Paper 14

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A SIMPLE, NON-INTRUSIVE TECHNIQUE FOR QUANTITATIVE FLOW TRACKING

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SUMMARY

The detection of a gas that has been injected at an upstream point source is a well established method for flow tracking but the technique is of very limited application. A method is presented that enables similar measurements to be made using smoke as the injected fluid and scattered light detection as the measurement system. The intensity of the scattered light resulting from the presence of smoke in a narrow, collimated light beam provides an accurate measure of the local smoke density and measurements across the flowfield therefore provide detailed information relating to the dispersion of the smoke downstream from the injection point. Such a system can be assembled at a fraction of the cost of a gas detection system but with the significant advantages associated with a non-intrusive, fast response technique.

INTRODUCTION

Fluid tracking techniques are widely used in aerodynamic investigations of all kinds. The most common method is undoubtedly the use of smoke to map the flow trajectory and to provide a qualitative insight into the nature of a flow. Although smoke flow visualisation has been successfully used in transonic and supersonic flows (e.g. [1] and [2]) its use in high speed flows has proved limited and the technique is generally associated with very low speed wind tunnel flows. A more widely adopted flow visualisation method in high speed flows and in particular, in such flows as they relate to turbomachines is surface oil flow visualisation. Although this often proves to be an invaluable aid to the interpretation of other measurements particularly when more than one dye colour is used [3] its value when making an analysis of the bulk flow is often overrated. Fluid tracking has also been achieved using the tracer gas method (e.g. [4]-[6]) in which a separate gas species is injected into the airstream at a particular point and its distribution at some downstream plane is determined by sampling the gas mixture over an appropriate area. Unlike smoke flow tracking the technique provides potentially accurate quantitative data and the method has proved to be particularly successful in the investigation of mixing in large scale, rotating albeit low speed rigs [6]. Probably the greatest limitation of the method is the time that is required to sample and analyse the gas mixture since sufficient gas must be collected to purge the analyser of any previous sample.

EXPERIMENTAL BACKGROUND AND DESCRIPTION

The Use of Smoke in High Speed Flows.

In high speed flows it is necessary to record flow patterns photographically since simple observation generally provides little useful information. The widest use of the method has been for the study of flow deflections in shock systems (Fig. 1). For such applications the smoke particles must be small enough to faithfully follow the true flow path yet large enough to scatter sufficient light to allow the smoke stream to be photographed. To meet both of these requirements smoke particles should lie in the range 0.15μm to 1.00μm and the most commonly used smoke source, as in low speed work, is kerosene. Much high speed flow visualisation has centred on the schlieren technique and since the index of refraction of oil smoke is not very different from that of air it has proved necessary to investigate alternative smokes and gasses [7],[8]. In the turbomachinery context high speed smoke flow visualisation has been successfully used in transonic cascade flows [9].

Flow Tracking by Scattered Light Measurement

At its simplest level the concept of this new technique is to replace the photographic recording of illuminated smoke traces by the detection of the scattered light intensity at particular points in the flow by a an electronic opto-detector via an appropriate optical system. Unlike conventional smoke flow visualisation it is not necessary to illuminate the entire flowfield. Indeed, the illumination of the flow by a fine, collimated beam allows measurements to be made at a particular location in three-dimensional space with a very high degree of resolution. With appropriate traversing systems for the light source and the detector it is therefore possible to obtain high resolution, quantitative measurements throughout the flowfield. Since most of the rigs and wind tunnels that are used in turbomachinery studies are fitted with two or three dimensional traverse equipment it is a simple task to apply the Smoke and Scattered Light (SSL) technique. However, since this is essentially an optical measurement method it is possible to replace mechanical traverse gear by appropriate systems which allow high speed 'optical traversing' of the flowfield by means of rotating devices such as mirrors, prisms and lenses.

Although in principle it is possible to obtain quantitative measurements from smoke flow visualisation by the analysis of the density of photographic negatives the method is rarely, if ever used since it is both difficult and unreliable. The SSL method not only provides quantitative data but does so in real time. In smoke flow visualisation studies it is usual for the smoke to be injected into the flowfield at one or more point sources so the SSL method is particularly applicable to flow tracking. In this application the technique has major benefits relative to the tracer gas method. The most obvious is that the detection system is non-intrusive whereas the tracer gas method requires a probe in the flow for gas sampling. A possible disadvantage is the requirement for optical access to the test section but in most applications this is unlikely to present major problems. Unlike Laser anemometry there is no need for particularly high precision optics and the very much greater intensity of the detected scattered light in the SSL system allows much greater flexibility in terms of the direction from which the particles are illuminated.

A further advantage of the SSL system is its potential for high frequency measurements even when simple, low cost components are used. In most turbomachinery applications the scattered light intensity is likely to be sufficient to be detected using a single photodiode and such devices are generally able to respond to frequencies in excess of 50 kHz and very often the response may extend into the MHz range. Photomultipliers are unlikely to be required in the majority of cases.

The Prototype System

To investigate the feasibility of the SSL technique a simple system was constructed which consisted of just three components. These were a self contained laser light source, a single lens and a battery powered photodiode (figure 2). The chosen light source was a 'Pocket Laser' produced by ILEE (figure 3). This was a 1mW hand held laser which was designed as a pointing device for visual presentations. The red light is produced by a laser diode with appropriate optics for the creation of a collimated beam. Further details are given in table 1. Numerous similar laser sources are readily available giving outputs of up to 7mW and often providing features such as variable output power and adjustable focus. Major benefits from the use of this kind of laser source are small size (typically 10mm diameter, 40mm long), light weight (50g) and the need for only a low voltage battery power supply. Such compact devices can easily be fitted to typical cascades and wind tunnels and they also offer the potential for use on rotating blades in large, low speed rigs. Monochromatic light is not an essential element of the SSL technique but there are practical advantages that are associated with its use. The adoption of a monochromatic light source allows experiments to be conducted in typical laboratory lighting conditions by including a narrow bandpass optical filter on the detection side of the system to minimise the influence of background light. The frequency spectrum of a typical laser diode is shown in figure 4 and matching bandpass filters are available from most suppliers of optical components. For the purposes of this study a filter was not used and the measurements were made in low ambient light levels. The detector used in this study was a photodiode device with integral amplification giving a high level voltage output in proportion to the detected light and hence approximately in proportion to the smoke density. The accuracy of this approximation needs further investigation since the measurements will undoubtedly be influenced by factors such as secondary scattering and beam attenuation across the flowfield as well as by the linearity of the detecting sensor itself. However, other techniques that make use of light measurements from a beam that is fired across a flow such fluorescence techniques (e.g. [10],[11]) suggest that as a first approximation linearity may be assumed. Focusing of the scattered light emissions onto the detector was achieved using a single, uncoated spherical lens of 50mm focal length and 38mm diameter. The lens together with the laser and the detector is shown in figure 5. For high resolution measurements in a complex flowfield it is anticipated that the sensor would receive light through a slit which would be set perpendicular to the beam that is produced by the laser source.

Type	ILEE 'Pocket Laser'
Output Power	< 1.0 mW [Laser Class 2]
Beam Divergence	0.7 mrad
Wavelength	670.0 nm [continuous]
Power Supply	2 x 1.5V batteries
Weight	0.1 kg

Table 1 : Laser Specification

Type	IPL10530D
Supply Voltage	9.0V dc
Output Voltage	27.0 mV/μW/cm^2
Active Area	1.75 mm^2
Peak Spectral Response	820.0 nm
Frequency Response	65.0 kHz [-3dB]

Table 2 : Photodiode Detector Specification

SAMPLE RESULTS AND DISCUSSION

For the purposes of this initial study measurements were made in a low speed wind tunnel at a maximum airspeed of 40m/s and the chosen subject for investigation was the flow just downstream from the exit of the smoke injection probe. The smoke probe diameter was 4mm giving a probe Reynolds number of 10500 and the measurement plane was approximately 5 diameters downstream from the probe. All measurements were made at a fixed point near the axis of the smoke probe. The data was collected using an Elonex portable 386sx based PC via a 12bit ADC card logging at 10kHz.

Figure 6 shows the signal that was recorded at a probe Reynolds number of 2250. The response of the system to the unsteady nature of the trailing vortex structure is immediately apparent. The measured frequency is consistent with approximate Strouhal number calculations and doubling the Reynolds number is seen to double the recorded frequency (figure 7). The rate of smoke generation was unchanged between these two tests so a lower smoke density occurred at the higher Reynolds number resulting in a lower mean light emission. At the higher Reynolds number it is seen that the laser was not switched on until approximately 0.015s into the run. The values recorded during this initial period correspond to the combined effects of the ambient light level and the dark output from the detector. Further doubling of the Reynolds number again resulted in a consistent increase in the emission frequency (figure 8). The drift of the mean recorded light level over the sampling period is due to fluctuations in the rate of generation of the smoke. The influence of particle size on light scattering is shown clearly in figure 9 which records the passing of a small unburnt kerosene droplet.

Limitations of the Method

No experimental technique is without its limitations and the SSL method is no exception. The problem of optical access to the flowfield has already been touched upon as has the possible need for more sensitive detection devices in flows where the smoke is diffuse. However, sensitive detection systems have been highly developed for laser anemometry and SSL light levels will always be large in comparison. The attenuation of the light beam as it passes through the smoke is a possible problem which deserves further attention but under 'normal' flow conditions it is unlikely that the density of the smoke or its overall quantity will cause significant difficulties. Surface reflections may create misleadingly high local scattered light levels but corrections for such effects are generally straightforward and methods that have been developed for the well established electron beam fluorescence technique to minimise surface effects may be adopted [12]. If the smoke is injected directly from a simple smoke generator it may be necessary to cool the smoke to the ambient rig flow temperature. Cooled smoke systems have been widely developed over a long period and the field is summarised in reference 7. It is also essential that the smoke density is uniform and steady when it is introduced into the flowfield. In some situations it may be beneficial to monitor the consistency of the smoke near its source.

Suitable Applications for the SSL Technique

Within the context of turbomachinery studies the technique has many potential applications. Of these perhaps the most significant lies in the study of film cooling since cooling holes and slots provide an ideal smoke injection source and the flow path and mixing of the cooling air is currently of great interest. Other applications include the direct replacement of tracer gas methods both in cascade and in rotating rigs and also in studies of boundary layer behaviour and growth including separation studies.

CONCLUSIONS

A low cost technique has been demonstrated that is suitable for the quantitative measurement of steady and unsteady flow features that relate to flow tracking and mixing processes. Significant advantages over established tracking methods have been shown. The simplicity of the method and the compact nature of the components of the system allow the SSL technique to be easily adapted for use in most typical cascades and rotating rigs.

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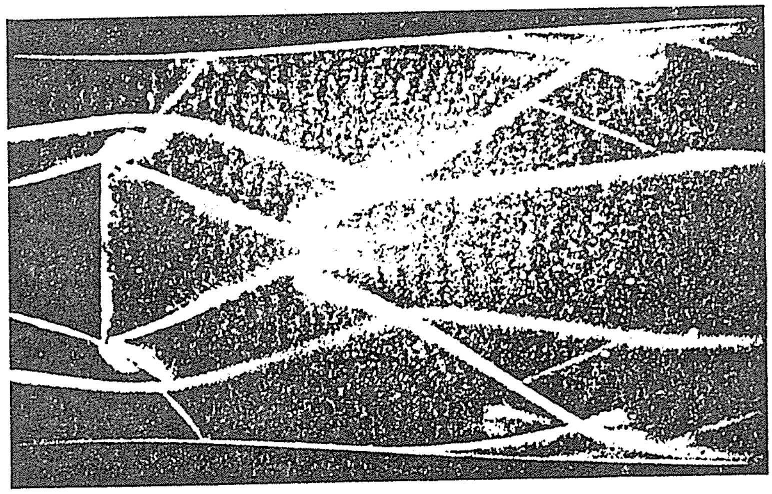
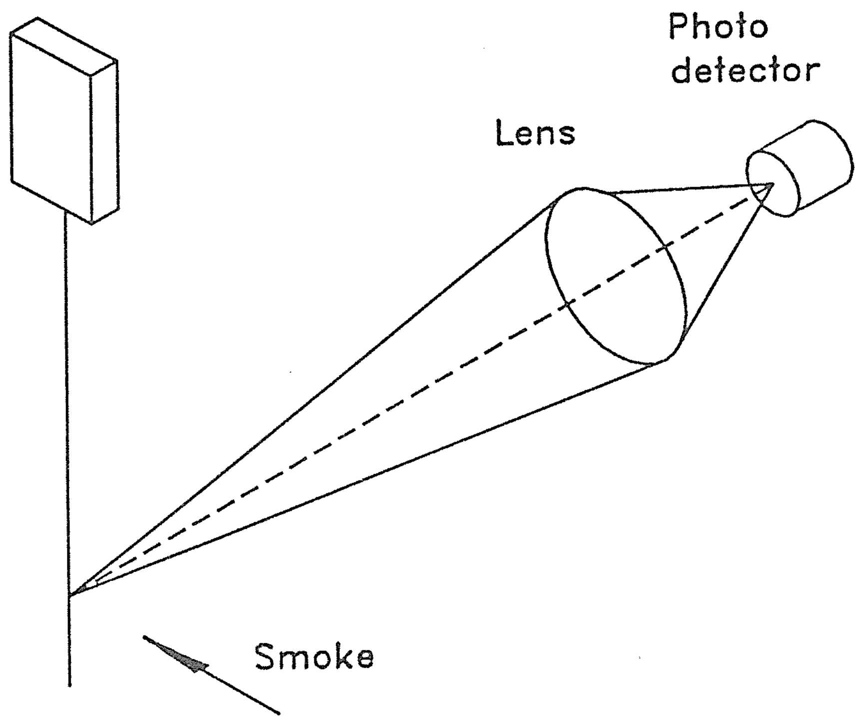


FIGURE 1
Simultaneous smokeline and opaque-stop schlieren photograph of wake flow with laser light source. (from Mueller [1])



Layout of Simple Detection System

FIGURE 2

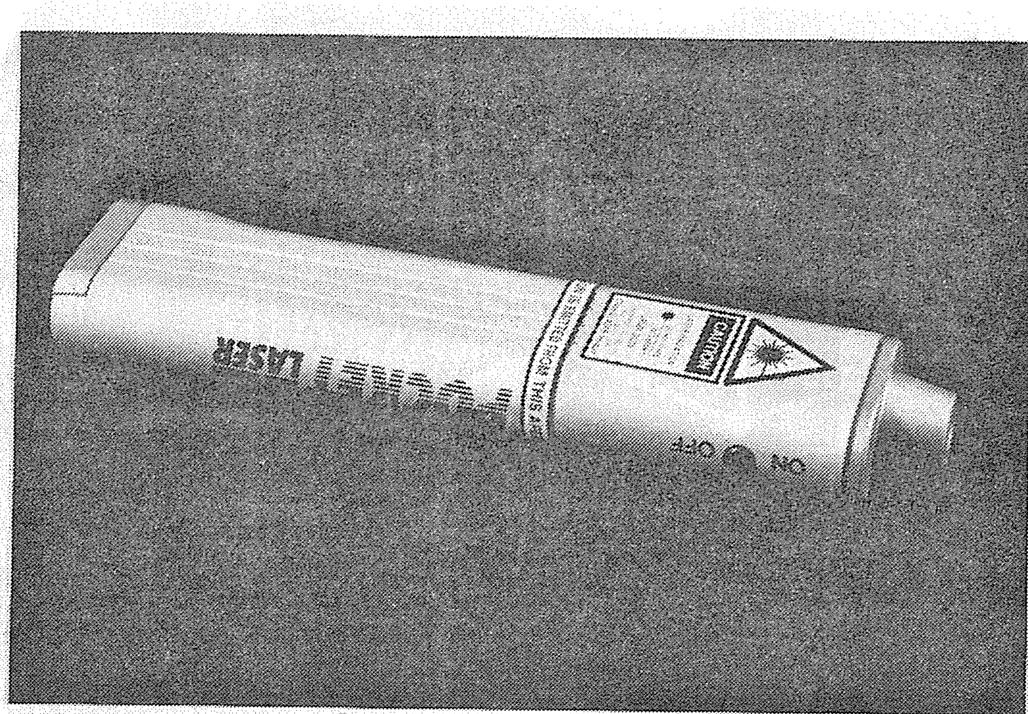


FIGURE 3
The laser light source

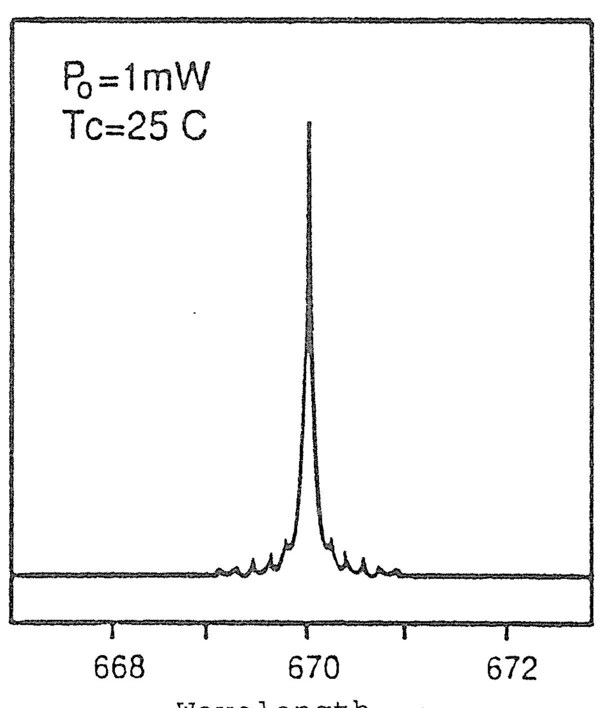


FIGURE 4
Typical spectrum of a laser diode

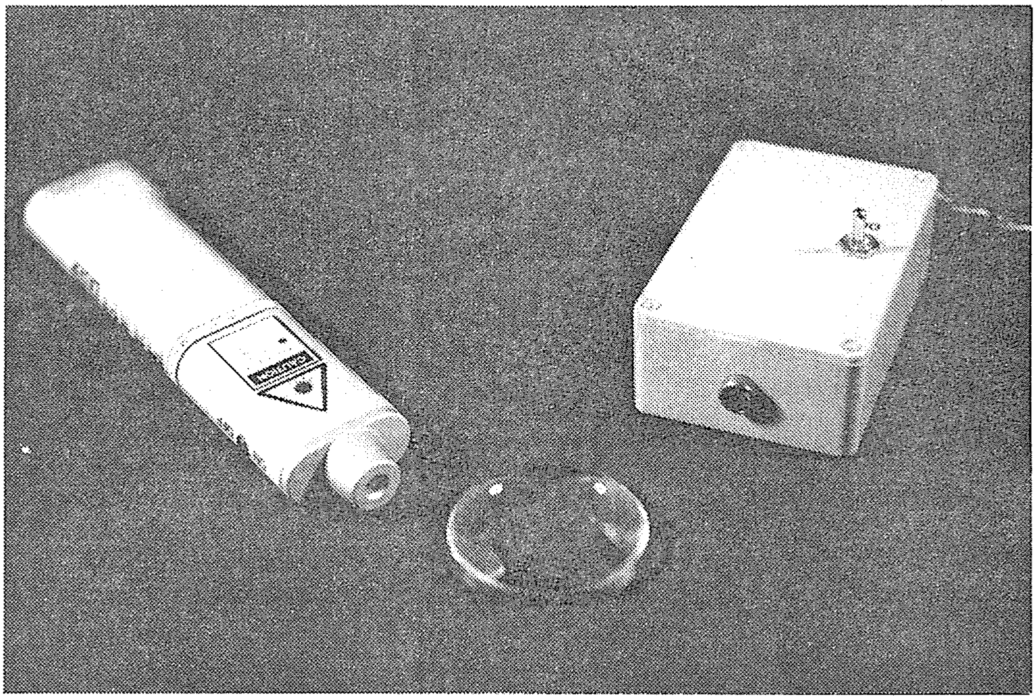


FIGURE 5
The three components that make up the SSL system : laser, lens and photodiode detector

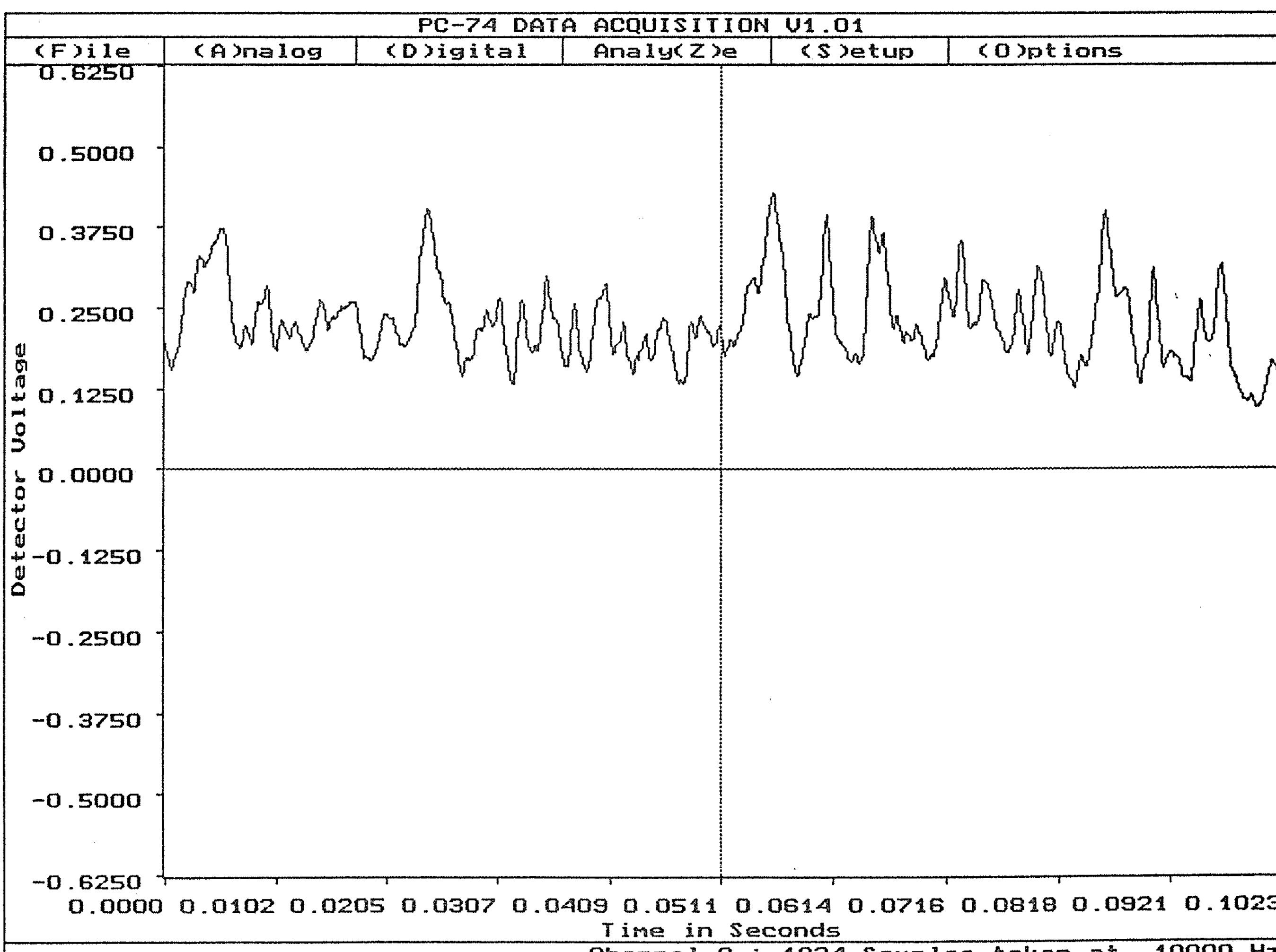


FIGURE 6
Scattered light detection downstream from the smoke injector (Re = 2250)

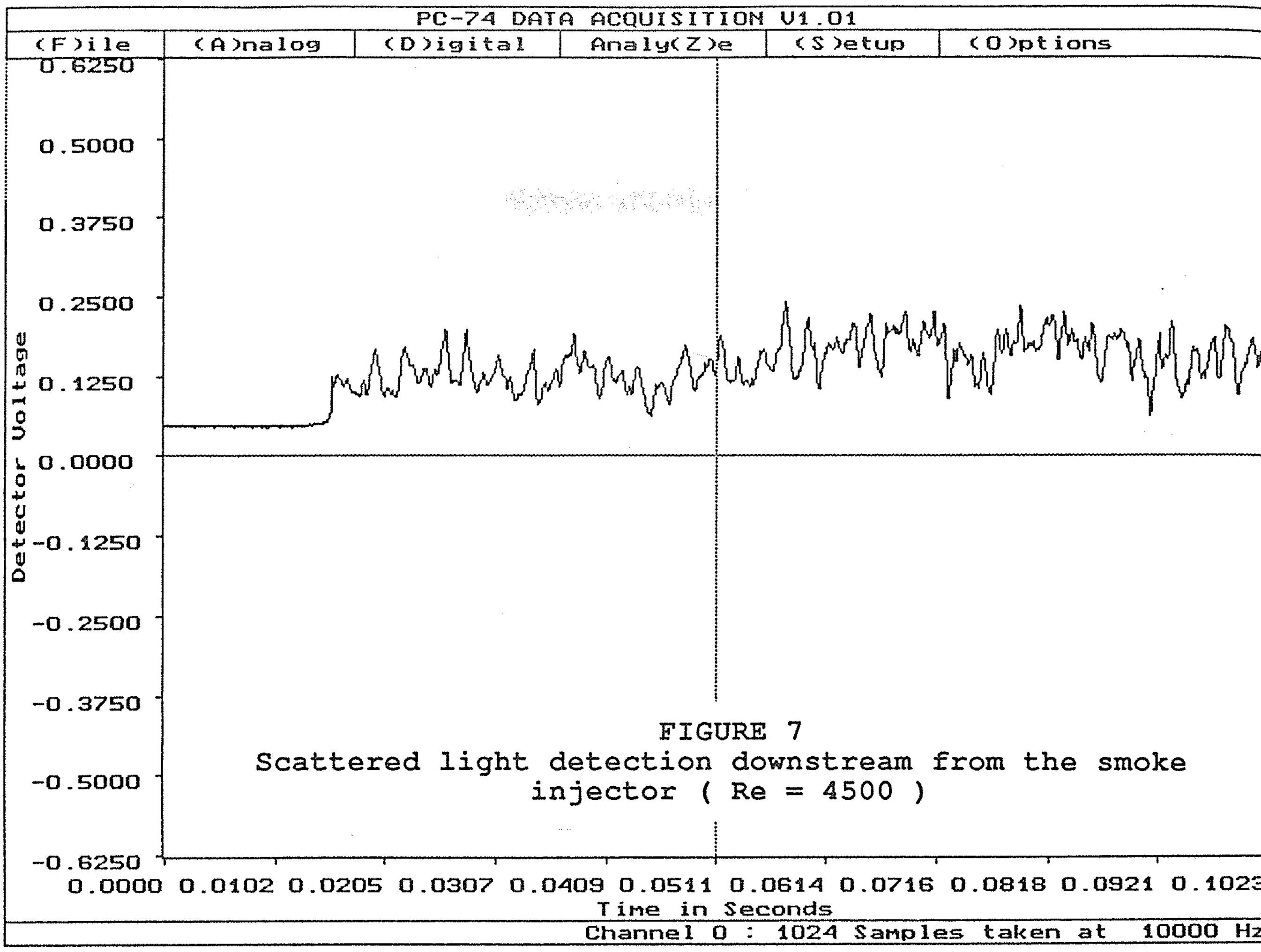


FIGURE 7
Scattered light detection downstream from the smoke injector (Re = 4500)

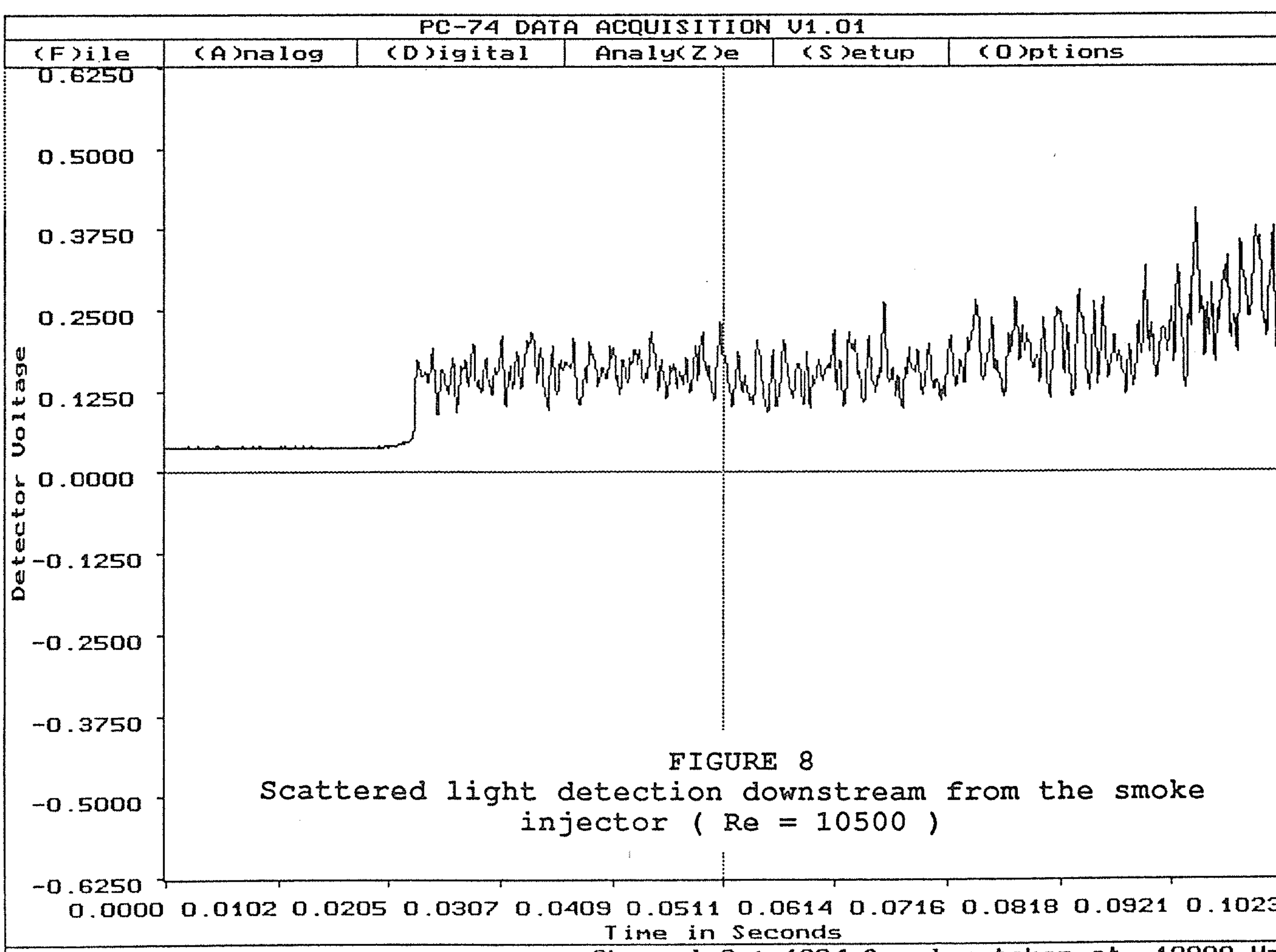


FIGURE 8
Scattered light detection downstream from the smoke injector (Re = 10500)

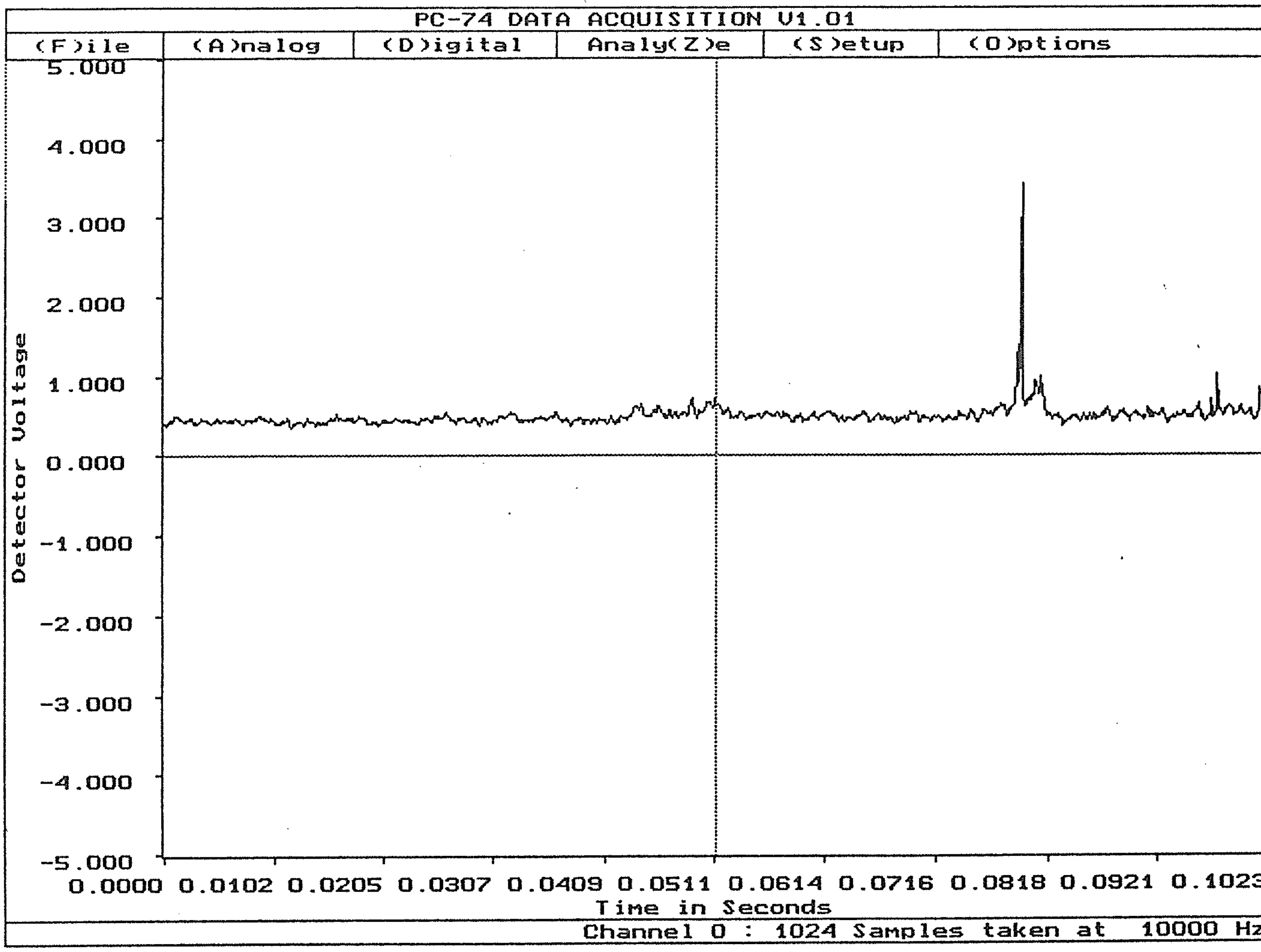


FIGURE 9
Scattered light signal showing a high intensity peak caused by an unburnt oil droplet