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NON INTRUSIVE MEASUREMENTS OF A LPP COMBUSTOR UNDER ELEVATED PRESSURE CONDITIONS

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ABSTRACT

To meet increasingly tight regulations on emission control appropriate combustor designs need to be developed. With different combustion concepts like RQL (Rich Quench Lean) and LPP (Lean Premixed Prevaporized) it has been proven that it is possible to reach the objective of a significant reduction of the NO_X emissions. To gain further insight into the real combustion process it is of importance to be able to "look into" the flame without interfering with the actual combustion process. At the combustion laboratory of the Institute of Flight Propulsion at Munich University of Technology a combustion test facility is set up to study combustion characteristics under pressure up to 6 bar and inlet airflow temperature up to 650 K. A newly designed LPP concept was adapted into an optically accessible model combustion chamber. The objective of the study was to operate the LPP combustor under semi-realistic conditions and to obtain more knowledge on the influence of pressure on the combustion process. With suitable non-intrusive laser-spectroscopic measuring techniques like LIF (Laser Induced Fluorescence) the fuel spray, the nitric oxides and the hydroxyl radical were detected in several planes parallel to the combustor axis at different combustor pressures.

As expected the pressure has a strong effect on droplet distribution and evaporation. Also with increasing pressure it was possible to operate the combustor under leaner conditions. A strong dependence on pressure of the formation of nitric oxides was detected. To quantify these results samples with a water-cooled probe were taken, analyzed and compared with the non intrusive measurements.

INTRODUCTION

The reduction of jet engine pollutants is an important technical criterion when developing future jet engines. Therefore, it is of great interest to gain more knowledge on the origin of the pollutant sources and subsequently searching for ways of their reduction. The European Research Program LOW NO_X in its first phases has done excellent work in creating a knowledge database for developing low emission combustors. With the two concepts RQL and LPP it has been demonstrated that it is possible to achieve an 80% reduction of the NO_X emissions compared to today's limits [1-3]. The research on these combustors, as well as the need to reduce cost and time for development has stimulated work on new design tools, like 3-D computer codes to predict the combustor performance, and new non-intrusive measurement approaches to study the flow field and the combustion process inside of the combustor during operation.

Up to now numerous studies have attempted to employ laser-induced fluorescence for two-dimensional determination of species concentrations in atmospheric flames [4, 5]. It has proven to be a suitable tool to obtain time and space resolved information from the combustion process. Koch et al. [5] utilized the LIF technique to analyze spatial distributions of O_2, OH and NO in liquid spray flames of commercial oil burning furnaces. However, the operation under "semi-realistic" pressure conditions is quite challenging and has to overcome many obstacles at the test setup and in choosing the right excitation and detection strategy for the non-intrusive measurement procedure [6, 7].

EXPERIMENTAL SETUP

The schematic of an experimental setup used for the non-intrusive spectroscopic measurements complete with detection system and laser beam path is shown in fig. 1. The investigations were carried out in a rectangular model combustion chamber. The duct has provisions for optical access, all four sides are fitted with fused silica quartz windows (80 mm by 150 mm). The test rig was designed for maximum pressures up to 10 bar and is supplied with electrically preheated air at temperatures up to 675 K. Supplemental air at ambient temperature is provided for cooling of the windows.

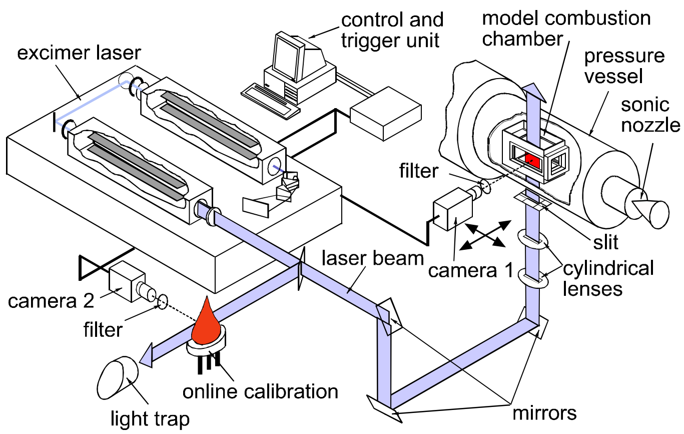

Figure 1: Experimental setup for the non-intrusive spectroscopic measurements

For the various tests n-heptane (n-C_7H_{16}) was used as fuel. This hydrocarbon fuel is nearly transparent to UV laser radiation when vaporized. The inherent properties are similar to those of kerosene and with the use of such pure substances it is less complicated than with the use of multi-component fuels to assign and quantify the fluorescence signals. A further advantage is the absence of higher hydrocarbons. Such higher hydrocarbons can cause deposits at the quartz windows and soot formation and can produce spurious signals disabling proper measurements.

For the laser-based measurements a tunable excimer laser (Lambda Physik EMG 150 T-MSC) is operated at the ArF 193 nm or at the KrF 248 nm transition. Details of the laser used are stated in table 1.

wavelength [*nm*]	193	248
gas	ArF	KrF
tuning range [*nm*]	193±0.5 nm	248±0.5 nm
max. pulse energy [*mJ*]	100	250
pulse rate [*Hz*]	0-80	
pulse length [*ns*]	15	17
band width [cm^{-1}]	0.3	
beam divergence [*mrad*]	≤0.2	

Table 1: Deatils of the laser EMG 150 TMSC

The laser beam passes an online calibration section and several mirrors and is formed to a sheet of about 20 mm x 1 mm by cylindrical lenses and a slit. The resulting laser sheet passes through the model combustion chamber from bottom to top. The natural or laser-induced fluorescence light exits the combustor through a side window. The signals, filtered with transmission filters or dielectric mirrors, are imaged onto a photometric digital camera (LaVision Flamestar II) via a Nikkor UV lens (105 mm, F/# 4.5). The resulting grayscale pictures are digitized and stored in a computer. On an online monitor, the images can be reproduced in false colors with various resolutions, i.e. the given range of colors, spanning from dark-blue (minimum intensity, usually zero) over red, yellow, and green to light-blue indicating maximum intensity. All the LIF results presented are averaged over 100 single shot pictures. The measurement equipment together with optical components is mounted on a table. This table is movable in two directions and thus it is possible to take measurements in several planes. A more detailed description of the experimental setup is given by Hupfer et al. [8].

A detailed cross section of the LPP burner-head, the model combustion chamber and the pressure vessel is shown in fig. 2. The burner-head was designed and build by RR Germany. The entire unit was flanged onto a plenum to ensure a reproducible air flow into the model combustion chamber. The LPP burner is divided into two sections. The outer contains two vortex generators into which the fuel is injected. Ideally the injected fuel breaks up and evaporates until it reaches the end of the burner-head. Into the inner section of the burner-head a radial vortex generator is fitted. The air passing through this section is used to break up the complete flow through the burner-head and thereby creating a recirculation zone. The burner-head and the model combustion chamber are integral part of the pressure vessel.

A movable water cooled sonic nozzle is used to adjust the static pressure inside the vessel. For this setup direct cooling of the pressure windows was not used. Instead the ambient temperature pressurizing air for the vessel was also used for cooling the outer windows. About twice the amount of air passing through the combustion chamber was used for cooling. In order to keep the thickness of the pressure windows as small as possible, the visible area of the model combustor was only 1/3 of the total length. By changing the frame in which the pressure window was fitted, the entire length of the model combustor could be used for measurements.

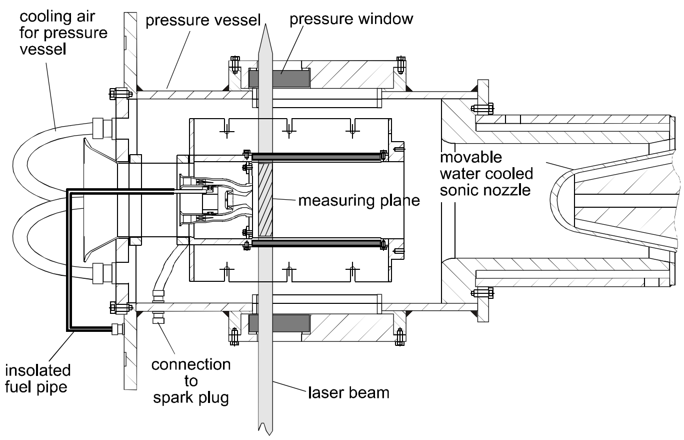

Figure 2: Cross section of the model combustion chamber with integrated LPP burner-head and the pressure vessel

DETECTION STRATEGIES

In general, the laser beam is expanded by cylindrical lenses to a sheet of light which crosses the flow field to be studied in the plane of interest. The various subsequent emissions from this area are imaged onto a highly sensitive fast-gated camera system. Spectral filtering of the emissions and state selective excitation in the case of LIF allows determination of spatial distributions of liquid fuel droplets, OH and NO. For the various measurements, different excitation and detection strategies are employed as listed in Table *2*. Details of the different detection techniques are described by Allen et al. [9] and Koch et al. [5].

An excitation spectrum was recorded in preliminary experiments with a methane-air flame. In the narrow tuning range of the laser different vibrational-rotational transitions of OH were found and compared to literature data. Fluorescence signals of the excited OH molecules were recorded through a UG 11 filter in a range of about 250 nm to 400 nm. With help of the online calibration unit (also a methane-air flame) in the experimental setup the correspondence between laser and excitation wavelength is adjustable. The laser was tuned to the desired "peak" determined in the preliminary experiments. Further details of this kind of calibration are described by Lachner et al [4]. According to Upschulte et al. [10] the laser tuning over an atmospheric flame is sufficient to account for the thermal laser drift during the experiment in the pressurized combustion chamber.

Object	Excitation: wavelength; absorption line	Detection: type of emission; detected wavelengths; filtering
Liquid fuel droplets	≈ 248 nm (KrF);	Mie scattering; ≈ 248 nm; no filtering
Nitric oxide (NO)	≈ 193 nm (ArF); $R_1(26.5)$ (ν=51713.0 cm^{-1}) of the vibrational transition 0←1 in the $D^2\Sigma^+ \leftarrow X^2\Pi$ absorption band	LIF: ≈ 208 nm; 2 x 208/45° reflection filters
Hydroxyl radical (OH)	≈ 248 nm (KrF); $P_1(8)$ line (ν=40296.25 cm^{-1}) or P2(8) line (ν=40248.48 cm^{-1}) of the vibrational transition 3←0 in the $A^2\Sigma^+ \leftarrow X^2\Pi$ absorption band	LIPF: ≈ 250 - 400 nm; UG11 band pass filter

Table 2: Excitation and detection techniques for different objects

To detect nitric oxide (NO) in combustion processes by means of the LIF technique the laser must be operated with an ArF (193 nm) gas filling. With this excitation typical fluorescence emissions of NO molecules have a wavelength of about 208 nm. Therefore two 208/45° reflection filters were used in parallelogram formation. With this kind of filter arrangement exclusively light with a wavelength of 208 nm is reflected and recorded. More details of NO detection strategy are described by Lachner [11], Fink [12] and Stoffels [13].

EXPERIMENTAL RESULTS

The experimental results presented in this paper are compared to those of investigations under atmospheric conditions. The bondary conditions for the experiments under elevated pressure conditions, i.e. the dimensions of the model combustor and the inlet temperature remained unchanged. In this way changes in the flame characteristics could be attributed to the higher pressure conditions. For all the measurements presented the combustor inlet temperature was T_{in} = 650 K and a pressure drop of 4% over the combustor head was maintained. In table 3 the operating conditions for the LPP combustor are shown. The operating points were chosen with a sufficient margin from the lean blow-out limit to ensure stable operation.

	1 bar	2 bar	4 bar
$\dot{m}_{air,burner}$ [kg/s]	31.6	65.6	141.0
$\dot{m}_{fuel}$ [g/s]	2.4	3.8	7.6
Equivalence ratio Φ [-]	1.15	0.87	0.81

Table 3: Operating conditions of the LPP burner-head

Distribution of the liquid fuel

Liquid fuel droplets have been visualized by Mie scattering adding 20 single laser shots to one picture ($\tau_{pulse} = 20$ ns). Interference with Rayleigh scattering or fluorescence emissions can be neglected, because their intensity ratios scale by about $10^7 : 1 : 10^{-1}$. The laser was operated at the KrF 248 nm transition, with dimensions of the beam set to $0{,}7x21\ mm^2$. Figure 3 shows the measured distribution of the injected but still liquid n-heptane in the reacting flowfield in the center plane of the combustion chamber. At a chamber pressure of 1 bar hardly any pre-vaporization of the fuel can be detected at all. With rising pressure a strong reduction of the detected signals are being noted. The structure of the spray can clearly be identified and the spray angle as well as the length of the spray cone can be determined from the picture. As illustrated the spray is not symmetrical in this test, showing a greater amount of fuel in the upper region of the chamber (it is not an effect of absorption, because the laser sheet passes the combustor from bottom to top). This clearly shows that with rising pressure conditions the mixture state in the burner-head moves towards the design point and the fuel evaporates before entering the combustion chamber. This is accounted to the proportional rise of the fuel pressure with the combustor pressure. In detailed studies Becker et al. [14] and Heitor et al. [15] found a change in the break up process. With rising combustor pressure and fuel velocity the "surface breakup mechanism" is the dominating one which causes a faster break-up of the fuel jet.

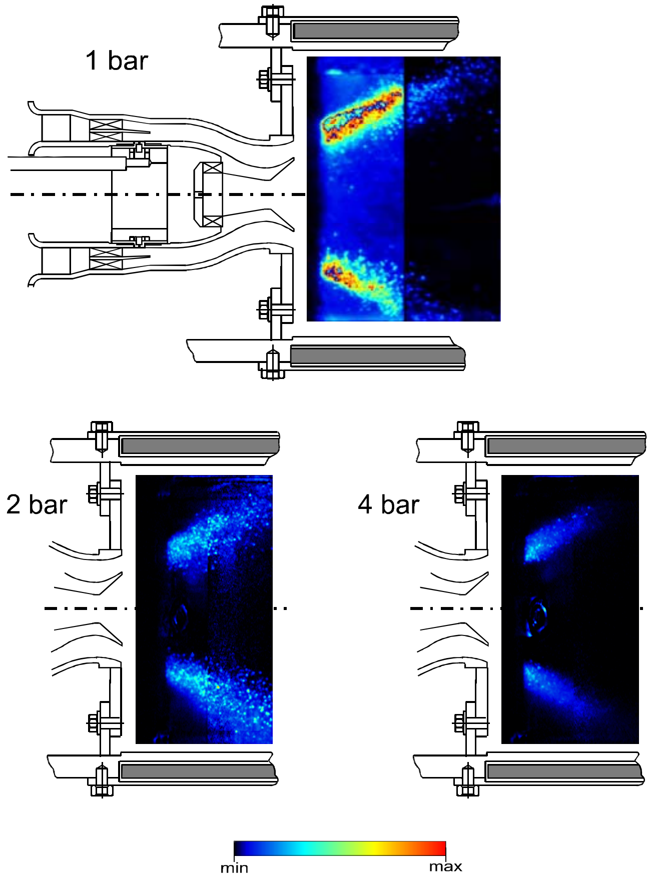

Figure 3: Distribution of the liquid fuel at different pressure levels in the center plane of the combustion chamber

Distribution of the OH radicals

The measured OH distribution in the center plane of the combustion chamber are given in fig. 4. As mentioned in the previous section we used a UG-11 Schott glass filter instead of an interference filter, so that no elastically scattered light was transmitted onto the CCD camera.

As one of the most important combustion intermediates, the OH molecule indicates the extent of combustion and the position of the flame front at these moderate pressures (1-4 bar). The cone shape of the flame can clearly be observed. The combustion mainly takes place in the outer regions of the cone. Hardly any OH can be detected at all in the center of the cone. This indicates that there is no combustion in the recirculation zone and only hot gases are transported to the root of the flame to stabilize the combustion process. With rising pressure the combustion process becomes increasingly intense. Comparing these pictures with the distribution of the liquid fuel shows that especially at 4 bar the zone of the most intense reaction begins were the evaporation is finished. A decrease of the signal intensity with rising pressure was not detected as the fluorescence rate is up to one order of magnitude higher than the quenchrate. This fact has also been observed and mentioned by Behrendt et al. [16].

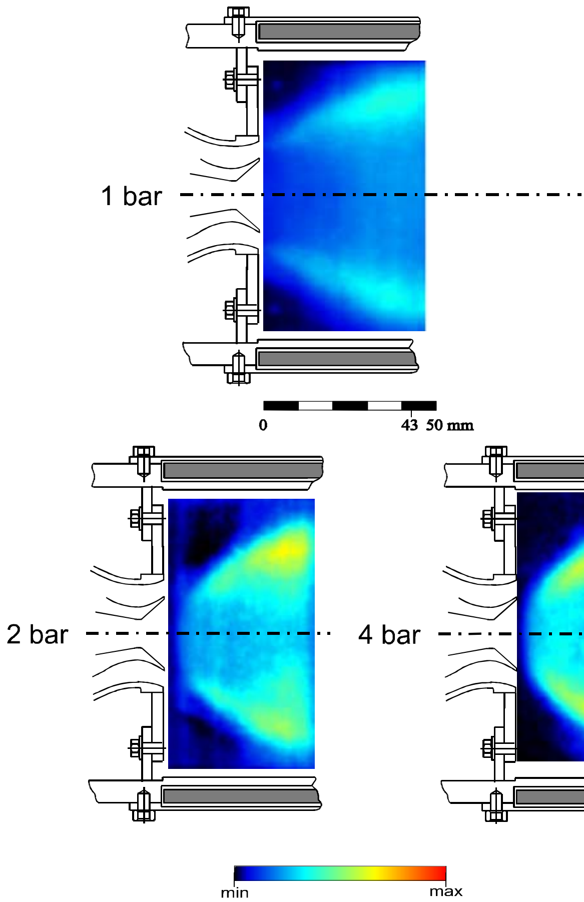

Figure 4: OH-radical distribution at different pressure levels in the center plane of the combustion chamber

The sharp concentration drop and the end of the pictures do not indicate the end of the flame but the limit of the detection window. The study only focused on the primary zone of the combustion chamber.

Distribution of NO

The used $D^2\Sigma^+ \leftarrow X^2\Pi$ transition for the detection of NO is strongly pressure dependent. The laser beam is directly absorbed by fuel fragments under pressure over 10 bar. At combustor pressure up to 2 bar a strong LIF signal was detected. But an obvious influence of the pressure was observed when increasing the combustor pressure from 2 bar to 4 bar. With higher pressure a decrease of the overall signal intensity was detected although the opposite effect was expected. To compensate for this effect a water cooled probe shown in fig. 5 was used. A line measurement was made in the same plane as the LIF signals were detected. It was ensured that the gas entered the probe directly, without being cooled or influenced by the probe itself. With the results from the probe measurements a point by point calculation of the LIF images was done. By using this procedure an overall quantification of the LIF signal became possible.

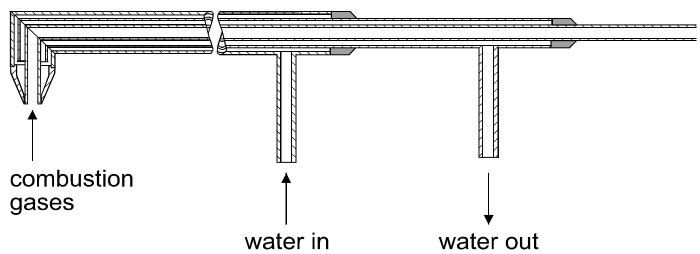

Figure 5: Sketch of the water cooled probe used for calibrating the LIF signal

The distribution of NO, obtained by LIF, is given in fig. 6. Two 208/45° filters were used to suppress unwanted scattered light and emissions. As described above and shown by Fink [12] the influence of the pressure on the LIF signal can be corrected at moderate pressures by the use of a conventional exhaust probe. Figure 6 shows a strong change of the NO formation area when raising the pressure from 1 to 2 bar. At atmospheric pressure almost the whole NO is formed in the recirculation zone. This is normally a typical indication of a diffusion type burner and not a LPP flame. At 2 bar the expected NO formation is nearly that of a LPP type burner. Most of the NO is formed at the side of the cone shaped flame and only a small rest is formed in the recirculation zone. The results of the measurement at 4 bar indicate that the NO is only formed at the shell of the cone-shaped flame. Noteworthy is the drop of the NO signal towards the end of the cone, near the sidewalls of the model combustor. This was attributed and confirmed by PIV measurements to the window cooling air that thins the NO concentration in this area.

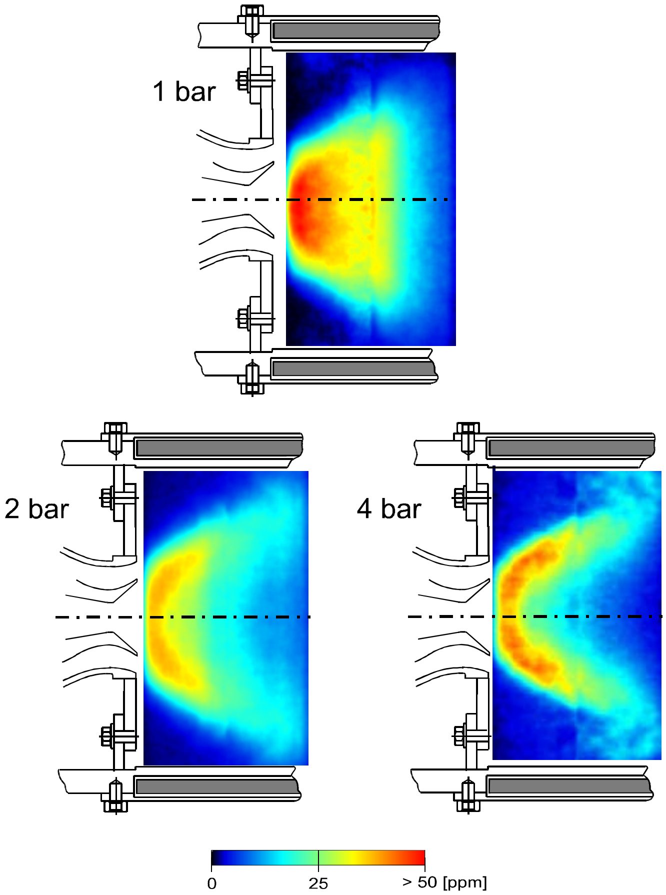

Figure 6: Corrected NO distribution at different pressure levels in the center plane of the combustion chamber

CONCLUSIONS

For the development of new combustor concepts it is important to verify theoretical results by time and space resolved measurements. LIF has proven to be a good tool for application in atmospheric flames, but the use under higher pressure conditions is not trivial. LIF applications for these conditions have been published for SI engines and spray flames. The goal of the present work was to apply the LIF technique to a LPP model combustor under semi realistic operating conditions. It was shown that a molecule selective two-dimensional detection of the major species for the LPP environment is feasible. For the detection of the NO, it was necessary to calibrate the LIF signal with the ones obtained by a water-cooled probe. Thereby, a quantification of the LIF signal was possible.

In previous experimental investigations we have shown that under ambient pressure conditions a good insight to some principle processes in the combustor reaction zone is possible. But additional experimental investigations under higher pressure levels are necessary and essential to obtain increased knowledge of the real processes which are going on under realistic aero engine operating conditions.

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