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Simultaneous Observation of Liquid Phase Distribution and Flame Front Evolution during the Ignition Transient of a LOX/GH_2-combustor

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***Abstract*:** Phenomena such as flame propagation, flame/spray interaction and flame stabilization during the transient ignition process in a cryogenic model rocket combustor are investigated on sub-millisecond time scale. Diagnostic techniques developed to characterize the stationary spray flame are applied to investigate the transient evolution of the LOX-spray and the flame front during the ignition process. Ignition is initiated by focusing a pulsed laser into the combustion chamber. Thus, ignition time as well as the position of ignition is well defined. This and the exact control of the delay between ignition and detection time allowed the observation of the evolution of the flame front. The distribution of the liquid oxygen phase and the velocity of LOX droplets and ligaments are determined by light sheet techniques using a double-pulsed laser system. Simultaneously the position of the flame front is measured by recording the spontaneous emission of the OH-radical. By varying the delay time t between ignition and detection in a series of test runs, the transient ignition phenomena has been investigated in the interval from 0 to 5 ms after ignition.

***Keywords*:** cryogenic, rocket engine, laser ignition, spontaneous emission, laser light sheet.

***Nomenclature*:**

d	diameter of the LOX post
I	intensity of OH emission
$\dot{m}$	mass flow
p	pressure
v	injection velocity
r	density
t	delay time
n	viscosity

Subscripts

c	conditions in the combustion chamber
O_2	(liquid) oxygen
H_2	hydrogen
of	oxydator-fuel (in relations)
fo	fuel-oxydator (in relations)

1. Introduction

An essential feature of the Ariane 5 rocket is its ability to carry two satellites in one launch into orbit. The payload of Ariane 5 today is 6.5 t and will be increased to 11 t by 2005, which will mainly be achieved by the use of a new cryogenic LOX/LH$_2$ driven upper-stage engine. Positioning two satellites into orbit requires the upper-stage engine to be re-ignitable. The need for guaranteed reliability and minimised energy consumption for ignition motivates the investigation of the ignition process of LOX/GH$_2$-spray flames.

During the last year stationary burning LOX/GH$_2$-sprays have been investigated by several diagnostic methods, yielding information on the LOX-jet disintegration process at sub- and supercritical pressures (Vogel, 1994; Mayer and Tamura, 1995), injector/injector interaction (Haidn et al., 1998), the flow field (Sender et al., 1997; Pal et al., 1993), the temperature distribution in the burning spray (Clauβ et al., 1999; Smirnov et al., 2000) and the structure and position of the flame front (Brummund et al., 1995; Tripathi et al., 1999).

First investigations of the transient sprays behaviour of the LOX-jet disintegration during the ignition phase have been done by Mayer et al. (1998). Based on the observed disappearance of tiny droplets and the change of the spray phenomenology the upstream movement of the flame during the stabilization process could be recorded. However, the experiments suffered from the fact that the ignition time of the spray ignited by a pilot flame was not reproducible on millisecond timescale. Thus, the necessary synchronization with the high-speed film camera was difficult.

The use of a pulsed laser for flame ignition allows adjusting the ignition time and placing with high accuracy. Thus, a synchronization of other events, like the detection of temporal resolved flame emission by an intensified CCD camera or the detection of droplets illuminated by a pulsed laser, can easily be realized. The use of laser radiation to initiate combustion events in reactive gaseous mixtures has been the subject of investigations in several laboratories (Forch and Miziolek, 1985), (Hurlbert and Moreland, 1995). For the tests under discussion ignition by non-resonant spark formation is used (Syage et al., 1988; Weinberg and Wilson, 1971). This study reports first results of recent laser-ignition tests in the micro-combustor, a LOX/GH$_2$ combustion chamber at DLR Lampoldshausen. For a typical injection condition, flame propagation and LOX-phase distribution has been determined for various times after the ignition time. Transient spray evolution, flame propagation, the interaction of the combustion process with the LOX-spray and flame stabilization on sub-millisecond time scale has been investigated.

2. Experimental Set-up

2.1 Micro-combustion Chamber

The M3 test site is a versatile experimental set-up for basic investigations of LOX/GH$_2$-Spray combustion. Inner dimensions of the micro-combustor are 60 mm × 60 mm in cross section and 140 mm in length, which implies a larger aspect ratio of injection to combustion chamber area than in real liquid rocket engines. Small slit windows are inserted at top and bottom panels to allow for laser light sheet applications; both side panels are equipped with quartz glass windows for optical access to the entire combustion chamber. For details see Vogel (1994) and Oschwald et al. (1996).

2.2 Optical Set-up

The optical set-up includes several components: the optical arrangement for the ignition laser, the PIV system consisting of a pulsed laser system and a digital camera for liquid phase observation and the intensified CCD camera for the observation of flame emission (See Fig. 1).

For these tests ignition by non-resonant spark formation is used. The ignition energy is delivered by a single laser pulse of a Q-switched Nd:YAG-laser with wavelength of 532 nm, pulse length of about 10 ns and pulse energies of about 200 mJ. With this method, it is possible to control both ignition time and location.

In order to record the liquid phase distribution a light sheet is formed using a double pulsed Nd:YAG laser at λ = 532 nm with energies of 250 mJ per pulse for each laser. The light sheet enters the combustion chamber through the window in the bottom panel. The light sheet dimensions are 0.5 mm of thickness and about 5 cm of width. The light scattered from the LOX droplets was recorded with a digital PIV camera (PCO Sensicam), which is able to make two separate images in short times.

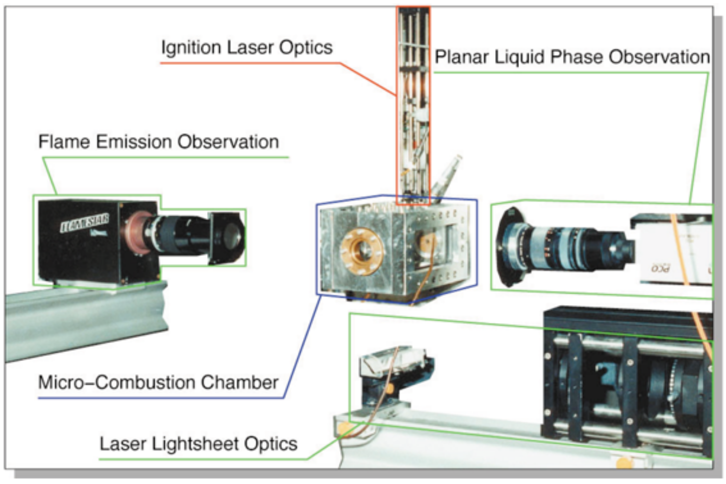

Fig. 1. Experimental set-up showing micro-combustion chamber PIV optic, and camera set-up.

The flame front in O_2/H_2 flames is determined by the emission of the OH radical in the $A^2\Sigma^+$-$X^2\Pi$-system around λ = 310 nm. The OH emission is detected by a gated intensified CCD camera (LaVision Flamestar). The gating time is 10 μs permitting the recording of the flame front between the two PIV laser pulses, which have a temporal separation of 13 μs (See Fig. 3). Thus, data on liquid phase distribution flow field and flame front has been taken quasi-simultaneously. To suppress light from sources other than the OH radical, an optical filter (λ = 309.9 nm, band width = 7.5 nm) is used. Both camera systems record the same areas of interest (36 mm × 24 mm). Two adjacent imaging areas in two test series have been observed, first starting directly attached to the injector face-plate and the other area starting at 36 mm downstream the injector (See Fig. 2).

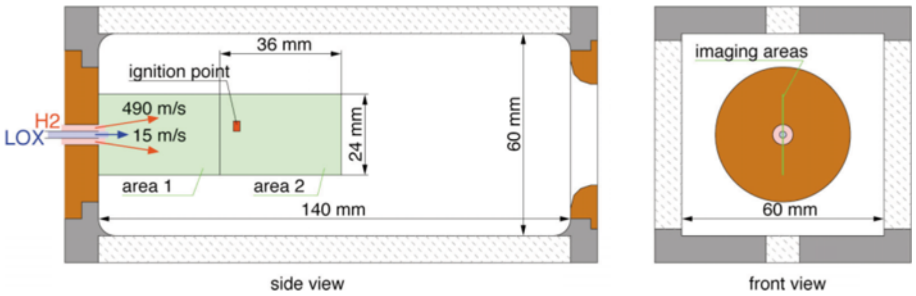

Fig. 2. Combustion chamber schematic sketch showing observation areas.

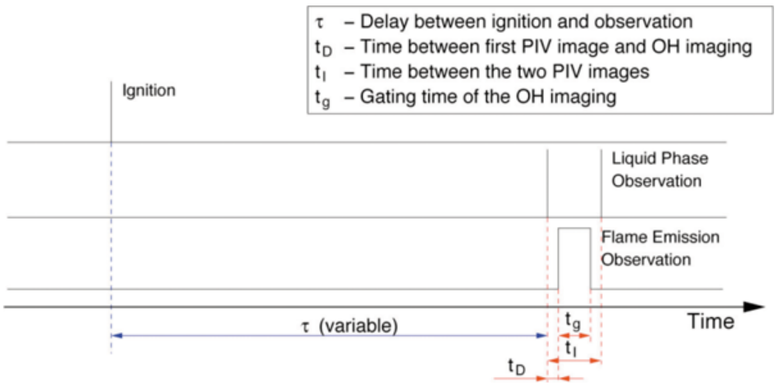

Fig. 3. Timing diagram of image acquisition time τ in relation to the ignition time.

2.3 Timing and Synchronization

The limited data acquisition rate of the PIV system as well as the intensified CCD camera used for OH-imaging allows the recording of data only once during the transient ignition sequence at a specified delay after the ignition laser was fired. The transient phenomenology has been investigated by repeated firing of the experiment and varying the delay t between ignition and detection. For external synchronization of the test bench, the ignition system and the observation systems two digital delay generators have been used (See Fig. 3). With this method a maximum jitter < 100 ns is achieved. Using the system clock of the Trigger Control Unit (TCU) of the PIV system as the master clock for all systems, the test bench computer starts the test sequence and gates the PIV and the ignition laser systems. Varying the delay between the PIV system, the ignition laser and the test bench allows the adjusting of the delay in a range of $t = -5$ ms ... 5 ms relative to the ignition laser. Two images of the liquid phase distribution have been taken with a delay of 13 ms to allow the determination of LOX droplet velocities. Within this time interval an image of the flame emission is recorded using the Flamestar system.

2.4 Combustion Chamber Conditions

Experiments at one specific operating condition have been performed. The parameters were calculated for stationary injection conditions reached after 5 ms (Vogel, 1994). These are the combustion chamber pressure with $p_c = 0.15$ MPa, mass flow and velocity of LOX with $\dot{m}_{O_2} = 36$ g/s and $v_{O_2} = 27$ m/s and of H$_2$ with $\dot{m}_{H_2} = 8$ g/s and $v_{H_2} = 491$ m/s. The propellants are injected into the combustion chamber at a temperature of 85K. The flow conditions and typical non-dimensional parameters are listed below.

Weber number	$We = r_{H_2} \cdot (v_{H_2} - v_{O_2})^2 d_{O_2} / s_{O_2}$	$= 8.22 \cdot 10^3$,
Reynolds number	$Re_{O_2} = (r \cdot v \cdot d)/v$	$= 2.79 \cdot 10^5$,
momentum ratio	$J = (rv^2)_{H_2} / (rv^2)_{O_2}$	$= 0.119$,
mixture ratio	$r_{fo} = (m_{O_2})/(m_{H_2})$	$= 4.0$,
velocity ratio	$V_{fo} = v_{H_2}/v_{O_2}$	$= 18.2$.

The ignition was initiated 20 ms after opening the main valves, when stationary cold flow conditions inside the combustion chamber were reached.

3. Results

3.1 Flame Emission

The evolution of the flame front during the ignition transient can be seen in Fig. 6. The OH emission intensity is plotted in a false colour representation in the upper half of the images. Note that the OH emission intensity is shown on a logarithmic scale.

The beginning of the ignition process is characterized by a slow increase in OH emission intensity. The small ignition kernel from laser ignition extends with small growth rates. The flame front moves slowly in downstream direction. After about 500 ms, the situation changes dramatically, the flame spreads suddenly all over the combustor volume. The intensity increases rapidly to a value more than 10 times higher than during the primary ignition period. After abound 1 ms the intensity of the flame emission decreases to intensities similar to the ones at the beginning. After about 5 ms the flame stabilizes to stationary hot fire conditions, is anchored at the LOX post and fully enfolds the liquid oxygen spray.

3.2 Liquid Phase Distribution

The distribution of the liquid phase is shown in the lower half of the images in Fig. 6. Regions still not burning are characterized by a mist of tiny droplets that could not be resolved with the CCD camera. In the regions with flame, the LOX mist is completely vaporized, and bigger ligaments and LOX droplets become visible. With increasing combustion chamber pressure p_c during the explosive phase the fluid is jammed forming a helix-like shape near the injector (See Fig. 6, middle images). Further downstream, the LOX jet is disrupted leading to isolated lumps of fluid when the maximum pressure is reached. In the period of flame stabilization, a continuous LOX spray is forming again and the typical pattern of coaxial injection is seen (Sender et al., 1997).

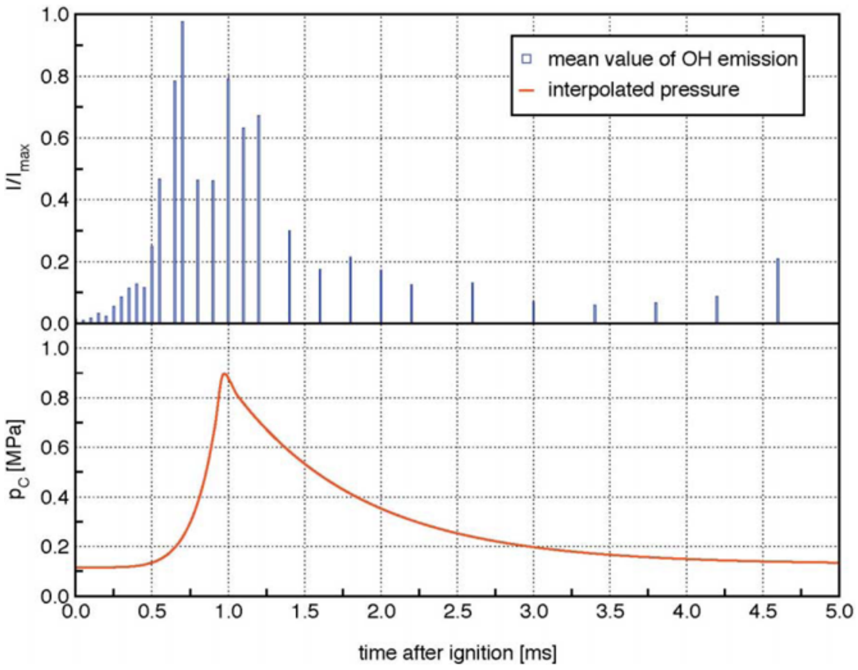

Fig. 4. Mean value of OH emission intensities, I, scaled with the highest intensity from all tests, I_{max}, (integration time 10 μs) and interpolated combustion chamber pressure, p_C, in time interval from 0 to 5 ms.

3.3 LOX Velocities

Imaging of liquid phase at two different times allows the determination of LOX droplet and ligament velocities. During the beginning of the ignition, these droplets aren't visible due to LOX mist. At the time when the flame emission increases dramatically, there is a significant lateral velocity component, so most of the droplets leave the light sheet during the time between the two laser pulses. Therefore, velocities can only be obtained during the period of flame stabilization where the fluctuations in the flow field decreases again. Figure 5 shows an example of velocity distribution at 45 mm downstream the injector varying with time. 1.8 ms after ignition, the velocities are around 80 m/s. The velocity decreases reaching after about 2.5 ms a value near the calculated injection velocity of 27 m/s. The velocities near the injector axis are slightly higher than in the outer regions of the spray.

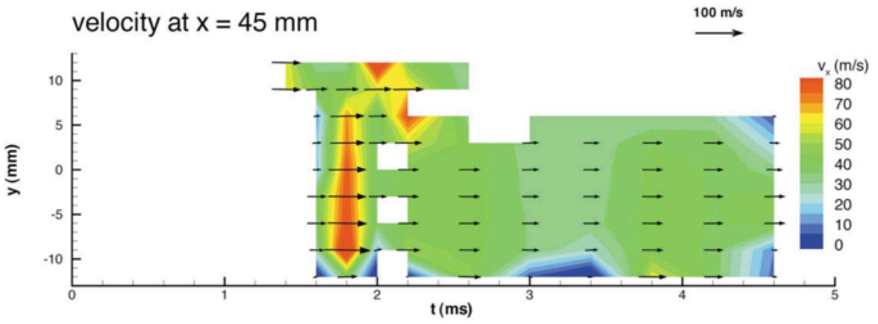

Fig. 5. Instantaneous velocities of LOX droplets near the location of ignition at different times after ignition (abscissa) and different distances from the symmetry line (ordinate).

4. Discussion

Based on the information gained from OH emission, liquid phase distribution and pressure recordings (See Fig. 4), three distinct phases can be identified: Primary ignition, explosive phase and flame stabilization.

(i) The first phase, the primary ignition (0 - 500 *m*s), is characterized by a slight downstream movement of the flame kernel expanding around the laser-initiated plasma (Fig. 6, left images). The high velocity flow of the reactants is balancing the flame velocity and the flame is not anchoring at the injector. At the position of the flame, the tiny droplets are vaporised and the core of larger droplets and ligaments become visible.

(ii) The second, explosive phase, starting at around 500 *m*s is characterized by explosive flame propagation. All premixed O_2/H_2 in the whole combustor volume burns within a very short time. This can be seen from the synchronous recorded high emission intensities and a distinct pressure peak. Due to low cut-off frequency of pressure sensors of 4 kHz, the exact pressure peak cannot be determined with high accuracy (see Fig. 4). The LOX-jet is disrupted (Fig. 6, middle images). About 500 *m*s after the beginning of the second phase the flame outside the region around the central LOX core is extinguished. This indicates that the previously premixed gases outside the spray have burned. This phase ends at about 1 ms after ignition.

(iii) In the phase of flame stabilization, stationary conditions for both spray forming and combustion are reached. The images of the flame front show typical structures resulting from instabilities of the shear layer between oxygen and hydrogen. These phenomena are already known from experiments recorded during stationary combustion (Sender et al., 1997). No oxygen droplets have been found outside the flame-front that encloses completely the area of the LOX-spray (Fig. 6, right images).

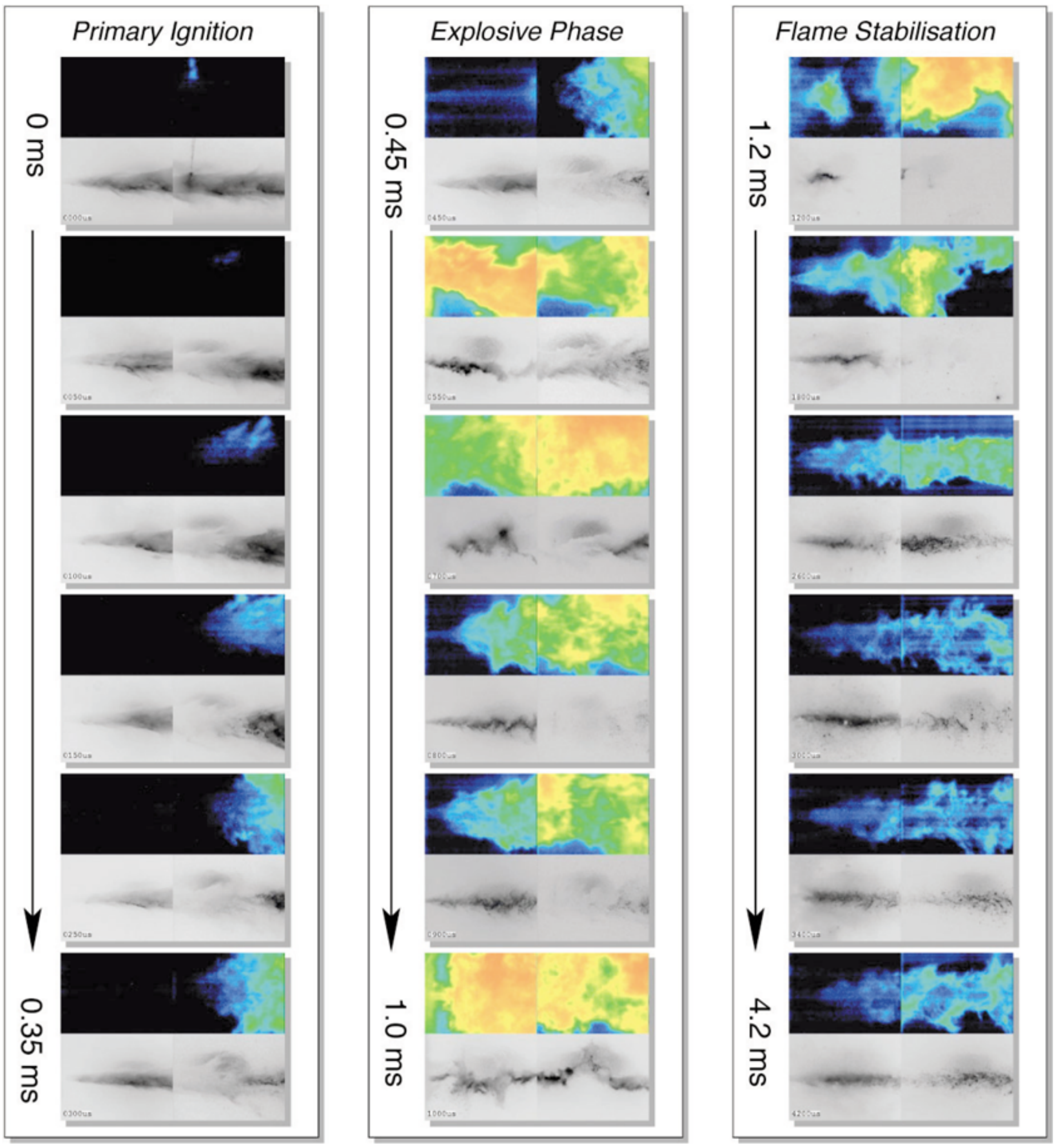

Fig. 6. Examples of flame evolution (upper part of sub-images) and liquid phase distribution (lower part) during ignition phase.

5. Conclusion and Outlook

It has been shown that the ignition process is reproducible with respect to the time scales on which flame-front and spray pattern develop in the transient ignition phase. Thus, the temporary evolution of the ignition process could be resolved in a series of test runs by variation delays between ignition and data recording. This is not true concerning the movement of the LOX-jet and the flame propagation during the explosive phase. The liquid phase distribution is strongly distributed by the gas flow. The images recorded in different test runs did not allow developing a coherent model for the flow dynamics during the explosive phase. To gain insight more detailed into these phenomena the application of high-speed diagnostics is planned for the future, which allows recording the flow dynamics with high temporal resolution during one test run.

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