OPTICAL MEASUREMENT TECHNIQUES IN ENGINES: PIV AND OET

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ABSTRACT

The paper describes two optical techniques, which are capable of providing high frequency, non-intrusive measurements in harsh engine environments. Particle Image Velocimetry (PIV) has been used to provide an instantaneous intra-rotor transonic flow mapping. Optical Emission Tomography (OET) is being developed for the study of gas turbine combustors and IC engines. Both represent novel measurement applications.

INTRODUCTION

Engine developers need measurements that are obtained in environments that are as realistic as possible, and which do not influence or disturb the processes taking place in the engine. Generally, optical measurement techniques are well suited for this, as they are either non-intrusive or minimally intrusive. Furthermore, they often provide a visualization, which even if it is not quantitative, does provide engine designers with often otherwise unobtainable insight into e.g. flow or flame behaviour within the engine. This paper discusses the application and development of two optical techniques used in cascades and combustion monitoring, Particle Image Velocimetry (PIV) and Optical Emission Tomography (OET). Specific problems encountered in obtaining measurements in harsh engine environments are discussed.

NOMENCLATURE

PIV: Particle Image Velocimetry
OET: Optical Emission Tomography

PARTICLE IMAGE VELOCIMETRY IN CASCADE FLOW

To understand effects occurring in a high-speed flow, with turbulent processes, requires high-speed measurements, preferably taken instantaneously of a complete field. Furthermore, the flow should not be influenced by the measurement, i.e. it should be non-intrusive. One technique used for measuring high-speed flows is Particle Image Velocimetry. It has the potential to make a measurement of the instantaneous velocity across a (2D-section of a) complete flow field. PIV is a conceptually simple and inexpensive technique, where particles are introduced in the flow under study and where a sheet of light is used to image those particles (Figure 1). By imaging the particle distribution at two instants with a known time interval the velocity of the particles can be

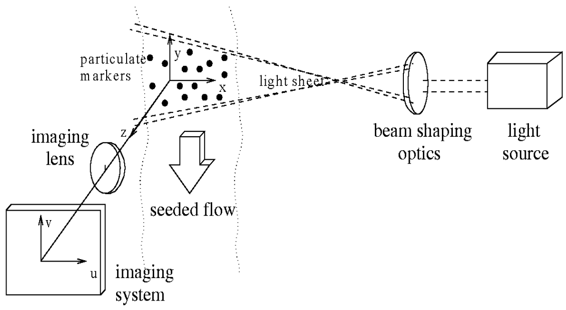

Figure 1: Schematic representation of a PIV system

determined, and hence the velocity of the flow in the plane covered by the light sheet. In the results shown here, the velocity at a point is determined using cross-correlation techniques to find the main velocity in a small area surrounding that point in the flow. Thus, the flow measurement problem has become an imaging problem. For this, the assumption is that the particles follow the flow exactly. This is reasonably easy to achieve for low-speed flows, in high-speed flows however flow seeding becomes more problematic. To accurately follow the flow, particles should preferably be as small as possible (0.2 –1 micrometer in high-speed flows). However, to be able to detect the particles they must reflect sufficient light, which generally requires a reasonable size of particle. The higher the velocity, the smaller the particles need to be for them to accurately follow the flow. A further problem in PIV that becomes more severe in the application of PIV to high-speed flows is to obtain adequate seeding density throughout the whole field of interest to provide velocity data. This becomes especially difficult in wakes and boundary layers. Furthermore in high-speed flows, the timing between the two images has to be very short (microseconds) to ensure particle correlation between the images, so that particle pairs can be found and the flow velocity determined. This can e.g. be achieved by using a pulsed laser, providing short, high-repetition-rate pulses with sufficiently

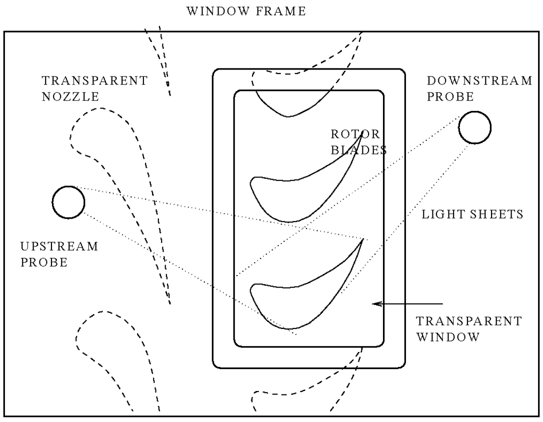

Figure 2: Schematic of optical set-up for illuminating annular cascade flow.

high intensity. A further problem in turbulent, 3-dimensional flows is that particles may move in or out of the plane illuminated by the light sheet.

Thus, the achievable resolution is determined by the accurate tracking of the flow by the tracers, by the amount of tracers present in a flow area, by the thickness of the laser sheet, which defines the 2-D plane that is imaged, by the pulse frequency of the illumination system and by the image capturing system.

A PIV study was made of the transonic flow through a rotating annular cascade. A major problem in using optical techniques in turbomachinery and cascade research is how to get the light into the flow. Here, two different methods are used.

Figure 2 shows a schematic of the one of the optical arrangements used to illuminate the flow in

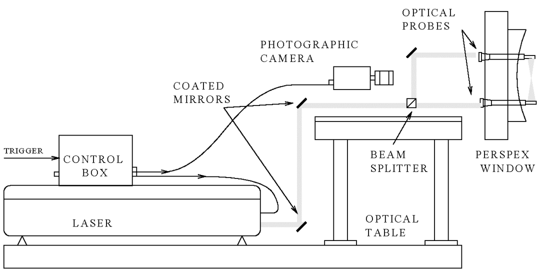

Figure 3: side view of an optical arrangement for PIV measurements of flow in an annular cascade.

an angular cascade (*Epstein and Bryanston-Cross*, 1997). The rectangular area shows the transparent window through which images were obtained of the flow around the moving rotor blades. Figure 3 shows a side view of the optical arrangement. The optical probes providing the light sheet in the flow are mounted through the walls of the cascade housing, on either side of the window, illuminating the area of interest from two sides to minimize the non-illuminated area. This is necessary, as when the rotor blades move through the field of view, they block a large region of the areas illuminated by either probe. Using two illumination sources

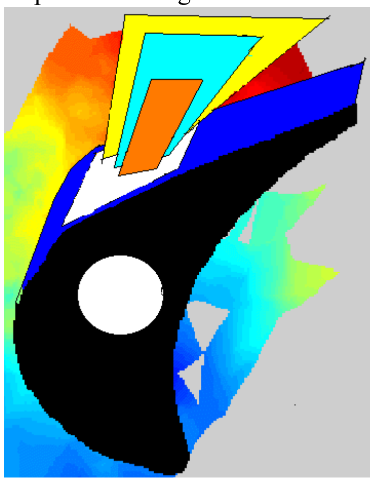

Figure 4: Hollow stator blade providing illumination of flow in annular cascade.

allows most regions to be illuminated at least by one probe during the transition of the rotor blades. To produce the light sheet on the upstream side provides an extra problem, as that beam needs to be steered past a stator blade. However, as that blade is stationary it was possible to make it out of transparent material, without influencing either the illumination or the flow behaviour.

A second arrangement that was used is shown in Figure 4 (*Bryanston-Cross and Chana*, 1997). In this case the stator blade has been hollowed out, so that the light probe could be mounted inside and the flow could be illuminated from the stator blade through a transparent window. The advantage of this arrangement is that there is less disturbance of the light sheet by the material of the stator blade. Furthermore, there is slightly less disturbance of the light sheet by the flow around the stator blade in this case.

Using these arrangements, it has been possible to obtain measurements of the instantaneous velocity distributions at 4% accuracy (*Bryanston-Cross and Chana*, 1997). An example of the measurements that were obtained using the hollow stator blade of Figure 4 is shown in Figure 5 (*Bryanston-Cross and Chana*, 1997). It shows a comparison between numerical predictions (performed by RAe Pyestock) and PIV measurements of the velocity in the wake flow region of a spinning rotor in a blow down transonic turbine test facility (RAe Pyestock). The PIV measurements were obtained using a Nd:YAG laser with pulse separation of 0.7 microseconds and using seeding particles with 0.2 µm diameter. Although not all regions could be imaged in the

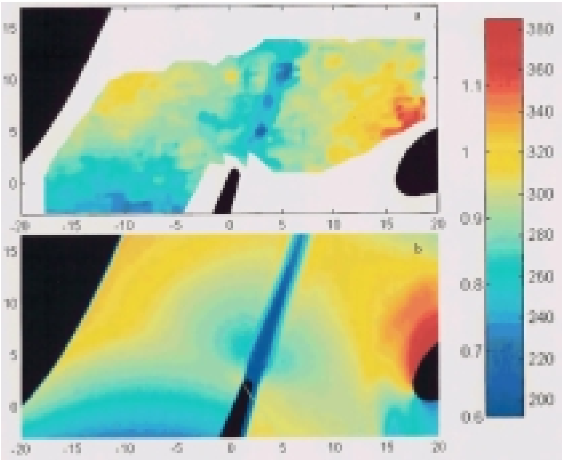

Figure 5: Comparison between PIV measurements (top) and numerical predictions (bottom) of velocity in wake flow region of spinning rotor in transonic flow. Velocities are shown as local Mach number (left side of legend) and in m/s (right of legend), x,y-coordinates in mm.

PIV measurements, the obtained data do show a very good agreement with the numerical predictions. The flow in the trailing edge shows up very clearly. Although measurements have been taken in similar flows using other techniques (e.g. using LDA), those do not provide instantaneous whole field measurements of velocity, and thus do not allow the study of the instantaneous behaviour of the flow. From the instantaneous PIV velocity measurements also vorticity could be determined, which allows the study of turbulent structures in the flow. Using a high-frequency PIV system, providing short light pulses at high frequency and a high-speed image capturing system to obtain multiple sequential images within one cycle, would allow tracking of the large-scale turbulent structures in the flow. To obtain three-dimensional information the light sheet may be translated through the field. To obtain instantaneous three-dimensional information, however, a two-camera system is required.

OPTICAL EMISSION TOMOGRAPHY: A NEW FLAME FRONT DIAGNOSTIC

The need for a better fuel efficiency and low pollutant emission from engines for legislative and economic reasons has meant that engine designers have needed to improve their understanding of the combustion processes. A possible solution to improving the fuel efficiency and minimizing harmful emission has been found to be using premixed combustion. Incomplete combustion causes high emissions of CO, NO and NO_2 exhaust gas, which are damaging to the environment. Premixed combustion systems offer more efficient burning, and thus enable to reduce emissions. However, a serious problem in using premixed combustion is that it is unstable. Unsteady heat release produces acoustic oscillations in an enclosed combustion chamber. These acoustic oscillations can propagate up and down the combustion chamber, which may cause several problems. Firstly, the oscillation can drive the combustion process close to the injector, which may ignite the gases in the premix chamber. Furthermore, the acoustic waves may cause components in the combustor to resonate, which will weaken the structure and possibly destroy the chamber. To study these instabilities, instrumentation is needed to monitor and evaluate the flame dynamics within a combustor. This requires high-speed data-capture (~2 kHz) to track the changes during a cycle, which typically lasts about 4 ms, and also a high, instantaneous spatial resolution (~10 mm^2) to map out the spatial behavior of the instabilities. The measurement technique also has to be able to perform within an extremely hostile environment with high temperatures (~1500°C), high pressures (ranging from atmospheric to 40 bar) and containing corrosive fluids and/or gases. Furthermore, to be of use to engine designers, the diagnostic technique should not interfere with the processes taking place (i.e. be non-intrusive) and should moreover function with the combustor requiring as few changes as possible from normal operation.

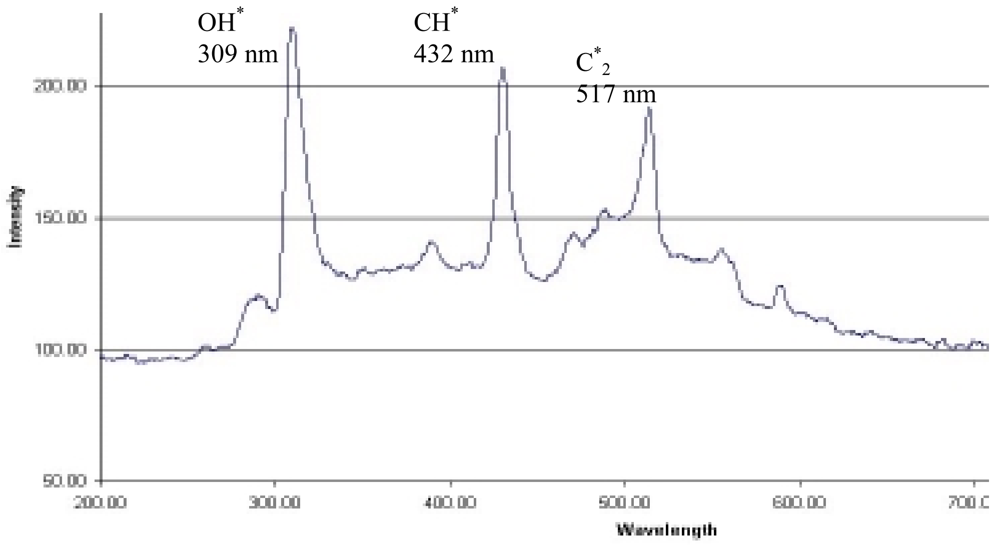

Figure 6: Emission spectrum from a natural gas (methane) flame. The bright peak at 309 nm is attributed to OH* (*Gaydon*, 1957), that at 432 nm to CH*.

The flame dynamics in combustion is important because it controls the heat release in the combustor, which determines the efficiency. Of particular interest for this is the light produced in the UV band by the hydroxyl radicals (OH^*) by chemiluminescence. These radicals are generated during the initial stages of burning in the combustion of hydrocarbon fuels and provide a qualitative indicator for the boundary between burnt and unburnt fuel (*Allen et al., 1993*). Furthermore, it was found that the OH radical emission is directly proportional to heat release in premixed flames (*Diederichsen & Gould, 1995*).

A single, 1 mm diameter silica fibre has been used to record the emission spectrum of a natural gas flame using a PC based spectrograph with a response extending from the UV to the near IR. As can be seen in Figure 6, three main peaks can be distinguished. The one at 309 nm is associated with OH radicals, the one at 432 nm to the CH radicals and finally the one at 517 nm to the C_2 radicals. The fact that the chemiluminescence from the hydroxyl radical forms a clear, well-separated peak in the spectrum allows the use of a passive, optical technique for monitoring the amount of heat release in an engine. Using spectroscopic filtering, the light coming from the hydroxyl radical at 309 nm can be filtered out from the total emission spectrum of the burning process. Using a sensitive detector, this can be measured at very high speeds (kHz range). However, this only gives information about the total amount of heat release at any instant. To furthermore obtain spatially resolved data tomographic techniques may be used.

In tomography, the goal is to obtain data about the internal structure of an object based on external ´observations´. These observations can be obtained by sending probe beams through the object and observing the projected beams using appropriate detectors. This is transmission tomography, used in e.g. computed tomography (CT) scanning in medicine, but also in interferometric tomography as used in high-speed flow diagnostics (*Timmerman and Watt, 1997*). In the case where the object emits radiation, and where the goal is to locate the sources of the emission, the data can be obtained without need for a probe source, but using only detectors. This is emission tomography, which is used in e.g. positron emission tomography (PET) in medicine. In that case a radiation source is introduced in the patient. When using emission tomography on flames however, the diagnostic can be completely passive, as in that case the radiation source is inherent in the flame. Thus, optical emission tomography (OET) can provide a passive, non-disturbing diagnostic.

However, to be able to use OET directly to monitor heat release, the flame that is studied needs to be ´optically thin´, i.e. the light that is generated

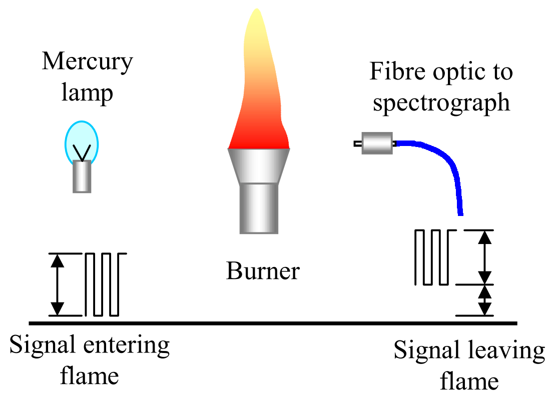

Figure 7: Set-up for measuring absorption of light by a flame.

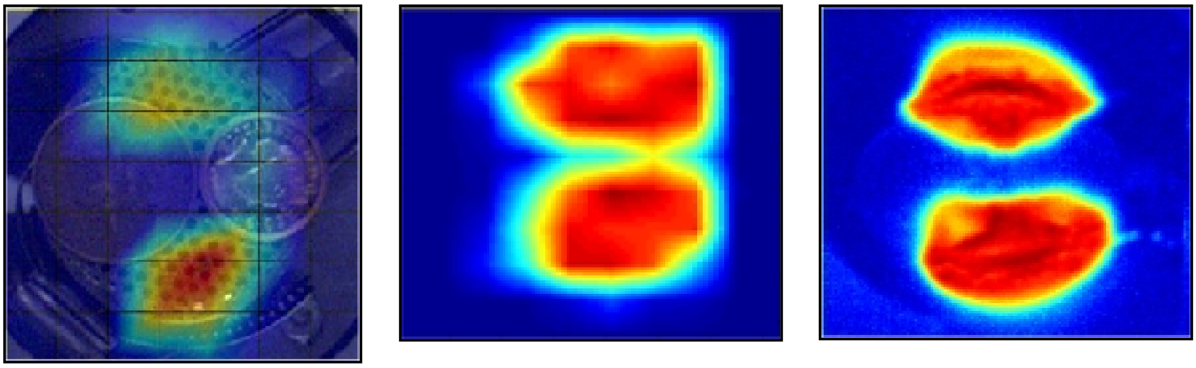

Figure 9: Measurements in methane flame disturbed by coins obtained by OH* detection using OET (left), averaged thermocouple measurements (middle), averaged OH* photograph (right).

in the flame at the wavelength of interest should not be absorbed or scattered while passing through the flame. To assess this, absorption measurements need to be carried out on the flame. Figure 7 shows the experimental set-up for measuring the absorption of light by a flame. First, the light from a mercury lamp is detected by a fibre optic connected to a spectrograph to determine the light emitted by the mercury lamp. Then, the flame under study is placed in between the mercury lamp and the detector and the spectrum reaching the detector is again recorded, once with the calibration lamp on, once with the calibration lamp off. Thus the spectra for the flame, for the calibration lamp as well as the combined lamp and flame are obtained. From this, the transmitted fraction of the light emitted by the calibration lamp and hence the optical thickness is determined. To test the applicability of direct passive OET in premixed natural gas flames the absorption and emission coefficients were determined on a 40 mm diameter premixed methane flame (*Dunkley*, 2002), which mainly emits by hydroxyl chemiluminescence at 309 nm (*Gaydon*, 1957) as shown in Figure 6. The optical thickness was found to be 0.33; the average absorption and emission coefficients were 0.08 mm^{-1} and 31 mm^{-1}, respectively. Thus, as the optical thickness is much smaller than 1 (*Klingenberg and Lawton*, 1991), and the emission coefficients are orders of magnitude bigger than the absorption coefficients, the premixed methane flame can be considered optically thin. For a flame that is not optically thin, not only the emission, but also the absorption needs to be determined, which may be achieved by sending external probe beams through he medium as well.

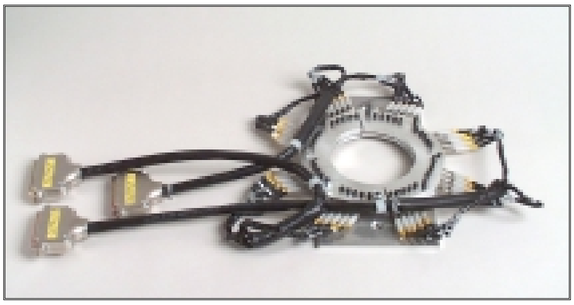

Figure 8: Detector array for optical emission tomography.

Secondly, to obtain the best spatial resolution in the tomographic reconstruction requires that the ´observations´ be taken from as many directions surrounding the object as possible. The data that is obtained is then combined to compute the internal structure of the object. Obviously, a compromise has to be made between achieving the best resolution and keeping the cost, size and computation times of the system within limits.

In the system used here, a set of forty fibre-optic detectors is mounted annularly so that they can be fitted around a combustion field as shown in Figure 8. This configuration allows mounting of the array on real engines and combustors requiring only little modification in most cases. The detectors are arranged in such a way that the sensitivity of the array is as homogeneous as possible across the circular area surrounded by the detectors. In order for the detectors to only perceive light coming from a thin, two-dimensional slice in the flame field, fibres are mounted between metal plates, effectively narrowing their field of view to the plane of the array.

The OET system was designed to operate using different detectors, depending on the need (high sensitivity, high-speed, etc.). Also, it can be used to monitor a specific wavelength, used e.g. for tracking of heat release, or a wavelength range can be detected. The intensities detected by each detector are used as input to a tomographic reconstruction algorithm based on the Multiplicative Algebraic Reconstruction (MART) technique.

Preliminary tests were performed on the methane flame used in the optical thickness measurements. Figure 9 shows the results of the OET measurements for this flame. To test the ability of the configuration for coping with asymmetric data, the flame was modified by placing coins on the burner grid. The left image in

Figure 9 shows a picture of this modified burner, with the OET reconstruction overlaid. To validate the results, also thermocouple measurements were obtained (middle image in Figure 9), as well as photographs of the total radiation from the hydroxyl radical taken from well above the flame using an optical band-pass filter (right image in Figure 9). As can be seen, the general shape is well reproduced, especially taking into account that the OET result represents an instantaneous measurement of a 2-dimensional slice in the flame, whereas the thermocouple represents an average of several point measurements in the slice, taken sequentially, and the OH^*-photograph represents an (averaged) image of the total emission from the 3-dimensional flame seen from above.

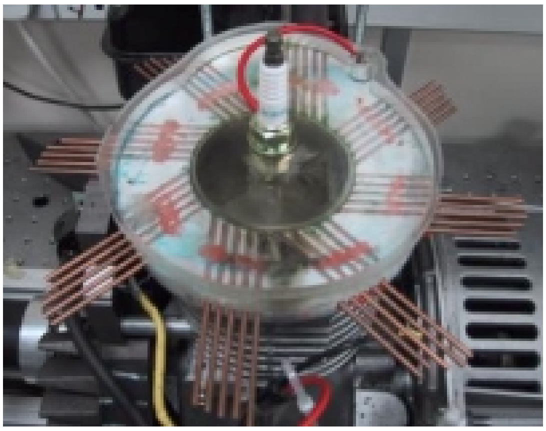

Figure 10: Side valve engine OET array design, allowing direct optical access to spark region from above.

The array has been used successfully to study high speed acoustically driven flow oscillations found within a gas turbine combustor (*Dunkley*, 2002). Also, current work is performed to use it on an internal combustion engine. Tests are performed on two types of engines. The first engine is a side-valve engine from Briggs and Stratton featuring a 5:1 compression ratio, which has already been used for testing several types of engine measurement techniques (Wilson, 2002). Its side-valve design allowed an optical view into the combustion chamber by replacing the engine head by an in-house manufactured perspex head (*Fok et al*., 2002). Figure 10 shows the tomographic array mounted in this transparent head. This configuration allows the simultaneous visual and OET monitoring of the flame propagating from the spark plug in the center of the tomographic array. Furthermore, the OET array is being developed for use on an overhead engine from Briggs and Stratton. This design does not allow a direct optical view into the combustion chamber but does permit the use of a much thinner tomographic array. The mounting required to hold the fibre optics in place and transmit the light to the photodiodes in this case is made of a very thin layer of aluminium (2 mm), clamped between the combustion chamber and the engine head (*Fok et al*., 2002). The array is thin enough to be able to totally replace the gasket in the engine making the system truly non-intrusive since neither the volume nor the size of the combustion chamber are modified. Furthermore, again, this also insures that the fibre optics will only "see" a horizontal cross section of the combustion.

CONCLUSIONS

Two techniques were discussed which are capable of providing quantitative measurements in environments that are difficult to get access to: particle image velocimetry (PIV) and optical emission tomography (OET). Both presented examples represent novel measurement applications of the technique.

The problem in obtaining measurements of velocity fields around objects in a rapidly changing environment such as around rotating machinery was solved using PIV with two opposite light sheet sources. These sources were mounted either inside a stator blade or just in front of a transparent stator blade as well as downstream in a supersonic flow, to cause only minimal disturbance to the flow under study. Thus, measurements of instantaneous velocity fields were obtained, allowing the study of turbulent unsteady effects.

Optical emission tomography allows truly non-intrusive measurements in combusting flows by passively recording the light emitted during the combustion process. The recording array can be placed around the field of interest requiring very little, if any, modification to the combustor.

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