Laser Induced Fluorescence in High Pressure Cryogenic LOx/GCH$_4$ and LOx/GH$_2$ Jet Flames

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Introduction

This article deals with the application of OH planar laser induced fluorescence (PLIF) to the study of high pressure cryogenic flames. High pressure conditions require a careful choice of the excitation wavelength based on a detailed analysis of the absorption coefficient dependence with respect to pressure and temperature. The present study focuses on cryogenic methane/oxygen flames because there is current interest in the development of reusable liquid rocket engines operating with these propellants. Experiments are carried out on the Mascotte test bench of Onera. Liquid oxygen at a temperature below critical and a pressure above critical is introduced in the chamber through the central tube of a coaxial injector. Gaseous methane is injected at high speed around the liquid oxygen stream. Below 3 MPa the PLIF system provides good quality data. Above that pressure, in addition to the OH fluorescence, a non resonant fluorescence interference is detected and the corresponding signal increases rapidly with pressure. Examination of the spectrum of this interference indicates that it originates from hydrocarbon fuel fragment species convected in the fuel rich zone of the flame. A cryogenic LOx/GH$_2$ flame, free from such hydrocarbon molecules is also investigated to see if the interference occurs in that case too. It is shown in this case that OH PLIF provides good quality images up to 6.3 MPa. The resulting data can be used to examine the flame structure in the nearfield of the injector. It is known from a previous analysis [1] of the flame holding mechanism that the low speed wake established just behind the oxygen injector lip and generated by the two propellants must be thicker than the flame edge thickness to ensure a stable anchoring. PLIF images indicates that the flame thickness, especially for the LOx/GCH$_4$ flame, often exceeds the transverse wake size and it is found that the flame is quite sensitive to the high speed annular stream. On the other hand, PLIF images obtained for the LOx/GH$_2$ flame indicate that the thickness of the flame edge is of the order of the wake size and the flame is suitably anchored in the near vicinity of the oxygen tube lip.

Cryogenic combustion facility

High pressure experiments are carried out on a cryogenic model scale combustor designated as Mascotte. This facility operated by Onera and represented schematically in Fig. 1 can be used to study LOx/H$_2$ or LOx/CH$_4$ combustion (version V04). The most notable changes with respect to the previous versions of Mascotte concern the fuel feed line which was modified to allow injection of either hydrogen or methane. The flame spreads in a combustion chamber capable of withstanding pressures up to 10 MPa. The visualization module equipped with 75 mm long windows on its four sides can be placed at various axial locations along the chamber (425 mm). The quartz windows transparent to near UV radiation are cooled by a gaseous helium film. In the present experiments, the visualization module was placed against the injection plane, providing a full view of the initial flame. Interchangeable converging-diverging nozzles made of graphite define the operating pressure.

Diagnostics and processing methods

A detailed analysis of the fluorescence signal indicates that under the conditions prevailing in the present experiments, the pressure dependence of the fluorescence signal is mainly governed at high pressure by the overlap integral of the laser and absorption lineshapes while the temperature dependence is mainly controlled by the Boltzmann fraction of the molecular transition divided by $T^{1/2}$. Using the $Q_{11}(9.5)$ absorption line, one finds that the fluorescence signal becomes essentially proportional to the OH mole fraction X_{OH} with a maximum variation of about $10\,\%$ for a temperature ranging from $2000\,$K to $2500\,$K. At elevated pressure it is important to determine the collisional broadening and frequency shift of the selected absorption line to optimize the laser pumping efficiency. The set up shown in Fig. 1 includes an OH PLIF system, an optical multichannel analyzer for spectroscopic investigations and light emission imaging using an intensified CCD camera. The laser sheet used to excite the OH radical is generated by a Nd:YAG - pumped frequency doubled dye laser tuned to the $Q_{11}(9.5)$ transition of the $A^2\Sigma^+ - X^2\Pi\ (v' = 1,\ v'' = 0)$. The typical pulse energy in the UV around $284\,$nm is $42\,$mJ with a duration of $10\,$ns. The typical laser bandwidth FWHM is $0.15\,\text{cm}^{-1}$. Sheet dimensions are approximatively $41\,$mm by $500\,\mu$m to keep clear of the gaussian wings of the laser beam distribution.

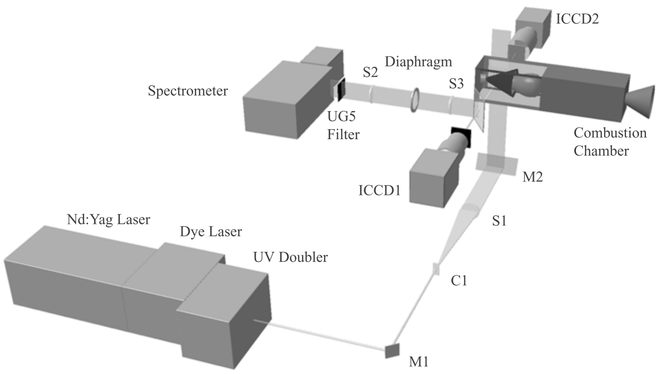

Figure 1: Schematic representation of the experimental setup.

The fluorescence signal is collected by a Princeton Instrument $5\,$MHz ICCD camera with a $120\,\mu$m resolution (close up on the injector nearfield) at a rate of $10\,$Hz. Exposure time is fixed at a value of $50\,$ns. The intensifier is used to gate the fluorescence signal to achieve a higher signal to noise ratio. Light is collected by a UV Nikkor $105\,\text{mm}/f\ 4.5$ objective. Various combinations of glass filters and interference band pass filters were used to optimize the OH fluorescence collection efficiency while minimizing transmission of elastically scattered laser light from the liquid oxygen jet and fluorescence interference signal. The ICCD camera is fitted with two WG305 filters to block (1) The elastic scattering from the incident beam (2) The liquid Raman signal at $295\,$nm. A 308BP15 band pass filter with a FWHM of $15\,$nm and a peak transmission of $25\,\%$ at $308\,$nm is used to transmit fluorescence from the $A - X\ (1, 1)$

and $A - X\ (0,0)$ vibrational bands $(306\ -\ 320\,\mathrm{nm})$. Spontaneous light emission of OH* and CH* radicals is recorded at a rate of $10\,\mathrm{Hz}$ with a Princeton Instrument $5\,\mathrm{MHz}$ ICCD camera with a resolution of $200\,\mu\mathrm{m}$. Light emission is recorded along the line of sight during $1\,\mu\mathrm{s}$. The camera is equipped with a UV Nikkor $105\,\mathrm{mm}/f\ 4.5$ objective fitted with adapted glass filters. OH* or CH* emission measurement is delayed by $1\,\mu\mathrm{s}$ to eliminate any fluorescence signals.

High pressure OH PLIF imaging

The main hot fire test parameters are displayed in Fig. 2. Several intermediate pressure conditions can be considered. In the first case, the chamber pressure is below the critical pressure of oxygen ($p_c = 5.04\,\mathrm{MPa}$) and the injected liquid stream undergoes a classical cascade of processes associated with break-up, atomization, vaporization and combustion mainly controlled by the gas to liquid momentum flux ratio J. As the pressure exceeds the critical pressure of the oxygen, the liquid jet undergoes a transcritical change of state. Under these conditions, the flame structure is controlled by the ratio of mass transfer from the liquid oxygen rather then by break-up and atomization [2].

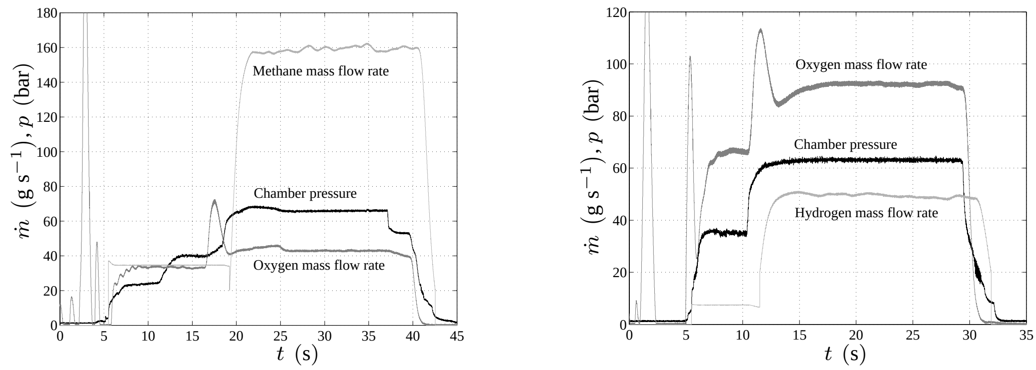

Figure 2: Injection parameters for operating point imaged. Left: LOx/GCH_4. Right: LOx/GH_2.

The cryogenic LOx/GCH_4 flame structure is first investigated. Typical distributions of OH fluorescence intensity are displayed in Fig. 3. For pressure below $2.5\,\mathrm{MPa}$ the signal to noise ratio is sufficient and well defined PLIF images are obtained. As the optical depth in the medium increases with pressure, the laser beam is partially attenuated by the OH absorption before being totally distorded by the high density liquid oxygen jet. As the pressure increases beyond $3.2\,\mathrm{MPa}$, an interference signal arises (Fig. 3) in the fuel rich zones close to the methane gaseous stream. The intensity of the interference signal is of the order of the OH fluorescence signal. Both the low fluence and the shape of the fluorescence spectra are inconsistent with laser induced incandescence of soot particles [3]. Major combustion species such as CH_4, CO, CO_2, H_2O, or H_2 do not absorb significantly at this wavelength. It is shown from some previous experiments that fluorescence of PAH may occur in hydrocarbon/air diffusion flames. This is observed under low power excitation near $283.5\,\mathrm{nm}$ [4]. A comparison between PLIF data for LOx/GCH_4 and LOx/GH_2 supports the view that the parasitic signal observed at high pressure is related to the presence of intermediate hydrocarbon species. This is clearly demonstrated by high pressure LOx/GH_2 experiments. At operating pressure of up to $6.3\,\mathrm{MPa}$ the signal to noise ratio is still acceptable (Fig. 4). The OH fluorescence signal is clearly detected without interference. An examination of the instantaneous OH PLIF images recorded in this case indicates that the flame spreads in a standard way. It begins as a thin layer and rapidly features wrinkles and pockets. The flame edge is close to the oxygen injector lip and begins at various locations on the downstream side of this unit.

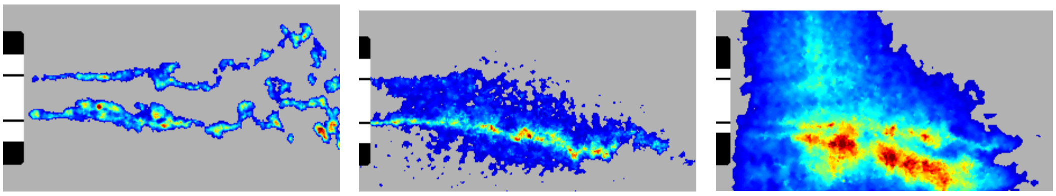

Figure 3: OH PLIF images of LOx/GCH_4 cryogenic jet flame in the injector nearfield. Left: $p = 1.5$ MPa, Center: $p = 2.5$ MPa, Right: $p = 3.2$ MPa.

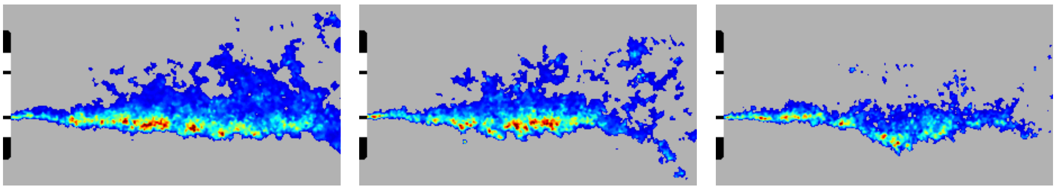

Figure 4: OH PLIF images of LOx/GH_2 cryogenic jet flame in the injector nearfield recorded during the high pressure stage, $p = 6.3$ MPa. The image ends at 8 d_{LOx} from the injection plane.

Conclusion

It is shown in this article that high quality laser induced fluorescence images may be obtained up to 6.3 MPa for a cryogenic flame free from PAH. Indeed, as hydrocarbon (methane) is used, fluorescence from PAH generated by fuel oxidation at high pressure interferes with OH fluorescence. The laser beam is absorbed by PAH limiting the application of fluorescence at pressure below 3.5 MPa. OH PLIF instantaneous images can be used to verify the stability criterion defined by the thickness and the position of the flame edge behind the oxygen injector lip. Instantaneous emission images (OH^* and CH^*) can be averaged and Abel transformed to analyze the mean flame structure.

Acknowledgements

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