Cryogenic Spray Ignition at High Altitude Conditions

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Results obtained from investigations of the transient ignition process of a cryogenic GH2/LOX spray under vacuum conditions with a model rocket combustion chamber are reported. Ignition of the propellants has been initiated with a laser pulse. Transient spray and flame behavior have been analyzed using high-speed visualization methods. Jet spreading angles as well as flame front positions are determined by image processing. Cold flow LOX jet angle is found to be dependant on initial combustor pressure level. Ignition behaviour is compared to that observed under atmospheric conditions.

Nomenclature

d_i	=	LOX-post inner diameter
d_o	=	H_2 annulus outer diameter
J	=	momentum flux ratio
M	=	Mach number
p_C	=	combustion chamber pressure
R_{OF}	=	mixture ratio
Re	=	Reynolds number
t	=	LOX-post thickness
u	=	velocity
We	=	Weber number
z	=	flame front position

I. Introduction

Reliable re-ignition of upper stages is a key capability for multiple payload launchers. During the ignition transient the conditions in a cryogenic combustor vary strongly: mass flows have a transient behaviour, chamber pressure is increasing, the developing flame interacts with the flow of the injected fluids. It is therefore a challenging task to design an ignition system based on general principles and numerical modelling. Smooth and reliable ignition has to be assured under high altitude conditions, where the ambient pressure is near to zero.

At the M3 test bench at DLR Lampoldshausen ignition transients are investigated for LOX/H_2-sprays as well as for gaseous injection of O_2 and H_2 at ambient temperature [1-3]. LOX and GH_2 are injected using a coaxial injector. Combustion is initiated by a laser-induced gas break-down by focusing a pulsed high-power laser into the mixing layer of the propellants. Thus location and time of ignition can be well controlled. Applying high speed visualization techniques for the spray pattern and the flame the phenomenology of the transient processes and quantitative data e.g. flame front velocities can be determined during the ignition transient. Procedures for both experimental setup and transient data evaluation had been developed.

Experience from ignitions tests at ambient pressure cannot be transferred to ignition at high altitude conditions. Liquid oxygen is injected in a low pressure environment and its temperature may be above the boiling temperature at those pressure conditions. The amount of gaseous oxygen available in the ignition transient is therefore expected to be higher than at ambient conditions. The density of the annular co-flow of gaseous hydrogen is significantly smaller and its velocity is much higher and can approach sonic velocities at high altitude conditions. Thus the atomization process and the distribution of the propellants in the combustor at time of ignition are different from the situation at ambient pressure. The kinetics is also pressure dependent and the propagation velocity of the flame is expected to be different at low pressure as compared to ambient pressure conditions.

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For a better understanding of the ignition transient at high altitude conditions the M3-test facility has now been upgraded. Ignition phenomena under near vacuum conditions can now be investigated at pressures as low as 20mbar. The ignition of a cryogenic GH_2/LOX spray has been investigated for different injection conditions characterized by non-dimensional numbers. Flame front positions, flame front velocities and spray spreading angles of cold flow are determined from high speed flow visualization data. Relations between injection conditions and spray and flame behavior are investigated, and compared to data from ignition tests performed under atmospheric conditions.

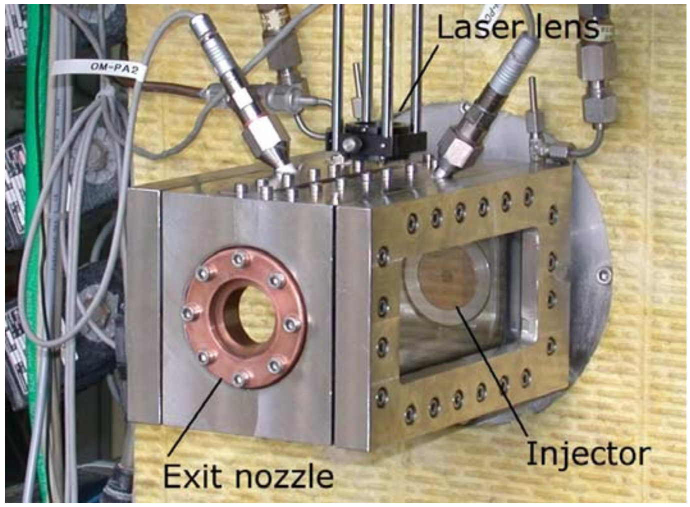

Figure 1: The micro combustor at the M3-test facility with laser ignition setup and coaxial single injector

II. Experimental Setup

A. The Micro Combustor

The micro combustor [4] is a model combustion chamber for cryogenic spray combustion (see Figure 1). Mounted on the M3 test bench tests can be performed with cryogenic propellants at representative temperatures. The set-up allows a high test cadence and thus systematic parameter variations at reasonable effort. The micro-combustor set-up is dedicated to basic research in cryogenic spray atomization and combustion. Furthermore it is used as a test object for the adaptation of optical diagnostic techniques which later on will be applied at the P8 test facility at cryogenic model combustors operated at representative pressure conditions.

The feed system and the run-tanks for the propellants GH_2 and LOX are submerged in a liquid nitrogen reservoir and thus cooled down to 77K. To minimize thermal transients during the start-transient in the injector head is in tight thermal contact to the LN_2-bath. The H_2-mass flow is determined by a sonic nozzle, the LOX mass flow is measured with a turbine flow meter.

Two fast opening valves with 5 ms opening time guarantee a short injection transient to assure stationary cold flow conditions prior to ignition. A single shear coaxial injector without recess and without tapering is used. Nozzle diameter and propellant supply pressures are chosen to keep the chamber pressure constant for different mass flow rates.

B. The Vacuum Installation

An ejector mounted at the outlet of a 1500l vacuum tank is supplied with gaseous nitrogen at 2.5 MPa. It enables to evacuate the combustion chamber down to 85 mbar. The ejector design follows experiences derived from the engineering of the high altitude test facility P4.1 [5].

An oil-sealed rotary vane pump is used to reach a vacuum level of up to 20 mbar prior to injection. While the pump is not running during a test, the ejector is continuously operating in order to maintain the pressure constant in the chamber. The vacuum installation diagram is shown in Figure 2.

The pressure level in the combustor at the valve opening time can be adjusted between 20 mbar and 1 bar and mass flow rates have been chosen to reach 2 bar chamber pressure during stationary combustion.

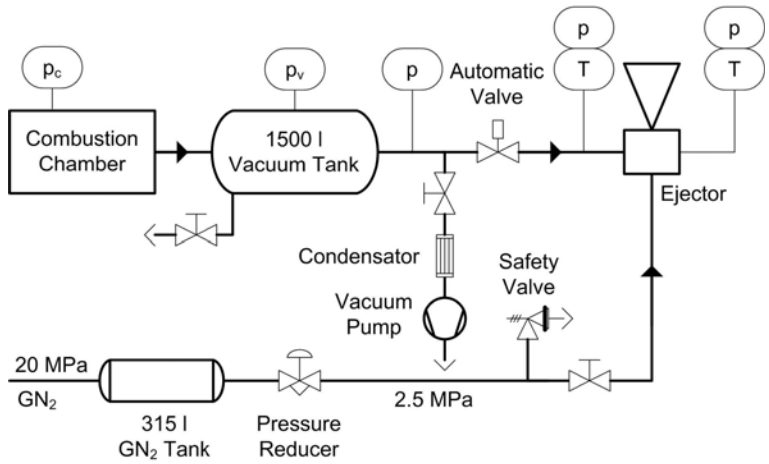

Figure 2: The vacuum installation

C. Optical Diagnostics

A standard Schlieren setup together with high speed recording at 4000 frames per second is used to record the flow structure. The Schlieren edge has been setup in vertical position in order to observe horizontal density gradients.

The chemiluminescence of the OH-radical in the spectral range of λ=310nm±5nm is used to identify the position of the flame front. An intensified high speed CCD camera records images with with an acquisition frequency of 18000 fps. This provides the histories of the flame position from which it is possible to extract information about the spatial evolution of the flame.

III. Test Configuration

A. Injection Conditions

In order to obtain a wide range of experimental conditions, it was decided to use two different exhaust nozzles, and a single coaxial injector with fixed geometry (LOX-post diameter d_i=1.2mm, LOX-post thickness t=0.4mm, H_2 annulus outer diameter d_o=5.0mm).

The vacuum tank pressure was varied between 20 mbar and 0.8 bar resulting combustion chamber pressures at stationary cold flow conditions of 230-970 mbar. This enabled to vary both the momentum flux ratio *J* and Weber number *We*

$$J = \frac{(\rho u^2)_{H2}}{(\rho u^2)_{LOX}}$$

$$We = \frac{(u_{H2} - u_{LOX})^2 d_i}{\sigma}$$

for cold flow conditions as listed in Table 1. For hot flow conditions the injector geometry being fixed and the combustion chamber parameters (p_C, R_{OF}) being kept constant, the *J* number remains quasi constant.

The injection conditions are summarized in table 1, where p_C is the combustion chamber pressure, R_{OF} the oxidizer to fuel ratio, *Re* the Reynolds numbers for both fluids, and M_{GH2} the H_2 Mach number.

B. Ignition Conditions

A frequency doubled Nd:YaG-laser (λ=532nm) has been used for ignition with a pulse length of 10ns and 175mJ pulse energy. The laser light was focussed with a lens of f=60mm focal length. This results in a focal volume of a length of about 0.5mm, and a waist of about 60µm [6].

The location of the laser focus, i.e. the position of the laser induced plasma, has been determined from a Schlieren image under atmospheric condition. The plasma has been setup at x~30d_i from the injector plate, and y~4d_i from the jet-axis. At this position reliable ignition in atmospheric conditions has been observed for rather all laser pulses.

Parameter	Ranges	
	cold flow	hot flow
p_C	230-970 mbar	0.88-0.1.58 bar
R_{OF}	5.6-6.8	4.7-7.3
J	0.07-0.46	0.23-0.41
We	5400-11000	9800-18100
Re_{LOX}	59000-123000	47000-115000
Re_{GH2}	41000-11500	87000-223000
M_{GH2}	0.62-1.00	0.47-0.80

Table 1: Injection condition ranges

IV. Data Processing

A. Sensor Data

For each test, mean values and standard deviation are extracted from the pressure, temperature and volume flow sensor data sampled at 10 kHz for both stationary cold flow and hot flow conditions. These values have been used to calculate the dimensionless test parameters (*J, We, Re, M*) and their variation during the stationary cold and hot flow phases. Pressure peaks at ignition are measured for each test.

B. LOX Spray Spreading Angle

An important parameter for analyzing the cold flow in vacuum is the jet spreading angle that characterizes the atomization quality. Image processing tools have been used to process each image individually. The spray boundary has been determined for $z=15\cdot d_i$ downstream the injector face plate. The spray boundary shows a quasi linear spreading in all observed test conditions in this area. In each pixel column the liquid jet boundary is determined by the highest gray value gradient in radial direction as shown in Figure 3. Then a linear interpolation is carried out on the upper and lower spray boundary and the full spreading angle is determined.

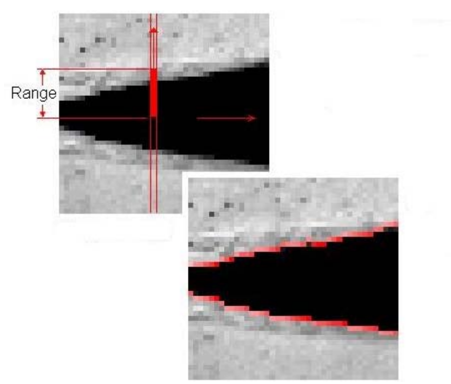

Figure 3: Jet spreading angle determination

C. Flame Front

From the UV video recordings, each single frame was analyzed to generate up stream and downstream flame front time series $z_U(t_i)$ and $z_D(t_i)$ respectively, where the image have been recorded at time t_i after ignition [1-3]. This operation consists of scanning the vertical lines of the previously binarized image. From these data the velocity u_D of the downstream flame front and the velocity u_U of the upstream flame front have been determined by calculating the difference quotient $u=(z(t_{i+1})-z(t_i))/(t_{i+1}-t_i)$.

The downstream front is only tracked in the first images of the ignition transient before the flame reaches the nozzle. The upstream front is tracked for the whole ignition transient, and is particularly useful for characterizing the different phases of the ignition process.

During about 1ms after ignition the flame kernel initiated by the gas-break down is moving by convective transport through the chamber and at the same time is expanding due to the progress of combustion. Thus the measured downstream flame front u_D is the sum of the convection velocity u_C and the flame velocity u_F

$$u_D = u_C + u_F$$

and similarly

$$u_U = u_C - u_F \, .$$

By simple arithmetics the convection velocity of the flame kernel and the flame velocity with which its size is expanding can be calculated:

$$u_C = \frac{u_D + u_U}{2}$$

$$u_F = \frac{u_D - u_U}{2}$$

V. Results and Discussion

Figure 4 shows a typical pressure plot of the transient pressure evolution until stationary cold flow conditions are reached. Although the LOX-valve is opened about 15ms prior to the H2-valve, due to the high inertia of the high density liquid oxygen, hydrogen is injected into the chamber first. The pressure increase Δp_{H2} due to the H_2 preflow is clearly visible in Figure 4. About 10ms later liquid oxygen enters the chamber and due to evaporation of the LOX droplets the pressure increases by Δp_{O2} as indicated in Figure 4. The well resolved increase of the chamber pressure by Δp_{O2} may be used to determine the global evaporation rate of the LOX spray in the combustor. A preliminary analysis however showed that the results are very sensitive to the temperature of the gaseous components in the chamber. More detailed temperature measurements are necessary for reliable results than that available in the tests presented here.

In Figure 5 the pressure evolution during an ignition test in the combustion chamber and the vacuum tank is shown. It is apparent that stationary cold flow conditions are reached prior to ignition. Furthermore, the initial pressure rise due to the propellant injection is only observed in the combustion chamber, the pressure in the vacuum tank shows a constant value.

At t=0 the laser induced gas break-down initiates combustion. The combustion of the unburned mixture injected during the preflow results in the ignition pressure peak observed at t~0. After 50-100ms stationary combustion is achieved and the combustion chamber pressure adjusts to about 1.5 bar. At t=0.8s the propellant valves are closed.

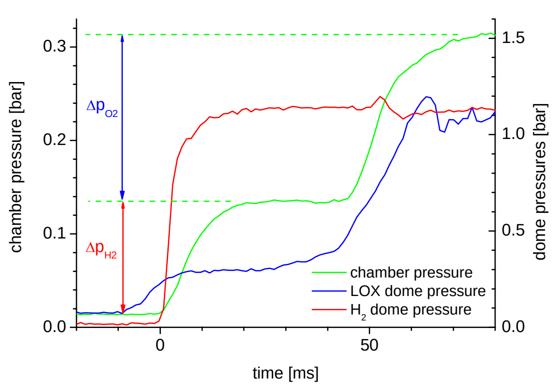

Figure 4: Pressure evolution in the combustor and the propellant domes during the early cold flow transient.

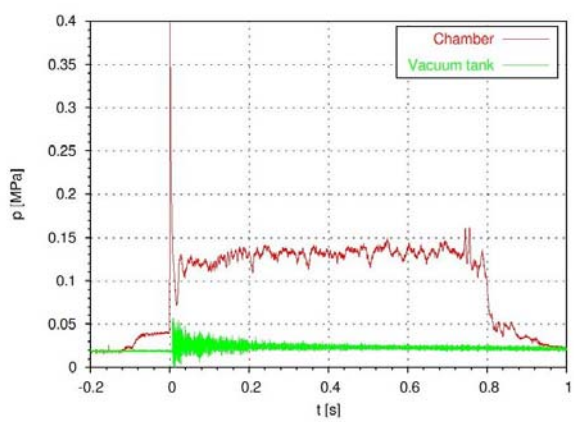

Figure 5: Pressure evolution in the combustion chamber and in the vacuum tank during a ignition test.

A. Cold Flow

For each test, the angle of every image is measured during the stationary cold flow period and the mean value and its standard variation are considered. The injection conditions of cold flows at different combustion chamber pressures and the resulting LOX spray angles are summarized in Table 2. Figure 6 shows the averaged images corresponding to these cases. Figure 7 plots the spreading angle versus the ratio between LOX injector dome pressure $p_{i,LOX}$ and the combustion chamber pressure p_C.

Being the injection pressure quasi-constant for the cases considered, the inverse dependence of the spray angle versus the initial combustion chamber pressure becomes obvious from Figure 7. With decreasing chamber pressure the spray angle increases, thus resulting in a wider dispersion of the liquid phase at low pressure conditions.

case	p_C[mbar]	We[-]	J[-]	Angle[°]
1	292± 10	7660± 270	0.084± 0.010	17.1± 0.9
2	330± 7	8150± 200	0.085± 0.007	13.4± 1.8
3	374± 7	8650± 170	0.102± 0.007	11.2± 0.8
4	401± 7	8950± 170	0.106± 0.006	9.5± 0.8
5	458± 6	9470± 150	0.124± 0.008	7.6± 1.0

Table 2: Test conditions

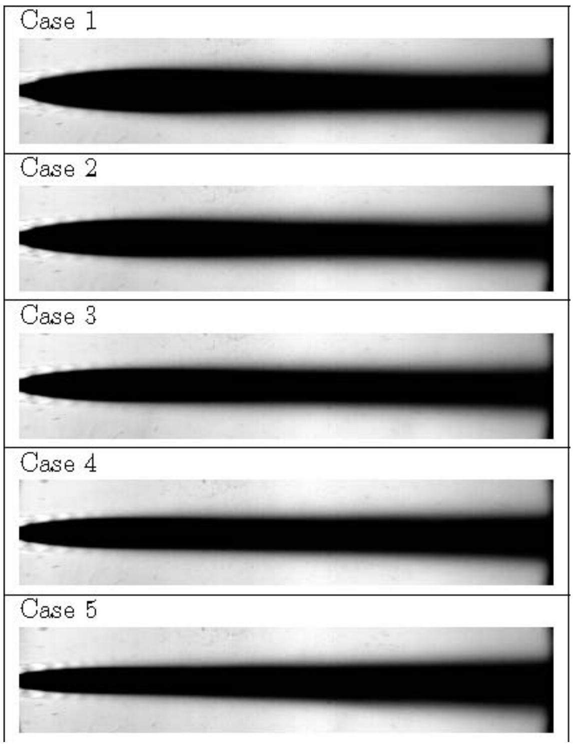

Figure 6: Spray spreading angle at different pressures

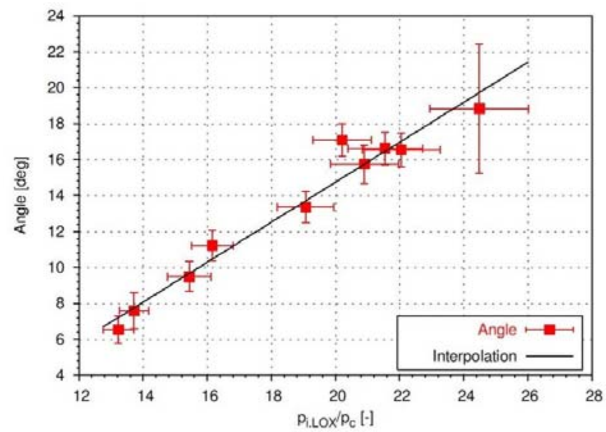

Figure 7: Spray spreading as angle function of LOX injection pressure ratio

It was impossible to obtain cold flow combustion chamber pressures below 230 mbar: as soon as the liquid oxygen reached the chamber, the pressure would rise to values between 230 and 300 mbar, even though the vacuum tank pressure downstream the supersonic nozzle kept values down to 20 mbar. The injection temperature of LOX was for each test between 77 and 80K. A higher accuracy in the determination of the LOX-temperature is not possible with the sensors used. The vapor pressure of LOX in this temperature range is between 200 and 300 mbar (see Figure 8). Therefore, it can be supposed that in the very first moments of the LOX injection, a so-called flash evaporation occurs, which explains this lower pressure limit: because of the large pressure drop, part of the fluid is in a superheated state and vaporizes extremely rapidly. Flashing is a process which leads to more significant vaporization rate than that obtained during simple vaporization. This is accompanied with a subsequent temperature drop of the liquid [7]. The phenomenon is very significant at the surface (see Figure 9) and forces the liquid to take on very heterogeneous temperature profiles, composed of superheated, saturated and subcooled areas [8].

The flashing fluid is in a confined region (the combustion chamber), hence the pressure rises until the fluid is completely vaporised, or in the present case until the coexistence pressure and temperature are reached.

In tests with lower mass flows ($\dot{m}_{LOX}$ =16±2g/s, compared to $\dot{m}_{LOX}$ ~30g/s for tests in Figure 7), the LOX jet angle fluctuates unpredictably, as can be seen in Figure 9 (p_C=307± 7mbar, $\Delta t=5\cdot10^{-4}$s per frame). For these low mass flow conditions, a higher LOX fraction has to be vaporized in order to obtain the same pressure between 200 and 300mbar. Therefore flash vaporization is clearly visible for the whole stationary cold flow period.

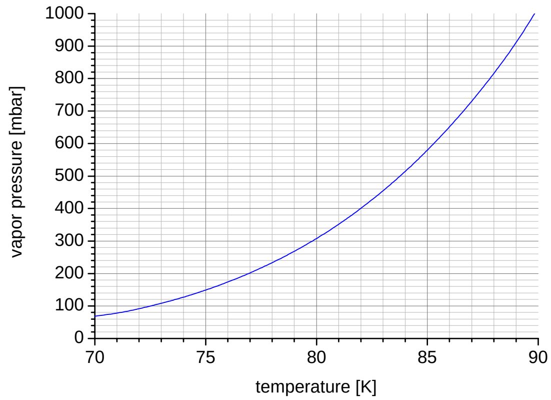

Figure 8: Vapor pressure of LOX

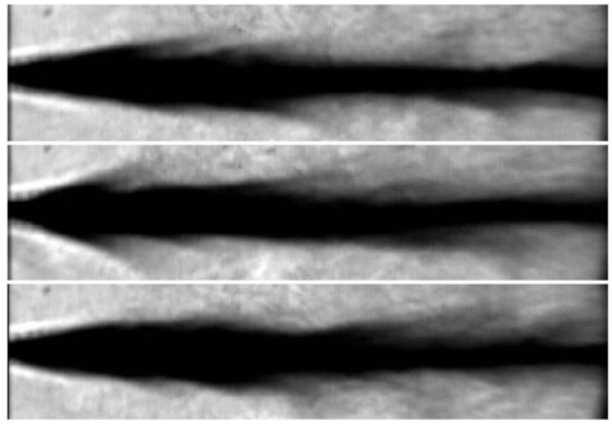

Figure 9: GH2/LOX flashing jet sequence

B. Ignition Transient

The ignition pressure peak p_{peak} is dependent on combustion chamber pressure prior to ignition. The ratio p_{peak}/p_C was found higher than in atmospheric ignition [1]. Further investigations on this phenomenon are needed, to obtain more quantitative results. Due to the flash vaporization of LOX, it is expected that in vacuum ignition the mixture ratio R_{OF} of the gas phase is much higher than the total R_{OF} (see Table 1). Therefore it is possible that ignition occurs in conditions near to stoichiometric and this would explain the harder ignition.

From the high-speed OH-images average flame front velocity u_F and convective velocity u_C have been determined. Results are compared to data obtained at atmospheric ignition [3]. The flame front velocity u_F is shown as function of Weber number in Figure 10, the convective velocity u_C as function of the H2 momentum flow $I_{H2}=(\dot{m}\, u)_{H2}$ in Figure 11. In vacuum conditions, velocities similar to the tests at atmospheric conditions obtained for similar We and I_{H2}.

The image sequence in Figure 12 shows the flame development (OH-images) coupled with the LOX-jet (Schlieren images). The times are relative to the time of laser-induced ignition.

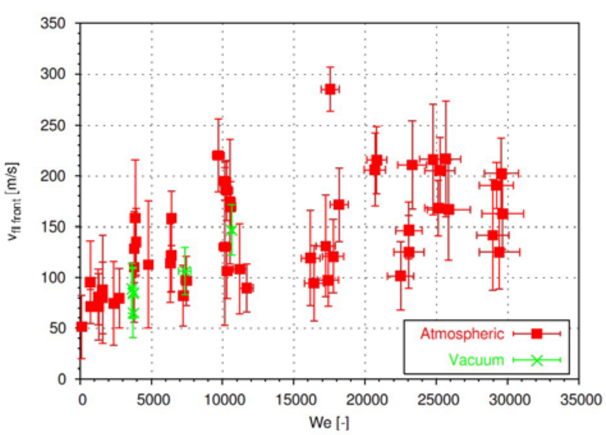

Figure 10: Flame front velocity as function of Weber number

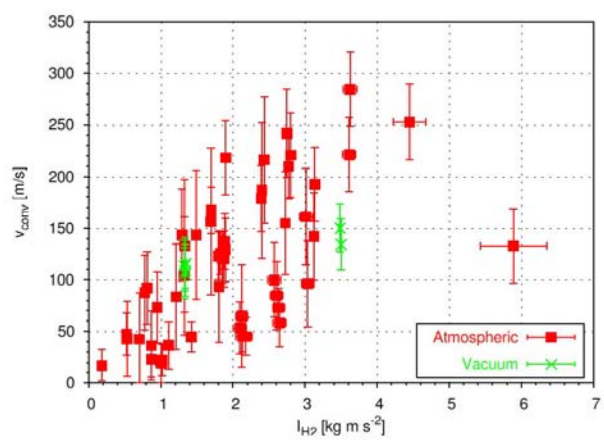

Figure 11: Convection velocity of the flame kernel as a function of GH2 momentum flow

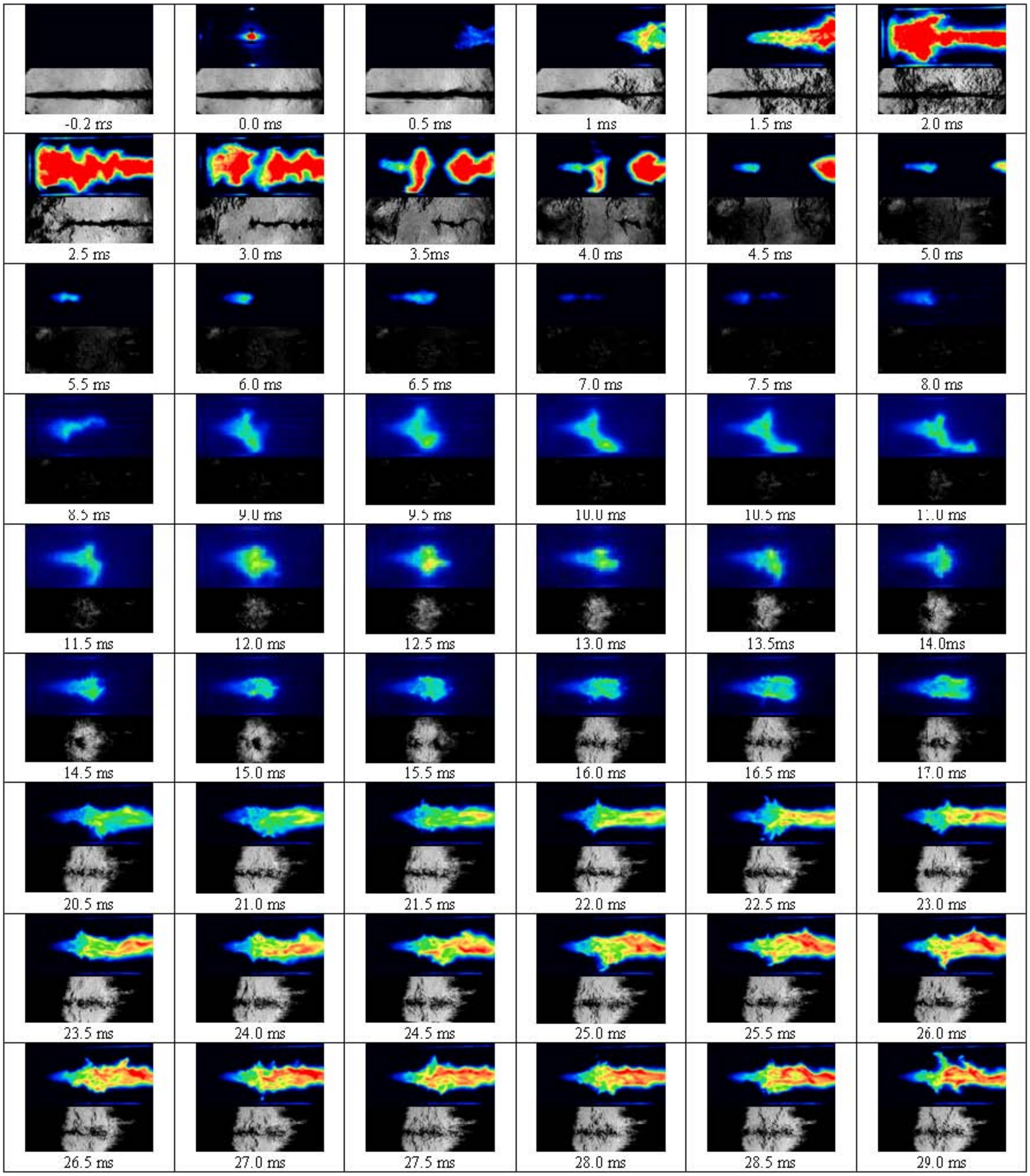

Figure 12: Typical ignition under vacuum (p_C=250mbar in combustion chamber, p_V=20mbar in vacuum tank). False color OH-chemiluminescence visualization on the top and Schlieren image on the bottom.

After combustion has been initiated by the laser pulse the flame kernel expands. All the unburnt propellants present in the combustor that had been injected during the pre-ignition flow are reacting. This is accompanied by a sudden pressure increase, the ignition pressure peak. During this period, that lasts about 1-2ms the flame intensity shows a pronounced peak as well. As can be seen in Figure 12 the camera is in saturation during this phase. Then the intensity decreases as the pressure wave finishes propagating into the combustion chamber. The pressure difference at the injector decreases for some time strongly, thus the LOX jet is temporarily broken (t=3-5ms). Finally, the peak pressure relaxes to the level of stationary combustion and the mass flows through the injector recover to their stationary hot fire values. The flame intensity increases again and reaches finally steady state. No Schlieren pictures can be analyzed between 4ms and 45ms because water condensates on the cold windows.

In near vacuum conditions, for the conditions studied, the ignition process is similar to the 4 phase scenario described by Schmidt et al. [3,4,6,9]. Figure 13 shows a time plot of the upstream flame front position (cold flow combustion chamber pressure p_C=302± 7mbar, We=3730± 00, J=0.011± 0.002).

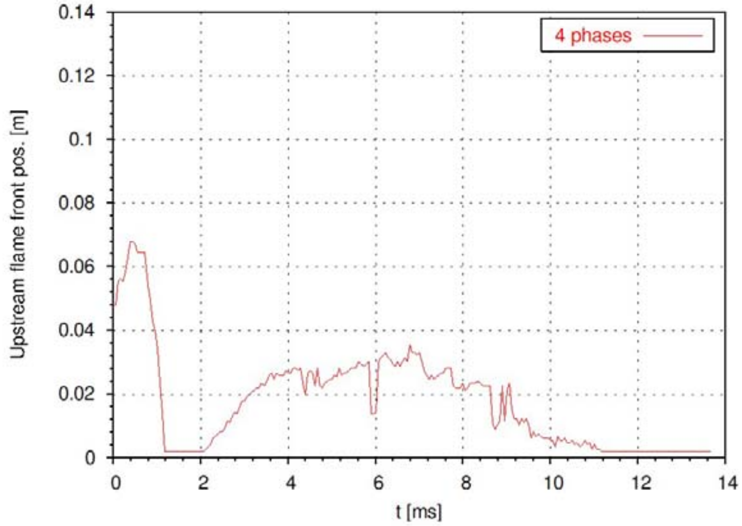

Figure 13: Upstream flame front behavior under vacuum conditions

VI. Conclusion and Outlook

The extension of the micro-combustor test bench M3 with a vacuum system allows the experimental analysis of cryogenic spray ignition under high altitude conditions. The main results obtained during the run-in tests of the new facility are:

- Spray spreading angle is linearly dependent on the pressure ratio between LOX-dome and combustion chamber.
- Flashing of the superheated LOX-jet has been observed at low pressure conditions. The flashing phenomenon could result in a faster LOX vaporization.
- Under the conditions tested, laser ignition has always been observed down to p_C=250mbar cold flow combustion chamber pressure
- Flame front velocities and convective flame velocities are found to be similar to those measured in atmospheric conditions with same parameters (We, I_{H2}).
- Flame behavior in the whole ignition transient is similar to the one observed in atmospheric conditions.

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