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FEASIBILITY STUDIES AND APPLICATION OF LASER /OPTICAL DIAGNOSTICS FOR CHARACTERISATION OF A PRACTICAL LOW-EMISSION GAS TURBINE COMBUSTOR

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ABSTRACT

The present paper presents applications and feasibility studies of a number of laserspectroscopic techniques in a lean premixed prevaporised (LPP) combustor. Four different laser diagnostic techniques were investigated. The two more mature techniques, Planar Mie Scattering/Laser Induced Fluorescence and Planar Laser Induced Fluorescence of OH were used for fuel- and OH- visualisation, respectively. In addition, the applicability of some novel techniques in harsh industrial environments were investigated, two-line atomic fluorescence (TLAF) to obtain 2-dimensional temperature distributions, and two-photon LIF for the detection of CO. In order to investigate the degree of turbulence an ultrafast framing camera was employed to record spontaneous emission.

1. INTRODUCTION

In order to meet high efficiency combined with ultra-low emission from gas-turbine combustion special low emission concepts have to be designed and evaluated. One such concept to meet this requirement is the LPP concept [1,2]. During LPP combustion the preheated fuel/air mixture is in strong excess of air, and the liquid fuel is vaporised. To achieve optimum combustion, special care must be taken to optimise the degree of vaporisation and fuel/air mixing in the combustion chamber. However, the residence time of the fuel/air mixture in the duct must be minimised to prevent autoignition.

Numerical simulations of the combustion process [3] play an important role in the engine design and optimisation procedure. Some significant features of technological combustion systems can however not be modelled in adequate detail. In this situation laser spectroscopic diagnostic techniques serve a main purpose. Despite their relative novelty they can provide in-situ information on the basic combustion processes and thus help to validate current model assumptions.

The harsh conditions prevailing in the LPP combustor present a severe challenge to laser diagnostics. Absorption of laser light, LIF signals from multiphase-fuel components and combustion products, limited optical access, long term operational drifts, and other factors, make quantitative application of these techniques for species concentration and temperature measurements difficult.

Planar Mie scattering/laser induced fluorescence (Mie/LIF) for fuel visualisation and OH visualisation using planar laser induced fluorescence (PLIF) were employed to give qualitative information on the LPP duct. In order to develop and investigate the applicability of novel laser techniques in LPP environments two-line atomic fluorescence (TLAF) for thermometry and CO detection using two-photon LIF were employed.

2. METHODOLGY

FUEL AND OH VISUALISATION – Different laser diagnostic techniques have been applied in practical combustion to

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measure the air/fuel distribution [4]. The importance of local mixture fraction in the context of NO_x emission has been discussed, for example, by Warnatz [5]. Recently, planar laser induced fluorescence (PLIF) using acetone was reported for the

Fig. 1: Transmission spectra of vaporised JET-A (no combustion) determined using a deuterium lamp.

measurement of the mixture of fuel/air in a gas turbine [6]. The result shows the importance of knowing both the temporal and spatial homogeneities of the mixture for the design of low emission concepts.

When liquid fuel is used the degree of vaporisation is also important in order to achieve complete combustion. In the present experiments a combination of Mie scattering and LIF from the fuel (JET-A) was used to visualise the vaporisation. The method uses the fact that high liquid content gives a high ratio of Mie to LIF signal. The approach does not give absolute results, but give valuable qualitative information on the vaporisation performance of LPP ducts [7]. A potential problem for laser diagnostics is the absorption of the UV laser light from large hydrocarbon species in the fuel, which increases with pressure. In order to handle this problem a YAG pumped dye laser with frequency doubling was used. This gave the possibility to choose a wavelength at optimum spectroscopic conditions.

To find a suitable wavelength for the Mie/LIF visualisation, the broadband transmission in the pre-vaporised JET-A fuel was measured without combustion. Experiments were made using a deuterium lamp in order to establish the expected laser beam attenuation at different wavelengths. The result is shown in Fig. 1. Tuning the dye laser to 290 nm and collecting the fluorescence from the fuel without combustion generates a broadband spectrum from 300-420 nm with a peak occurring around 350 nm.

The visualisation of the OH distribution provides information about the flame. As the LIF signal from Jet-A interferes with the OH signal one needs a method to separate the signals. In this work excitation was done at about 284 nm and a narrow band filter centred at the OH signal at around 310 nm was used to suppress the Jet-A signal. The fluorescence from the fuel, collected when the laser was tuned off the OH absorption line, was used as background and subtracted from OH signals. Thus small OH signals were not detectable.

Another strategy to meet this problem is to use two separate laser systems, which is discussed in [8].

HIGH SPEED PHOTOGRAPHY -The stability of the LPP-combustor was investigated by time resolved studies of the flame. A high speed CCD camera was used to image the flame emission. The flame emission is chemiluminescence; i.e. radiation emitted by chemically excited molecules in the flame. With the high-speed camera, which is capable of framing rates up to 100 MHz, the flame could be studied in real time in a film like manner. The aim of this experiment was to establish the time scales at which the main- and the pilot-flames of the LPP- combustor fluctuate. To establish the time scales image sequences with time resolutions ranging from 1 μs up to 1 ms were recorded.

Imaging of flame emission, as used in this study, is not optimal, as it is a line of sight technique, which makes the interpretation of the images more difficult. The problems involved with line of sight techniques could be avoided by use of a high-speed laser together with the high-speed CCD camera. One could record, for example, two-dimensional images of the OH concentration in a plane, cutting through the flame. The high speed CCD camera has been successfully used in experiments together with a high-speed laser for visualizations of turbulent flame phenomena [9, 10].

CO MEASUREMENTS – The purpose of the presented investigations was to study the applicability of two-photon excited LIF for imaging of CO molecules in a LPP combustor burning commercial fuel. The measurements in the LPP-combustor at Volvo Aero Corporation were preceded by extensive investigations of the behaviour of two-photon LIF signals from carbon monoxide. These preliminary investigations were performed in a laboratory environment at the Lund Institute of Technology.

Carbon monoxide, like many other important combustion species, has its first electronic resonance in the vacuum ultraviolet region of the electromagnetic spectrum. In order to overcome the problems of both generating and using vacuum UV laser light, a multiphoton excitation scheme was chosen for the detection of this molecule. For further details concerning detection of the CO molecule in flames we refer to [11].

We have applied laser-induced fluorescence by exciting the CO molecules using two photons at 230.1nm. The fluorescence was detected in the spectral range between 451 nm (v’=0, v’’=0) and 662 nm (v’=0, v’’=5). Spectrally and spatially (in one dimension) resolved measurements were carried out in a test cell, as well as in two different flame environments. Thereafter, the experimental equipment was transferred to Volvo Aero Corporation in Trollhättan, Sweden, in order to perform on site measurements in the LPP-combustor.

TEMPERATURE MEASUREMENTS – The aim of the experiment was to investigate the applicability of a novel laser technique for measurements of temperature distributions in the LPP environment. The technique is based on two-line atomic fluorescence (TLAF) from seeded indium atoms and has for the first time been applied in an LPP-combustor.

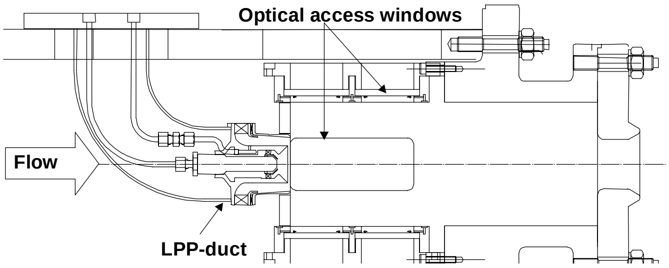

Fig.2 : LPP-combustor

Different laser diagnostic techniques have been applied in practical combustion to measure temperature field distributions [4]. The present group has demonstrated the capability of precise, temporally resolved 2-dimensional temperature measurements using TLAF in practical combustion systems [12,13]. The basic principle of TLAF is that suitable metal atoms, having two optically accessible and temperature sensitive energy states, are seeded into the combustion environment. Depending on the temperature the atomic energy levels are populated according to a Boltzmann distribution under conditions of local thermodynamic equilibrium. Two time delayed laser sheets are used for excitation and two filtered detectors collect the LIF signals corresponding to F_{20} and F_{21}. In thermal equilibrium the ratio F_{21}/F_{20} is proportional to the temperature T of the system. It can be shown that

$$T = \frac{\varepsilon_{01} / k_B}{4 \ln \frac{\lambda_{21}}{\lambda_{20}} + \ln \frac{I_{12}}{I_{02}} + \ln \frac{F_{21}}{F_{20}} + C}, \qquad (1)$$

where ε_{01} is the energy difference between the two lower states involved (in J), k_B is Boltzmann's constant, λ_{2i} are the excitation wavelengths, and I_{i2} and F_{2i} (i=0,1) are the laser and the fluorescence signal intensities, respectively. C is a system dependent calibration constant. Equation 1 is valid under the assumption of a linear relationship between laser intensity and LIF signal [14].

3. EXPERIMENTAL AND SET-UP

LPP SET-UP - The LPP combustor, see Fig. 2, was designed, manufactured and tested at Volvo Aero Corporation. The LPP duct consists of a central pilot pressure swirl fuel injector and air swirl, an annulus premixing duct fed by two counter rotation radial air swirlers and a main fuel injector consisting of 8 discrete holes. The pilot fuel is used for light–up and flame stabilisation. In the annulus-premixing duct, main fuel is injected, evaporated and premixed with the air before entering into the combustor.

The combustor has a quadratic cross-section with air-cooled quartz-windows for optical access. The combustion process is stabilised by a recirculating flowpattern in the combustor, which is set up by strong swirling flow in combination with a sudden area change between the LPP-duct and the combustor. Due to durability of the quartz-windows, most of the optical measurements had to be carried out close to the LPP-duct outlet.

The combustor was operated with JET-A as fuel and the tests were performed at a pressure of 6,7 bar and with preheated non-vitiated air at an inlet temperature of 630K. The overall equivalence ration was 0.4. The fuel flow in the central pilot was 0,9 g/s and the main fuel flow was 6,1 g/s. At these operating conditions Volvo Aero Corporation had earlier made emission measurements resulting in EICO = 0,4 g/kg and EINOx = 2 g/kg. More detailed information concerning the duct is presented in ref. [15].

FUEL AND OH VISUALISATION - The set-up is shown in Fig. 3. The laser power at each 10 ns single shot was monitored with two photo-diodes, one placed before and the other behind the test section. The ratio of the signals from the two diodes gave a rough measure of the attenuation of the laser

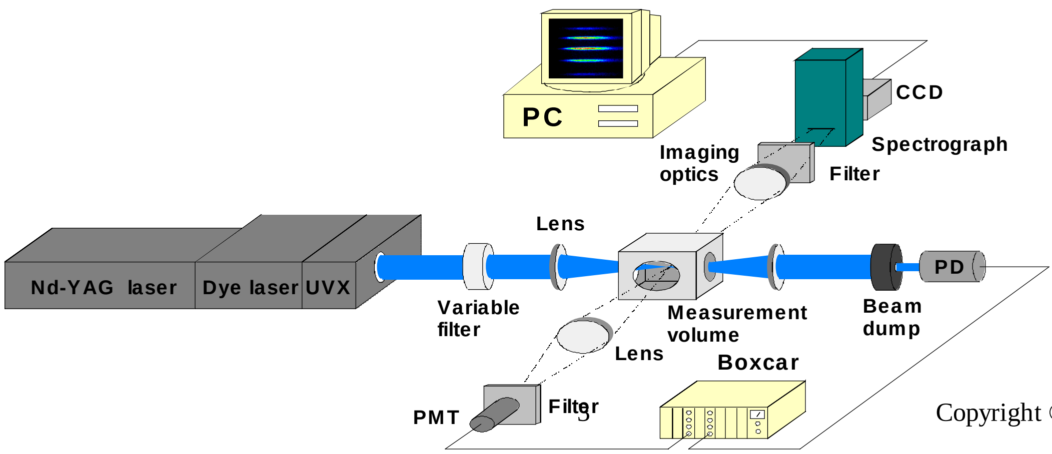

Fig.3 : Experimental set-up

beam at each laser shot. The collected images were corrected for the attenuation of the laser beam. The laser energy at 290 nm was on average 2 mJ in each 10ns single shot. The laser beam was formed into a thin horizontal sheet with a width of about 15 mm and a thickness of about 0,5 mm. Before and after each measurements set, an average profile of the laser sheet inhomogenieties was recorded using a reference cell. This was a quick operation since the laser and camera unit was placed on a XYZ translation table. The images could thus be corrected for the beam inhomogenieties.

A horizontal area of about 63 x 15 mm, starting about 6 mm from the duct outlet, was imaged with a mirror on the CCD camera. Note that the imaged area during OH LIF differs somewhat from the area during fuel LIF.

To simultaneously record Mie scattering and LIF, a stereoscope was placed in front of the 50 ns gated image intensifier. By placing different filters in the two channels of the stereoscope, Mie scattering and LIF were recorded on different positions on the same CCD detector.

When recording only Mie or LIF images the stereoscope was removed. For spectroscopic measurements a monochromator was placed in front of the intensifier. For broadband transmission measurements a deuterium lamp was used as light source.

HIGH SPEED PHOTOGRAPHY - The detector used for the stability investigations was an ultra fast CCD camera, (Imacon 468, Hadland Photonics, England). The camera consists of 8 independent CCD detectors. The image is split into 8 identical images by an 8-facet pyramid beam splitter and the resulting images are relayed to the individual CCDs. Each CCD is precisely aligned with respect to a common optical axis. The individual CCDs have their own intensifiers and are independently gateable, thus giving full timing control.

It is possible to attach an extra three-stage intensifier to the Imacon CCD camera. This intensifier increases the detection sensitivity of the camera and also extends its operation into the UV spectral region, which is necessary to register, for example, emission from the OH radical. With this extra intensifier the gain approaches that of conventional ICCDs at an overall dynamic resolution of 8 bit. The camera can take a sequence of 8 images with time separations down to 10 ns, when the extra intensifier is used the minimum time separation increases to 1 µs, due to the decay time of the phosphor inside the intensifier. More details of the camera are found in [10].

The emission from the flame was recorded with the high-speed camera looking through the fused silica window located at the bottom of the chamber. The imaged area was 28x68 mm, starting a few mm from the duct outlet.

The camera was used with the optional extra intensifier to make it UV sensitive, as some of the flame emission is in the UV region. Image sequences of 8 images were recorded with various time separations between the individual images, ranging from 1 µs to 1ms. The emission was imaged without any filter as well as with interference filters for OH and C_2, thus enabling studies of the emission from individual species.

CO MEASUREMENTS - The basic layout of the experimental set-up used during the laboratory measurements can be seen in Fig. 3. The investigated gas mixtures were kept in a stainless steel cell with quartz windows. A dye-laser pumped by the second harmonic from a YAG-laser, produced radiation at 587.2nm. After frequency doubling and mixing with the IR fundamental from the YAG, approximately 4.5 mJ of excitation light at 230,1 nm was generated. The laser beam was focused to a line by a single spherical lens. The focal area was imaged onto the slit of a spectrometer equipped with an image intensified CCD camera. In addition, the absorption of laser radiation was monitored by a PM-tube.

During the laboratory flame measurements the cell showed in Fig. 3, was replaced by a suitable burner. A similar set-up was also built up around the LPP-combustor for the measurements performed at Volvo Aero Corporation.

TEMPERATURE MEASUREMENTS – In additional to the experimental set-up shown in Fig. 3, two lasers and two CCD cameras were employed to perform the TLAF measurement. The time delay between the laser pulses was chosen to be 500 ns, which is sufficiently short to ensure that the measurements are not affected by turbulence. The laser beams were formed into light sheets, approximately 20 mm in width and 200 µm in thickness. The two laser sheets were carefully aligned with each other to ensure probing of an identical measurement region. The two cameras used to collect the fluorescence signals were aligned on a pixel by pixel basis to image identical regions in the chamber. The fuel was seeded with InCl3 salt. The salt was dissolved in isopropanol before the seeding solution was admitted into a 30-litre tank with JET-A.

4. RESULTS AND DISCUSSION

FUEL AND OH VISUALISATION - By investigations of Mie images only, it was difficult to judge whether there was combustion or not. However, when studying LIF images of the fuel distribution a clear difference could be seen between images from a situation with and a situation without combustion. During combustion there was no fuel vapour in the area between the pilot and the main fuel channel.

It became clear from the combined LIF and Mie scattering images that the area in the duct available to visualisation had a large content of fuel even in the case of combustion. It could also be shown that some of the preheated fuel leaves the main channel still in liquid phase. This might however be due to the low air preheating temperature of 630 K.

Figure 4 shows single shots of simultaneously recorded Mie and LIF signals in the situation with combustion.

Mie signals above a certain level were interpreted as liquid, and marked in false colour. LIF signals outside this area were then attributed to show the vapour distribution.

The authors believe that the method of combined LIF/Mie can give valuable information, when different ducts are to be tested at different operating conditions, and when visualisation is made further away from the duct outlet.

Figure 5 shows a time-averaged image and some single shot images of the OH distribution. This figure shows no sharp flame front, but gives an OH distribution in the central position of the duct, in the pilot area. The average image shows that the flame has a tendency to bend to the right. This was consistent with the observation that steel plates in this area easily got overheated and became red.

If there was OH at the outer main flame, its concentration was too low to be detected because of the problem with spectrally interfering fluorescence from unburned JET-A.

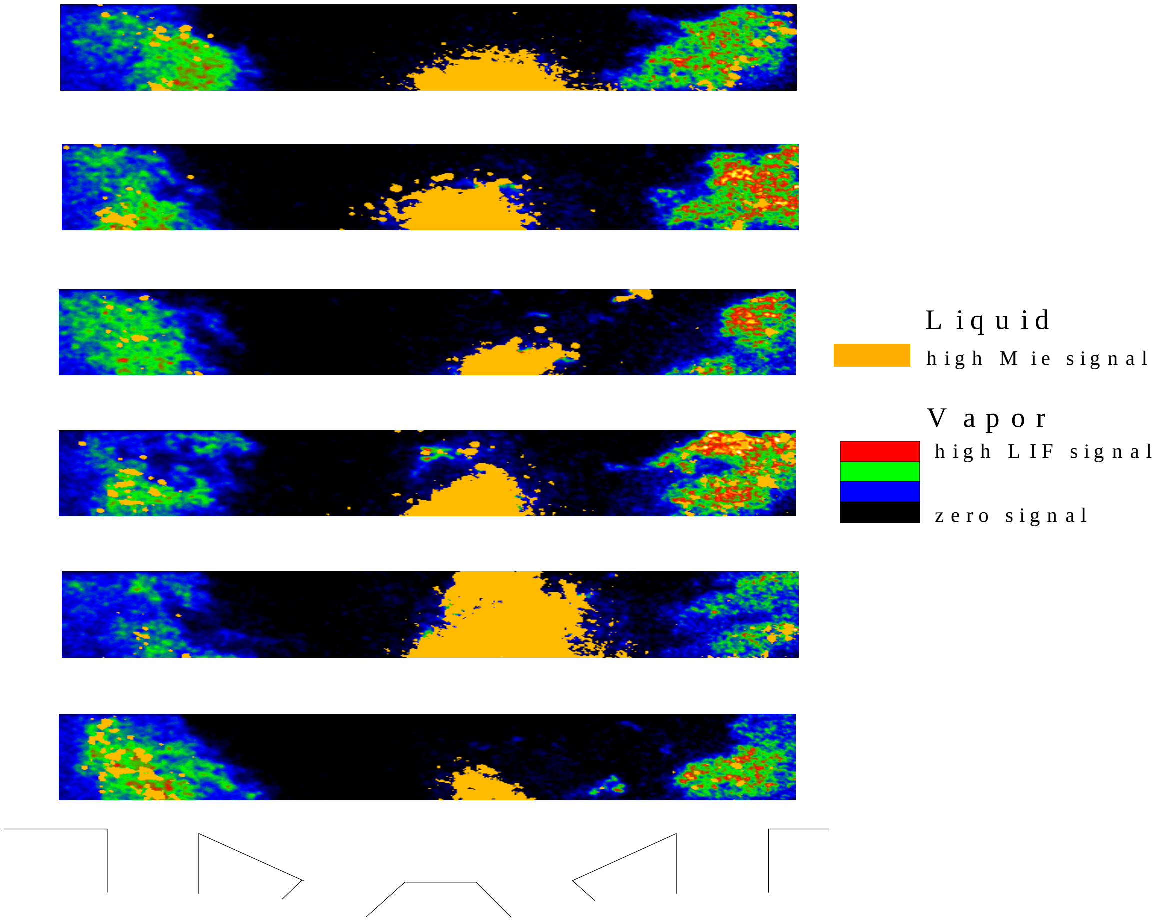

Fig.4: Combined LIF and Mie images during combustion. Mie signal indicates high liquid content and LIF signal indicates vapour in areas where Mie signal is absent.

HIGH SPEED PHOTOGRAPHY - The aim of the high-speed studies of the flame emission was to study the flame stability, especially the stability of the outer boundary of the main flame and of the pilot flame. A typical image sequence is shown in Fig. 6. Identification of the outer flame boundary was difficult because the pilot flame emission was much stronger than the emission from the main flame. As the exposure is determined by the strongest emission in the image the signal level at the outer main flame boundary is close to the noise level. For the stability studies the images recorded without filter were the most useful. The OH images showed a behavior similar to the images recorded without filters. The C_2 signal was too low to yield useful data.

From the image sequences some conclusions could be drawn: The outer boundary of the main flame was quite stable at time scales below 1 ms, at the 1 ms scale it moved a few mm between consecutive images. The pilot flame was stable at times below 100 µs, at longer time scales it moved up to 5 mm between consecutive images. In some image series, as in Fig.

6, bright structures could be followed in time, the velocity of these structures was around 60 m/s which corresponds well to the velocity of the main flow, which was around 70 m/s at the duct exit.

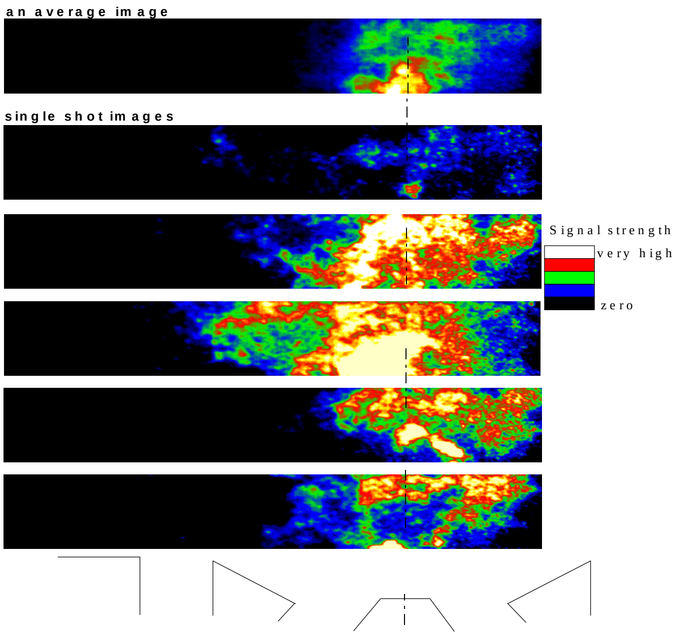

Fig.5 : OH fluorescence images.

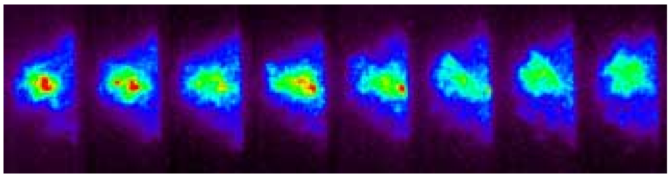

Fig.6 : Emission images recorded with a high-speed camera. The time separation between the images is 50 µs.

CO MEASUREMENTS

Laboratory

In order to perform quantitative LIF measurements it is necessary to control a range of properties affecting the relation between laser power and the generated signal level. The laboratory experiments served to map these properties in simulated combustion environments, i.e. to map the dependencies on laser energy, pressure, temperature and stoichiometry, as well as, the influence from other present species.

Measurements in the cell with and without buffer gases were carried out at pressures from 0.1 up to 8 bar. It was revealed that the signal strength dropped by, approximately, a factor of 10 as the ambient (nitrogen) pressure was raised from 1 to 8 bar.

In the flame investigations, the behaviour of spectral interference from non-resonantly excited C_2 molecules, produced by photodecomposition of fuel and fuel fragments, were studied at various stoichiometries and laser intensities. The first flame measurements were performed in a premixed methane/air flame. The results showed, as expected, that the photodecomposition, i.e. production of C_2, is more pronounced at higher ϕ-numbers. Additionally, the total signal strength from CO was found to decrease under lean conditions.

In order to check the applicability when using a multi-component commercial fuel, measurements were carried out in

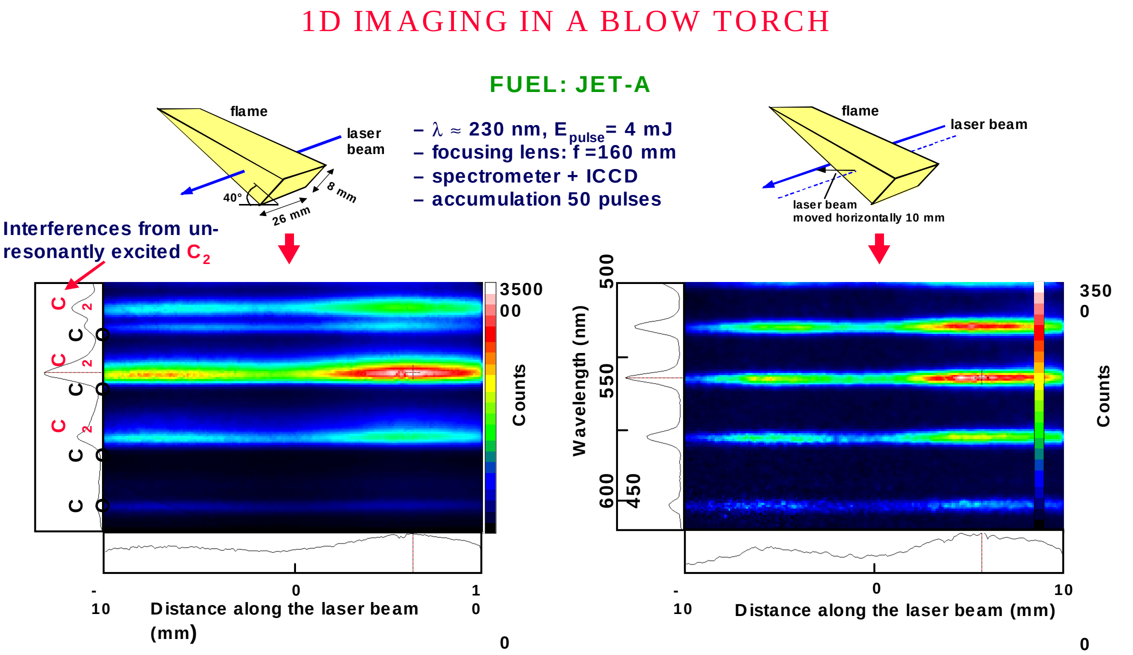

Fig.7 : CO measurements in a pre-vaporised JET-A diffusion flame.

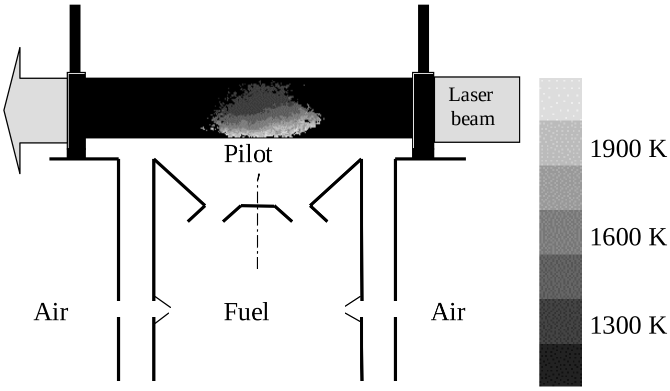

Fig.8 : A TLAF image of mean temperature distribution

a pre-vaporised JET-A diffusion flame. The results from two different measurement points can be seen in Fig. 7. When the measurement volume was placed at the centre of the flame a significant interference from C_2 was detected. However, when measuring in the outer edge of the flame an undisturbed CO-signal could be collected. This is explained by the simple fact that the concentration of unburned fuel is higher in the core of the diffusion flame.

LPP-Combustor

The probe volume was placed at different heights approximately 10 mm downstream from the duct. From the laboratory experiment it is known that both high-pressure and lean combustion has a negative effect on the signal level. The absorption measurement performed earlier in this area revealed a severe absorption in the UV spectral region. In addition, at the time of the experiment a damaged laser system limited the laser output to 2 mJ.

All together this made it impossible to generate a strong enough signal in this specific LPP-combustor.

TEMPERATURE MEASUREMENTS - Initial feasibility experiments in laboratory flames and earlier successful applications of the technique in an SI engine [7] provided single shot temperature distribution with a precision of 14% over a range from 800 to 2800 K.

In the present case a mean temperature distribution referenced to a theoretically mean temperature based on 20 single shot image pairs was obtained, see Fig. 8. The procedure for the temperature calculation is discussed in detailed in [7]. In comparison with Fig. 5, which show the burning regions in the duct, it is seen in Fig. 8 that the TLAF signals were obtained in the same region, close to the pilot area.

The reason that no single shot temperature distribution could be obtained is probably a consequence of the LPP burning concept. Under lean burning conditions the oxidation of the indium atoms increase, which decrease the signal to noise ratio (SNR) of the TLAF signal. To improve the SNR a higher seeding concentration had to be used. Unfortunately, no higher SNR was achieved, even if the laser intensity was increased beyond saturation levels for indium LIF. This was due to a produced precipitation of indiumoxides, like a yellow/red coating, on the windows of the combustion chamber. This caused partial absorption of the laser beam without advantages in SNR being gained using higher seed concentrations.

5. CONCLUSION

A main conclusion from the Mie/LIF visualisation is that a tuneable laser around 290 nm was necessary to use due to strong molecular absorption from large hydrocarbons and the high pressure. This should be compared with the use of the quadrupled YAG laser at 266 nm, which was employed in previous measurements at atmospheric pressure, see ref. [7]. Using 290 nm excitation it was, however, still possible to use the combined Mie/LIF technique for qualitative visualisation of vaporisation characteristics.

During OH visualisation, the problem with interference from fuel fluorescence could be minimised using an OH filter, tuning the laser off OH resonance and subtracting the fuel fluorescence.

An ultra high-speed CCD camera was used to image flame emission from the combustor. This device can be of importance in overall characterization of the turbulent combustion phenomena. A disadvantage is of course the fact that these images are line-of sight images, still, however, qualitative information could be achieved. By using the high- speed camera in combination with a new high-speed laser the problems associated with the line of sight imaging can be avoided.

The detection of CO is of crucial importance in gas turbine characterisation and, therefore, the potential for CO detection at relevant conditions was investigated. It turned out that the CO signal suffers severe signal decrease as the pressure and ϕ-value is increased. Additional problems, which have to be taken into account in CO detection, are the influence from ionisation processes, two-photon absorption, and potential creation of C_2 radicals whose emission may spectrally interfere with the CO emission. All these effects may, however, be modelled and taken into account. The most severe problem in the present case seemed to be the strong molecular absorption by the fuel, JET-A, at the excitation wavelength 230 nm. Due to limited time at the rig in addition to a malfunctioning laser at Volvo Aero Corporation, no general statement of the applicability of CO detection in this environment could thus be made.

Finally a new technique, two-line atomic fluorescence, TLAF, was investigated for two-dimensional temperature visualisation. The technique has, generally speaking, distinct advantages compared to other 2D-visualisation techniques. However, a potential problem faced in the LPP duct was what was believed to be a strong oxidation in the lean combustion gases. If windows provide optical access the practical measurement time may be limited because of indiumoxide deposits on the windows. The investigation also revealed the increasing difficulties when performing a metal seeding procedure on a large scale. An alternative to TLAF thermometry in lean combustion is maybe OH thermometry in a two-line approach. But here problems with absorption and fluorescence from JET A at the required wavelengths for OH spectroscopy may pose a problem.

To summarise, we believe that Mie/LIF and OH PLIF are techniques readily available for characterisation of LPP ducts. In the case of the ”new” techniques investigated, it is believed that TLAF has potential, although more laboratory work is needed before quantitative work in this environment can be made. The applicability of two-photon CO monitoring in the vicinity of the duct in a JET-A fuelled LPP combuster must be considered limited.

ACKNOWLEDGMENTS

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REFERENCES

1. B. Simon, F. Joos, and R. Walther, “*Possibilities and Limitations of Reducing Pollutions by Aero-Engines by Modification of the Combustror Process”*, Proceedings of the Second European Propulsion Forum, April 3-5, 1990
2. P. Johansson, A. Sjunnesson, and S. Olovsson, “*Development of an Experimental LPP Gas Turbine Combustor”*, ASME 94-GT-284
3. R. Rydén, “*CFD designsupport LPP duct RR/VAC comb.”*, VAC internal report 9970-2811
4. Eckbreth A. C., *Laser diagnostics for combustion temperature and species, 2nd ed.*, Gordon and Breach Publishers, Amsterdam, 1996
5. J. Warnatz J., ”*The formation of nitrogen oxides in combustion processes”*, Proceedings of First European Conference on Small Burner Technology and Heating Equipment, ETH Zürich, 1996
6. H.Krämer, F. Dinkelacker, A. Leipertz, ”*Optimization of the mixing quality of real size gas turbine burner with instantanous planer laser-inuced fluorescence imaging*”, ASME paper No.99-GT-135
7. C. Löfström, H. Kaaling, and M. Aldén,”*Visualisation of Fuel Distributions in Premixed Ducts in a Low-Emission Gas Turbine Combustor using Laser Techniques*” 26th Symp (Int) on Combustion/The Combustion Institute, 1996, pp 2787-2793
8. U. Meier, D. Wolff-Gassmann, J.Heinze, M. Frodermann, I. Magnusson, and G. Josefsson,”*LIF imaging of species and temperature in thecnical combustion at elevated pressures”*, 18th International Congress on Instrumentation in Aerospace Simulation Fascilities, (1999)
9. C.F. Kaminski, J. Hult and M. Aldén, “*High repetition rate planar laser induced fluorescence of OH in a turbulent non-premixed flame”*, Appl. Phys. B 68, 757-760 (1999)
10. A. Dreizler, S. Lindenmaier, U. Maas, J. Hult, M. Aldén and C.F. Kaminski, *“Characterization of a spark ignition system by planar laser induced fluorescence of OH at high repetition rates and comparison with chemical kinetic calculations*”, accepted for publication in Appl. Phys. B
11. M. Aldén, S. Wallin and W. Wendt, “*Applications of Two-Photon Absorption for detection of CO in Combustion Gases”*, Appl. Phys. **B 33**, 205 (1984).
12. C. F. Kaminski, J. Engström, *"Evaluation of 2-Line Laser Induced Atomic Fluorescence for 2-Dimensional Thermometry in Practical Combustion Applications"*, Laser Applications to Chemical and Environmental Analysis, Technical Digest, Optical Society of America, Washington DC, 1998, pp 190-192.
13. C. F. Kaminski, J. Engström, J. and M. Aldén, *"Quasi-instantaneous 2-dimensional Temperature Measurements in a Spark Ignition Engine Using 2-line Atomic Fluorescence*", 27th International Symposium on Combustion, The Combustion Institute, Boulder 1998, pp 85-93
14. G. D. Boutilier, M.B. Blackburn, J. M. Mermet, S. J. Weeks, H. Haraguchi, J. D. Winefordner and N. Omnetto. *“Steady-state atomic fluorescence radiance expressions for continuum excitation.”* Applied Optics, Vol. 17, No 15, 1978.
15. P. Johansson, *“Design and Test of the Fuel Injector to be used during Initial Tubular Tests.”*, VAC internal report 7080-1