A Novel Fluids Research Technique: Three-State Anemometry

M. Funes-Gallanzi
Optical Engineering Laboratory
Warwick University Engineering Department
Coventry, UK

ABSTRACT

A new flow measurement technique is described which allows for the non-intrusive simultaneous measurement of flow velocity, density, and viscosity. The viscosity information can be used to derive the flow field temperature. The combination of the three measured variables and the perfect-gas law then leads to an estimate of the flow field pressure. Thus, the instantaneous state of a flow field can be completely described.

Three-State anemometry (3SA), a derivative of PIV, which uses a combination of three mono-disperse sizes of styrene seeding particles is proposed. A marker seeding is chosen to follow the flow as closely as possible, while intermediate and large seeding populations provide two supplementary velocity fields, which are also dependent on fluid density and viscosity. A simplified particle motion equation, for turbomachinery applications, is then solved over the whole field to provide both density and viscosity data. The three velocity fields can be separated in a number of ways. The simplest and that proposed in this paper is to dye the different populations and look through interferometric filters at the region of interest.

The two critical aspects needed to enable the implementation of such a technique are a suitable selection of the diameters of the particle populations, and the separation of the velocity fields. There has been extensive work on the seeding particle behaviour which allows an estimate of the suitable particle diameters to be made. A technique is described in this paper to allow the separation of μm range particle velocity fields through fluorescence (separation through intensity also being possible). Some preliminary results by computer simulations of a 3SA image are also presented. The particle sizes chosen were 1 μm and 5 μm tested on the near-wake flow past a cylinder to investigate viscosity only, assuming uniform flow density. The accuracy of the technique, derived from simulations of swirling flows, is estimated as 0.5% RMS for velocity, 2% RMS for the density and viscosity, and 4% RMS for the temperature estimate.

INTRODUCTION

As the study of fluid mechanics has evolved from steady state investigations towards the reality of unsteady phenomena, it has become increasingly clear that instantaneous whole-field non-intrusive flow measurement techniques are required. PIV has evolved in recent years to provide such measurements for the velocity field. However, not only velocity gradients but viscosity is required to yield an estimate of the instantaneous rate of loss in turbomachines. The continuing pressure on manufacturers to raise efficiency remains the reason for interest in research into loss generation in turbomachines.

3SA represents a milestone in terms of the evolution of anemometry techniques. From its origins as a 2D velocity estimation technique, PIV evolved first to being extended to 3D, and then to mixtures of seeding being used. For the investigation of two-phase flows, there has been some work done using PIV and two seeding populations (McCluskey et al. 1993). However, in this instance the two populations were 1 μm and 75 μm in diameter, which readily allowed the distillation of the two populations. Gogineni et al (1995) also looked at using a combination of seeding sizes with their colour PIV system, which employs two lasers, a Nd/Yag and a Nd/Yag pumped dye laser. In this case the two populations were 0.5 and 1.0 μm. These two populations were differentiated by the intensity information. A colour film image was obtained and the intensity and colour information was used both to eliminate the usual PIV directional ambiguity and to distinguish between jet and cross-flow information.

Laser Induced Fluorescence has emerged as an attractive technique to measure pressure/temperature. There are different implementations of this technique but the most popular has been that based on an argon-ion laser with iodine as a seed (McDaniel, 1982). The argon laser excites iodine molecules that are not in the ground state. To calculate physical parameters from the measured LIF signal, therefore, the optical set-up and laser tuning become rather complicated, and difficult to apply for practical flows. Measurements of
temperature at a set narrow pressure range have been reported (Inoue et al., 1995). Pressure and velocity, based on the Doppler shift of the fluorescence spectral lines, measurements at a set narrow range of temperatures (Lemoine et al., 1995) have also been reported. In the case of air, however, which has a high expansion rate, flow cannot maintain equilibrium and differences occur between the translational, rotational and vibrational temperatures. The main problem with this technique is the cross dependence of the fluorescence on pressure and temperature.

For turbomachinery applications, pressure and temperature vary simultaneously over wide ranges, in an enclosed surrounding, and using a gas with a high expansion rate. Although there has been some variants which show good promise, the technique of LIF remains problematic and untried in turbomachinery. However, the basic idea of seeding a flow with fluorescent seeding to obtain more than just velocity estimates is attractive. Furthermore, one of the most difficult experimental problems with PIV is that of glare from near surfaces. By using fluorescent particles and interferometric filters, this effect can be minimised. In fact, fluorescent seeding has been shown to work in conjunction with PIV (for example: Northrup et al., 1991 & Philip et al., 1994).

The tracking capability of scattering particles is essential for reliable velocity measurements with laser anemometry. The study of the sizing criteria for laser anemometry particles is now highly refined and has been the subject of several excellent articles, e.g. Melling (1986) and Dring (1978, 1982). Therefore, the correct particle size for a faithful flow following can be reliably ascertained.

There are many aspects of loss generation in turbomachinery which need further extensive research. Given that efficiency for turbines is already in the region of 90%, the areas where losses are generated and magnitude of these effects is small and difficult to investigate. The efficiency achieved to date is primarily due to the fact that turbine flow is dominated by the laws of conservation of mass, energy, and momentum. Thus, the remaining sources of loss are mainly related to viscous effects. Denton (1993) has recently suggested that understanding would be improved by looking at loss in terms of entropy generation. More recent work has suggested kinematic properties of fluids as a useful marker for likely areas of high loss (Funes-Gallanzi, 1995). Studies of the relationship between viscous forces and entropy creation show that the entropy creation rate is likely to be high in regions where high velocities coincide with high viscous forces. These two factors are likely to result in rotation, dilution and shear strain. More specifically, the shear strain rate is related, in the case of simple fluids such as water or gases, to the shear stress by the following linear relation:

$$\tau_{xy} = 2\mu \frac{dv}{dx} = \mu_{eff} \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)$$

Furthermore, for boundary layers for instance, by relating the rate of shear stress to the rate of entropy generation per unit surface area, it is possible to investigate loss directly; assuming no skewing:

$$S_a = \int_0^1 \frac{1}{e} r dV$$

$$S_a = \frac{1}{\rho_{eff}} \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2$$

This approach can be simplified by looking at vorticity and rate of shear as a guide. The effective viscosity can be considered to be laminar if a suitable viewing scale is chosen in relation to the flow under consideration, and at low speeds where the temperature and density changes are negligible. By linking at the kinematics of the fluid, regions of high entropy generation can be investigated directly.

The rate of shear can be measured directly on full-size turbines vanes, economically, non-intrusively, and using PIV for instance. PIV results of a turbine wake and related vortex structure, in a hostile industrial environment, have recently been reported in the literature (Funes-Gallanzi et al., 1994). High speed 3DPIV measurements (Funes-Gallanzi et al., 1995) using the seeding optical characteristics to provide an accurate 3D data field have also been achieved. This approach both provides more accurate 3D PIV information and, more importantly, enables the classification of particle data according to particle size. Furthermore, while homologous relationships do allow the investigation of turbomachines through models, they do not permit viscous forces to be scaled properly; hence there is a slight difference in efficiency of the various sizes. The larger the machine, the more efficient it is, but the difference is normally not more than 2-3%. Therefore, in order to obtain the most reliable results, experiments have to be performed on full-size vanes at operating conditions.

The combination and refinement of anemometry techniques implied in 3SA which, for the first time, may provide instantaneous velocity, density and temperature whole field estimates, opens the way for a detailed investigation of mixing processes and unsteady effects. Some initial results, obtained from computer simulations, are described in this paper, together with some of the technique’s limitations, and current areas of development and testing are briefly covered.

**PARTICLE MOTION EQUATION**

All analysis of particle motion using PIV assume spherical particles. This is a valid assumption as the particles used for transonic flow research are often sub-\(\mu m\) styrene. Styrene, in particular, has a very high scattering cross-section which allows the imaging of particles down to 0.2 \(\mu m\). These are the two main factors as far as the light scattering characteristics are concerned. The aerodynamic behaviour depends on its inertia and the drag force. A common parameter for aerodynamic and scattering characteristics is the particle diameter. Interference between particles is neglected, as the highest concentrations possible, are still too low for such effects.

For flow following capability, subject to a prescribed tolerance, the diameter can be specified. For transonic flow, 1.0\(\mu m\) has been long established as the maximum permitted size for the faithful following
of unsteady flow in turbomachinery; with a tolerated error of about 1%.

The most important influences on particle motion are together with the fluid velocity gradients, the particle diameter \(d_p\), the particle and fluid densities \(\rho_p\) and \(\rho_f\), and the viscosity \(\mu\). An analysis of the relative motion of particle and fluid yields the following dimensionless equation as an approximation (Maxey & Riley, 1983):

\[
\frac{d \mathbf{v}}{dt} + \frac{1}{2} \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{1}{\rho_f} \nabla p + \frac{1}{\rho_f} \mathbf{f}_{\text{external}} + \frac{1}{2} \mathbf{v} \times \mathbf{\Omega} + \frac{3}{8} \mathbf{v} \nabla (\mathbf{v} \cdot \mathbf{v}) + \frac{1}{\rho_p} \mathbf{f}_{\text{inertial}}
\]

where \(\mathbf{v}\) is the particle velocity, \(\mathbf{v}_f\) is the fluid velocity, \(p\) is the pressure, \(\mathbf{f}_{\text{external}}\) is the external force, \(\mathbf{f}_{\text{inertial}}\) is the inertial force, \(\mathbf{\Omega}\) is the angular velocity of the fluid, and \(\rho_p\) and \(\rho_f\) are the particle and fluid densities, respectively.

The operator \(d/dt\) denotes a derivative following the particle and \(D/Dt\) a derivative following the fluid. In creeping flow these two derivatives are approximately the same. The characteristic time and fluid velocity have been used to make the foregoing equation dimensionless. The Laplacian operator is made dimensionless by the characteristic distance \(L\) of the flow, \(\alpha\) is the particle radius, \(\beta\) is the dimensionless density, \(\delta\) is the ratio of the dimensions \%L. The subscripts \(f\) and \(p\) refer to the fluid and particles respectively.

For turbomachinery flows, the characteristic distance of the flow might be based on chord length, and the Reynolds number calculated on the basis of the characteristic fluid velocity, and are generally in the 1.2e+06 range for stator vanes for instance. For particles, which need to have a Stokes number (St.) of less than 1 if they are not to be ultimately centrifuged out, the effective Reynolds number is calculated based on the particle diameter and slip velocity. Therefore, \(\mu_m\)-sized particles can be considered to exhibit creeping flow behaviour in turbomachines. This leads to a considerable simplification of the above equation which makes it possible to carry out 3S measurements and numerical simulations. The simplified equation of motion can then be expressed in terms of viscosity and fluid density which are the required unknowns. Thus, if a combination of particle sizes is used to seed the flow, both the instantaneous fluid velocity field and each particle sub-group velocity field can be ascertained. By using a marker particle size designed to follow the flow accurately, together with two other sub-group sizes, it is possible to solve a system of simultaneous equations of particle motion to yield density and viscosity. The viscosity data field can be transformed, through the use of Sutherland’s law, to yield a whole-field temperature estimate; with an estimated accuracy of 2%. This temperature estimate can then be combined with the density estimate to yield, through the use of the perfect-gas law, a whole-field pressure estimate. The seeding size distribution can be controlled to ensure a monodisperse population. For instance, at 1 \(\mu\) a typical seeding batch, produced at the Department of Chemistry of the University of Warwick, has 95% of the particles between 0.9 and 1.1 \(\mu\). Accuracy bounds are valid for the data range applicable for
turbomachinery applications and assuming air as the fluid being investigated. These are arrived at from an error analysis of the simultaneous equations and allowing a further error arising out of the spatial interpolation. A detailed analysis of the expected accuracies cannot be obtained analytically due to the large number of factors involved (seeding distribution, velocity gradients, measurable velocity dynamic range, pulse separation, heat transfer conditions, seeding size distribution, etc.) and because accuracy estimates are also dependent on the flow characteristics. The estimates mentioned in this paper were derived from simplified simulations of swirling flows.

**SEEDING MIXTURE**

The compromise required regarding the size of the intermediate and large particle sub-groups requires extensive research to determine the optimum sizes and proportions in the seeding mixture. The larger particles would provide more sensitivity to viscosity, and ease the particle population discrimination requirement to be able to separate the three velocity fields. On the other hand, the smaller the particles more closely they will follow the flow and therefore will provide more detailed coverage of the field for all three state variables.

Dring (1978) showed that the nature of a particle trajectory in a free-vortex swirling flow, is to a large degree, governed by the Stokes number. When this parameter is less than 0.1, the particle will closely follow the circular fluid streamlines. When St. is larger than 1.0 the particle will be ultimately centrifuged out across the fluid streamlines in swirling flows. For particle Stokes values higher than 0.1 in high Reynolds number flows, two extra parameters are required to describe the nature of the particle trajectory; one essentially dependent on viscosity and the other on density. Thus, the ideal composition of the seeding mixture depends on the expected radius of curvature the particles are expected to undergo before being centrifuged out. The Stokes number consideration determines the upper particle size limit, while discrimination between particle velocity fields determines the lower bounds.

Research now centres on the optimum composition for turbomachinery research. Seeding distribution across the flow field will be more uniform for the marker population than for the others. Therefore, the seeding mixture has to take this into consideration and increase the marker seeding proportion. More recent research by Rudoff & Bachalo (1991), looked at the response of seed particles ranging between 0.7 and 8.7 pm by a Phase Doppler Particle Analyzer, which simultaneously measures particle size and velocity. The stagnant seed particles were entrained into a high speed free jet at velocities ranging from 40 to 300 m/s. From this work, it was confirmed that at the lower speeds, seed particles up to approximately 5 pm are adequate, but as velocities approach 300 m/s only particles of the order of 1.0 pm are suitable. The most severe accelerations shown are larger than would exist in most practical flows, except for shocks.

The reflectivity of the seeding particles is however a major aspect of the seeding mixture requirements. The imaging is performed through the use of digital CCD technology. Now, although CCD is more sensitive than film, its dynamic range is two orders of magnitude smaller. Therefore, the reflectivity of the larger particles has to be adjusted, to bring the intermediate and large particle sub-groups back into a range the CCD is able to image without saturating, and to ensure separability of the convolved velocity fields. Four processes are possible on the polystyrene resins currently being investigated: dyeing, fluorescence, and phosphorescence and grey level information.

The marker styrene is more difficult to inject with additives but particles above 1.0pm can easily have additives. Therefore, the easiest way to discriminate between the populations is to make the larger seeding populations fluoresce at different frequencies in order to discriminate between the three velocity fields. This is the approach being pursued with a set-up as shown in Figure 1. In this arrangement two simultaneously triggered CCD cameras are employed looking at the region of interest through a beam-splitter arrangement. In the general case, one of the three populations appears in both views with one of the other two in each of the two images. Narrow-band filters have to be used. They are required so that they reject the uniform background fluorescence likely to appear on the blade surfaces, walls, etc. Previous experience with 10-nm bandpass filters has shown that image contrast can be reduced because of the collection of more background fluorescence. Dyeing is required to bring the dynamic range of the three populations within that of the CCD cameras for the case of characterisation by grey levels.

The system shown in Figure 1 will be tested with styrene doped with Fluorescein dye (514.5 nm) and Rhodamin-B (575nm) and viewed through two interferometric filters after separation by the beam-splitter. Since the two dyes' spectra overlap, there is a calibration step involved to separate the two populations. The light sheet is created by way of an Argon ion laser (λ = 488 nm). This arrangement has previously been described in the literature (Broquet & Simoens, 1995) in an application involving simultaneous measurements of two species concentrations in turbulent flow by planar LIF.

The melting temperature of styrene however is 250 °C, while its glass transition temperature is 90 °C, and so it is currently applicable to turbomachinery running at up to 90 °C. However, a facility such as the DRA Pyestock ILPC facility which is capable of running at full engine representative conditions - matching both heat transfer and aerodynamic information - requires a temperature of 190 °C. Therefore, a new high temperature version of the resin has been made which is highly cross-linked, and can stand up to a temperature of approximately 200 °C. Further study is being made of alternative and complementary materials.

**VELOCITY ESTIMATES**

At high speeds, due to the low seeding density and small scale information contained in regions of interest, such as wakes or boundary layers, the spatial approach to PIV is employed. The spatial approach to PIV analysis allows, due to the large data compression, an intensive amount of processing to be performed on any identified...
particles. Due to the well known geometric difficulties in generating 3DPIV data, an approach has been developed which makes use of the particle grey level information to obtain an accurate estimate for the out-of-plane velocity component; as well as sub-pixel accuracy in the light-sheet plane. This approach enables the use of small angles between the viewing cameras.

A diffraction limited optical component is used to provide aberration free particle images. The sensitivity of the CCD cameras and hardware is altered with the use of bespoke tuning for laser operation. It has been found that it is possible to record doublets, with a lower displacement than in the past, thus leading to an increase in dynamic range. The particle data can be automatically analysed in software. Finally, since the data is recorded in stereo, it is possible to obtain an instantaneous 3D particle whole field velocity map. In this way, the 3D velocity map is made accurate to the order of at least 30 μm in the out-of-plane component and 1/100th of a pixel in-plane. Using CCD technology at only 768x576 pixel resolution, PIV data of the order of 700 points has recently been obtained. It is estimated that in order to separate three velocity fields with velocity accuracy of the order of 0.5%, at least 1000 measurement points should be obtained for each field, and possibly more if high velocity gradients are to be investigated. This is a starting assumption and a demanding accuracy which would require the use of high precision position estimation techniques, such as those due to Havelock (1989) and applied to PIV data (Funes-Gallani, 1996). Clearly, if this assumption cannot be met, all the accuracy estimates have to be scaled accordingly. Therefore, combined with high accuracy techniques, a 12 bit 2048x2048 digital camera will also be required to make these measurements for industrial applications with the required accuracy if grey level information is required, and 8 bit would be sufficient for velocity fields separated by fluorescence.

An aspect of the technique which is of particular importance is that, since three convolved randomly distributed particle populations are being sampled, the three measurements will not refer to the same position in space. Therefore, interpolation is necessary to be able to provide three estimates of the seeding velocities at the same position. Therefore, a large number of velocity samples are required to provide well-conditioned velocity field matrices.

A limitation of the 3SA technique is that the larger particle subgroups do not follow the flow as closely as the flow marker particles by definition, and therefore some regions of the flow would not be suitably covered by all three seeding populations. In regions of high turning or back flow, it is very difficult to inject seeding at all, and if the velocity is very low, the dynamic range constraints would have to be altered together with the seeding rate. Therefore, regions of high velocity gradients remain a challenging area of research. However, this limitation might be overcome by complementing 3S data with CFD calculations to help fill in the detail.

DENSITY AND VISCOSITY ESTIMATES

The coefficient of viscosity of a Newtonian fluid is a thermodynamic property in the macroscopic sense, varying with temperature and pressure. No single functional relation describes any large class of fluids, but reasonable accuracy(± 20 percent) can be achieved by non-dimensionalizing the data with respect to the critical point. This procedure is referred to as the principle of corresponding states (Keenan, 1941). This principle is justified by dimensional analysis and experimental observation. It can be deduced that the viscosity of dilute gases increases with temperature, viscosity increases with pressure, and poor accuracy obtains near the critical point. Given the critical for air, aerodynamically the pressure dependence of gas viscosity can be ignored and be considered to depend only on temperature variations.

Thus, by solving the deconvolved velocity data field as described previously, it is possible to solve the simultaneous equations for both density and viscosity. The expected accuracy for the viscosity and density estimates is of the order of 2%.

Chapman and Cowling (1970) derived the generalised kinetic-theory formula for dilute-gas viscosity which is of the form:

\[ \mu = \frac{2.68E^{-6}\sqrt{MT}}{a^2 \Omega} \]  

(5)

where \( a \) is the collision diameter, \( M \) the molecular weight, \( \mu \) the viscosity, \( \Omega \) is the collision integral, and \( T \) the absolute temperature. For routine calculations in air, Maxwell's power law or an approximation due to Sutherland (1893) can be used:

\[ \mu_d = \mu_0 (\frac{T_0+S}{T+S})^{1.5} \]  

(6)

The error of the temperature estimate is the same as that for density, plus that involved in using an approximation to provide the temperature data from viscosity information. Thus, for the current set-up, the accuracy of the temperature estimate is 4%.

PRESSURE ESTIMATES

All the common gases follow with reasonable accuracy, at least in some finite region, the perfect-gas law. According to the perfect-gas law, the compressibility factor should be unity for gases. It varies from zero to 4.0 or greater, depending upon temperature and pressure. This effect was investigated by Weber (1939). Over the range of values applicable to turbomachinery flow, the perfect gas law is accurate to less than 1% error. Therefore, the temperature and density fields can be combined to provide a pressure field. Thus, the flow under study can be completely described. Due to the combination of factors involved in making the pressure field estimate, an accuracy in the range 5-10% is expected. However, such an estimate would be almost instantaneous. Typically, the pulse separation for turbomachinery research, is of the order of 0.5 μs.

This method of arriving at an estimate of pressure yields the thermodynamic pressure. On the other hand, Stokes (1845) pointed out an interesting consequence of the deformation law:

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\[ \tau_{ij} = -p \delta_{ij} + \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \delta_{ij} \lambda \text{div} V \]  

(7)

namely, that if the average compression stress on an element is defined as the mechanical pressure \( p \) then, by summing the above equation, we obtain:

\[ \bar{p} = p - (\lambda + \frac{2}{3} \mu) \text{div} V \]  

(8)

Thus, the mechanical pressure in a deforming viscous fluid is not equal to the thermodynamic property called pressure; \( \lambda \) is known as the Lame constant. This distinction is important in the compressible flow regime, except where viscous normal stresses are negligible such as boundary layers. Stokes himself simply resolved the issue by the assumption:

\[ \lambda + \frac{2}{3} \mu = 0 \]  

(9)

This simply assumes away the problem and it is essentially what is commonly done.

DISCUSSION

Both the frequency and spatial techniques for PIV can be employed to obtain density and viscosity estimates. The spatial approach has been chosen as the basis of this technique due to the wider dynamic range available and the ability to use lower seeding densities such as those commonly found in transonic flow of turbomachinery.

In spite of its current limitations, the technique provides for the first time a viable whole field instantaneous means of obtaining all three state variables from a single measurement. In mixing studies for instance, both velocity and a scalar property, e.g. temperature or species concentration, are to be determined. A technique such as 3SA, will enable CFD code for mixing to be validated.

3SA like PIV has a limited range of velocities it is able to measure. Currently, using the spatial approach, it is possible to achieve a velocity ratio of the largest to smallest velocity of the order of 7. Thus, if the middle velocity, for which the optimum pulse separation was chosen, was 200 m/s then a measurement range of 50 m/s to 350 m/s would be possible. Therefore, this measurement range would be adequate for the likely velocity gradients present in transonic flows. However, regions of high entropy generation would also be difficult for the larger seeding populations to enter, and therefore it may not be possible to make 3SA measurements inside the very near wake region behind trailing edges for instance. These regions tend to be areas of high viscosity also, in some instances up to 100 times higher, which would help to keep the larger particles in but a comprehensive investigation of this issue has not been completed yet.

A technique providing an instantaneous snapshot of all three state equations could lead to a complete measurement flow model and the
subsequent increases in efficiency. In order to estimate the instantaneous rate of entropy generation, as described earlier, only the rate of shear and the viscosity are required. Therefore, it could be estimated with an accuracy of the order of 5%, or almost an order of magnitude more accurately than the best current CFD estimates for an attached boundary layer.

PRELIMINARY RESULTS.

The validation procedure for this technique can be separated into four steps. The first consists of developing the means to deconvolve the three sub-group velocity fields. The second involves the use of computer simulations on a modelled flow to investigate the correct proportions, size, and characteristics of the seeding required for turbomachinery applications. The third stage will consist of making some experimental measurements of the well-known flow in the near wake of a cylinder or wedge, and compare to the simulated data. Finally, the development will involve the testing of the technique on a practical industrial flow.

The first stage of the validation process has been completed. Monodisperse fluorescent styrene particles have been produced. Interferometric filters are able to discriminate between the seeding dyed with Fluoresein and that dyed by Rhodamin-B, though other dyes are also being investigated. Further work is currently under way to try to discriminate by using the grey-level information. In this way, the two camera arrangement will be used to provide 3D information rather than a beam-splitter arrangement which only yields 2D information.

The second stage, involving the simulation of a flow past the near-wake of a cylinder, has also been completed and is described in this paper. For this case, the density is assumed to remain constant and therefore only two seeding populations are needed. A first order approximation (Hinze, 1959) to the particle motion equation reduces equation (4) to:

$$\frac{dv_p}{dt} = a v_f + b \frac{dv}{dt}$$

(10)

where $a = \frac{36\mu_p}{2\rho_p + \rho d^2}$ and $b = \frac{3\rho_f}{2\rho_p + \rho_f}$.

As previously mentioned, if creeping flow is assumed (technically $Re < 1.0$ but still broadly similar for $Re < 5.0$, Houghton & Carpenter 1993) then $D/dt$ and $d/dt$ are approximately equal. This can be combined with the inclusion of small diffusion terms to yield:

$$\frac{dv_p}{dt} + \alpha \frac{dv_p}{dx} + \alpha \frac{dv_p}{dy} + \alpha \frac{k_1}{\alpha} \frac{dv_p}{x^2} + k_2 \frac{dv_p}{y^2} - \alpha v_f + b \frac{dv}{dt}$$

(11)

The diffusion terms can be justified on physical grounds, relating to the pressure drop in the surrounding fluid, but their real purpose is to damp down any artificial diffusivity resulting from the numeri-
the above equation then becomes an almost straight forward transport equation. It was solved by a split formulation and the application of the Galerkin finite element method with bilinear rectangular elements, to solve the unsteady particle velocity problem (Fletcher, 1990). The program was used to solve for different particle diameters and provide a particle velocity field. By including the viscosity tensor into the particle velocity field calculation, the heat transfer and aerodynamic characteristics of the flow are coupled. A simulated 3S image was then produced, deconvolved and analysed. The program used for analysing the velocity fields was APWin, a program which employs the spatial approach to PIV analysis. The viscosity and the rate of shear could then be used to provide an instantaneous estimate of the rate of entropy generation.

As part of the research program on 3D PIV, the author has produced an integrated software package to validate and simulate PIV data (Funes-Gallanzi et al, 1996). This consists of three parts: the first is a CFD code based on the NSC2KE code by INRIA together with an unstructured grids mesh, the second is a particle imaging code (Udrea, 1995), and lastly a particle velocity field estimation code, as previously described, which is still under development.

Flow past the near wake of a cylinder at a Reynolds number of 140,000 is being used as test flow. It was the CFD predicted data which was used to produce a simulated 3S image with particle imaging partly based on the description by Adrian (1991). The CFD calculation used a Navier-Stokes second order scheme, Roe solver and the abibactic wall model. The turbulence model used was a k-ε model and wall laws. The experimental parameters considered were a cylinder of diameter 10mm with a mean flow velocity of approximately 100 m/s. The region of interest, at a magnification of 1, was set to 25x25mm at a distance of 600 mm; 1 mm behind the cylinder to provide a clearance to ensure there is no glare from the laser light hitting the cylinder surface. The CCD imaging modelled was that of a 2048x2048 8-bit system. The simulated 3S image contained approximately 1000 samples per seeding population, seeding density proportional to flow velocity, included CCD noise, and assumed a light-sheet thickness of 1mm.

For the flow under consideration, only the viscosity is a variable in the derivation of the particle velocity fields. Therefore, only two sizes of particle are required to fully describe the flow under consideration. Figure 2 shows a plot of the flow being investigated. Figure 3 shows the particle velocity field for a 5 μm particle and a zoomed-in CFD view of the near wake region. The particle velocity field for a 1 μm particle with a Stokes number of 0.1 varied by 1% RMS from the computed velocity field in the u-direction, as expected from experimental data. The 5 μm particle velocity fields differed by 6.7% in the u-direction and 13.4% in the v-direction. Its Stokes number is 2.5 and as can be seen from Figure 3, it would be ultimately centrifuged out in a swirling flow. The quoted RMS error values are not indicative of the likely accuracy of the viscosity estimate because the error value is global whereas the changes due to the viscosity occur only in a sub-region. In large parts of the area, the errors remain low whatever the particle size. Furthermore, the accuracy of the measurement is sensitive to the flow velocity gradients and geometry. The error of the inferred to the computed viscosity was 6% RMS, for the cylinder flow under the aforementioned conditions. A wake flow such as the one described is more challenging than a swirling flow, and since the model included the varying seeding concentrations through the field, together with all the other modelled factors, all these effects contributed to the higher than expected error. A value for the viscosity was obtained in the u and v-direction and averaged to arrive at the final estimate. The actual experimental results can be expected to be very close to those of the simulation, since all the most important factors were taken into consideration. Many aspects of the technique however, can be expected to be improved and so the theoretical accuracies for swirling flows are the long-term goal.

A further study will commence shortly by looking at computed flow around a wedge profile in the transonic region, where both temperature and density changes occur. This work has been previously investigated by comparisons with interferometric measurements (Bryanston-Cross & Denton, 1982) and therefore can be used as a benchmark. Thus, from the computed flow, a simulated image will be generated by inserting into the computed flow three different particle sizes. This 3S image will then be subjected to the process of velocity fields deconvolution and the resulting temperature and pressure estimates will be compared to the calculation and experimental data. The fourth stage is expected to be achieved over the next three years.

CONCLUSIONS

PIV has been previously successfully tested for high-speed unsteady non-intrusive measurements in turbomachinery. 3SA is a development of and experimentally very similar to PIV, and so would be applicable to either compressor or turbines. It provides, for the first time, a means of instantaneously estimating all three state variables, enabling a full description of the flow. It is therefore, directly applicable to mixing and trailing edge loss, investigation of leading edge shocks in gas turbine compressors, stator/rotor interactions, and the validation of CFD codes; assuming enough seeding is able to enter the region of interest.

The theory of the technique is fully described. Much work remains to be done to make this a practical method but the potential rewards make it worthwhile. The results shown in this paper prove the theoretical feasibility of the technique. The simulation experiments are currently being further investigated to yield resolved temperature and velocity fields of a NACA 0012 at an attack angle of 10 degrees, and provide comparisons to the CFD prediction. Progress towards a 3D measurement of velocity, density and temperature for a steady flow is feasible in the foreseeable future. The expected experimental accuracies for a benchmark swirling flows, are 0.5% for the velocity field, 2% for the density and viscosity fields, and 4% for the temperature estimates. Therefore, 3SA (if experimentally validated for the likely velocity gradients in regions of high loss) would be able to derive an estimate of the whole-field instantaneous rate of entropy generation, a measurement which cannot currently be done by any means.
REFERENCES


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