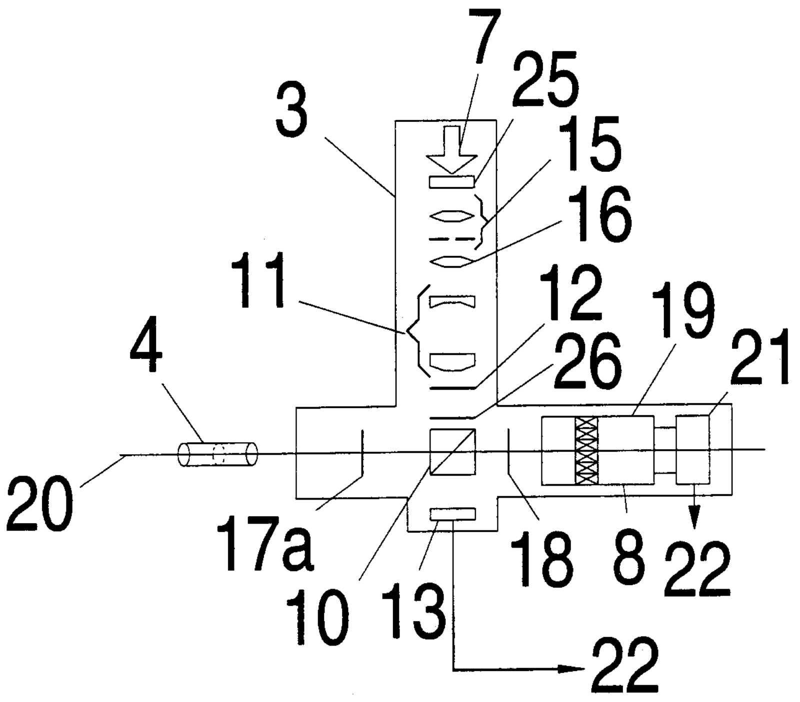


Figure 3

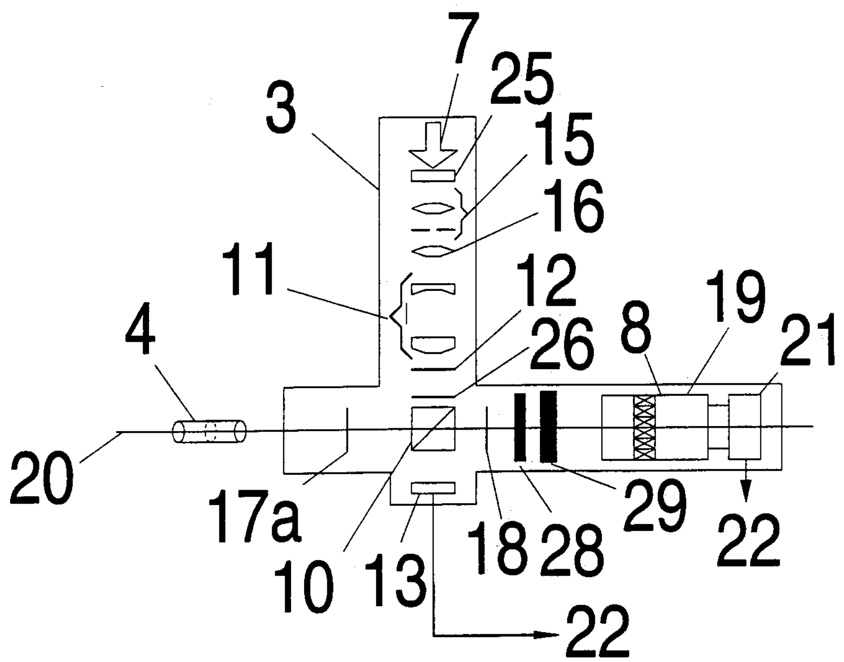


Figure 4

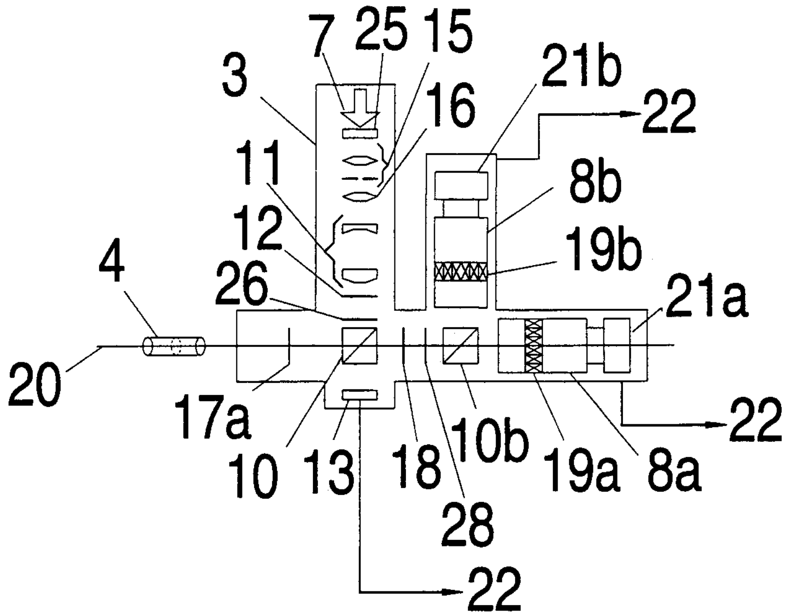


Figure 5

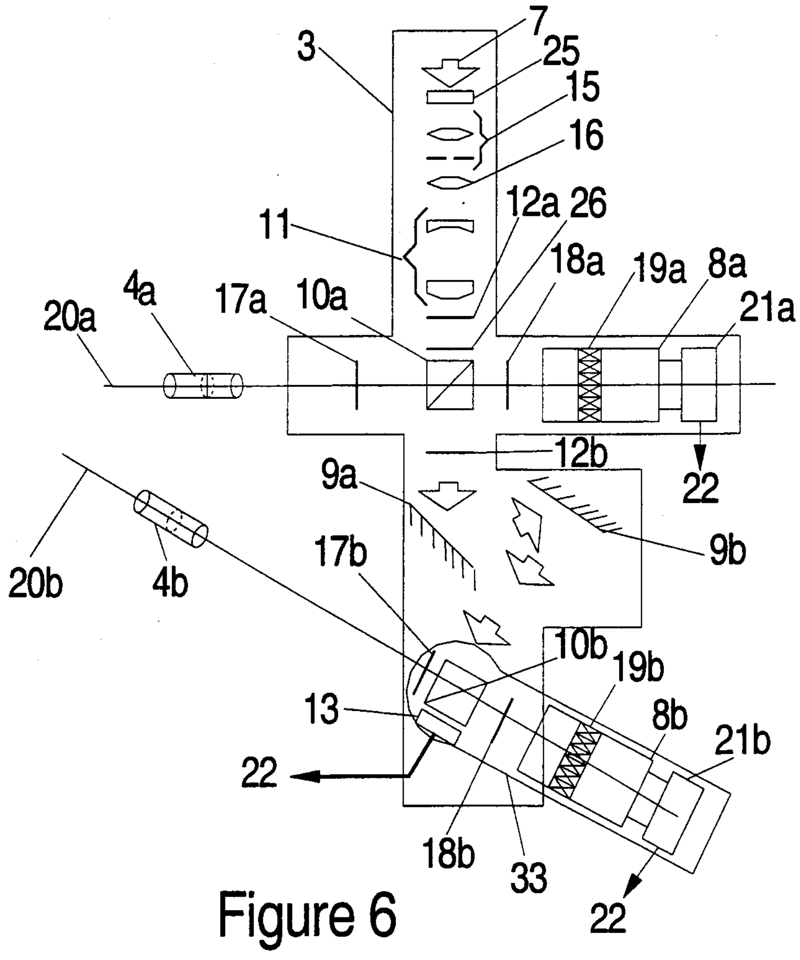


Figure 6

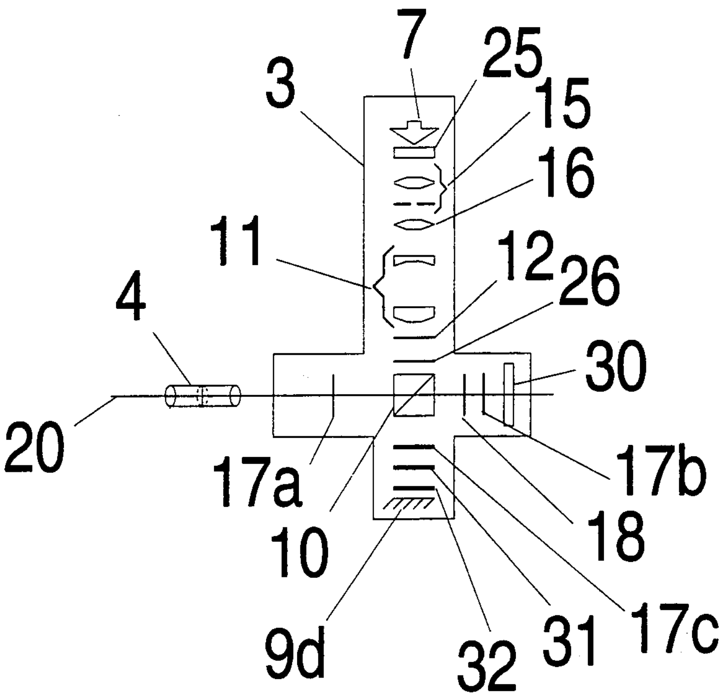


Figure 7

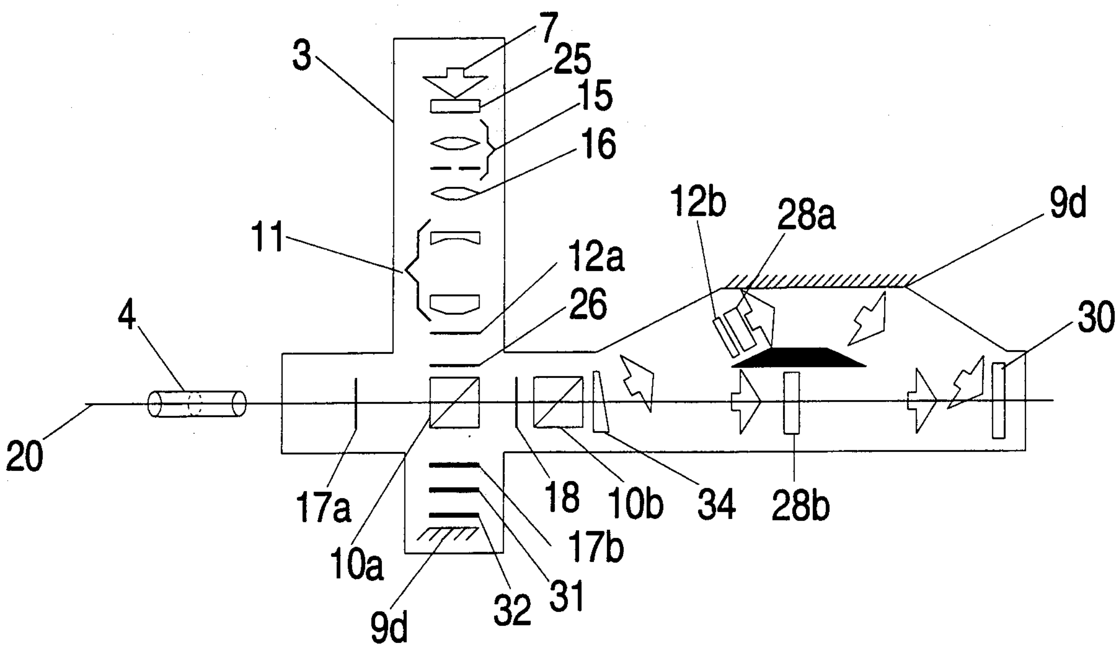


Figure 8

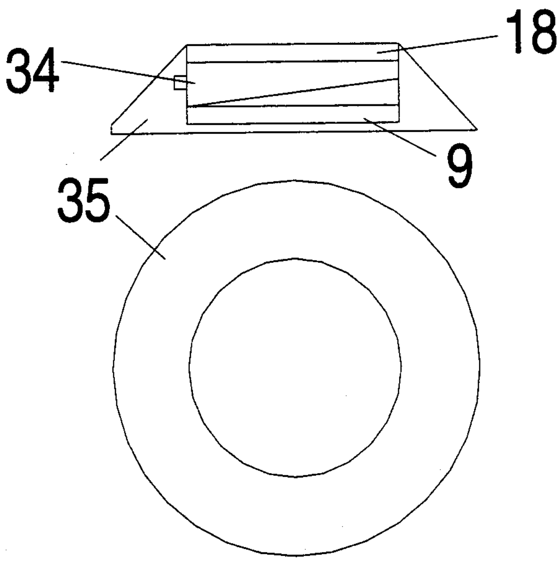


Figure 9

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 00/02742

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01F1/708

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC, COMPENDEX, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	M. FUNES-GALLANZI: "TUNNELING VELOCIMETRY:CONSILIENCE COMES TO THE STUDY OF FLUID DYNAMICS" TENTH INTERNATIONAL SYMPOSIUM ON APPLICATIONS OF LASER TECHNIQUES TO FLUID MECHANICS, 10 - 13 July 2000, XP002147526 LISBON,PORTUGAL abstract; figure 1 ---	1,30, 38-42
A	US 5 751 410 A (I. ROELE ET AL) 12 May 1998 (1998-05-12) cited in the application abstract; figure 1 ---	1,30, 38-42
A	DE 44 08 072 A (DEUTSCHE FORSCH LUFT RAUMFAHRT) 3 August 1995 (1995-08-03) abstract; figure 1 -----	1,30, 38-42

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
2 October 2000	18/10/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Vorropoulos, G

INTERNATIONAL SEARCH REPORT

Information on patent family members

Int(ional Application No
PCT/GB 00/02742

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5751410 A	12-05-1998	DE 4443069 A	05-06-1996
		GB 2295670 A,B	05-06-1996
DE 4408072 A	03-08-1995	DE 19502993 A	03-08-1995
		GB 2286669 A,B	23-08-1995
		US 5610703 A	11-03-1997