INFLUENCE OF J AND WE NUMBER ON GH_2/LOX IGNITION PROCESS

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Abstract

First results obtained from investigations of the transient ignition process of a cryogenic GH_2/LOX spray in a model rocket combustion chamber are reported. Ignition of the propellants has been initiated with a pulsed laser and ignition and flame stabilization process have been analyzed using high-speed visualization methods. Local flame velocities as well as local convection velocities at the point of ignition are determined by image displacement velocimetry methods. During the ignition process four distinct phases could be observed.

1 Introduction

Although the problem of ignition in rocket engines has been of interest for years, detailed insight into the ignition transient is still missing. High speed visualization techniques have been successfully applied for combustion of hydrocarbon sprays [1] but has not being used for H_2/LOX spray ignition due to high data rates required for. Recent investigations of high-pressure cryogenic combustion have mainly been focused on stationary conditions up to now [2, 3, 4, 5]. Hence, only very little experimental data are available on transient ignition phenomena in cryogenic rocket combustors. No systematic investigation of the influence of the injection conditions on the evolution of the flame, the interaction of the flame with the atomization process of the liquid oxygen, and the flame stabilization process is known.

The objectives of this study were to visualize the entire ignition process, identify the relevant physical phenomena, and determine the effect of injection conditions on the ignition behaviour. At stationary cold flow conditions the LOX/GH_2-spray has been ignited by laser-induced gas breakdown. Simultaneous imaging of the OH-emission and Schlieren photography during the ignition process delivers information on the evolution of the flame and the flow field. From high-speed visualization of the flame front local burning velocities as well as convection velocities can be obtained. Furthermore, the temporal evolution of the distance of the upstream flame edge from the injector is the main feature to characterize the flame anchoring and flame stabilization process.

The use of high speed video recording sets a synchronization problem. The reduced observation time allowed by this diagnostic method requires an exact synchronization between ignition and recording so that the classical ignition methods such as pilot flame are not possible [6]. With laser ignition it is possible to exactly synchronize the time of ignition with high speed data acquisition. Furthermore, as compared to electric spark ignition which has been used by Quintilla et al. [7] laser ignition gives high flexibility in choosing the location of energy release.

Additionally, temporal evolution of combustion chamber pressure and flame emission intensity are applied for a further characterization of the different phases of the process.

2 Experimental set-up

2.1 The micro-combustion chamber M3

The M3 micro combustor is a cryogenic test bench for optical investigations on LOX/GH_2 spay combustion. Two fast opening valves of 5 ms opening time guarantee a short injection transient. The injector used is a single shear coax injector without recess and tapering. The geometry of the LOX post is fixed while the outer diameter on the H_2 side can be varied in order to vary the flow parameters at the injector exit (J, We, Re). Nozzle diameter, and propellant supply pressures are then adjusted to keep the chamber pressure constant. For more details about the test bench, see [3, 8].

The figure 1 shows a schematic of the M3 combustion chamber with a single injector arrangement. Planar quartz glass windows on both sides of the combustor are used for flame observation while a small upper slit quartz window allows an optical access for the igniter laser.

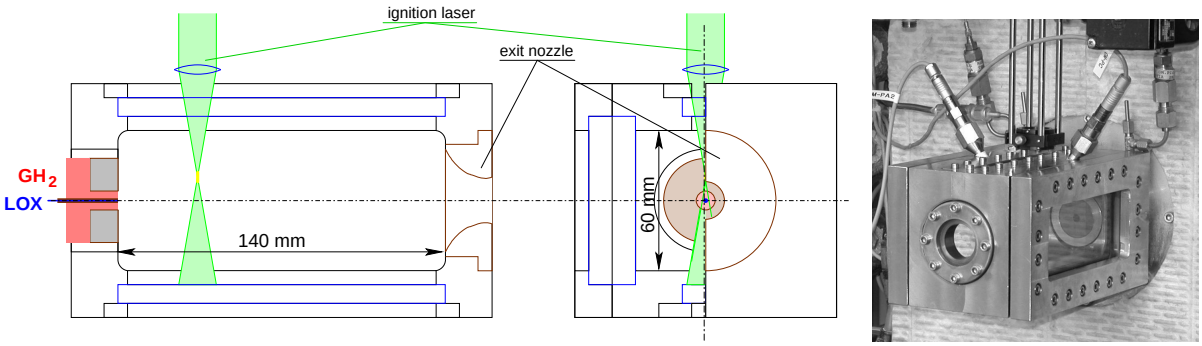

Figure 1: Schematic of the M3 micro combustor with laser ignition set-up and coaxial single injector arrangement. Right image: photography of the combustion with mounted optic for laser ignition.

2.2 Optical set-up

The flame has been directly observed in the UV range (λ= 310 nm $\pm$ 5 nm) with a high speed video camera (Fastcam I^2) at 18000 fps. This provides images of the flame evolution from which it is possible to extract information about the spatial development of the flame as well as the evolution of the chemical activity.

A standard Schlieren setup coupled with high speed recording (Photron Ultima 1024) at 4000 fps is used to observe the flow structure. This provides images of liquid phase distribution as well as density gradients in the gas flow. Each test condition has been fired twice in order to change the knife orientation and get both horizontal and vertical gradients.

A frequency doubled Nd:YAG laser ($\lambda = 532$ nm) has been used for ignition with a pulse length of 10 ns and 120 mJ pulse energy. The laser light was focused with a lens of $f = 60$ mm focal length. This results in a focal volume with a near ellipsoidal shape of a length of about 0.5 mm, and a waist of about 60 μm diameter.

3 Operating conditions

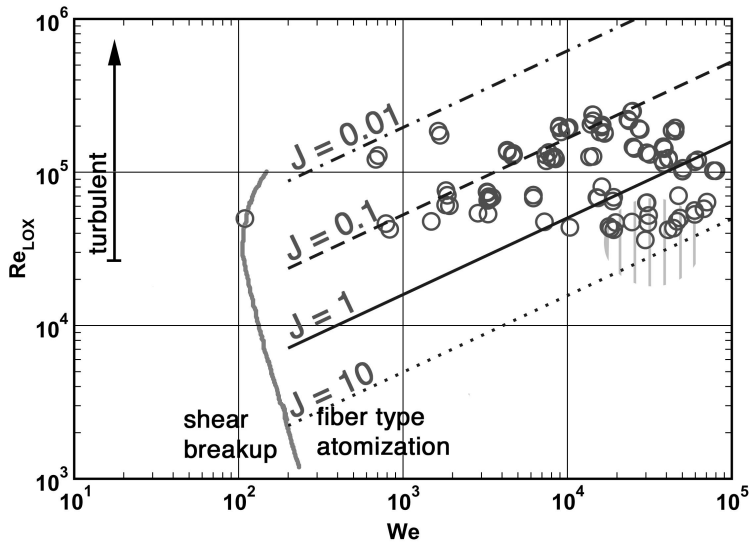

Figure 2: Operating conditions in parameter space Re_{LOX}-We, dashed area (|||) marks regime of rocket engines. (taken from [9]).

The pre-ignition condition are dominated by the thermodynamical properties of the injected propellants as well as the flow properties characteristics. The parameters which are used to describe atomization, vaporization, mixing and turbulence intensity are the Reynolds numbers of gas and liquid, the Weber number and J, the momentum flux ratio of gas-to-liquid with the latter being of major importance for shear co-axial atomization [10, 9].

$$Re_x = \frac{\varrho_x v_x}{\nu} d_x, \quad (x = \mathrm{H_2}, \mathrm{LOX}), \quad We = \varrho_{\mathrm{H_2}} \frac{(v_{\mathrm{H_2}} - v_{\mathrm{LOX}})^2}{\sigma_{\mathrm{LOX}}}, \quad J = \frac{(\varrho v^2)_{\mathrm{H_2}}}{(\varrho v^2)_{\mathrm{LOX}}}. \tag{1}$$

3.1 Injection conditions

The purpose of this study is to observe the influence of the injection parameters on the ignition process. The following parameters have been kept constant: mixture ratio of propellants $R_{of} = 5.0$, propellant temperatures $T_{\mathrm{H_2}} = T_{\mathrm{LOX}} = 78$ K, chamber pressure under cold flow conditions $p_c = 0.12 \pm 0.01$ MPa and chamber pressure at steady state combustion $P_c = 0.155 \pm 0.015$ MPa. By adjustment of the injection velocity the characteristic dimensionless numbers were then varied in the following ranges: $3 \cdot 10^4 \leq Re_{\mathrm{LOX}} \leq 3 \cdot 10^5$, $1.2 \cdot 10^5 \leq Re_{\mathrm{H_2}} \leq 3.75 \cdot 10^5$, $10^2 \leq We \leq 10^5$ and $0.01 \leq J \leq 4.0$. Figure 2 summarize all the performed tests in a Re_{LOX}-We diagram.

3.2 Ignition conditions

H_2/O_2-mixtures are ignitible in a very broad range of mixture ratios between 6% and 96% oxygen content. A position in the chamber had to be determined where a reliable ignition could be achieved for all operating conditions under investigation. Assuming thermodynamic equilibrium between the liquid oxygen and the gaseous hydrogen in the shear layer for a temperature of about 80 K and the initial chamber pressure p_c of around 0.12 MPa yields maximum oxygen concentrations of about 30%. The vaporization of LOX needs some time so that GO_2 concentrations in the shear layer increases with the distance from injection face plate. All experiments presented in this paper have been performed with the laser focus at $x = 41$ mm and 7 mm off-axis. Figure 3 presents a Schlieren picture of the shear layer at the time of the laser deposition of energy into it.

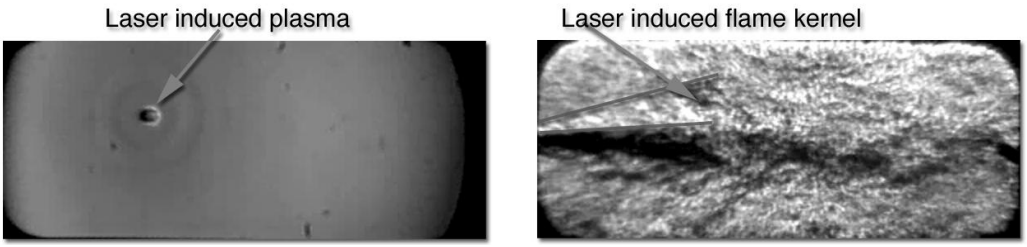

Figure 3: Schlieren pictures from laser induced plasma without flow using a vertical Schlieren edge (left image) and laser induced flame kernel using a horizontal Schlieren edge imaged directly after ignition laser pulse.

Syage et al. [11] have determined the minimal ignition energy for laser-induced spark ignition at 532 nm in premixed H_2/air mixtures. The limits were between 0.11 mJ/pulse (equivalence ratio $\Phi = 0.8$) and approach 10 mJ/pulse near the flammability limits. For H_2/O_2 mixtures the minimum ignition energy can be assumed to be below these values. The laser pulse energy of 120 mJ in our experiments is significantly higher than these values. The energy flux in the laser focus is 420 $\mathrm{GJcm^{-2}s^{-1}}$ and due to the high field strength the molecules are ionized [12]. No attempt has been made to quantify the amount of absorbed energy in our experiment. The laser energy has been increased until reliable ignition has been obtained.

4 Data processing

The purpose of the data processing is to extract from the OH images information concerning the cold flow at ignition time as well as information concerning the ignition, flame development and stabilization process. During the early stage of ignition, one can observe a small growing flame kernel. By getting the evolution of the upstream and downstream front of this kernel, it is possible to determine their velocities, (v_{up}) and (v_{down}). As long as the both fronts are observable, the local flame velocity (v_f) and the local convection velocity (v_c), which are representative of the shear layer cold flow parameters, can be deduced:

$$v_f = \frac{v_{down} - v_{up}}{2}, \quad v_c = \frac{v_{down} + v_{up}}{2}. \tag{2}$$

Since the upstream flame front is observable during the whole test, its position is used to describe the spatial evolution of the flame. A front tracking has been performed and provides a time series of the upstream flame front position. In the same way time series of the global flame intensity is calculated. It is representative of the chemical activity evolutions.

5 Results

5.1 Cold flow conditions

For a better understanding of the ignition phenomena it is mandatory to know the characteristic features of the underlying flow in the combustion chamber at the time of ignition. Derived from what is seen in the Schlieren

images (figure 3) a sketch showing the basic cold flow structure in the combustor is shown in figure 4. The injected LOX is seen as a compact dark jet until atomization has resulted in a diluted spray of LOX-droplets. The LOX-flow is surrounded by the annular H_2-flow, generating a diverging shear layer between the LOX-jet and the H_2-flow. A recirculation zone extends along the total length of the combustor confining the injected propellants and thus reducing the cross section actually available for the injected propellant flow.

Quantitative information about the shear layer are the mean convection velocity v_c and the flame velocity v_f. The mean convection velocity v_c describes how the flame will be transported downstream while the flame velocity v_f represents the capability of a flame to propagate in the shear layer with its specific properties such as mixture ratio, turbulence level etc.. The competition between these two velocities not only controls whether the flame is blown out or stay — successful ignition or not — but may also be used as a marker to distinguish between different phases of the ignition process (see 5.2).

The velocity in the shear layer between the LOX and the GH_2-flow decreases continuously downstream of the injector due to the entrainment of ambient gas and the momentum transfer to the LOX jet. The transfered kinetic energy is used to increase the surface of the liquid (atomization) and to accelerate small droplets and ligaments. The amount of energy transfered at the ignition position is determined from the measured convection velocity according to

$$\text{momentum transfer} = \left(1 - \frac{v_c^2}{v_{H_2}^2}\right). \tag{3}$$

Figure 4 shows that momentum transfer strongly correlates with the We number, a finding which corresponds to the obvious fact that atomization increases with increasing We number. Unfortunately, we are not yet able to quatify the different contributions of this cumulated energy transfer. A better atomization also furthers the flame velocity v_f, see figure 6, since a larger liquid surface finally yields an increased content of gaseous oxygen in the shear layer.

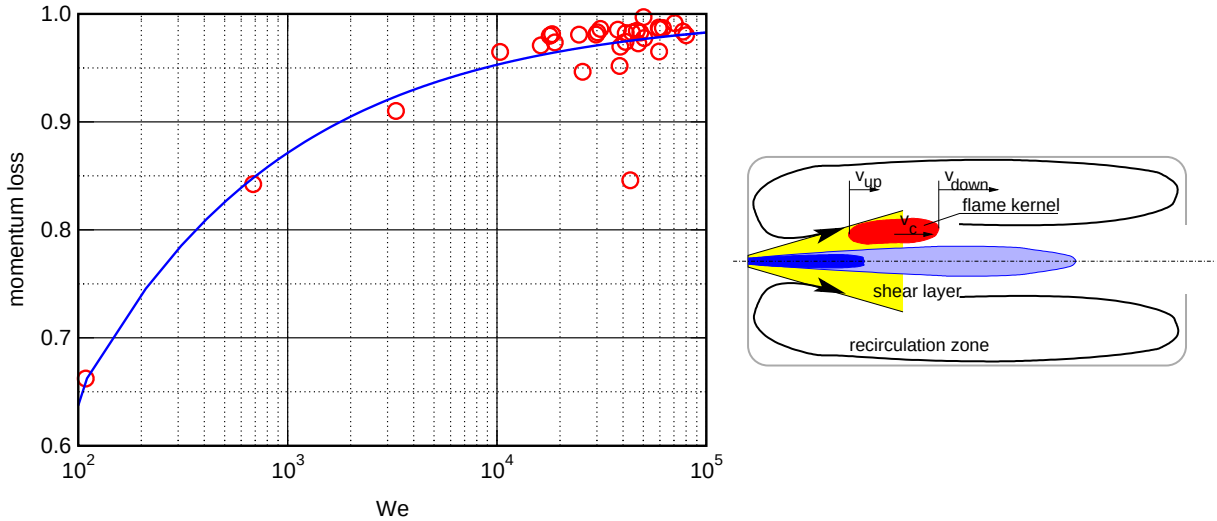

Figure 4: Momentum loss as a function of We number (left image). Sketch showing the basic cold flow structure (right image).

In case of big gas momentum loss, atomization of LOX would be better than in case of small gas momentum loss. This is confirmed by the evolution of the flame velocity. It is related to the oxygen concentration in the shear layer, and it increases with We number.

5.2 Ignition transient

During the present study high-speed imaging provides detailed information about the temporal behaviour of the ignition process. The flame front tracking shows that the flame evolution is similar at all operating conditions. Figure 5 presents this typical ignition behaviour showing the upstream flame front position as a function of time. It is possible to characterize the ignition process by dividing it into four different phases: the primary ignition, the flame propagation phase, the flame lift off phase and the final flame anchoring phase. The different ignition phases are described in more detail in the following paragraphs.

Primary ignition phase: The primary ignition phase begins at the time of deposition of the laser energy into the shear layer. The flame kernel expands in all directions and is convected downstream by the flow. This phase

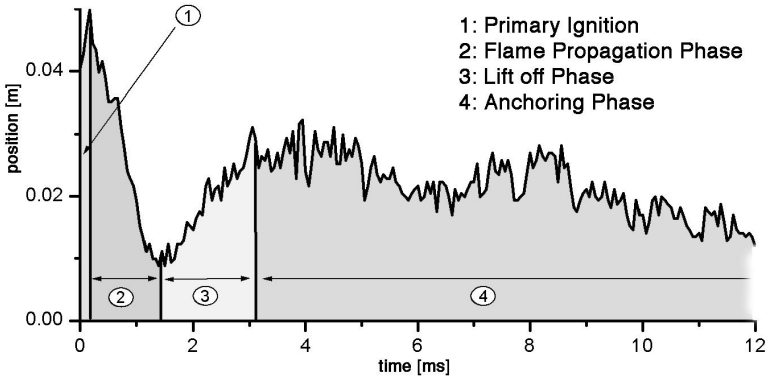

Figure 5: Example of typical upstream flame front evolution with a visualization of the different phases.

is dominated by the shear layer parameters, namely the local competition between the flame propagation velocity resulting from the vaporization and mixing in the shear layer, and the local convection velocity. This phase lasts typically about 0.5ms and ends when the propagation of the upstream flame front changes the direction, i.e. begins to move upstream.

Flame propagation phase: The flame propagation phase begins when the flame moves upstream. This corresponds to the time span when the flame reaches the boundary of the shear layer, expands in the recirculation zone and propagates there until it has consumed all the premixed propellants. This period lasts between 0.1 and 2 ms and is characterized by an upstream movement of the upstream flame front until it reaches a minimum distance from the injector face plate. This phase is typically accompanied by a strong rise of the flame intensity and by a peak in the combustion chamber pressure. Cold flow conditions which support a poor enrichment of the recirculation zone with gaseous oxygen will yield a smooth ignition while flow conditions which support a good enrichment of GO_2 will yield a strong ignition. Generally, at the end of this phase all premixed propellants in the combustion chamber are burnt.

Flame lift-off phase: The flame lift-off phase starts when the upstream flame front begins to move downstream away from the injector until it reaches a maximum distance. This period lasts between 1 and 5 ms. All premixed propellants in the recirculation zone have been consumed. Flame intensity as well as the combustion chamber pressure decrease. The flame has to retreat to areas where fresh vaporized oxygen is mixed with hydrogen: the shear layer. The situation is now similar to the primary ignition phase, the significant difference is that the recirculation zone now is filled with hot combustion products.

Flame anchoring phase: The flame is now moving upstream in the shear layer. The flame anchoring phase lasts from 20 ms to more than 50 ms, depending on the injection conditions. Hot products from the recirculation zone is entrained into the shear layer increasing the vaporization of liquid oxygen. This increases both, the reaction rate and the local flame velocity. The increase of the reaction rate yields to higher temperatures and pressures and a larger reaction zone. The increase in reaction zone reduces the available space for the recirculation zone. With the increasing pressure the injection velocity of GH_2 are reduced and as a consequence we have lower convection velocities $v_{\mathrm{H_2}}$. Higher flame velocities and lower convection velocities shift the upstream flame front equilibrium position closer to the injector.

It has been shown earlier that characteristic parameters of ignition phase one such as velocities strongly depend on the injection conditions. In phase two only pressures and emission intensities ate avalable which also correlates on the injection conditions.

Depending on the duration of this phase, as well as the levels of intensity and pressure peaks reached, the ignition process can be described as either smooth or strong ignition. The smooth ignition is characterized by a long flame propagation phase duration of about 2 ms, while it can last less than 0.2 ms in the strong ignition case. During this phase, intensity and pressure peaks are detected. The highest peaks were observed in case of strong ignition while they were limited in case of smooth ignition. We conclude that a good mixing of O_2 into the re-circulation zone yield a strong ignition while a poor mixing gives a smooth ignition. A strong correlation between We number and the pressure rise has been observed (see figure 6), while no significant dependency with J number has been seen.

6 Conclusion and Outlook

The experiments proofed that for all test conditions the transients after laser-induced ignition follow a similar road on their way to stationary combustion conditions. Four different phases have been identified which are to sum extend present for all discussed operating conditions. Time scales of primary ignition, flame development,

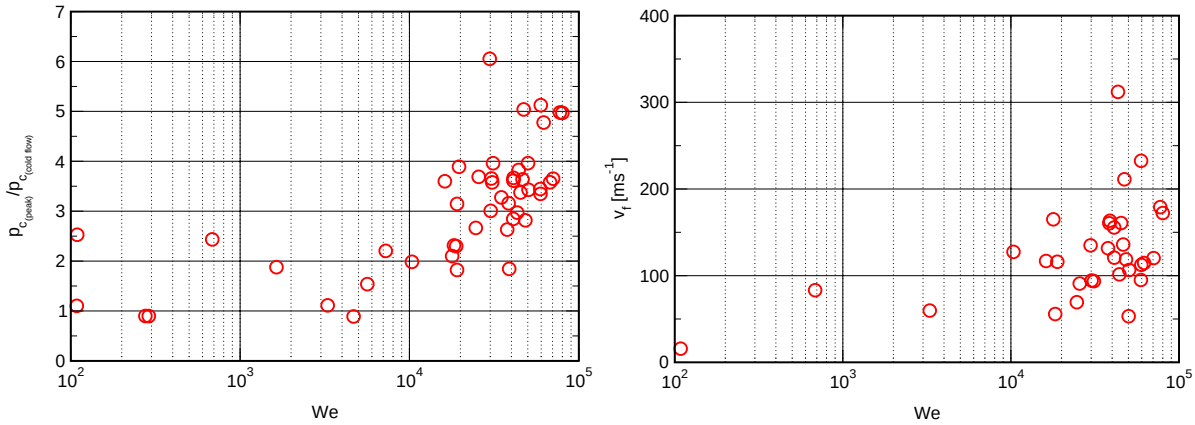

Figure 6: Chamber peak pressure ratio $p_{c_{\text{peak}}}/p_{c_{\text{cold flow}}}$ (left image) and flame velocity v_f (right image) as a function of the We number.

lift-off, and anchoring depend strongly on injection conditions. For a further evaluation local GO_2 concentration measurement are necessary.

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References

[1] M. Arai, H. Yoshida, and H. Hiroyasu. Ignition process of compound spray combustible mixtures, dynamics of heterogeneous combustion and reacting systems. *Progress in Astronautics and Aeronautics*, 152:306–316, 1993.

[2] B. Ivancic, W. Mayer, G. Krülle, and D. Brüggemann. Experimental and numerical investigation of time and length scales in LOX/GH_2-rocket combustors. *AIAA 99-2211*, 1999.

[3] J. Sender, R. Lecourt, M. Oschwald, and O. J. Haidn. Application of droplet-tracking-velocimetry to LOX/GH_2 coaxial-spray combustion with varying combustion chamber pressure. In *13th Annual Conference on Liquid Atomization and Spray Systems*, Florence, 1997.

[4] S. Candel, G. Herding, R. Snyder, P. Scouflaire, C. Rolon, L. Vingert, M. Habiballah, F. Grish, M. Péalat, P. Bouchardy, D. Stepowski, A. Cessou, and P. Colin. Experimental investigation of shear coaxial cryogenic flames. *Journal of Propulsion and Power*, 14(4):826–834, 1998.

[5] S. Yeralan, S. Pal, and R. J. Santoro. Experimental study of major species and temperature profiles of liquid oxygen/gaseous hydrogen rocket combustion. *Journal of Propulsion and Power*, 17:788–793, 2001.

[6] W. Mayer, B. Ivancic, A. Schik, and U. Hornung. Propellant atomization and ignition phenomena in liquid oxygen / gaseous hydrogen rocket compustors. *Journal of Propulsion and Power*, 17(4):794–799, 2001.

[7] V. Quintilla, M. Cazalens, R. Lecourt, and G. Lavergne. Experimental and numerical study to predict spray ignition. In *Proc. of ILASS-Europe 2001*, 2001.

[8] V. Schmidt, J. Sender, and M. Oschwald. Simultaneous observation of liquid phase distribution and flame front evolution during the ignition transient of a LOX/GH_2-combustor. *Journal of Visualization*, 4(4):305–396, 2001.

[9] J. C. Lasheras and E. J. Hopfinger. Liquid jet instability and atomization in caxial gas stream. *Annual Review of Fluid Mechanics*, 32:275–308, 2000.

[10] E. Villermaux, H. Rehab, and E. J. Hopfinger. *Breakup Regimes and Self-Sustained Oscillations in Coaxial Jets*, pages 393–401. Meccanica 29. 1994.

[11] J. A. Syage, E. W. Fournier, R. Rianda, and R. B. Cohen. Dynamics of flame propagation using laser-induced spark inition: Ignition energy measurements. *Journal of Applied Physics*, 64(3):1499–1507, 1988.

[12] I. P. Shkarofsky. Review of gas-breakdown phenomena induced by high-power lasers—i. *RCA Review*, 35:48–78, March 1974.