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The RELIEF flow tagging technique and its application in engine testing facilities and for helium–air mixing studies

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Abstract. Raman excitation plus laser-induced electronic fluorescence (RELIEF) images the motion of oxygen molecules in air and other gas mixtures. This is accomplished by tagging oxygen molecules through vibrational excitation and imaging them after a short period of time by laser-induced electronic fluorescence. The vibrational lifetime of oxygen is sufficiently long and the signal sufficiently strong to allow this technique to be used over a wide range of flow conditions, from low subsonic to hypersonic, and in a variety of gas mixtures including high humidity environments. The utilization of a molecular tagging technique such as this is critical for environments in which seeding is impossible or unreliable and for measurements in which a wide range of scales needs to be observed simultaneously. Two experiments which have been conducted at national laboratories in medium- to large-scale facilities are reported. At the Arnold Engineering Development Center, RELIEF was used to examine velocity in a 1 m diameter tunnel for applications in the area of engine testing. At the NASA Langley Research Center, RELIEF is being used to examine supersonic mixing of helium in air in a coaxial jet in association with studies of fuel–air mixing in hypersonic engines. These applications are two examples of the wide range of practical uses for this new technology.

Keywords: fluid flow velocity, mixing, turbulence, vorticity, transport, RELIEF, flow tagging, Raman excitation, oxygen, oxygen laser-induced fluorescence, engine inlet monitoring, flow field monitoring, combustion diagnostics, mixing studies, turbulent studies

1. Introduction

The Raman excitation plus laser-induced electronic fluorescence (RELIEF) flow tagging concept was developed over a decade ago to obtain velocity profiles in unseeded air flows [1]. Most other nonintrusive approaches to the measurement of velocity or velocity fields in air use scattering from particles seeded into the flow. These include laser Doppler velocimetry and particle imaging velocimetry (PIV). Although both have been very successful, there are two important areas of application in which they cannot be used. The first is in those cases in which seeding is undesirable or cannot be done. These include large-scale facilities, in which seeding is exceedingly difficult; devices which cannot tolerate seeding (such as aircraft engines); environments in which seeded particles may influence reactive processes; the earth's atmosphere, in which seeding is unreliable; and flows with high accelerations, in which particle lag is significant. The second area of application is the measurement of velocities in complex flows, in which seeding densities cannot be made high enough to capture relevant structure. These include turbulent flows, flow mixing processes, free shear layers and flows with high vorticity. Examples of RELIEF measurements in both of these areas of application are included in this paper, namely velocity measurements for engine testing at the Arnold Engineering Development Center and for tur-

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bulent velocity profiles associated with supersonic mixing of air and helium at the NASA Langley Center.

Flow tagging has also proved a useful tool for visualizing the velocity structure on a quasi-instantaneous basis. In contrast to particle-based techniques, the velocity profile can be seen immediately, with no data reduction or data analysis. Each experiment consists of a tagging step during which a line or pattern is written into the flow, a time interval during which the flow evolves and an interrogation step during which the displaced pattern is imaged. Each image consists of a pattern of an easily identifiable displaced line or lines whose centres can be accurately located. Nonuniformities in the flow field and turbulence levels are easily seen by observing the distortion of the line(s) and the displacement is an immediate measure of velocity.

Flow tagging has recently been recognized to be a powerful diagnostic method and various approaches, both for liquids and for gases, are being developed. The concept was first introduced into the study of fluid motion through the hydrogen bubble technique [2]. Electrolytic decomposition of water along a thin wire electrode forms a line of small hydrogen bubbles which follow the flow. More recently, laser activated photochromic molecules have been used to track the motion of organic solvents [3, 4] and laser activated phosphorescent molecules [5] and laser photolysed caged dye molecules [6, 7] have been used for flow tagging in water. In the gas phase, approaches other than the RELIEF method have concentrated on laser-induced molecular dissociation and subsequent tracking of long-lived radical species. In the ozone tagging velocimetry approach [8, 9], molecular oxygen is laser dissociated and forms ozone, which is subsequently observed by laser-induced fluorescence. Similarly, water vapour can be dissociated with a laser to form OH radicals, which, again, are observed by laser-induced fluorescence [10, 11]. The latter approach is particularly useful for studies of combustion [12]. Laser-induced phosphorescence from biacetyl [13] or laser enhanced ionization of sodium [14] can be used in seeded gas phase flows to improve on PIV-type velocity field measurements. An overview of molecular tagging velocimetry by Koochesfahani further discusses the various approaches [15].

The RELIEF concept takes advantage of the long-lived vibrational metastable state of oxygen to achieve the tagging. The overall process involves vibrational excitation of the molecules by Raman excitation (RE) followed, after a short time interval, by interrogation using laser-induced electronic fluorescence (LIEF). Figure 1 is a simplified molecular energy level diagram for oxygen, showing the tagging and interrogation steps.

2. Flow tagging

The tagging step is accomplished by exciting oxygen molecules through stimulated Raman pumping. The energy of the first excited vibrational state of oxygen is 1556 cm^{-1} (0.2 eV) above the ground state. At room temperature, the thermal population of that state is approximately 0.04%. This population fraction can be increased in the pumping

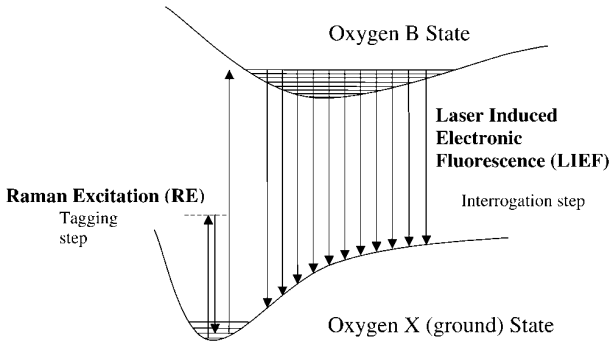

Figure 1. A simplified molecular energy diagram for oxygen showing the Raman excitation (RE) and laser-induced electronic fluorescence (LIEF) tagging and interrogation steps of RELIEF.

region to approximately 20% in about 10 ns by using a short-pulsed, two-colour, high power laser beam. The two colours are chosen such that the difference between the energies of the two beams is equal to the energy difference between the vibrationally excited and ground states of the oxygen molecule. A tagging region is created in the gas by focusing the two-colour beam to a high intensity line. In essence, the molecules are excited by the beat frequency between the two laser beams. Alternatively, one can consider the excitation process as equivalent to a transition into and out of a third 'virtual' state, whose energy above the ground state of oxygen is equal to the photon energy of the first (higher) energy laser beam and whose energy above the vibrationally excited state is equal to the photon energy of the second laser beam. This excitation 'picture' is shown in figure 1, in which the virtual state is indicated by a broken line. Since the identification of the tagged region will rely on the contrast between tagged molecules and surrounding untagged molecules, this approach to tagging is useful only in regions where the background thermal population of the excited vibrational state is small compared with the population in the ground state. In practice, this corresponds to an upper temperature limit of the order of 750 K. The selection rules associated with the tagging process prohibit a change in the rotational state of the molecule. This implies that there is very little addition of thermal energy associated with the tagging process since the vibrational mode is largely decoupled from the thermal motion of the molecule. As the tagging proceeds, photons are removed from the high energy laser beam and added to the lower energy laser beam. Thus, the higher energy beam loses intensity, while the lower energy beam gains intensity on passing through the tagging regime. Owing to the fact that the excitation is proportional to the product of the two intensities, tagging remains uniform for long distances in the tagging region. The length of the tagged line in practice is determined by the requirement for a high intensity. The diffraction limit states that the length of the high intensity portion of the line is proportional to the cross sectional area of the beam at the focus, divided by the wavelength. Thus, for long lines, the cross sectional area must be larger, so the laser must deliver more peak power per pulse to achieve the required intensities. This can be achieved by using a laser with higher energy per pulse, or a laser with the same energy per pulse, but a shorter pulse length. The two-colour

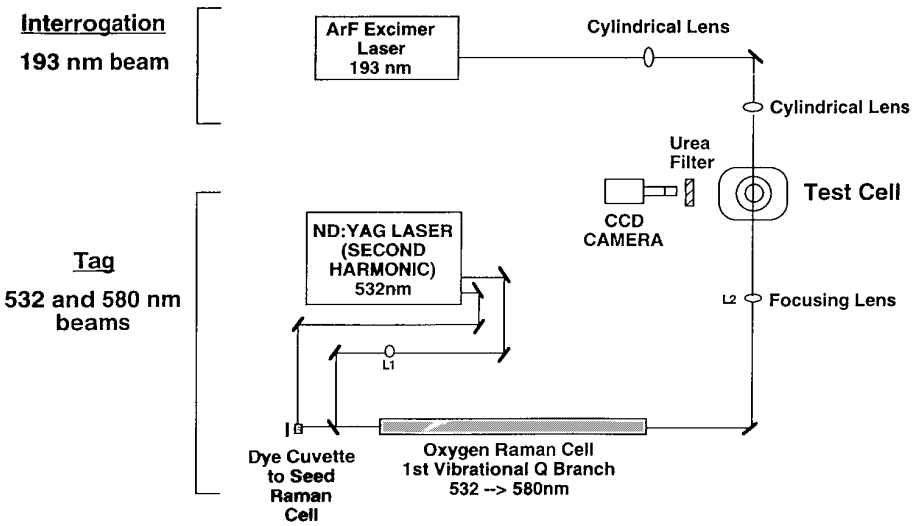

Figure 2. A schematic diagram of the RELIEF system.

laser beam can be re-focused back and forth through the sample volume to produce multiple tagging regimes, if so desired.

The lower portion of figure 2 is a schematic diagram of the tagging laser system. It is based on a high power, pulsed, frequency-doubled, Nd:YAG laser which is capable of generating on the order of 200 mJ per pulse in the green at 0.532 μm. The second colour is generated from this high power green beam by passing it through a high pressure mixture of oxygen and helium [16]. The high power laser beam interacts with the oxygen in the cell to produce gain at 0.580 μm through a stimulated Raman gain process. This gain amplifies background light and produces at the exit end of the cell a high-power laser beam whose energy is shifted by exactly the right amount for flow tagging. In order to enhance the conversion efficiency of this cell, a small amount of broad bandwidth light in the vicinity of 0.58 μm is injected into the cell from a low power dye laser. The injection process increases the conversion efficiency by approximately a factor of two, so that the output energy at 0.580 μm is approximately 20% of the original input beam. This configuration leads to a two-colour laser with the beams automatically propagating on top of each other and with coincident pulse timing. The stimulated Raman conversion is robust against noise and vibration since the frequency of the converted light is always separated from the initial light frequency by the vibrational energy of the oxygen molecules. This means that frequency jitter in the laser output that might result from vibration or acoustic noise has little impact.

Once the dual-frequency laser beam has been generated, it is then focused into the experimental area to tag the flow. This focusing is usually done rather gently in order to avoid chromatic aberration effects from uncorrected lenses, and it results in a line which is of the order of a few centimeters long and 100 μm or so in diameter. In some cases, it is desirable to put patterns into the flow; these can be created by using multiple beams to tag or by reflecting the tagging beams back through the flow field.

During the excitation period and in the time between excitation and interrogation, collisional processes which can have a significant impact on the signal level occur. The tagging process itself lasts on the order of 10 ns, during which numerous rotational transfer collisions occur in atmospheric pressure air. Since the stimulated Raman process accesses only several low-lying rotational levels of oxygen ($J \cong 7$), the rotational collisions help to increase the tagging efficiency. As those rotational levels become depleted, they are collisionally refilled from more populated levels and excitation continues. It is through this collision-enhanced mechanism that such strong pumping can occur.

3. Collisional process and transport during convection

Since oxygen is a homonuclear diatomic molecule, the vibrational state does not generate an induced dipole, so the molecule does not radiate. Vibrational de-activation is by collision and is slow. Oxygen at 1 atm has a vibrational lifetime of the order of 30 ms. This lifetime can be significantly shortened by the presence of tri-atomic molecules, particularly water vapour. Figure 3 is a plot of the estimated maximum time between tagging and interrogation as a function of the mole fraction of water vapour [17, 18]. For saturated air at room temperature ($X_{H_2O} \cong 0.026$) the maximum time interval is on the order of 6 μs, which corresponds to several de-excitation time intervals. These curves are based on a minimum signal level greater than 10% of the signal measured for 298 K, 1 bar and 0% H_2O (i.e. 10% of the ideal signal in standard air). It should be noted that, in many cases, the displacement distance between tagging and interrogation must be as short as a few hundred micrometres in order to avoid significant line distortion and break-up in highly turbulent flow environments. This still yields highly accurate velocity measurements since the line centre can be located to on the order of a few micrometres.

Another type of collision of importance is the vibration-to-vibration up-pumping collision which is characteristic of

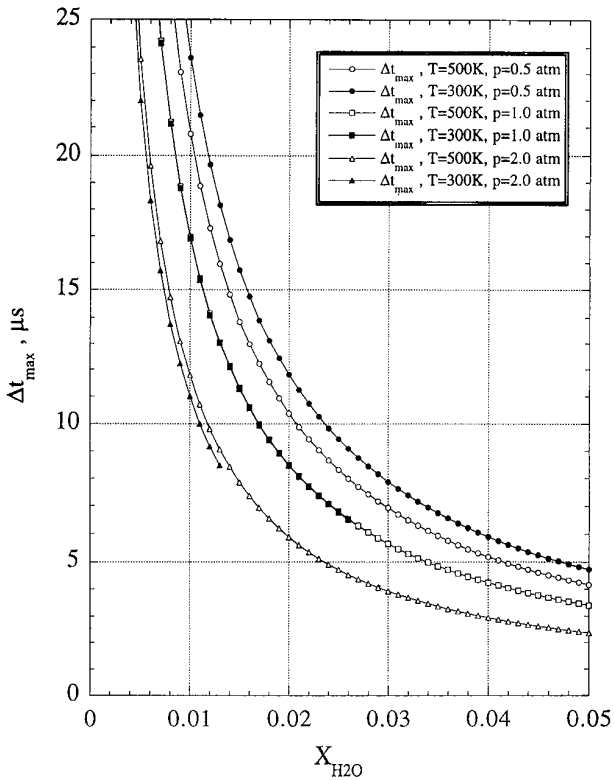

Figure 3. The maximum time between tagging and interrogation as a function of the mole fraction of water vapour based on a signal level >10% of that in standard dry air.

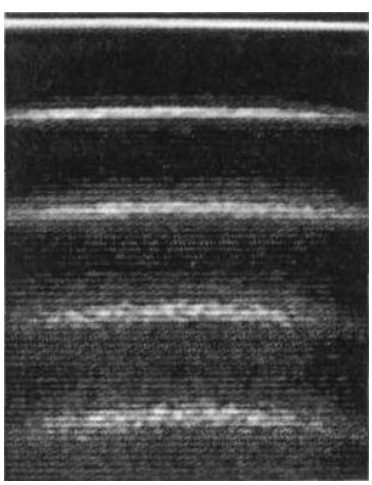

Figure 4. Tagged lines after 1, 100, 200, 300 and 400 μs delays in pure oxygen at 362 K. Images are 100-frame averages.

diatomic molecular collision processes [19]. This vibrational up-pumping is used, for example, to produce population inversions in vibrationally excited states of CO for the carbon monoxide laser. It arises from the anharmonicity between vibrational states and, particularly, from the decreasing energy between states with increasing vibrational quantum number. This up-pumping has been observed to occur in microsecond timescales [18]. Although this up-pumping process is not a critical feature of RELIEF flow tagging, it does tend to enhance the interrogation signal brightness

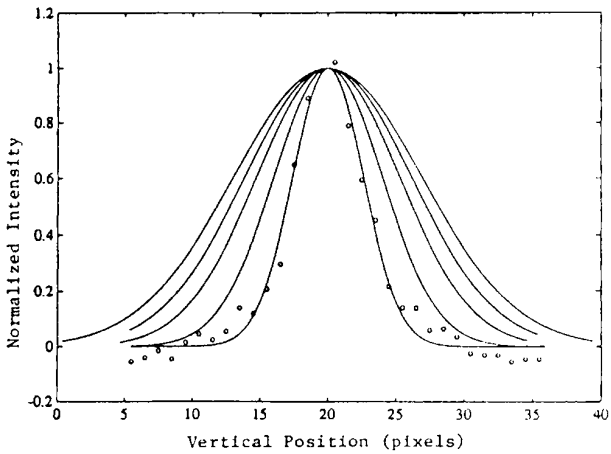

Figure 5. Normalized Gaussian fits to the centre profile of the lines in figure 1. Data points are shown only for the line taken after 1 μs delay. Calibration is 20.33 μm per pixel.

by allowing access to states with higher fluorescence yields.

During the time between tagging and interrogation, the line is broadened somewhat by thermal diffusion of vibrationally excited molecules. The line profile is initially Gaussian due to the Gaussian nature of the pumping beams, and the Gaussian linewidth is increased by thermal diffusion

$$\omega^2 = 8\tau D \ln(2) + \omega_0^2 \qquad (1)$$

where ω is the full width at half maximum (FWHM), ω_0 is the FWHM of the original tagged line, D is the diffusion constant and τ is the time between tagging and interrogation.

With initial linewidths of approximately 100 μm and time delays of the order of 10 μs in air at atmospheric temperature and pressure, this thermal diffusion broadening is negligible. With longer delay times, or thinner tagging lines, thermal diffusion becomes measurable and has been proposed as a method for measurement of the translational temperature. Figure 4 shows a sequence of images of a 100 μm diameter line taken with time delays of up to 400 μs [20]. Figure 5 shows the normalized Gaussian fits across these lines and figure 6 gives a straight line fit for the diffusion data for dry air at 299 K. The straight line corresponds to a diffusion constant, D, of 0.26 cm^2 s^{-1}.

4. Interrogation

The interrogation process is achieved through ultraviolet laser-induced fluorescence, typically using an argon–fluoride (ArF) excimer laser in the vicinity of 193 nm. The schematic diagram of the excitation and fluorescence processes is shown in figure 1. Figure 2 is a diagram of the ArF laser interrogation subsystem. The tuning range of this laser overlaps with numerous oxygen lines associated with the Schumann–Runge band. Some of the oxygen lines that overlap the ArF laser tuning range are shown in figure 7. Although the interrogation can be done with a broad-band ArF laser, since some portion of the lasing energy overlaps with transitions from the vibrationally excited state, it is preferable to use a frequency-narrowed ArF laser which can be tuned directly

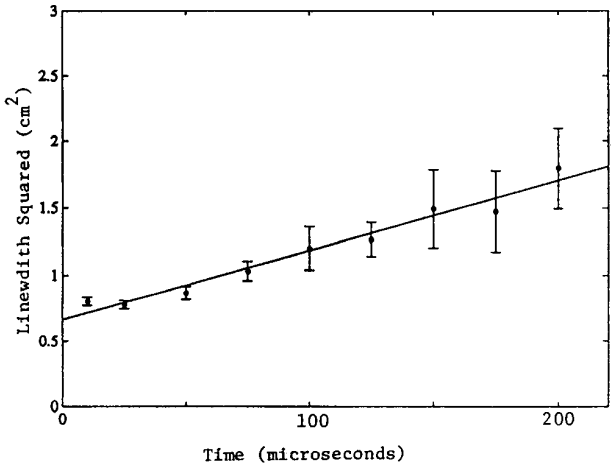

Figure 6. The straight-line fit used to obtain the diffusion rate for dry air at 299 K.

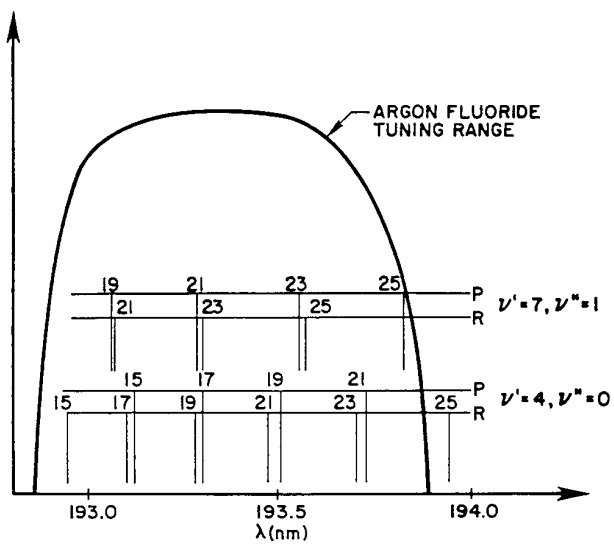

Figure 7. The overlap of the ArF laser tuning range with absorption lines of oxygen [1].

on resonance with a transition from the $v'' = 1$ vibrationally excited state to the $v' = 7$ state in the Schumann–Runge band. The ArF laser pulse lasts approximately 10 ns and the fluorescence occurs only during that period since the Schumann–Runge band is highly predissociative. The lifetime of the oxygen in the electronically excited state is only of the order of 2.5 ps before the molecule breaks apart into oxygen atoms [21]. Only those molecules that fluoresce during that very short period contribute to the signal. Since the fluorescence lifetime of the electronically excited state is of the order of 30–50 ns, this means that only 1 in 20 000 molecules fluoresces [18]. Images of the displaced tagged molecules are collected by using high sensitivity, intensified, ultraviolet-sensitive cameras. A urea filter (0.1 M, 10 mm thick) is placed in front of the camera to eliminate direct scattering from the ArF laser.

Signals from molecules in vibrational states higher than $v' = 7$ are enhanced due to the reduced predissociation rate of those states. Much stronger signal levels could be achieved by moving to different spectral regions within the Schumann–Runge band. It is also important to note that the ArF laser accesses only rather high-lying rotational states whose populations constitute a rather small fraction of the total rotational population in the $v'' = 1$ state. A laser at a shorter wavelength, for example, near 183 nm, could be used to excite molecules into the $v' = 14$ state of the Schumann–Runge manifold, which has a significantly lower predissociation rate. That source laser would also overlap with more highly populated rotational states. This, plus an increased Franck–Condon coupling factor, suggests that significant improvement in fluorescence intensity will be possible in the future. A typical RELIEF image is shown in figure 8, which was taken in a fully turbulent free air jet with a 7 μs time delay [22]. The initial tagged line is also shown for a quantitative comparison of the displacement.

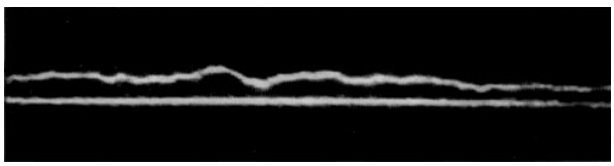

Figure 8. A typical RELIEF image taken in a turbulent free air jet with 0 μs (lower line) and 7 μs (upper line) time delays. The line is approximately 1.2 cm long.

5. Velocimetry in large-scale unseeded facilities

One of the important applications of RELIEF is as a tool for the accurate measurement of velocity under circumstances such that seeding is not practical. An example of such a circumstance is measurement of the flow velocity at the inlet for testing and evaluation of high performance engines, in which seeding could damage internal engine parts and affect combustion. For this application, it is particularly important that the velocity measurement technique be nonintrusive so that the engine performance is in no way affected. As a demonstration of this capability, a RELIEF system was assembled by M L Energia Corporation under sponsorship from the Arnold Engineering Development Center and tested in the R1D research facility in Tullahoma, Tennessee [23]. The R1D facility has a 1 m diameter test section and was operated over a velocity range from Mach 0.08 to Mach 0.8 at a pressure of the order of 1 atm.

The laser system was configured to generate two two-colour laser beams which intersected to form a cross at the measurement location. The cross pattern was chosen in order to establish a well defined tagging location in the flow. The tagging laser system was constructed around a Quanta-Ray PIV 400 Nd:YAG laser which produced two pulses, separated by a variable delay, each with approximately 385 mJ of energy at 0.532 μm. The laser output beams were split into two parts with a 50–50 beam splitter and passed through two separate high pressure oxygen–helium Raman cells which produced the 0.58 μm second-colour beams. A small fraction of the laser output energy was used to pump a dye laser oscillator which injected light into the high pressure helium–oxygen Raman cells to improve the conversion efficiency. The interrogation laser was a Lambda-Physik EOMPex 205 broadband ArF excimer laser, modified with a diffraction

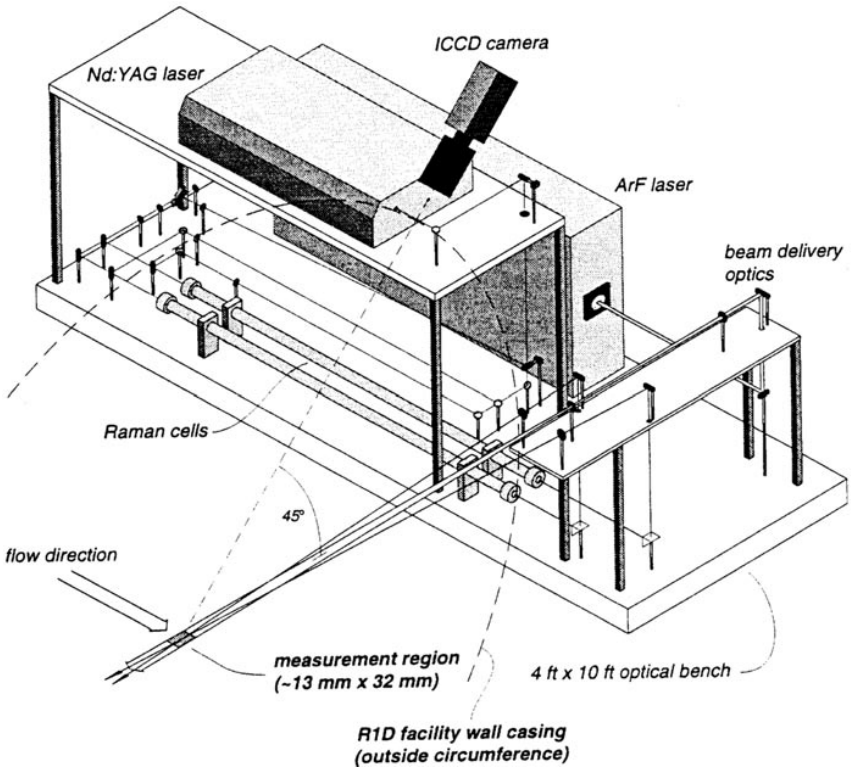

Figure 9. A diagram of the RELIEF system set-up for measurements in the R1D facility at the Arnold Engineering Development Center.

grating to produce narrow linewidth light (approximately 8 cm^{-1}), with an output pulse energy of 70 mJ. Images were taken using a Princeton Instruments intensified CCD camera and a Nye Optical Lyman alpha $f/3.7$ 400 mm focal length Cassegrain camera lens. The tagging and interrogation systems were all mounted on a single 4 ft $\times$ 10 ft optical table, as shown in figure 9.

The double-pulse capability of the tagging system was used to produce a reference tagging location on a shot-by-shot basis. Figure 10 shows a one-shot sample of the interrogated image. The first laser pulse wrote a cross pattern into the flow 30 μs before this image was taken. The cross has been displaced to the location on the left-hand side of the image. Simultaneously with the interrogation, the tagging laser was fired a second time and Rayleigh scattering from those crossing beams shows the location where the flow was originally tagged. Figure 11 shows pixel intensity values averaged along the centre portion (3.6 mm) of the cross as a function of displacement pixel number. By measuring the separation between the peaks and dividing it by the time, an accurate measurement of the flow velocity is obtained. In this single event, the velocity was measured to be 202.4 $\times$ 0.25 m s^{-1}. In general, the uncertainties in each single RELIEF measurement range between 0.18% and 0.5%. These high accuracies are achieved because the turbulence level in the flow is low enough to allow large displacements of the tagged region. Typically, displacements in excess of 5 mm were observed and these were measured to an accuracy of better than within 0.1 pixel by fitting the intensity profiles as shown in figure 11. The very high signal-to-noise ratio associated with these fitted data came from the fact that the central 3.6 mm portion of the line was summed, further increasing the signal by approximately a factor of 40. The uncertainty in the timing was of the order of 20 ns and did not contribute significantly to the measurement error. Figure 12 shows a comparison between the RELIEF measurements and velocities measured using a pitot probe. The errors in the pitot velocity were derived from the uncertainties in the measured pressures and temperatures. The results indicate that the RELIEF flow tagging technique can be a highly accurate method for velocity measurements in large-scale wind tunnel facilities.

6. Measurements of high-speed helium–air mixing

The other general class of applications for which RELIEF is well suited is measurements of turbulence and mixing. Here it is important to have a continuous line or pattern written into the flow so that structures over a wide range of scales can be examined. For these studies, particle densities are limited by secondary scattering and, often, the particles cannot follow the flow at the scales of interest.

An example of this is the study of fuel–air mixing in a SCRAMJET engine. This mixing takes place in the turbulent shear layer which develops between the fuel jet and the surrounding air. The RELIEF technique is currently being used at the NASA Langley Research Center as part of a computational fluid dynamics (CFD) code validation study of this process. The co-flowing jet apparatus is depicted in figure 13 and consists of a jet of helium at Mach 1.8 surrounded co-axially by a flow of air which is also at Mach 1.8 [24]. Helium is used to simulate hydrogen as the SCRAMJET fuel. Owing to the large difference between the

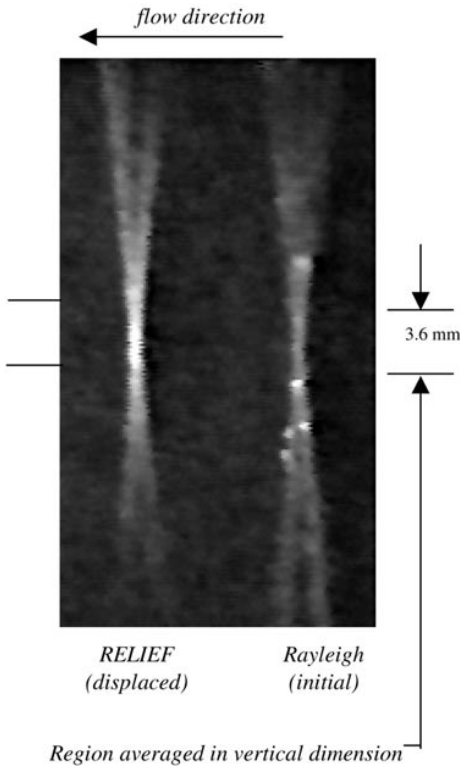

Figure 10. A sample single-shot RELIEF/Rayleigh image obtained in R1D at the Arnold Engineering Development Center. The field of view of the image in the measurement plane is approximately 13 mm × 32 mm. The time delay between tagging and interrogation was 30 μs, corresponding to a displacement of 6.06 mm. The indicated region was used to measure the displacement distance of the tagged molecules in the primary flow direction. Owing to the oblique viewing angle and the narrow depth of field of the camera system, only this small region is in proper focus.

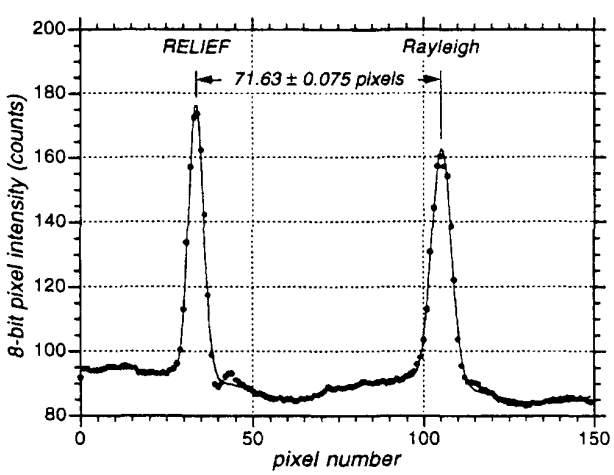

Figure 11. A vertically averaged (as shown in figure 10), horizontally resolved intensity profile of the image in figure 10, showing the displacement of the cross during the time interval between tagging and interrogation.

speeds of sound of the two flows, the velocity of the helium is over twice that of air and a highly compressible mixing layer ($M_c \cong 0.7$) is present at the interface. The development of this mixing layer is the subject of the CFD validation study. In order to be able to observe the velocity profile both in the air and in the helium using RELIEF, a small amount of oxygen (5% by volume) has been added to the helium flow. That oxygen then serves as a molecular tracer for the helium in the experiment. The diameter of the core flow is 10 mm and that of the surrounding flow is 60 mm. These diameters were chosen in order to provide a large enough scale to allow both high quality manufacturing and well resolved data, but were small enough to allow operation using the air supply system of the mixing studies facility. This set-up is, in many ways, similar to that of the free jet turbulent studies performed at Princeton using a 10 mm diameter subsonic air jet [22]. In that case, data were taken 40 jet diameters downstream in the region of fully developed turbulence. In these experiments, data are taken at 14 axial locations, ranging from close to the jet exit to 263 mm downstream.

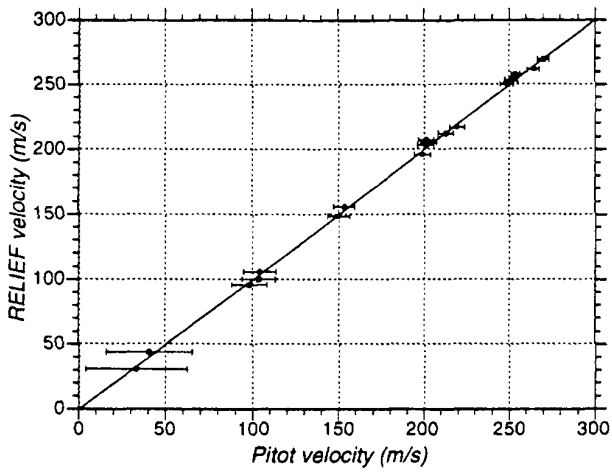

Figure 12. A plot of velocity measured with the RELIEF system versus simultaneous velocity measurements using a pitot probe. The error bars on the RELIEF measurement are less than 0.5% and cannot be shown on the diagram.

In addition to RELIEF velocity profiles, total temperature and pitot pressure probes, *schlieren* photography and a gas sampling probe are used to acquire data. The fact that the jet air is exhausted into the laboratory produces a challenge for the RELIEF technique. The noise generated by the flow of air prohibits occupancy of the lab during the test and the vibration induced by that noise requires all components to be firmly anchored to maintain optical alignment. Without the use of the stimulated Raman cell, this noise would have caused serious difficulty in tagging lines. Figure 14 shows the imaging and tagging components of the RELIEF system and their orientation relative to the co-axial mixing apparatus. The optics for tagging and shaping and pointing of the interrogation beam were mounted on a rail which was translated in the axial direction to each measurement location. The camera platform was moved independently to the same location. For the final measurement location (263 mm) the beams were located 85 cm above the optical table. The tagging laser was a Quanta Ray DCR-1A Nd:YAG laser with an output of 200 mJ at 532 nm. The beam was passed through a 2 m Raman cell filled to 7.0 MPa with a 50–50 mixture of helium and oxygen. The Raman cell was seeded with a few millijoules

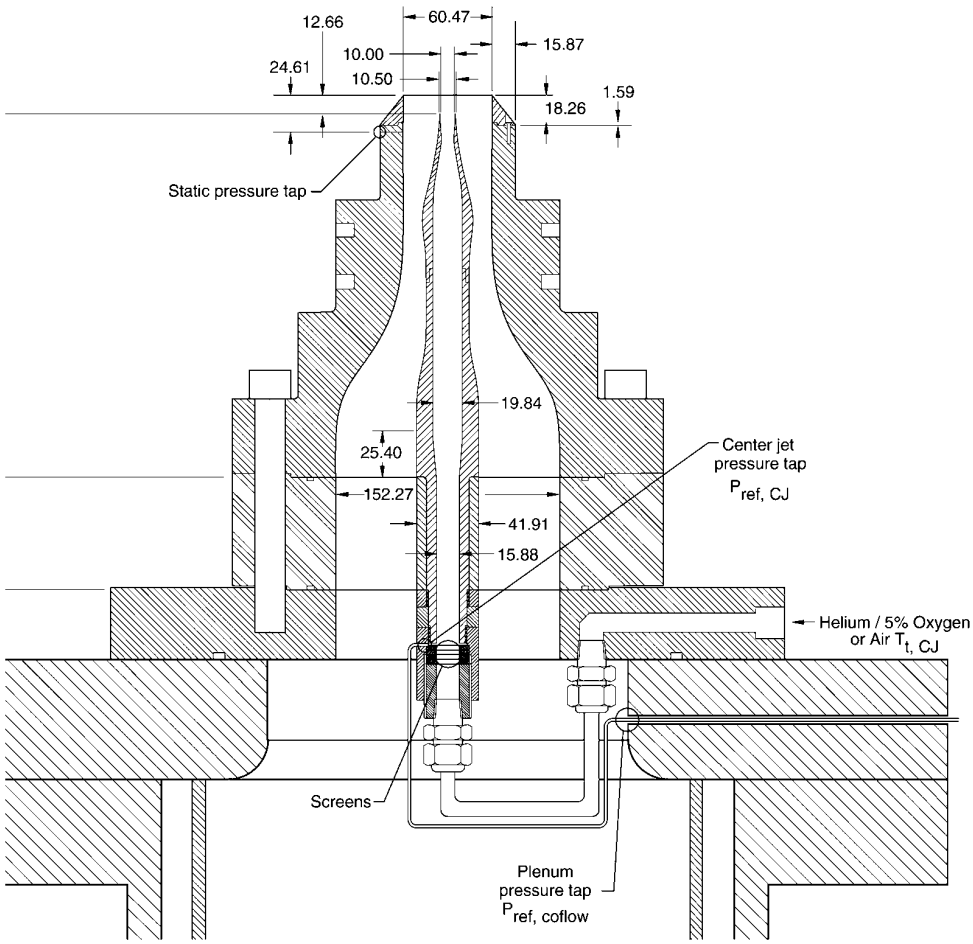

Figure 13. The co-flowing helium–air apparatus. The exit diameter of the helium core flow is 10 mm and the exit diameter of the air co-flow is 60.47 mm.

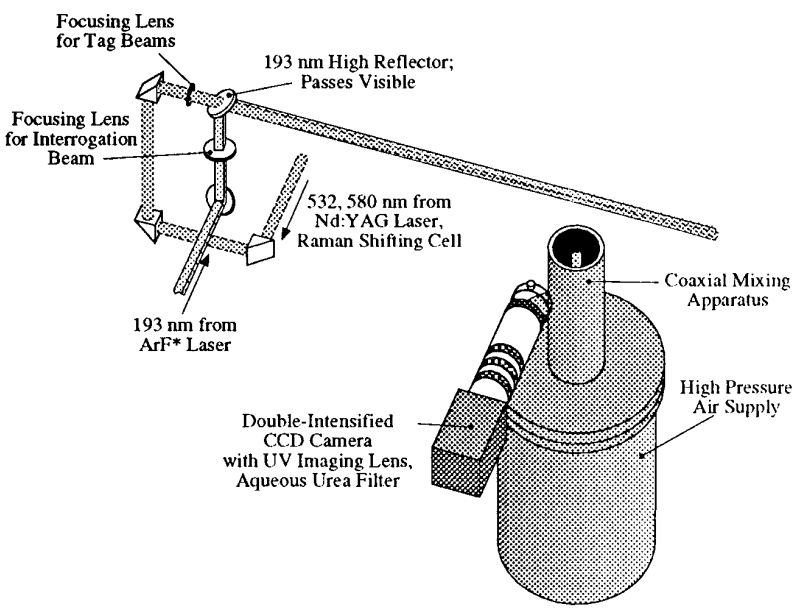

Figure 14. A schematic diagram of the RELIEF set-up around the helium–air co-flow apparatus showing the co-propagating tagging and interrogation beams.

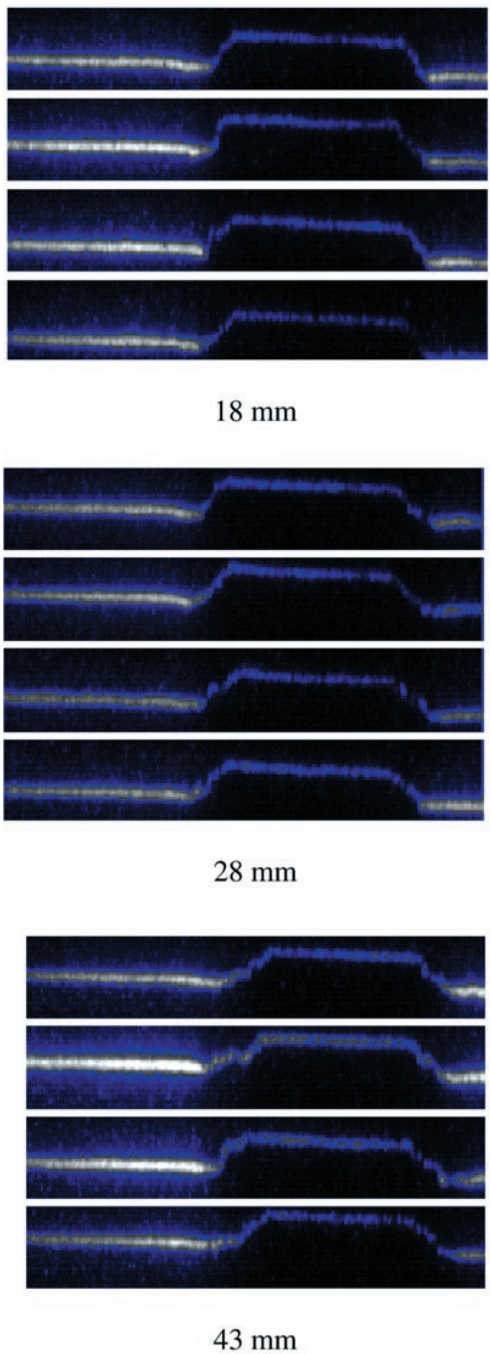

Figure 15. Images of helium (seeded with oxygen) and air velocity profiles taken 18, 28 and 43 mm downstream of the exits. Four instantaneous images are shown for each location.

of 580 nm light from a broadband dye laser. The dual-colour tag beam was focused across the co-axial jet using a 0.5 m focal length lens. The interrogation laser was a Lambda-Physik LPX150/50T ArF laser, operated with a narrow linewidth oscillator and a single-pass amplifier which yielded about 25 mJ at 193 nm. This laser was focused with a spherical–cylindrical lens combination to a sheet roughly 1 mm $\times$ 2 mm at the measurement location. The typical delay time between tagging and interrogation was 1.0 μs. The delay was controlled using a SRS DG535 digital delay generator and a zero time delay was determined using photodiodes and

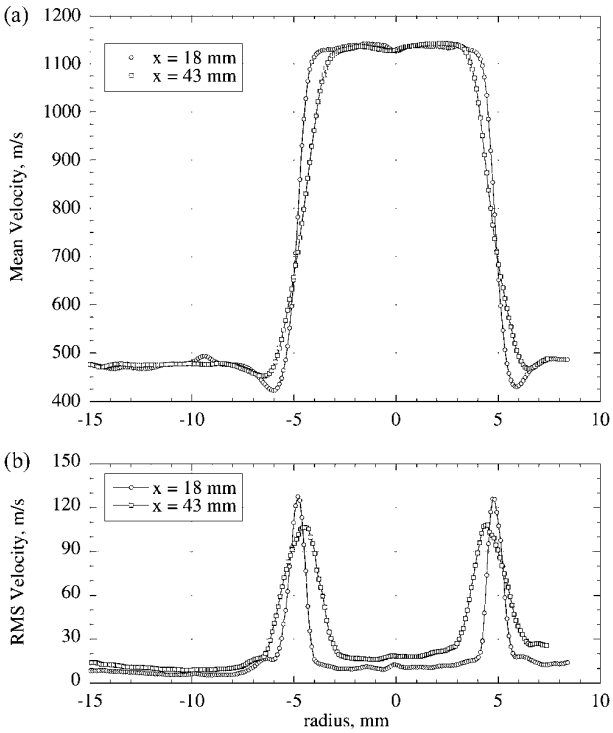

Figure 16. Mean velocity profiles (a) and RMS velocity fluctuations (b) 18 and 43 mm downstream of the co-flow nozzle exit.

a fast oscilloscope. The polarization of the tagging beams was vertical and the interrogation beam was horizontally polarized to reduce Rayleigh scattering interference. The signal was collected using an ITT double-intensified CCD camera with a UV Nikkor $f/4.5$ ultraviolet imaging lens and an aqueous urea filter. The camera was placed in the horizontal plane, as shown in figure 14, and installed on its side to increase resolution in the streamwise direction.

Sample single-shot images of the data taken 18, 28 and 43 mm downstream of the co-axial jet exit are shown in figure 15. In all of these figures, the core helium flow is apparent but somewhat weaker than the surrounding air flow due to the lower concentration of oxygen. The growth of the mixing layer and the instantaneous structure of that layer can be seen in this sequence of images. Preliminary velocity data are shown in figure 16. The growth of the mixing layer is evident both in the mean velocity profile (figure 16(a)), and in the RMS velocity fluctuations (figure 16(b)). A quantitative comparison of these data with code predictions is currently underway.

7. Summary

RELIEF flow tagging is proving to be a versatile method for the measurement of transport and mixing in oxygen-bearing gas flows. In most cases, the gas of interest has been air, but, as reported here, oxygen has been seeded into helium at low concentrations to allow measurements in that gas to be made. The high signal-to-noise ratio of the interrogation fluorescence means that velocity profiles are captured at each laser shot, yielding effectively instantaneous velocity

profiles. These profiles can then be analysed to yield average velocity mixing length scales, turbulence intensity or other transport properties of interest. As has been demonstrated in the experiments at the Arnold Engineering Development Center, multiple lines can be simultaneously written into the flow to create a pattern. The cross pattern produced in these experiments allowed point-to-point velocity measurements to be made, which, in this case, were observed with a single two-dimensional image, giving two components of the three-component velocity vector. The full three components could have been acquired in a straightforward manner by observing the displacement of the same pattern simultaneously with a second camera. The work at NASA is the latest result in a set of experiments applying the RELIEF technique to the study of SCRAMJET engine technologies. Earlier measurements performed there indicate that RELIEF flow tagging may also be applied in high humidity environments associated with vitiated air flow [18].

The RELIEF technique joins a family of new approaches to flow tagging in air and water and shares with them the promise of measuring transport phenomena, including velocity, vorticity, dilatation, shear stress, diffusion and mixing. As with other flow tagging techniques, the molecules in the flow are followed in the frame of reference of the flow itself, i.e. in the Lagrangian frame, in contrast to probe-type measurements which measure flow properties at a fixed location, i.e. the Eulerian frame. The flow tagging approaches do not require corrections for bulk transport via the Taylor hypothesis and can be used in highly turbulent environments, including those which have flow reversals. Owing to the imaging property of these approaches, a wide range of scales is simultaneously sampled and spatial correlations, as well as flow structure, are immediately apparent.

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