EXPERIMENTS AND SIMULATIONS OF LOX / CH_4 COMBUSTION AT HIGH PRESSURES

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Bakground

Recent interest in LOX / methane liquid rocket engines has arisen in Europe for RLV and / or large liquid booster application [1], [2]. “Two Stages To Orbit” launch systems with a reusable first stage using an oxygen / methane propellant combination and a second stage reusable or expandable based on the oxygen / hydrogen propellant combination are potential candidates for future transportation systems.

The VOLGA technology demonstration program is currently carried out between European industries (Snecma, EADS/ST, VAC and Techspace Aero), Russian industries (Energomash, CadB and Keldysh RC) and agency partners to maturate technologies for high performance reusable LOX / methane rocket engines [1]. In comparison to kerosene, methane offers several advantages: less soot production, better coking and cooling properties ... A first specification of the projected engine has been defined in order to quantify the objectives and to better focus the technologies (see figure 1, from [1]).

For preburner application, a research cooperation between Snecma, CNES and Keldysh RC was initiated on high pressure fuel rich combustion. Since 2002, activities were started to consolidate the design of efficient injection elements working with LOX / gaseous and liquid methane. In order to estimate the main functional performances in LOX / CH_4 injection, a set of experiments was carried out on the Onera Mascotte facility, in cooperation with the Keldysh Research Center. These investigations are directed at a fundamental understanding of the process and they also serve to guide the modeling of LOX / CH_4 combustion. These research activities were initiated as part of the Cnes / Snecma R&D program with specific cooperation between Onera, Cnes, CNRS and Snecma through the INCA initiative [3]. The main objectives are aimed at (1) Improving the knowledge of LOX / H_2 and LOX / CH_4 combustion, (2) Developing specific models of cryogenic combustion, (3) Generating quantitative ex-

perimental data for the validation of CFD tools.

Fig. 1. The VOLGA LOX / CH_4 Engine

Experimental configuration and diagnostics

Experiments are carried out on a cryogenic model scale combustor designated as Mascotte. This facility shown schematically in Fig. 2 was adapted to study the LOx/CH_4 combustion (version V04). The most notable changes with respect to the previous versions concern the fuel feed line, which was modified to allow injection of either hydrogen or methane. The heat exchanger, placed on the feed system, is powerful enough to liquefy the methane stream at a maximum mass flow rate of 250 g/s. This allows investigations of combustion conditions in which liquid methane is injected together with liquid oxygen [4]. The flow rate of oxygen ranges from 20 to 100 g/s. The flame spreads in a combustion chamber capable of withstanding pressures up to 10 MPa. This element has a square cross section of 50×50 mm^2. A visualization unit, with 75 mm long windows on its four sides, can be placed at any point along the chamber. The lateral windows are made of quartz, transparent to near UV radiation. In the present experiments, the visualization unit was located against the injection plane, providing a full view of the initial flame. A converging-diverging nozzle made of graphite defines the operating pressure.

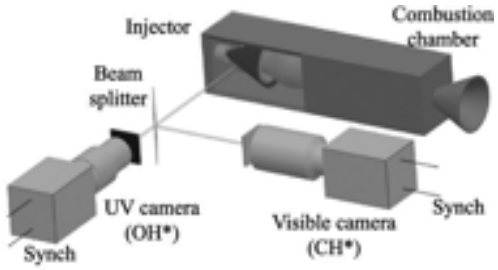


Fig. 2. Experimental configuration for OH* and CH* simultaneous emission imaging. A beam splitter is employed so that the two cameras visualize the region of interest.

The flame is formed by a coaxial injector fed with a low speed stream of liquid oxygen in the center surrounded by a higher speed stream of gaseous methane. Two operating conditions are considered. In one case the liquid oxygen is subcritical, in the second case it is transcritical (ie its temperature is below critical while its pressure is above critical). Gaseous methane is injected at room temperature in a supercritical state. The mass flow rate of oxygen remains constant at a value of 45 g/s. Consequently, the heat release is around 0.55 MW for all injection conditions if all the oxygen is consumed. The mixture ratio *E* (defined as the ratio of the oxygen and methane mass flow rates) is between 0.28 and 0.43 which is well below the mass stoichiometric value *s*=4 characterizing the oxygen/methane reaction.

Table 1: Selected operating conditions.

Name	$\dot{m}_{LOx}$ (g/s)	$\dot{m}_{CH_4}$ (g/s)	T_{inj}		π_r	
			O_2	CH_4	O_2	CH_4
G1	43.9	101.2	85	288	0.93	1.02
G2	44.4	143.1	85	288	1.11	1.22

Emission images from excited state OH ($A^2\Sigma$, denoted OH*) and CH ($A^2\Delta$, denoted

CH*) are recorded and averaged. The resulting average images are treated with an Abel transform to obtain a slice through the flame. This yields a distribution of the light intensity emitted by OH* and CH*. The flame position with respect to the LOx jet is obtained by averaging images recorded with backlighting. The flame structure is deduced from combined Abel transformed emission and backlighting images.

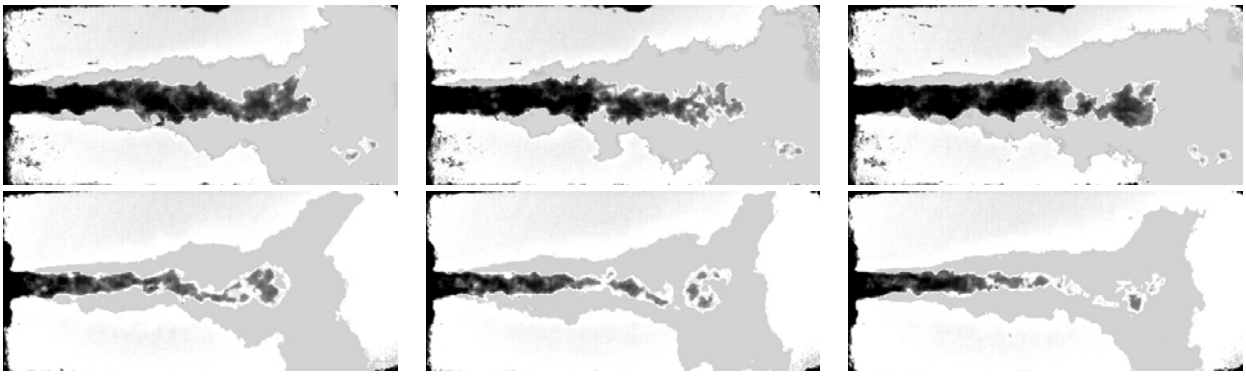


Fig. 3. Backlighting instantaneous images, t_{exp}=10 μs, f=2000 frames/second. The flame represented in a light gray is wrapped around the dark oxygen jet. Top : operating point G1. Bottom : operating point G2

Experimental investigation of LOX / CH_4 coaxial injection

Combustion of LOX / methane in rocket engine chambers operates at high pressure. As the chamber pressure exceeds the critical pressure of methane and / or oxygen (respectively 4. and 5.04 MPa), the propellants injected become transcritical or supercritical The vaporization process which prevails at low pressure when a propellant is injected in liquid form is replaced by mass transfer from the dense fluid to its lighter surroundings [5].

Comprehensive reviews of the state of knowledge in supercritical mixing and combustion were recently given by [6]. Depending on fluid properties and flow characteristics, two cases of study may be found. At subcritical chamber pressures, injected liquid jets undergo a classical cascade of processes associated with atomization. For this situation, inertial and surface tension forces promote the formation of a heterogeneous spray of ligaments, pockets and droplets which evolves continuously. When the chamber pressure and temperature approach the critical conditions, a jet of liquid undergoes a transcritical change of state. The fluid jet then exhibit many characteristics distinct from their counterparts at low pressure. Indeed, as surface tension and enthalpy of vaporization (Δh_v) become vanishingly small near the critical point, the interface separating the liquid and gas phases disappears. The fluid properties and their spatial gradients change continuously through the field. There are thermodynamic and transport anomalies near the critical point, a phenomenon commonly referred to as the near critical enhancement. As a result, volumetric changes induced by the unusual behaviour of the fluid near the critical point may play an important role in the structure of flame. Considering this, it is interesting to study the structure of the flame for several thermodynamic conditions of injection.

Injection conditions considered in the present article are summarized in Table 1. Operating point G1 corresponds to a subcritical injection of oxygen while point G2

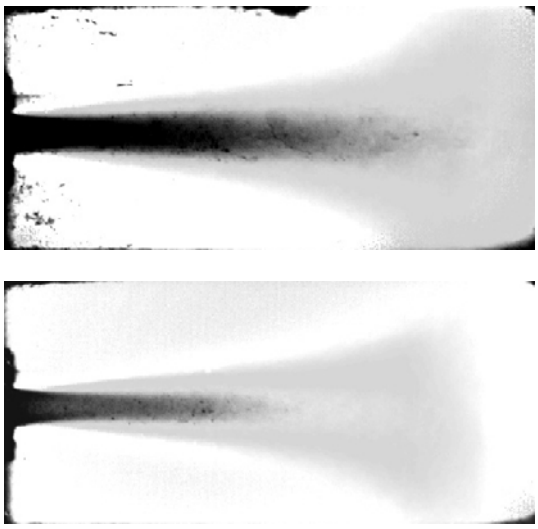


Fig. 4. Average images from 200 instantaneous backlighting images. Top: operating point G1. Bottom : operating point G2

jection of oxygen while point G2 defines transcritical injection conditions

Instantaneous backlighting images displayed in Fig. 3 show the cryogenic flame structure obtained when oxygen is injected as a subcritical or transcritical fluid in the chamber. The light emission from the flame, integrated on the line of sight appears in gray scale, while the instantaneous position of the liquid jet are described on a dark scale of grey levels. The average distribution of OH* light emission is obtained using an Abel inversion. The flame position with respect to the LOx jet may be obtained by averaging images recorded with backlighting. The central jet appears as a dark region while the flame is shown on a color scale around the jet (Fig. 6).

Light emission originates from an initially cylindrical envelope followed by an intense expanding zone. The reactive region closes abruptly before the end of the viewing window. There is a central zone corresponding to the oxygen jet devoid of luminosity, bounded by two narrow layers of light emission. The flame, stabilized on the lip of the injector, is wrapped around the oxygen jet. At a reduced pressure $\pi_r(O_2)<1$ (Fig. 4), the flame follows the surface of the cylindrical liquid jet for 5-6 d_{O2} before blooming rapidly with an expansion angle α of about 20°. When the reduced pressure exceeds one, $\pi_r(O_2)>1$ (Fig. 4), the flame expands more progressively up to 7 d_{O2} where its blooming is less pronounced (α=10°). The flame length L_f is shorter at $\pi_r(O_2)>1$ ($L_f = 11d_{O2}$) than at $\pi_r(O_2)<1$ where $L_f = 14d_{O2}$. The time averaged emission intensity in the near injector region is more important when oxygen is injected in a transcritical state in the chamber. The reduction of the flame length is associated with a shorter oxygen jet. The length and thickness of the internal core diminish as the chamber pressure increases ($L_{O2}=7d_{O2}$ at $\pi_r(O_2)>1$ while $L_{O2}=10$ d_{O2} at $\pi_r(O_2)<1$), but the observed changes may be due in part to the augmented mass flow rate of methane which induces a 40 % increase in methane flow velocity.

Modeling of LOx / CH_4 combustion at high pressure

As indicated in the previous section, when the critical mixing point is reached the surface tension and latent heat vanish and the injection process is governed by the turbulent mixing of real fluids. Theses fluids may have liquid-like density but gas-like properties. Real gas effects are then prevalent and must be accounted for by a well-chosen equation of state (Soave-Redlich-Kwong, Peng-Robinson or Benedict-Webb-Rubin for example) and adapted transport coefficients. For the combustion process of LOX / CH_4, the estimation of the characteristic scales shows that the chemical time is much smaller than the flow time and correspondingly that the Damköhler number is very large. One may then assume that the chemistry is infinitely fast and that burnt gas conditions are those can be approximated by those characterizing chemical equilibrium.

Following these assumptions of supercritical turbulent flow of real gases and infinite Damköhler number, a locally homogeneous flow model is used to calculate 2D and 3D reactive flows. This implies that both phases have the same velocity and are in a local thermodynamic equilibrium state at each point of the combustion chamber [7].

In a first step, all flow variables (density, species mass fraction, temperature) are determined by an equilibrium calculation of the mixture. The pressure is fixed and the Gibbs free energy of the mixture is minimized to estimate the fluid properties at equilibrium. It should be noticed that a real gas formulation is implemented in order to estimate thermodynamic functions pertaining to the different species. This is necessary to correctly predict the properties of methane and oxygen in the very low temperature regions, where real gas effects are important. All the thermodynamic variables ϕ are then characterized by a single scalar: the mixture fraction f.

As the flow is highly turbulent, the probability density function P of the mixture fraction is determined by solving a balance equation for the mean mixture fraction f and its variance $\widetilde{f}''^2$. Presuming a beta pdf for the mixture fraction, the mean density, mass fraction, temperature are estimated by the following expression [7]:

$$\tilde{\phi} = \int_0^1 \phi(f)\, P(f)\, df$$

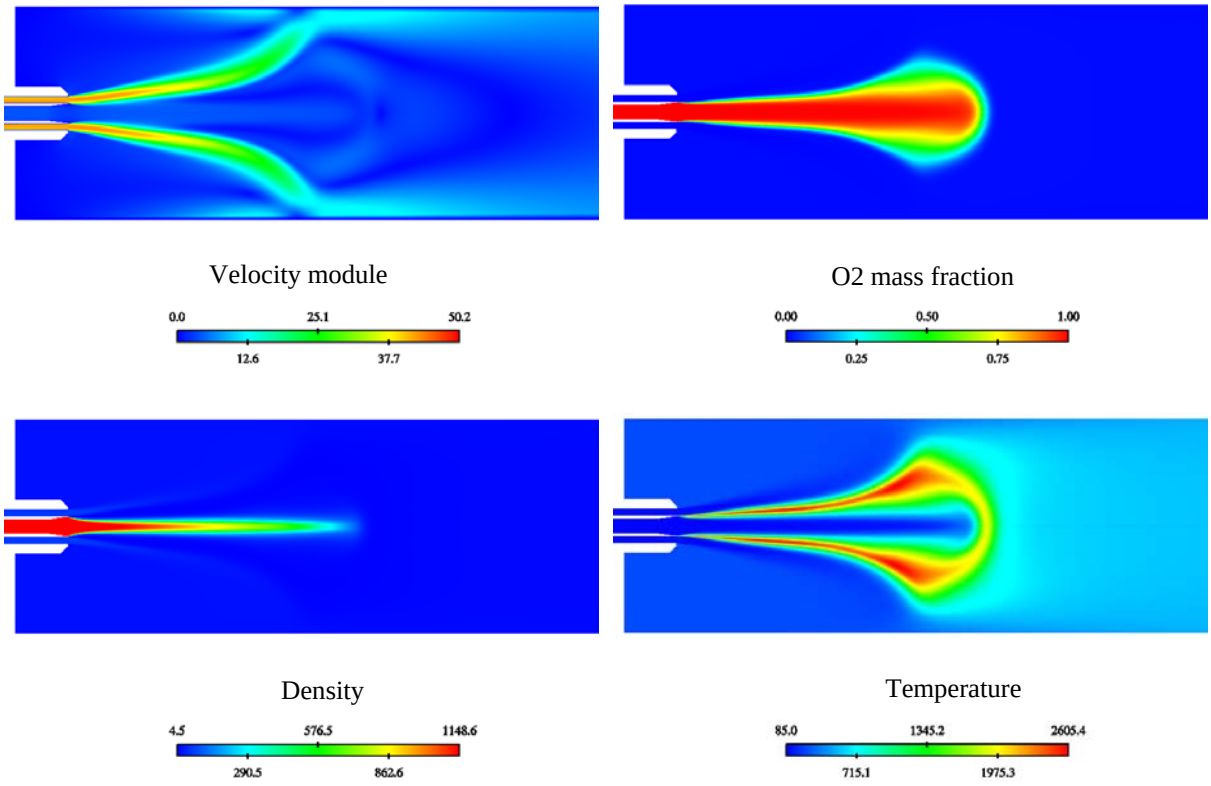


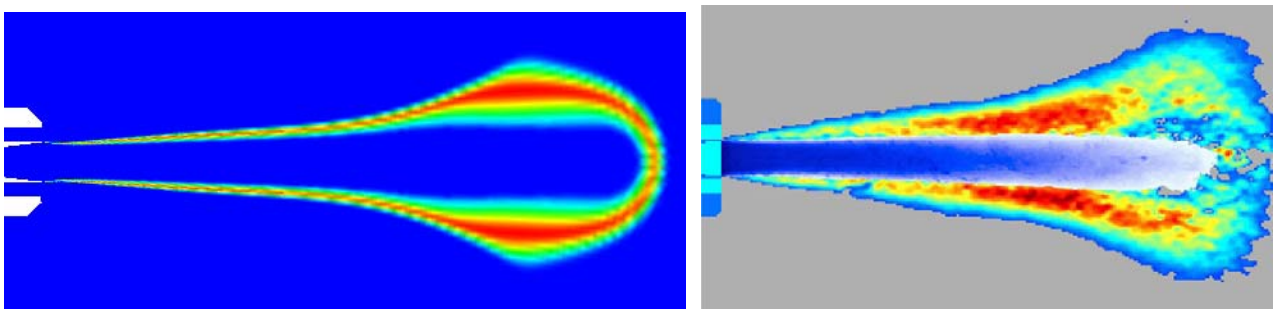
Fig. 5. Operating Point G1

Turbulence is represented by a k – ε model. Nevertheless, due to strong gradients of density in the flow, the classical k – ε formulation is not well suited to the prediction of mixing between fluids featuring widely

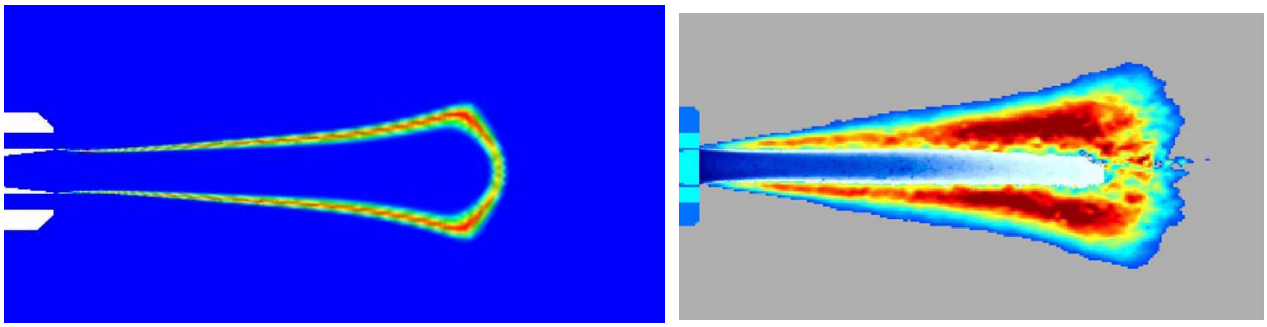
different densities. Based on DNS studies of mixing layers of fluids with large density ratios, correction terms were introduced in the modeling of the turbulent mass and momentum fluxes [8]. The Mascotte configuration and LOX / methane injection were calculated using the previous formulation. Both operating points were computed. A 2D axisymmetric mesh with 42 000 hexahedral elements was constructed. A typical result is shown in Fig. 5. The operating point G1 (chamber pressure of 4.6 MPa) is shown here. shorter and the O2 jet because of the heating of the LOX by the high heat release. From the mean temperature field, we can also infer that the mean flame front is rather close to the oxygen jet.

Figure 6 presents a comparison between the Abel transformed mean spontaneous OH* emission of the flame and the predicted mean OH radical. While the OH radical is also present in the burnt gases contrary to OH*, its maximum mean value may be used to identify the location of the mean flame front. For operating point G1, the flame features the characteristic shape of a “light bulb”. This feature is well recovered in the simulation and the length of the flame is also well estimated. For operating point G2, the calculated flame length is shorter and the expansion of the flame is also reduced and this is in agreement with experimental data.

The reduction of the flame angle and length is mainly due the increase of the methane jet velocity. A detailed comparison of the two results of calculations shows an enhancement of the mixing region on the downstream side of the oxygen jet. Strong recirculation regions can be identified close to the tip of the oxygen jet. For operating point G2, these recirculation regions have a significant influence driving the mixing of the heated propellants and burnt gases.



Comparison of the measured Abel Tranformation of the OH* emission
and the predicted OH radical concentration for operating point n°1



Comparison of the measured Abel Tranformation of the OH* emission
and the predicted OH radical concentration for operating point n°2

Fig. 6. Comparison between the predicted and observed mean flame front (all figures at the same scale)

Conclusion

This article discusses experimental data and numerical calculation of liquid oxygen/gaseous methane cryogenic flames. The flame structure is investigated in two typical situations. In the first case, the liquid oxygen is injected in subcritical state. In the second case, the pressure is above critical and the oxygen stream is transcritical. The oxygen flow is surrounded by a gaseous stream of methane. Backlighting and spontaneous emission are used to examine the flame structure. Two types of flames are observed. In one case, the flame features the shape of a "light bulb". In a second situation, the flame takes a jet like shape and spreads in the near vicinity of the liquid oxygen jet.

Calculations are carried out using a turbulent combustion model based on a locally homogeneous flow description of the injected liquid oxygen. Real gas thermodynamic properties are used to represent the evolution of the liquid jet. A presumed PDF in combination with local equilibrium assumption provides the mean flow variables. The calculations suitably retrieve the two flame structures observed in the experiment.

Acknowledgements

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References

[1] Beaurain A., Souchier A. Demonstration for future LOX/CH4 rocket engine. *Presented at AAAF Meeting, 13-17 may 2002, Versailles, France*.

[2] Pempie P. et al. *LOX/methane and LOX/kerosene high thrust engine trade-off*. 37th JPC, AIAA 2001-3542, 2001.

[3] Zurbach S., Thomas J.L., et al. *Recent advances on LOX / methane combustion for liquid rocket engine*. 38th JPC, AIAA 2002-4321, 2002.

[4] Singla G., Scouflaire P., Rolon J., Candel S. Transcritical Oxygen/Transcritical or Supercritical Methane Combustion, *Proceedings of the combustion institute*, 30th, 2921 pp, 2005.

[5] *Combustion dans les Moteurs fusées*. Cnes, 2001, Cépaduès-Editions.

[6] Bellan J. Supercritical (and Subcritical) Fluid Behavior and Modelling: Drops, Streams, Shear and Mixing Layers, Jets and Spays, *Progress in energy and combustion science*, pp 329, 2000.

[7] Zurbach S., Thomas J.L., et al. *LOX / methane studies for fuel rich preburner*. 39th JPC, AIAA 2003-5063, 2003.

[8] Silvani X., Demoulin F.X. et al. Simulation numérique et modélisations des couches cisaillées à grand rapport initial de masse volumique. Page 101-114 in reference [5]