Experimental Studies on Atomization, Vaporization and Combustion for Liquid Rocket Propulsion

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Abstract

The M3 micro-combustor is a test facility for basic investigations of cryogenic oxygen gaseous hydrogen (LOX/GH2) rocket propulsion. The model combustor is operated at pressures up to 2 MPa and has full optical access to study the LOX-spray combustion phenomena with non intrusive optical diagnostic techniques in detail. Oxygen and hydrogen are injected at 77 K through a single coxial injection element. The phenomenology of jet break up has been investigated with flashlamp photography to determine the distribution of the liquid phase. Information of the location and structure of the flame front has been extracted from the spatial distribution of spontaneous emission of the OH radical and the laser induced fluorescence of OH.

Introduction

The application of optical diagnostic techniques, especially laser-based diagnostic techniques to flames and complex combustion phenomena has become commonplace(1-3). Nonintrusive measurements of temperature, species, velocities and drop field distributions provide a lot of detailed insight into the combustion phenomena. These significant advances have led to a growing number of studies addressing combustion environments typical of rocket engines(4-8). Experiments in model rocket combustor chambers at high pressure offer an attractive environment for the application of laser based diagnostics, however there are also a lot of disadvantages to conduct such studies. Due to this fact the application of laser-based diagnostics to high pressure combustion environments has been limited (9,10). One difficulty in performing rocket-like combustion studies involve facilities and safety. Rocket combustion chambers require high flow rates of hydrogen/oxygen propellants. This requires serious handling and safety concerns which usually require excellent facility development and remote operation capabilities. Furthermore the rocket injector spray is characterized by two-phase flows, high temperatures, pressures, velocities and number densities demanding stringent requiremnets for the applied measurement instruments.

The aims of the experiments presented here are twofold. First we are interested in developing and testing the performance of optical diagnostic techniques for the application in reactive two-phase flows at high pressures. Second, the investigations are part of a series of experiments to characterize the phenomenology of jet atomization, vaporization, mixing, and combustion. The development of computational fluid dynamics (CFD) models is creating a need for sufficiently detailed experimental studies to allow for model validation. Our effort concentrates on the development of such validation data sets using experimental geometries which provide extensive measurement capability.

We therefore have applied flash lamp photography to investigate the phenomenology of jet breakup and to determine the liquid phase distribution. Both spontaneous OH emission and laser induced OH fluorescence provide information on the evolving flame structure under rocket-like conditions.

Experimental

Test Facility: The Micro Combustor

The Micro-Combustor shown in figure 1 has been described in detail in (11), so only a brief description is given in this paper. The combustion chamber has a length of 140 mm and a cross sectional area of 60x60 mm^2 with optical access from all four sides to permit all optical diagnostic methods mentioned above. The fluid supply lines, flow meters, and valves are palced in a liquid nitrogen (LN_2) bath to reach propellant temperatures similar to real rocket engine conditions. The geometry of the single injector element has been designed with respect to the geometry of the HM7B injector type. The LOX tube of the injector has a length of 40 mm, an inner diameter of 1.2 mm and an outer diameter of 2.0 mm. From the chosen mixing rate, chamber pressure and nozzle diameter the mass flow rates of LOX and GH_2 can be calculated. Typical ranges of the injection velocities are from 15 m/s to 50 m/s for LOX and from 200 m/s to 600 m/s for gaseous hydrogen.

Due to the high temperatures and large heat transfer to the uncooled windows the test duration time is limited. With the single injector element and chamber pressures up to 1.0 MPa a test duration time of one second can be achieved. Various tests have been performed and show that the system allows constant operating conditions for at least one second. Due to the short burning duration it is necessary to reach a stationary state (in comparison to the time scale of the injection) within 50 ms. Two fast pneumatic drives for the hydrogen and oxygen valves have been developed to reach an opening time of less than 5 ms.

The experiments discussed in this paper were done at combustion chamber pressures of 0.14 MPa, 0.6 MPa and 1.0 MPa. Typical operating conditions of the micro combustor can be find in table 1.

Operating conditions	Micro-Combustor	HM7
max..pressure MPa	**2.0**	**3.2**
mass flow rate kg/s	**0.064**	**0.154**
H_2 inj. temperature K	**77**	**≅130**
O_2 inj. temperature K	**77**	**≅90**
density ratio $\rho(0_2)/\rho(H_2)$	**180**	**162**
gas density in chamber kg/m^3	**0.5**	**1.3**
velocity difference m/s	**180-400**	**255**
aerodynamic Weber number $We_g = d_i \cdot \rho_g \cdot v_g^2 / \sigma_{O2}$	**3.8 10^3**	**12 10^5**
mixture ratio $\dot{m}_{O2} / \dot{m}_{H2}$	**1.0 12.0**	**5.1**

Table1:

Principle operating conditions and similarity numbers, calculated for v_{LOX}=40 m/s, v_{H2}=400 m/s and P_C= 1MPa

Optical Diagnostics

As an important tool for the visualization of the atomization phenomena during combustion the flash light photography in a shadowgraph set up was used. Utilizing high energy spark flash lamp with a pulse width of 300 ns the fast motion of the droplets and flow structures can be freezed. The images were recorded with a Hasselblad 6x6 cm^2 camera with a 100 ASA film was used to study these phenomena. We use a 120 mm lens and a bellow extension for the camera which results in a magnification factor of two. With this set up droplets with diameters down to 80 µm can be observed(11). A disadvantage of using a film camera is that only one single image can be recorded during one single run of the experiment. Using a standard video camera repetition rates of 25 frames per second can be achieved.

The planar laser-induced fluorescence and OH emission measurements have been performed with an UV Diagnostic System. This system has also been described before (10) so that we concentrate only on the relevant part of the system. This system consists of an injection-locked narrowband, tunable excimer laser, two intensified CCD cameras, beam shaping ultraviolet transmitting optics and electronic components to drive the whole system automatically.

The excimer laser consists of a separate oscillator and amplifier part. It yields tunable radiation between 248 nm and 249 nm (KrF operation) with an energy of 250 mJ/pulse and a bandwidth of 0.4 cm^{-1}. The pulse duration is 20 ns which is essentially instantaneous in comparison to the combustion time scale.

Prior to the rocket experiments, the laser system was tuned to the particular OH-radical absorption of interest using a propane fueled bunsen burner flame. The OH-radical fluorescence from the flame was imaged at 90° to the laser beam onto an intensified CCD camera. The wavelength of interest was then tuned by maximizing the fluorescence signal.

For the two-dimensional OH LIF images the laser was formed into a sheet of 35 mm x 0.2 mm using a combination of a spherical and a cylindrical lens. For reasons explained below the laser was tuned to the P1(9) or to the Q2(10) absorption line whereas for recording the spontaneous OH emission images the laser beam has been blocked. The main aim of the laser induced fluorescence study was to visualize the loaction and flame structure qualitatively. Because of this fact no attempt has been made in the present experiments to place the OH-radical concentrations on an absolute basis which would require complementary temperature and species measurements. The qualitatively measured OH species concentrations have been representated in the pictures in a false colour scale.

The intensified CCD camera was placed at right angles to the laser sheet and detect the emission light intensity. For the induced fluorescence images a combination of a 20 mm long-pass liquid butyl acetat filter and four dielectrical bandpass filters centered at 297 nm are put in front of the CCD camera, for the OH emission images we used an interferential bandpass filter centered at 308 ± 15 nm and an UG11 Schott glass filter. The gate time of the intensifier is always set to 100 ns for the induced fluorescence measurements and to 10 μs for the spontaneous OH emission images.

Results

Figure 2 and 3 show spark flash lamp images of the liquid oxygen jet 0-70 mm downstream the injector for combustion chamber pressures of 0.7MPa and 0.14MPa, respectively. The flow direction is always from left to right. Due to the high velocity of the liquid oxygen of about 43m/s the atomization is poor. The jet is very confined to the central axis. The large combustion chamber and the low flow rate from one single injector element leads to a calculated average flow velocity in the chamber of about 39 m/s. The higher gas density and pressure leads to fine droplets close to the jet. The atomization process for a combustion chamber pressure of 0.14MPa differs remarkably from that of 0.7MPa. Large droplets and thick ligaments of liquid oxygen are observable. 70mm downstream the injector the liquid jet has been disintegrated and ligaments pointing in backward direction can be observed. With the decreased pressure the calculated average flow velocity in the chamber increased to 190 m/s.

Applying laser induced fluorescence in high pressure, two-phase combustion systems may lead to fluorescence interferences of the OH signal with O_2 transitions, beam attenuation due to high OH number density and strong Mie scattering and stray light problems from the liquid oxygen core. These problems have been overcome by the following steps:

The beam attenuation problem is much reduced when using the excitation of the OH A $^2\Sigma$ (v'=3) <- X $^2\Pi$ (v''=0) transition, because no self-absorbing states are excited. The KrF excimer laser is ideally suited for this OH transition leading to no or very reduced attenuation(12). The Mie scattering caused by the liquid oxygen core can be strongly reduced by effective filtering with the butyl acetat filter having a steep cut-off at 248 nm and small bandwidth detection of the OH fluorescence with the dielectrical filters. In this way effective stray light suppression (rejection ratio better than 10^{-10}) is additionally achieved.

To reduce interferential effects arising from O_2 fluorescence with increasing chamber pressures we have calculated the OH and O_2 absorption spectra to locate wavelength ranges of interferential free regions. Pressure dependent dispersed laser induced OH fluorescence spectra recorded within the combustion chamber show that the Q2(10) absorption line is well suited for OH PLIF imaging for chamber pressures up to 10 bar.

Figure 4 and figure 5 show typical PLIF images measured at a combustion chamber pressure of 0.12 MPa and 0.7 MPa, respectively. All PLIPF images have been obtained with a fixed field of view of 16 mm (V) x 25 mm (H), the injector is located at X=0 mm, Y=0 mm, the flow direction for all images is from left to right.

With this technique it is possible identify the location and distribution of the flame front and the spatial structures in dependence of the chamber pressure. It can be seen that the OH intensity, and therefore the flame zone, is generally confined to a narrow region along the combustion chamber axis. A thin flame expands near the injector more or less rapidly depending on the operating pressure.

Downstream the flame gets thicker and wrinkled. The high turbulence associated with the spray is reflected by the convoluted flame zone. Due to high stretch forces the flame may extinguish locally whereas at other locations there are zones of very high OH signal.

The PLIPF signal intensity is generally higher in the upper half of the combustion chamber because of strong attenuation of the laser sheet scattered by the dense liquid oxygen core in all directions. Travelling a long way through the dense spray this effect will be much enhanced.

From this image we observe that the flame zone along the combustion chamber does not sit directly on the liquid oxygen core, but is well seperated from it. We have made a lot of effort to enhance the LIF signal at that location. We applied smaller laser sheets to reach a higher energy density and enhancing the laser energy itself but it was not possible to detect a significant fluorescence signal directly at the injector. This is no stringent hint that there is a lift-off of the flame. The burning zone at that location consist of a very thin OH cone leading to very low OH fluorescence intensity. In a similar model rocket chamber study there was no indication of a flame zone lift-off(13). Results from our spontaneous OH emission images described below

For higher pressure conditions the spray angle decreases, the flame is much more confined to the center line and continues to burn near the surface of the liquid oxygen core. For the higher pressure cases the flame burns more effectively further downstream leading to high OH fluorescence spreading over locally expanded regions which come in close connection to the liquid oxygen. From these images it is not possible to decide whether the flame zone is in direct contact to the liquid oxygen cone. Simultaneously recorded laser induced OH fluorescence in combination with elastic laser scattering of the liquid oxygen core would give valuable information about this process.

Averaged images integrated over 50 laser shots which we have also measured show the global structure of a confined flame zone lying close to the liquid core as has already been observed from instantaneous images. Any turbulent structure is smoothed out due to the temporal integration process. Neither from instantaneous nor from the averaged images it is not unambigiously clear whether the flame is anchored directly at the outlet of the LOX injector due to the very small OH signal at that location showing that was impossible to detect a significant OH signal even with averadged LIF measurements.

Spontaneous OH emission images yield temporally and spatially averaged information of the flame zone structure and location due to a line-of-sight integration process. Due to this integration process it is to be expected to collect more fluorescence signal in the vicinity of the injector. Figure 6 shows the spontaneous OH emission image at a combustion chamber pressure of 0.6 MPa. This image clearly demonstrate that there is OH signal directly at the exit plane indicating that the flame begins at the lip of the injector. Although spontaneous

OH emission is a simple and easy to apply optical technique this demonstrates its capabilities for visualizing highly turbulent flowfields and complex combustion phenomena. However we have to keep in mind that the spontaneous emission technique detects electronically excited OH radical (caused by chemiluminescent reactive formation in the upper A $^2\Sigma^+$ state), whereas LIF detects ground state OH radicals. This different probing technique leads to different detected OH radical distributions clearly visible by comparing the LIF and the spontaneous OH emission images.

A surprising feature of the PLIPF images is that near the injector on the centerline, the signal is not zero. In the middle of the liquid oxygen jet there cannot be any OH fluorescence, and elastic scattering has been suppressed. The signal may be a shifted emission from the liquid oxygen, either induced Raman scattering and thus only partially blocked, or fluorescence from impurities in the liquid oxygen. In any event it indicates the presence of the dense liquid. The origin of this signal has to be analyzed in a forthcoming study.

Summary

We have applied different optical diagnostic techniques to a model rocket combustor operating at high chamber pressures. Preliminary results with respect of liquid jet breakup and OH radical fields have been reported. These results have demonstrated that the optical diagnostic technique especially the laser based diagnostics can be effectively applied for measurements for uni-element rocket chamber geometries.

Spark flash lamp measurements show that the liquid jet breakup process is much different at a combustion chamber pressure of 0.14 MPa than at higher pressures. The comparison of the flash lamp photos shows, that the velocity of about 40 m/s for the liquid oxygen is to high for complete atomization in this chamber, even with a high gas velocity of about 600 m/s. Higher chamber pressures and gas densities lead to smaller droplets in this case. In the low pressure case the atomization produces large droplets and thick ligaments of liquid pointing in backward direction.There is indication that the large droplets are able to cross the thin combustion region under these low pressure conditions. With higher pressure this phenomen was not observable from the spark flash photographs. An injector head with more injector elements will cause a higher mass flow rate which will lead to a higher flow velocity and gas density in the chamber. This would result in a better atomization.

OH LIF and spontaneous OH emission were used to qualitatively characterize the reaction zone in terms of its extent and structure. LIF yields temporally and spatially resolved images revealing the highly turbulent character of the flame zone. Spontaenous OH emission images yield valuable information about the global structure of the reaction zone, however the images are not resolved in time and space due to the line-of-sight integration process. The measurements generally indicate that the structure of the unsteady flowfield is directly related in the combustion zone flame structure.

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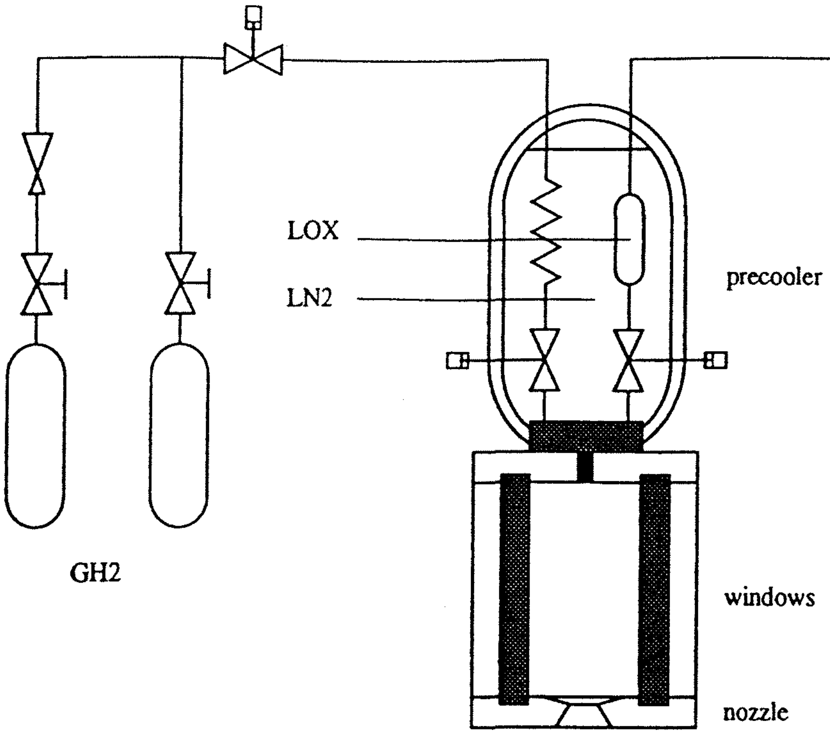

Figure 1: Sketch of the supply system and the combustion chamber

Figure 2 Liquid oxygen jet p=0.7 MPa, v=43 m/s, x=0-70mm

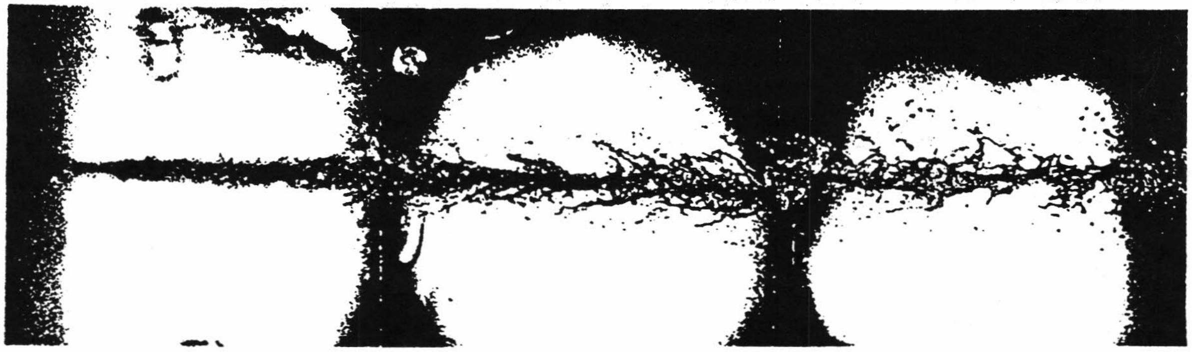

Figure 3 Liquid oxygen jet p=0.14 MPa, v=18 m/s, x=0-70 mm

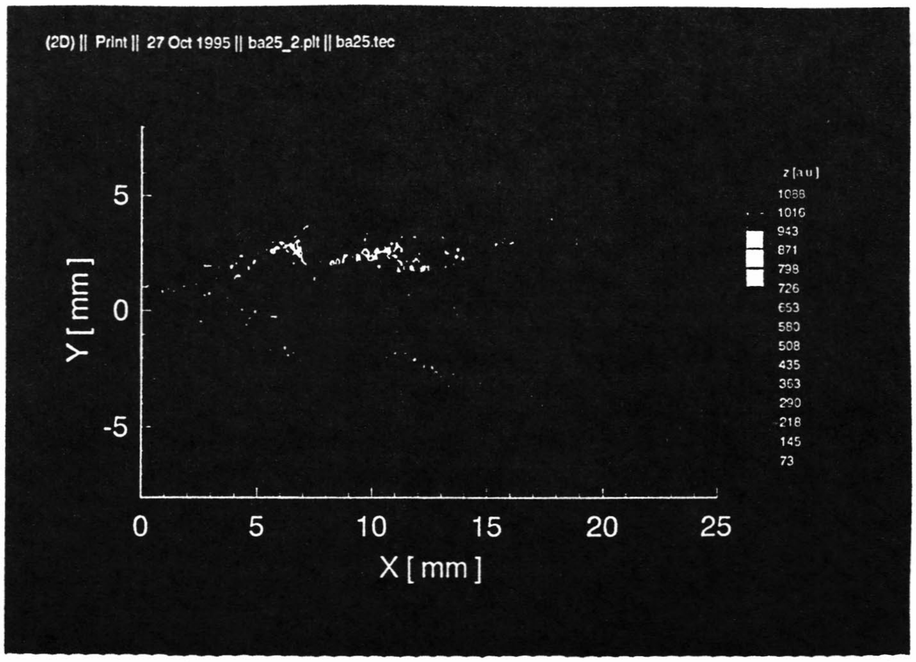

Figure 4 Single shot OH PLIF image p=0.14 MPa

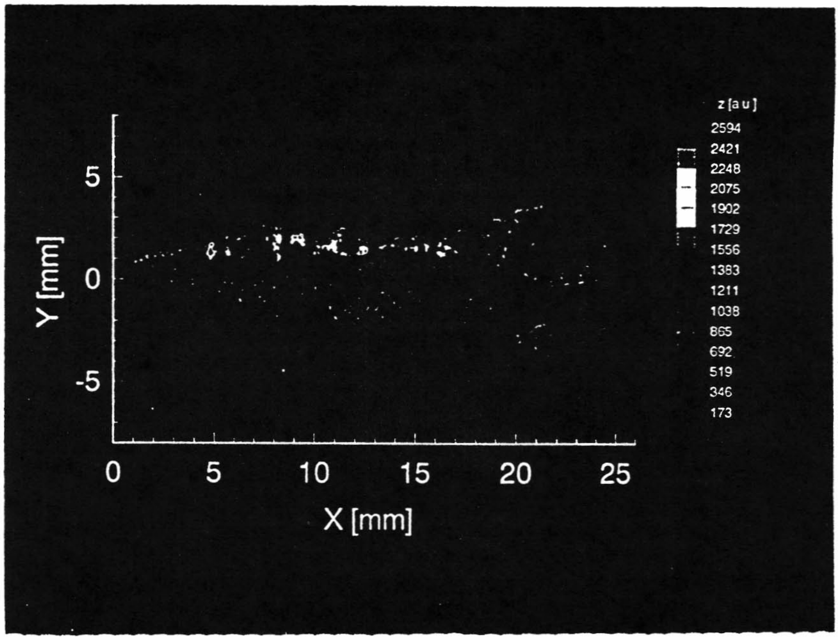

Figure 5 Single shot OH PLIF image p=0.7 MPa

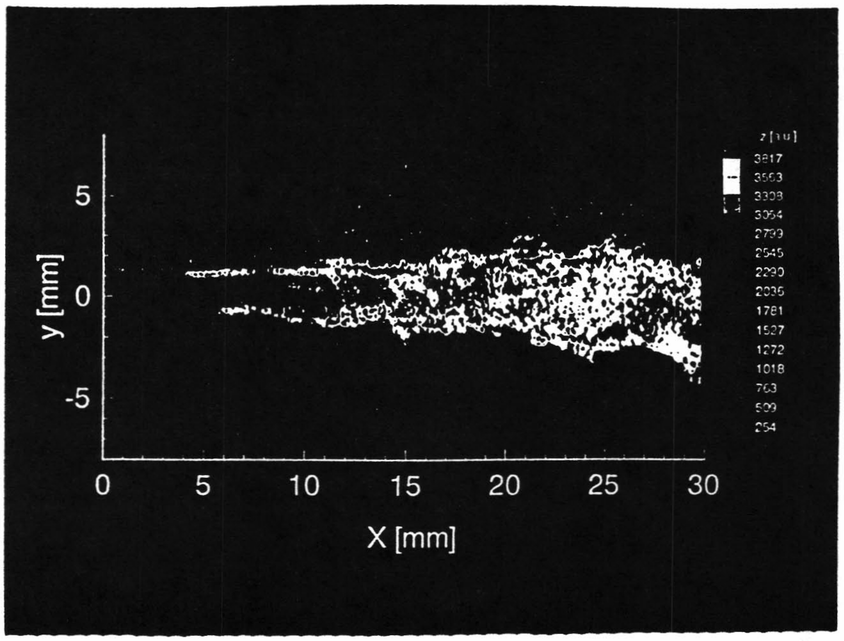

Figure 6 Spontaneous OH emission image p=0.7 MPa