Delivery of high peak power light through hollow waveguide fibres for particle image velocimetry

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ABSTRACT

The technique of particle image velocimetry (PIV) is widely applied to the measurement of high speed flows. In some applications, however, its use is restricted by the requirement for direct optical access. This is a particular problem for measurement of flows inside enclosed volumes, such as inside internal combustion engines, and although solutions exist, e.g. by using either customised transparent components or endoscopes, these are expensive to fabricate and/or inflexible. Conventional step-index optical fibres have been successfully demonstrated in such applications [Stephens *et al.*, 2003], but their relatively low damage thresholds mean that in order to deliver the required energy and beam quality a bundle of fibres is required, with concomitant losses at the input to the fibre. In this paper we present an alternative solution which makes use of a low-loss hollow waveguide fibre, capable of delivering pulse energies of 10's of mJ, with a beam quality suitable for small volume PIV measurements. The performance of such a fibre is demonstrated with example flow measurements inside an optically-accessed internal combustion engine.

A hollow waveguide fibre is essentially a long capillary tube internally coated with a reflective surface, typically silver with a dielectric polymer coating [Matsuura *et.al.*, 2002]. These waveguides, whilst performing similarly to conventional optical fibres, guide by fresnel reflection rather than total internal reflection (TIR) so are suitable, with the correct choice of coating, for a greater range of wavelengths than silica or glass fibre. They are also ideally suited to the transmission of high peak powers, particularly if filled with a gas of high ionisation potential; this increases the threshold for gas breakdown that can occur in the high optical field in the hollow core, resulting in damage to the fibre structure. Hollow core waveguides are available in a range of diameters, limited by the manufacturing process, from 0.3 to ~ 2mm.

One problem with light delivered through large core fibres such as these is speckle interference, which arises from the multimode nature of the fibre. This can lead to problems for PIV, with particles potentially moving between dark and bright regions of the speckled light sheet, which can result in loss of data [Stephens *et al.,* 2003]. In our paper, we will describe a novel technique to reduce the coherence of the laser beam and hence reduce the speckle visibility.

INTRODUCTION

Particle Image Velocimetry is a well-established technique for measuring high speed fluid flows over large areas [Westerweel, 1997., Keane and Adrian 1992].   Typically the light sources used are frequency doubled Nd:YAG lasers. These both provide sufficient pulse energies to illuminate large areas and short enough pulse durations to freeze the motion of high-speed flows. Because of the high peak power of these lasers, delivery of the beam is normally limited to bulk optics. This leads to problems of access in some cases, for example when taking measurements inside internal combustion engines. To gain good optical access to volumes of this type an experimental rig would normally have to be specifically designed with transparent components. Methods of improving access include the use of endoscopes [Dierkeide *et al.*, 2001]; articulated arms containing mirror assemblies; and optical fibres [Stephens *et al.*, 2003]. There are drawbacks to all of these methods, however. Endoscopes lack flexibility, whilst articulated arms are bulky and awkward to use. Optical fibres, meanwhile, are limited in terms of power delivery and produce a speckly output although this can be reduced by using a bundle of fibres of different lengths [Stephens *et al.*, 2003]. In this paper we demonstrate the use of hollow core fibres to deliver a light sheet used to take PIV data. These fibres are nearly as flexible as conventional fibres but are capable of delivering higher peak powers. We will also demonstrate a technique to improve the speckle contrast of the light from these fibres that may lead to improved PIV data.

HOLLOW CORE FIBRES

Hollow core fibres consist of a length of capillary tubing, usually glass, with a reflective internal layer. Typically silver is used as the reflective coating with a layer of a dielectric to both protect against oxidisation and to optimise reflection at the design wavelength [Matsuura *et.al.,*. 2002]. These fibres guide by Fresnel reflection, which leads to some important differences in characteristics over conventional silica fibre guiding by total internal reflection. With the correct choice of coating these fibres may guide a greater range of wavelengths then silica fibres, from 355nm [Matsuura *et.al.,*. 1998] to 10.6μm [Saitom *et al.*, 1994]. Most noticeable is that the core is filled with air, which has a much higher breakdown threshold than silica leading to the potential for high power delivery. Other gases (e.g. Helium) with a higher ionisation potential may be used to purge the core and further increase the capacity for the delivery of high power pulses [Sato *et al.*, 2000]. These fibres are more lossy than silica fibres as there is a small loss associated with each reflection, this also leads to higher bend losses [Nubling and Harrington, 1996]. Higher order modes are more lossy due to the greater number of reflections in a given length, which leads to the preferential guiding of lower order modes and means that the output beam quality is better for a hollow fibre compared to a step index fibre of similar diameter. The fibres used in this work were manufactured at Tohoku University and are available in a range of diameters, limited by the manufacturing process, from 0.3 to ~2mm.

BEAM QUALITY

An important parameter of a laser beam forming a light sheet is its M^2 value [International Standard Organisation (ISO) EN ISO 11146:2000]. This gives a measure of the focusability of the beam and compares the dimensions of a focused spot to the diffraction limited ideal using the formula:

$$\boldsymbol{w}_0 \boldsymbol{a}_0 = M^2 \frac{\boldsymbol{l}}{\boldsymbol{p}}$$

1.

Where ω_0 is the focal spot radius and α_0 is the cone angle subtended to the spot by the beam. A perfect laser beam will have an M^2 value of 1 but all real laser beams will have a value higher than this, in practice values range from about 1.05 to several hundred.

The hollow core fibres examined here had core diameters of 0.32mm, 0.54mm, 0.7mm and 1mm. These are all relatively large diameters and mean that the beam quality exiting these fibres will be worse than the input beam quality due to inter-modal coupling between the many modes delivered. If the output of any of these fibres is to be used for PIV the beam quality must be good enough that it can be focused into a thin light sheet over sufficient distance to fill the area of interest. In the case of an

internal combustion engine this means a light sheet of around 60mm $\times$ 60mm $\times$ 1-2mm and requires a beam with an M^2 value of <120. The measured M^2 values for these four different fibres is shown in table 1. As can be seen the larger diameter fibres give greater M^2 values due to the presence of a greater number of guided modes. The 0.32mm and 0.54mm fibres output a sufficiently good beam quality that they could be used to produce a light sheet for PIV.

Table 1: Measured M^2 and calculated NA of each diameter of hollow core fibre.

Internal Diameter	M^2	NA
0.32 mm	72	0.076
0.54 mm	121	0.078
0.70 mm	176	0.084
1.0 mm	370	0.125

SPECKLE

Hollow core fibres support multiple modes of propagation and when a coherent light source is used they will present a speckly output in a similar manner to multimode step index fibres. The speckle pattern arises from interference between the many guided modes each travelling slightly different path lengths within the fibre. Speckle can potentially lead to lost or incorrect PIV data in one of two ways [Stephens et al., 2003]. If the speckle pattern has a low spatial frequency, i.e. there are large bright and dark areas next to each other then in some regions there may not be sufficient illumination to acquire PIV data. Data may be lost over large parts of the image. Alternatively if the speckle pattern has a high spatial frequency so that there are many high and low intensity regions close together then data can be lost as particles move between regions. Particles illuminated in one image may not be illuminated in the other, which will lead to lost or anomalous data.

In the case of a fibre bundle [Stephens et al., 2003] it was possible to improve the speckle characteristics by making each fibre a different length from all the other fibres in the bundle. The variation in length was greater than the coherence length of the laser source so that the output from any one fibre would not interact with the outputs from other fibres. In this way the speckle patterns from different fibres were overlapped and averaged to give a more even light distribution that was suitable to take PIV measurements. Kotov et al [Kotov et al., 2001] have also presented a method of reducing the speckle contrast from a single multimode fibre with the use of an acousto-optic modulator (AOM). The AOM was used to split a laser beam into two parts that were then reflected back to the AOM and recombined with differing properties. The recombined beams differ in frequency by twice the driving frequency of the AOM, they have different polarisation states and divergence. These factors enable the reduction of the output speckle characteristics. This method was intended for low power continuous wave operation and has not been applied to short high power pulses of interest here.

The effect of the speckle from hollow core fibres was assessed by comparing the signal to noise ratio of PIV measurements made using these fibres with measurements made using a directly delivered light sheet. A new technique is also demonstrated that is shown to improve the speckle contrast, and may further improve the potential of these fibres for PIV.

POWER DELIVERED

Standard step index fibres are limited in terms of the energy that they can deliver for such short pulse lengths (8ns). The fibre may suffer from damage at the end face as a result of the high energy densities present there. Damage may also occur inside the fibre, a few millimetres away from the end-face, due to the nonlinear effect of self-focusing. Conditioning the beam before launching it into the fibre by using a Diffractive Optical Element (DOE) has been shown to increase the amount of power that can be delivered before damage occurs but even then it is only possible to deliver 10mJ through a 200μm core [Hand et al., 1999]. Increasing the core diameter will allow higher energy pulses to be delivered but this will be at the expense of a reduced beam quality and will mean that the output can no longer be focused into a light sheet of sufficient dimensions. In previous work this problem was overcome by

constructing a bundle of 19 fibres [Hand *et al.*, 1999] so that while the pulse energy delivered by each individual fibre was low the bundle overall was capable of delivering 30mJ pulses. A similar bundle was successfully used to take PIV data in an internal combustion engine [Stephens *et al.*, 2003]. A significant drawback in this bundle arrangement was its bulk and the inherent inefficiency of launching into multiple fibres, the total efficiency of the bundle was only 23%. Using a single hollow core fibre with a higher damage threshold will allow a more simple arrangement and greater efficiency.

To assess the capability to deliver high powers damage tests were conducted on all four fibres. A gas cell was constructed to purge the core with a flow of Helium, shown in figure 1. As Helium has a higher ionisation potential than air, larger pulse energies can be delivered before breakdown occurs in the core causing catastrophic damage to the fibre. The gas cell enables the input of the fibre to be immersed in Helium at a pressure slightly higher than ambient, whilst the output end is left open to allow a flow through the fibre. In all tests the fibre was held with a bend of 180° and a bend radius of 300mm. Higher energy pulses could be delivered if the fibre was held straight but in any real application some bend will be present.
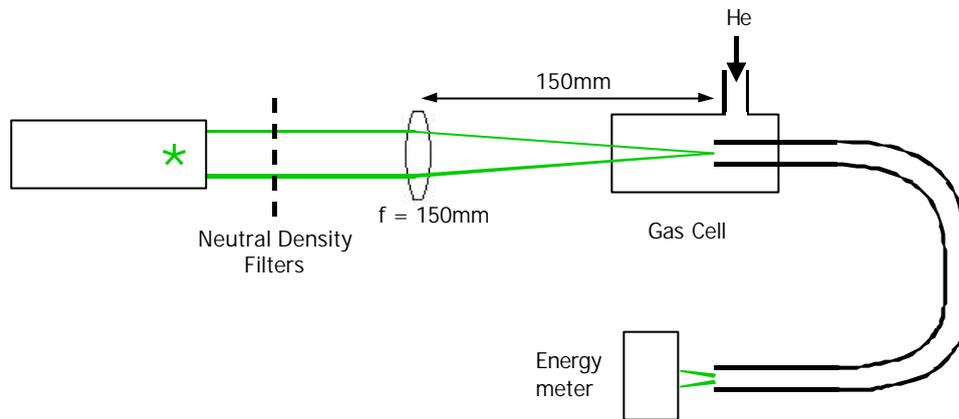

Figure 1: The arrangement used for damage tests.

The damage thresholds of the four fibres are shown in table 2. The 0.54mm fibre has both sufficient beam quality and an adequate damage threshold to produce a light sheet for PIV. Using this fibre we were able to carry out PIV measurements inside the cylinder of an optical test-bed automotive engine.

Table 2: Results from damage tests carried out at 532nm using 8ns FWHM
Q-switched Nd:YAG pulses at 10Hz repetition.

Internal Diameter	Pulse Energy Delivered	Efficiency
0.32 mm	1.75 mJ	59%
0.54 mm	14.1 mJ	39%
0.70 mm	18.2 mJ	44%
1.0 mm	31.6 mJ	48%

EXPERIMENTS IN OPTICALLY ACCESSED INTERNAL COMBUSTION ENGINE

The suitability of hollow core fibres for PIV was assessed through a series of back-to-back tests within the cylinder of an optically accessed internal combustion engine. The barrel and piston crown were formed from fused silica to allow optical access. One set of tests was conducted using a 540μm hollow core fibre, whilst the other used conventional (bulk) optics. In each set of experiments the light sheet was generated from below, through the piston, and was aligned parallel to the bore centreline of the engine as illustrated in figure 2. The flow was imaged through the cylinder barrel. To generate a light sheet using the 540μm hollow core fibre an arrangement was made that held the end of the fibre and two cylindrical lenses, these formed a telescope to produce the light sheet. A directly delivered light sheet was then produced using bulk optics. A negative lens was used to diverge the beam with an aperture placed before the lens to reproduce the NA of the fibre. The same cylindrical lenses were used

to form a light sheet of similar thickness to that delivered by the fibre. Both light sheets were approximately 1.1mm thick (measured by removing the mirror), and plots of the measured thickness of each light sheet as a function of distance are shown in figure 3.
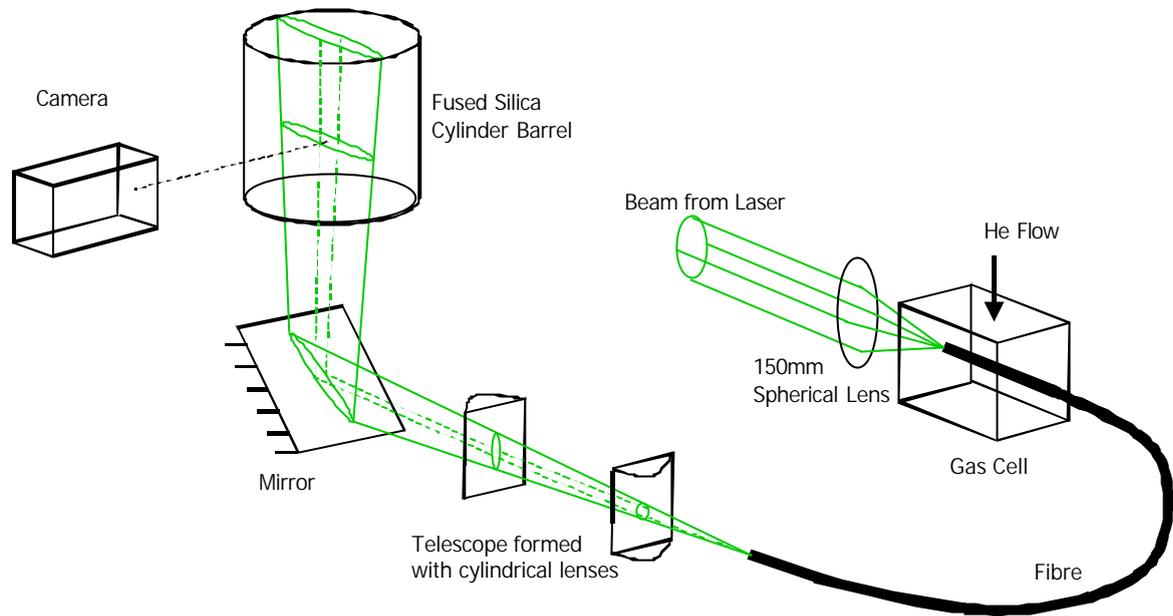

Figure 2: Experimental set up of light sheet optics used for in-cylinder measurements.
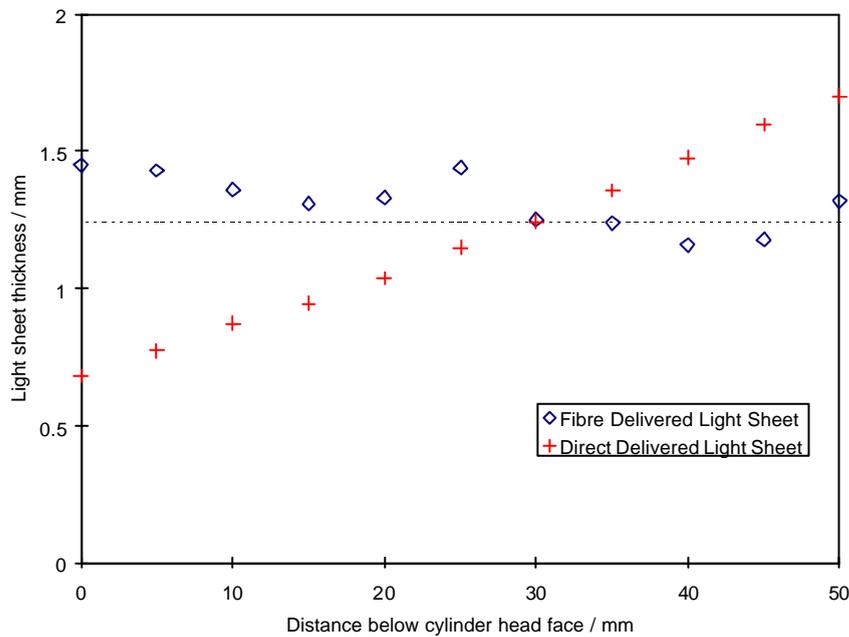

Figure 3: The thickness of the light sheet was measured and found to vary between 0.7 mm and 1.6 mm.

The light source used was a dual cavity q-switched, frequency-doubled Nd:YAG laser with a maximum pulse energy of 70mJ. The pulse energy delivered by each delivery system varies, primarily because the launch efficiency into the fibre will never be 100% and there will also be losses within the fibre at bends. To give a fair comparison between measurements the images from each delivery system were compared to ensure particles were of similar intensities. The delivered pulse energies were found to be approximately 7mJ in each case.

Experiments were conducted at two different engine speeds, 750RPM and 1500RPM. In each case, the engine was driven by an electric motor. For each engine speed three crank angles were used, 90°, 180° and 270° after top-dead-centre (ATDC) during the intake/compression stroke. Sample (negative) images taken at 1500RPM, 270° ATDC are presented in figure 4. Figure 4a shows a directly delivered light sheet, a fibre delivered light sheet is shown in 4b. The bright strip at the bottom of each image is the piston crown (60mm in diameter) where the light sheet enters the cylinder. Some reflected light from the spark plug is present at the top of both images. The seeding particles are droplets of olive oil, approximately 1-1.5µm in diameter.
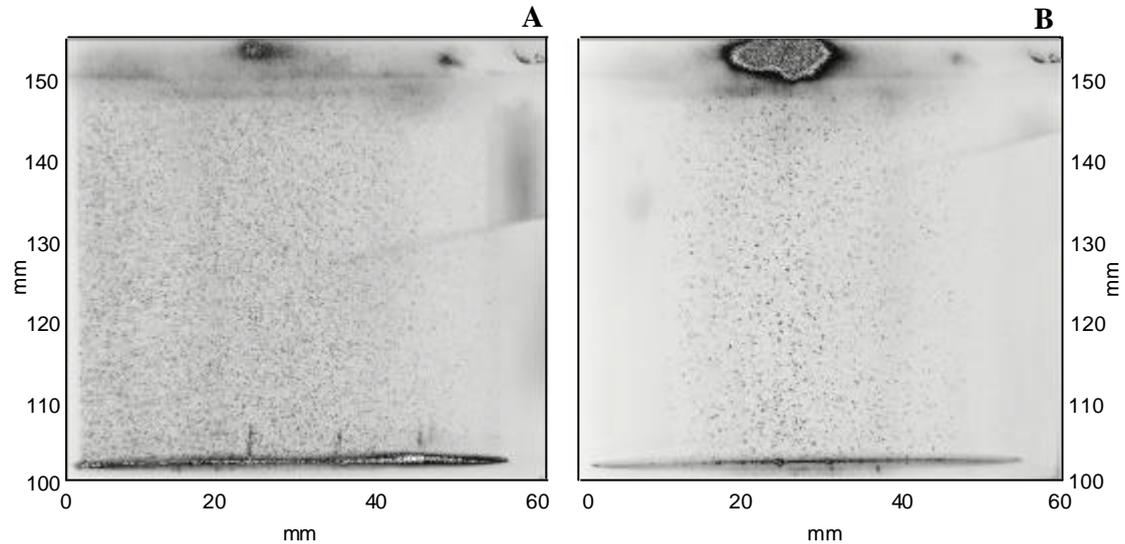

Figure 4: Sample images of light sheets at 270° ATDC for an engine speed of 1500RPM. Image A is delivered directly, image B is fibre delivered. The pulse energy of the laser was adjusted to ensure the intensity of the particles were similar in each image set.

PIV RESULTS

The pairs of images were processed using *LaVision* DaVis commercial PIV software. Multigridding was used with the grid dimensions set to reduce from 128×128 to 32×32 in four steps. The correlation results were not optimised, other than to remove vectors that were very different (r.m.s. > 2 × neighbour) to adjacent vectors, and therefore clearly incorrect. Figure 5 shows two sample vector fields taken at 270° ATDC for an engine speed of 1500 rpm. A directly delivered light sheet was used for the vector field shown in figure 5a and fibre delivery was used for that shown in figure 5b. There are a small number of vectors present in figure 5b that appear incorrect.
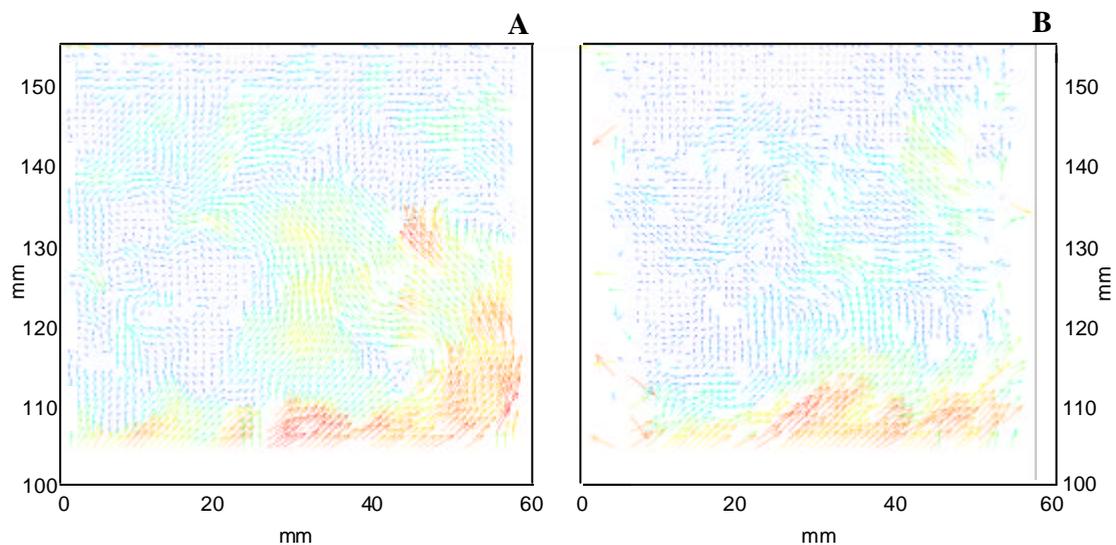

Figure 5: Sample vector fields images for 270° ATDC for an engine speed of 1500rpm. A directly delivered light sheet was used for A and a fibre delivered light sheet was used for B.

To determine confidence in measurements the signal-to-noise ratio (Q-value) for each set was found. The Q-value is defined as:

$$\frac{P_1 - \min}{P_2 - \min} \qquad\qquad 2.$$

where P1 and P2 are the heights of the first and second highest peaks in the correlation plane for each region and *min* is the minimum value in that region. For each velocity field the average Q-value was found and the mean for that set was calculated from these. The Q-values and standard deviations averaged from all the velocity fields in each set are shown in table 3.

Table 3: Mean Q-value and standard deviation for the PIV results at a crank angle of 270 degrees ATDC for both delivery methods.

	Q	Std. Dev.
750 RPM Fibre	2.627	0.0172
750 RPM Direct	2.659	0.0334
1500 RPM Fibre	2.657	0.0494
1500 RPM Direct	2.806	0.0285

The Q-value is dependent on the pulse separation, number of particles per region, velocity gradients within the region, interrogation region size, particle image size, light sheet thickness and intensity distribution. As far as possible these factors are all consistent between experiments. The pulse separation used, which was double at 1500 rpm when compared to 750 rpm, may have been more optimised for 1500 rpm, which could explain why the Q-values are higher for this engine speed. Otherwise the main difference between experiments is the speckle introduced by the hollow core fibre and this is believed to be the major reason for the slightly lower Q-values of the fibre results. The difference between the Q-values for each delivery system is not substantial and demonstrates that fibre delivery does not have a significant detrimental effect on the quality of the PIV correlation and still produces good data.

SPECKLE REDUCTION EXPERIMENTS

A method of improving the smoothness of the speckle pattern was devised that involves splitting the laser beam into a number of different components. The components are recombined each with a successive path length increase that is greater than the coherence length of the laser. This effectively reduces the interaction due to the coherence of the light source and results in several separate and non-interacting speckle patterns at the output of the fibre, which average to give an improved intensity distribution. The arrangement that was used to do this is shown in figure 6. Light passes through the first quarter-waveplate that is aligned to produce an elliptical polarisation state. When incident upon the polarising beam splitter cube the vertically polarised component is reflected toward the fibre and the horizontal component is transmitted. Light transmitted by the beamsplitter is sent around a loop comprising of three dielectric mirrors and the beamsplitter itself. If the polarisation state remains unaltered this light will be transmitted on its second incidence upon the beamsplitter and directed towards the fibre. Rotating the first waveplate allowed the ratio of light split between the beams to be varied. In this case it was desirable to have a 50:50 distribution, this gave two collinear beams that were launched into the same fibre. The path difference introduced was equal to the path length round the loop, approximately 300mm; this is substantially greater than the coherence length of the laser (16mm in glass).

Adding quarter waveplates into the loop produced an elliptical polarisation state so that the light was again split at the beamsplitter. A fraction of the light was transmitted in a second beam and launched into the fibre. The rest was reflected to make another pass of the loop before being split again to produce further beams. In this way several collinear beams were produced and were launched into the fibre. The waveplates in the loop could be varied to alter the rate of decay of light. For these experiments the light was split as follows: 23.0% in first beam, 27.0% in second beam, 31.8% in third beam, 15.7% in fourth, 2.4% in fifth, subsequent beams contained too little energy to measure. The

output from the fibre was viewed on a CCD camera and the images were compared and analysed. For each set of images taken it was ensured that the total energy output by the fibre was closely similar. This was done to avoid any effects that camera non-linearity may have on results.
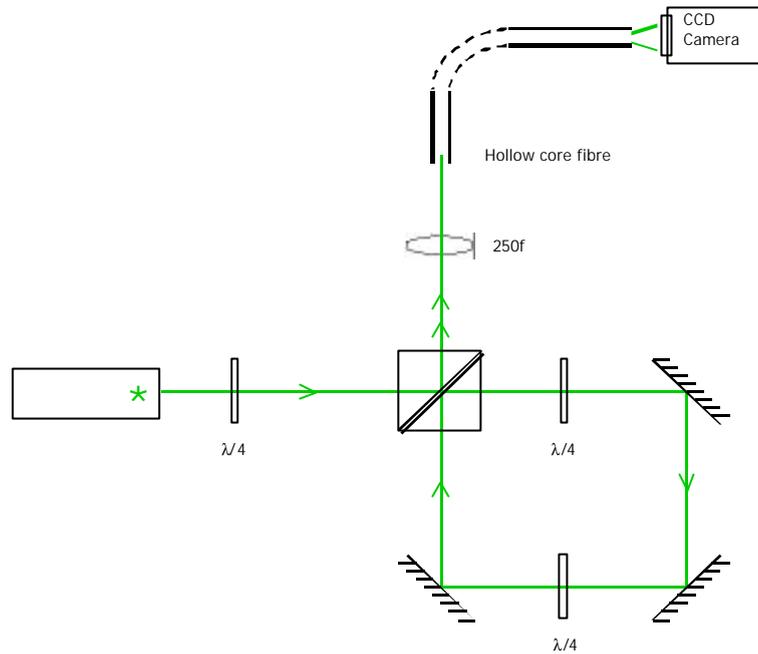

Figure 6: The experimental set up used to reduce the speckle contrast from the hollow core fibres.

SPECKLE RESULTS

532nm light from a Q-switched Nd:YAG laser was launched into a single hollow core fibre using the arrangement shown in figure 6. Figure 7a shows the speckle image produced when only one beam was launched, this shows the amount of speckle that will normally be present in the output from this sort of fibre. Figure 7b shows the speckle image when two beams were launched and figure 7c shows the image produced from multiple passes. By eye it is apparent that the evenness of the speckle has improved between these three images although this is a little subjective.
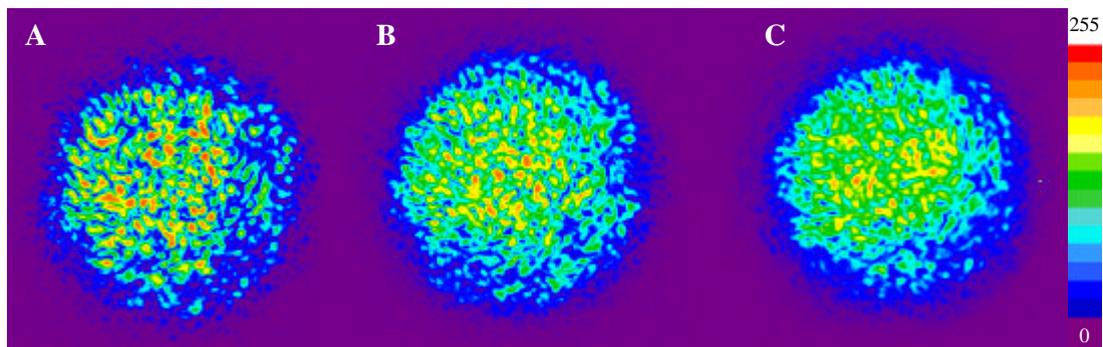

Figure 7: False colour images from the output of a 320μm hollow core fibre with colour scale to indicate relative intensity. A – a single beam was launched. B – the beam was split into two before launch. C – the beam was split multiple times before launch.

To provide a more quantitative comparison between the data a computer program developed in previous work [Stephens *et al.*, 2003] was used to analyse the data. This took a sample of ten rows of pixels from each image. Each slice was normalised to account for the intensity fall off at the edges,

leaving only the modulation due to speckle. This normalised data was analysed by counting the number of pixels with intensity values greater than a particular percentage of the maximum value. The number is plotted as a function of this percentage. For a perfectly even light sheet the plot would appear as a step with the edge at 100% on the x-axis. The three different real examples are plotted in figure 8. As the number of combined beams increases the plots move to the right and develop more of a shoulder. Plot B, where the light was split into two beams compared, to plot A, where only one beam was used, indicates a smoother light distribution in B. Similarly plot C, where the light was split multiple times, shows a smoother light distribution than plot B and plot A.
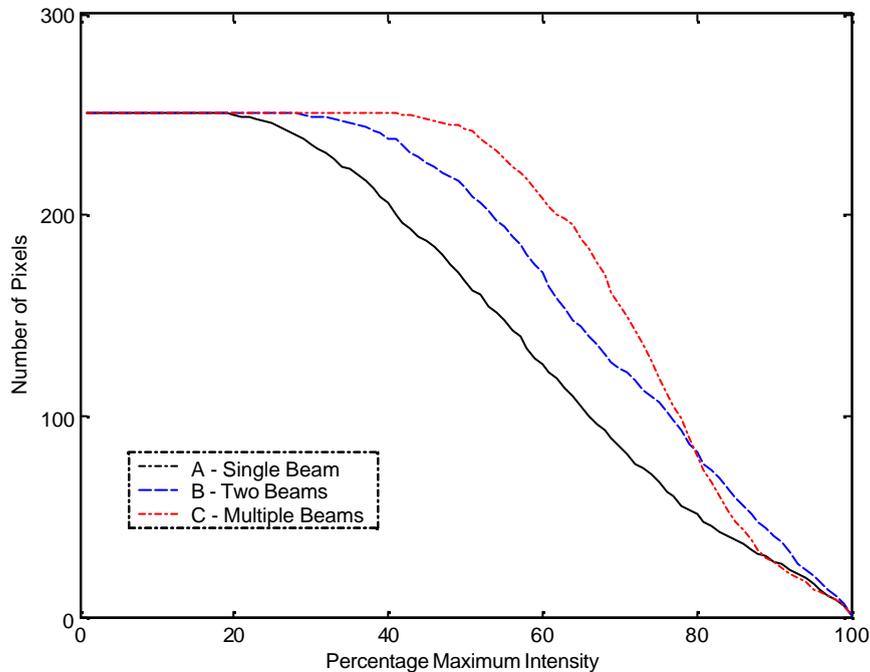

Figure 8: Speckle analysis for 320μm hollow core fibre corresponding to output images shown in fig. 7. A – a single beam was launched. B – the beam was split into two before launch. C – the beam was split multiple times before launch.

CONCLUSION

The use of hollow core fibres to provide a light sheet for particle image velocimetry has been evaluated. With the assistance of a helium gas flow the fibres were found capable of delivering laser pulses of sufficient energy and the output beam quality was shown to be sufficient to focus into a thin light sheet. Back-to-back experiments were carried out that compared the light sheet delivered from a hollow core fibre to a conventionally delivered light sheet. It was found that the quality of the images taken using each delivery method were similar which demonstrates that these fibres are suitable for such applications when complex access is required. The main drawback of fibre delivery is that it is impossible to achieve 100% launch efficiency so there will always be some loss.

A novel technique has been demonstrated that was shown to improve the evenness of the speckle pattern output from these fibres. This technique has the potential to improve the quality of PIV data acquired using fibre delivery. In future work we will be looking at ways to improve this technique and apply it to practical experiments.

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