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INFLUENCE OF LOX INJECTOR WALL THICKNESS ON ATOMIZATION AND COMBUSTION OF LOX/CH_4 SPRAYS

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ABSTRACT This paper summarizes the results of a liquid oxygen (LOX)/methane (CH_4) test campaign at the micro-combustor M3 in DLR Lampoldshausen; the microcombustor has complete optical access and is provided with a single coaxial injector. These experiments are a first attempt to show experimentally the influence of the LOX injector wall thickness on the atomization and combustion behaviors. Two LOX injector wall thicknesses (0.4 and 0.6 mm) have been investigated. At injection, the Weber number ranged between $2.0 \cdot 10^3$ and $1.2 \cdot 10^4$, the fuel to oxygen momentum flux ratio J between 0.1 and 0.7. The combustion chamber pressure ranged between 0.15 and 0.3 MPa. A high speed CCD camera with 4 kHz frame rate is used for shadowgraph, whereas an ICCD camera with 9 kHz frame rate is adopted for OH imaging in the UV range. In the thicker wall injection configuration, atomization is found to be more effective and combustion efficiency is enhanced, because of a more stable combustion, occurring nearer to the injector.

Keywords: Methane, Coaxial injector, Injector wall thickness, Liquid jet, Lift-off distance, Combustion efficiency

1. INTRODUCTION

In the last few years there has been an increasing interest in green propellants like hydrocarbons that likely will substitute hypergolic and solid propellants in the next future. Compared to hypergolic and solid propellants [1], hydrocarbons are environmentally friendly and require much less safety measures in handling operations; hydrocarbons are less chemically aggressive and this results in higher safety for engine components.

Among hydrocarbons, CH_4 seems to be particularly promising for several reasons: the couple LOX/CH_4 has the highest specific impulse [2]; considering the use of the fuel propellant in the cooling system, CH_4 has the best cooling capabilities and lower coking attitudes [3]. Compared to hydrogen, CH_4 provides higher density thus higher thrust-weight ratio, has much lower costs and it is easier to handle because of higher critical temperature.

Several test campaigns investigating cryogenic LOX/CH_4 spray combustion have been performed at M3 test facility at DLR Lampoldshausen [4, 5]: in the last test campaign the focus is moved to the near field zone that means the zone near the injector. Some authors have pointed out the importance of the LOX injector wall thickness: this geometrical parameter can affect the instability wavelength that occurs in the liquid jet [6] and therefore the process of atomization. Other authors [7] have shown how it may have an important role in the stabilization of the flame near the injector. Therefore it is worthwhile to understand if and how the LOX post thickness can affect the atomization and combustion processes when liquid oxygen and gaseous methane are injected through a coaxial injector.

2. EXPERIMENTAL SETUP

The experiments have been performed at the M3 test facility in DLR Lampoldshausen, The test facility has a horizontally mounted combustion chamber with uncooled optical quartz windows for the complete optical access in the chamber. The combustion chamber is equipped with a single coaxial injector. The coaxial annulus diameter can be varied in order to achieve different injection conditions. The LOX post inner diameter is fixed at 1.2 mm. Two LOX post thicknesses were used: 0.4 and 0.6 mm. The ignition source is provided by a glow plug fed by gaseous hydrogen and gaseous oxygen.

Tests last 2 seconds: steady conditions are reached after 300 ms; after this time it is also highly reasonable not to consider the influence of the pilot flame and of nitrogen purge (made before each test) on the main flame. Images and data are analyzed after this time so that, in this paper, we refer to steady conditions.

The diagnostic set-up is composed of sensors distributed along the whole test bench: in particular, piezoelectric sensors measured the combustion chamber pressure and thermocouples were used for the wall temperature of the combustion chamber.

The wide quartz windows allow using optical diagnostic techniques. The spray has been visualized by shadowgraph with Z-configuration set up. Images are recorded with a high-speed CCD camera (FASTCAM Ultima 1024) with high acquisition rate (4 kHz): the resolution is approximately 0.42 mm/pixel. A high speed intensified CCD camera (Photron Ultima I^2) fitted with a Nikkon UV objective and an OH filter has also been used for recording the OH radical emission; the acquisition rate is 9 kHz and the resolution is around 0.50 mm/pixel.

OH emission and shadowgraph images are processed through several scripts (two samples are shown in Fig. 1 and 2). Each frame of any single test has been analyzed in order to detect the position of the flame base with respect to the injector (lift-off distance), the flame spreading angle and the length of the liquid jet (that means the distance from the injector where the continuity of liquid jet is broken). Since the cameras record the emission of OH radicals and the liquid presence through the line of sight, uncertainties arise during the procedure: it is in fact possible that flame structures out of the focal plane are regarded as flame edge or liquid lumps out of the focal plane can cover the actual break-up region. However, the high acquisition rate, and thus the large number of images recorded, provides a sufficient statistics so a certain degree of confidence on the overall trend is reasonable.

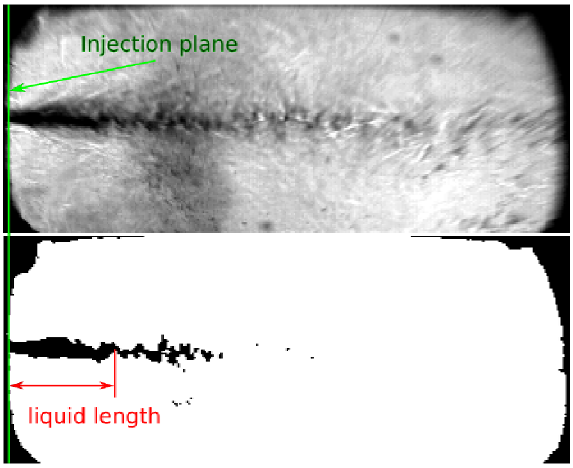

Fig. 1: sample of a shadowgraph image and its relative transformation: liquid length is considered as the distance from the injection plane at which the initial jet is reduced to 1 pixel

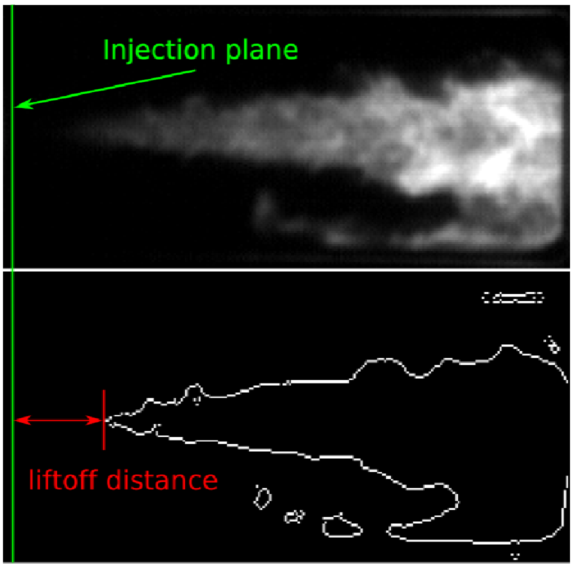

Fig. 2: sample of OH emission image and its relative transformation through the "edge" function

3. TEST MATRIX

The comparison between the two LOX post thicknesses is made on the base of similar Weber numbers, fuel to oxygen momentum flux ratios *J*, combustion chamber pressure. ROFs can be also reasonably considered similar. In Fig. 3 test conditions are presented in a *J*-Weber number graph. The error bars in this and in all following figures represent the fluctuations (standard deviation) of each parameter with time during the hot flow. Fluctuations in the injection parameters *J* and *We* during combustion are mainly due to the combustion chamber pressure fluctuations.

For all tests, combustion chamber pressure is limited between 0.15 MPa bar and 0.3 MPa to avoid dangerous pressure peaks during the ignition. This poses some limitations on Weber and *J* numbers, too: Weber number varies between $2.0{\cdot}10^3$ and $1.2{\cdot}10^4$, *J* number varies between 0.1 and 0.7. Tests were planned to be run at ROF=3.4: this value optimizes the vacuum specific impulse when the combustion chamber pressure is 13 MPa, and is therefore representative of a full-scale liquid rocket engine combustion chamber.

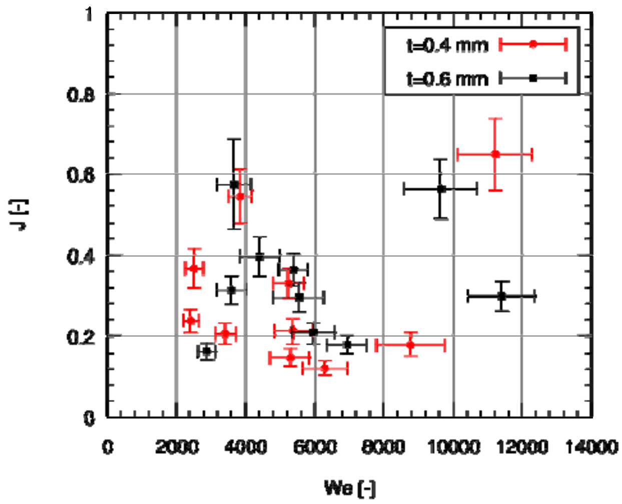

Fig. 3: test matrix

4. ATOMIZATION

Referring to Fig. 4, one can see that for *J* numbers lower than 0.3 the thicker post gives best results in terms of liquid length: the jet is broken in a shorter way. Going to higher *J* numbers no difference is found: similar liquid lengths are found using the two thicknesses. We can reasonably say that the liquid length is less sensible to *J* number if the thicker LOX post is used. In Fig. 5 and 6, two similar tests with the two different thicknesses are shown: the difference in terms of atomization can be clearly pointed out.

The order of magnitude of the data is quite similar to the one predicted by Villermaux in [6]:

$$\frac{L}{d_0} = AJ^{-1/2} \tag{1}$$

with A=6-8 and where d_0 is the inner diameter of the LOX post (fixed at 1.2 mm)

Moreover, setting the prefactor A from 8 to 12 leads Eq. (1) to represent our data in a significant way. This difference in the prefactor can be due to the role of the combustion, to the confining effect recirculation zone and to evaporation that may affect the atomization process.

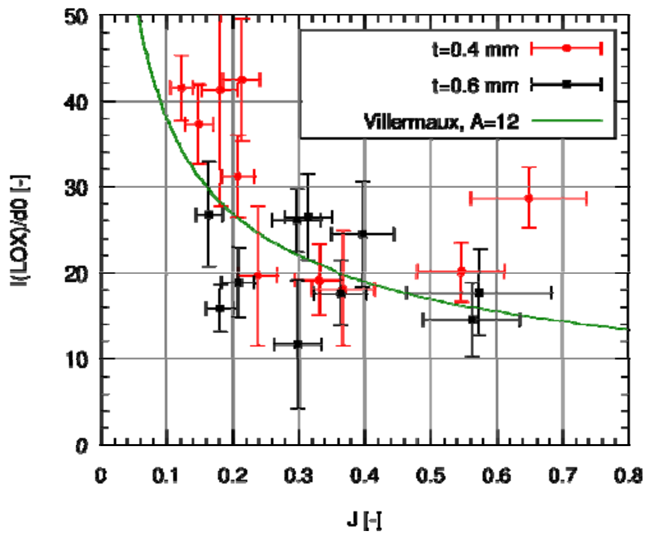

Fig. 4: liquid length vs. *J*

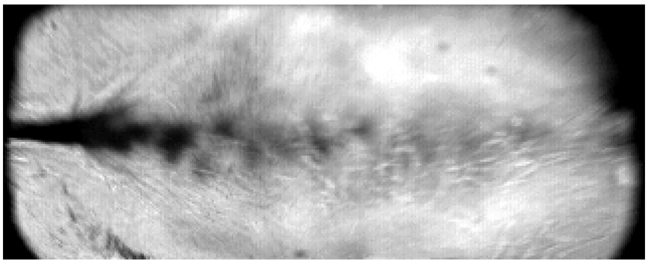

Fig. 5: *J*=0.18, *We*=6900, p_c=2.34, *t*=0.6 mm

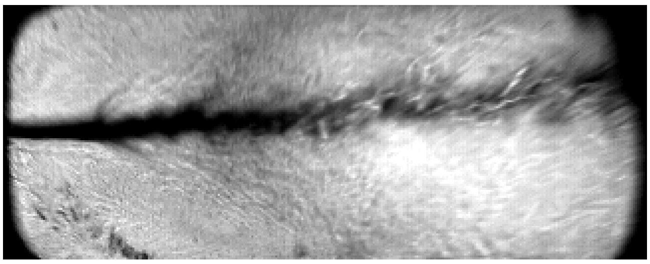

Fig. 6: *J*=0.15, *We*=5300, p_c=2.21, *t*=0.4 mm

Considering the relation with the Weber number (Fig. 7), we can see that atomization is still different with the two LOX posts. Again, liquid length is quite insensible at Weber number (or it slightly decreases) if the thicker post is used, while huge variations are obtained with the thinner post.

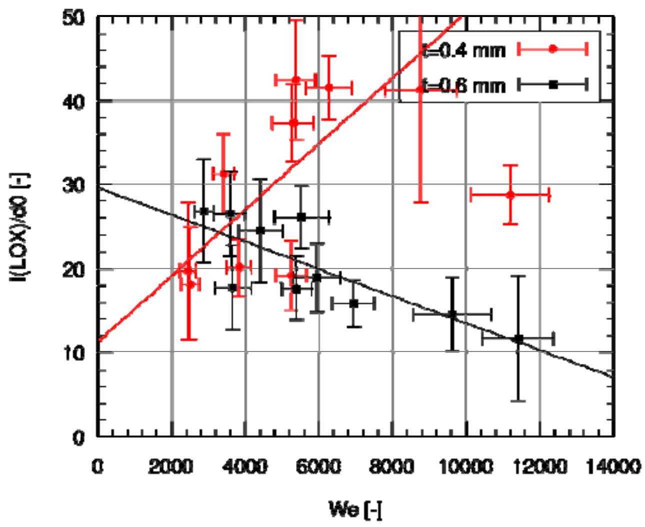

Fig. 7: liquid length vs. Weber number

5. COMBUSTION

As first, results about the lift-off distance are shown, that means the distance between the flame base and the injector. No particular differences can be seen between the two thicknesses. Nevertheless, it is apparent that atomization plays an important role in anchoring the flame near the injector: considering the 0.4 mm LOX post, for J<0.6 we see in Fig. 8 a decreasing lift-off distance with increasing J. For this plot the single data point at J=0.65 shows for unresolved reasons a significant deviation from the trend of all other data points in respect to the intact core length (Fig. 4) as well as for the lift-off distance (Fig. 8). For the 0.6 mm post, no significant trend for the dependence of the lift-off distance on J is seen.

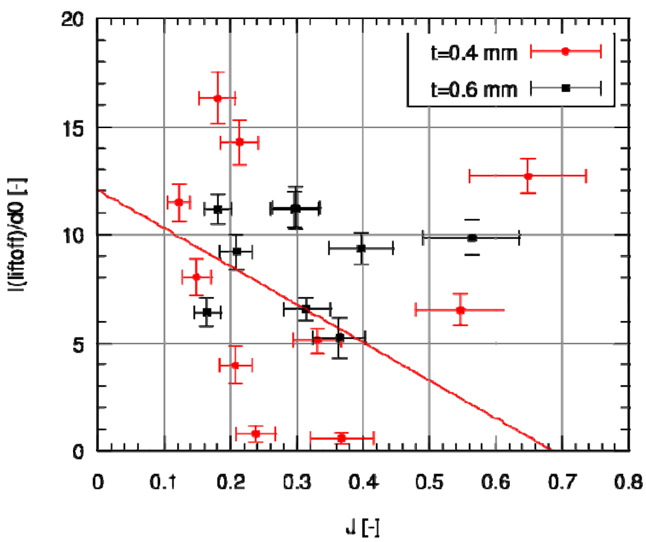

Fig. 8: lift-off distance vs. *J*

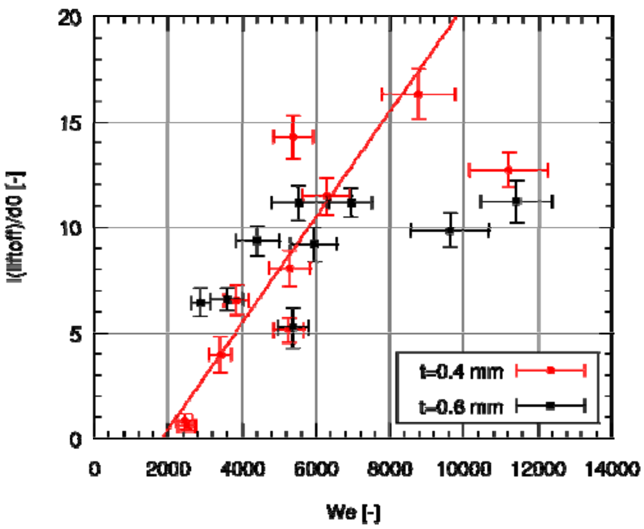

Fig. 9: lift-off distance vs. Weber number

For both LOX-post thicknesses, an increase of the lift-off distance with the *We* number is observed (Fig. 9), a dependency less pronounced in the case of the thicker post of 0.6 mm.

Eventually, it is interesting to note that in all cases the lift-off distance is shorter than the break-up length (Fig. 10): this means that the flame attaches in a zone where atomization is not complete at all; therefore, evaporation of LOX from the intact jet and its mixing with the methane recirculation zone downwards the post lip play a significant role. For the 0.4 mm post, a good correlation of the intact core length and the lift-off distance is observed. The data point for J=0.65 is well grouping with the other data. For the 0.6 mm post, no significant correlation between liquid core length and lift-off distance is visible.

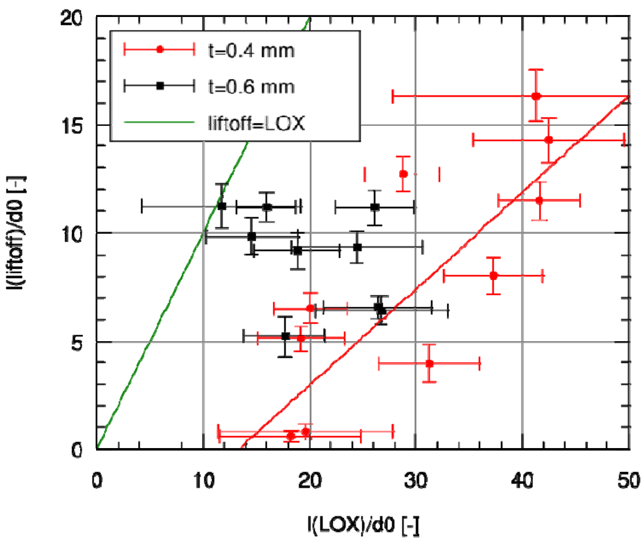

Fig. 10: lift-off distance vs. liquid length

The mixing of propellants can be favored with the thicker post because vortexes detaching from the post lip are bigger: this can explain why with the thicker post the lift-off distance is quite independent from the typical parameters of atomization *J* and Weber.

A parameter that shows the influence of the post thickness is the horizontal intensity center position of the OH emission. An intensity center near to the injector shows a flame developing early in the combustion chamber. Fig. 11 shows the horizontal intensity center non-dimensional distance from the injector head with respect to the Weber number. Nearly all tests with the thicker post of 0.6 mm show a flame nearer to the injector head than those with the thinner post of 0.4 mm. The flame is also found to be more stable with the thicker injector post, as can be clearly seen from Fig. 12. There, the standard deviation of the intensity center position indicates the amplitude of the horizontal oscillations of the flame during each test.

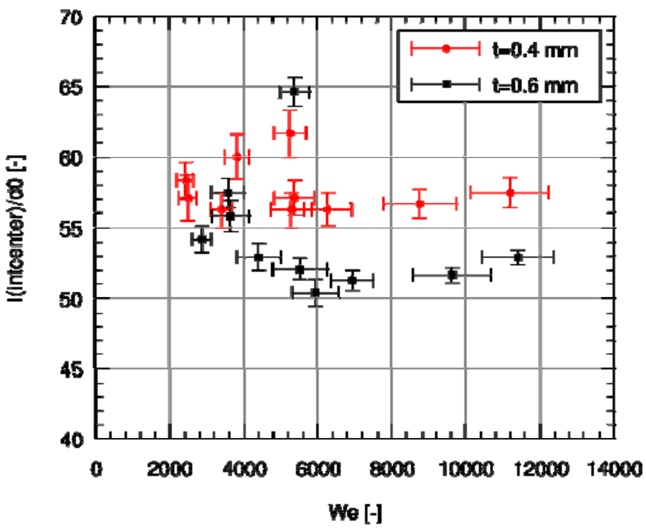

Fig. 11: Intensity center vs. Weber number

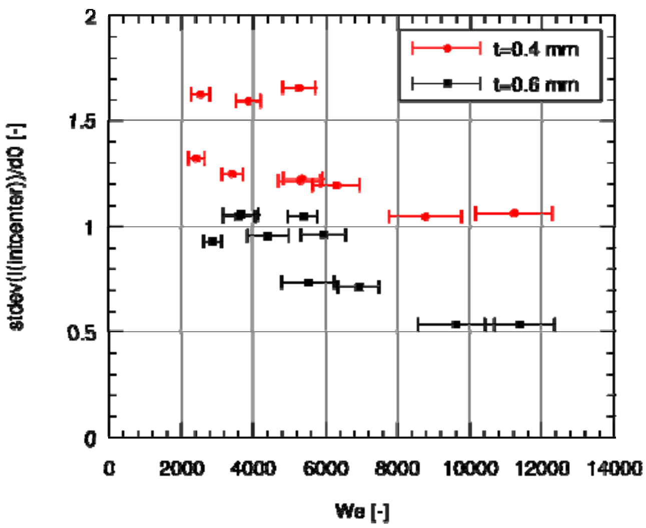

Fig. 12: Intensity center standard deviation vs. We

As no relation is found between lift-off distance and pressure or ROF, we can conclude that the anchoring of the flame is essentially dependent by what happens near the injector (evaporation from the intact liquid jet, mixing).

Another important parameter is the flame-spreading angle: it is an indicator of the spreading of fresh propellants in the combustion chamber. The flame angle on the average image of each test was calculated (Fig. 13): in fact considering the single frames, big uncertainties arise because the edge of the flame is irregular. Again, no particular difference is found using the two LOX posts, but there is a good linear relation between the flame angle and the Weber number (Fig. 14).

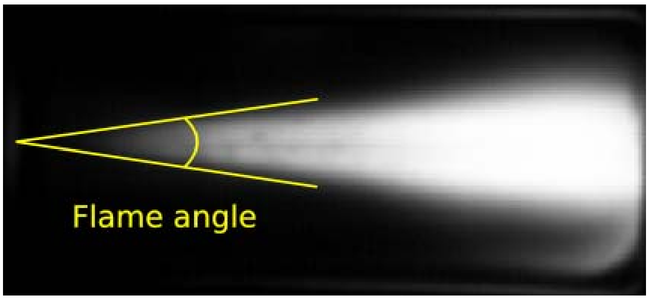

Fig.13: sample of an average image of OH emission: the edge is well defined and the flame angle is easy to be detected

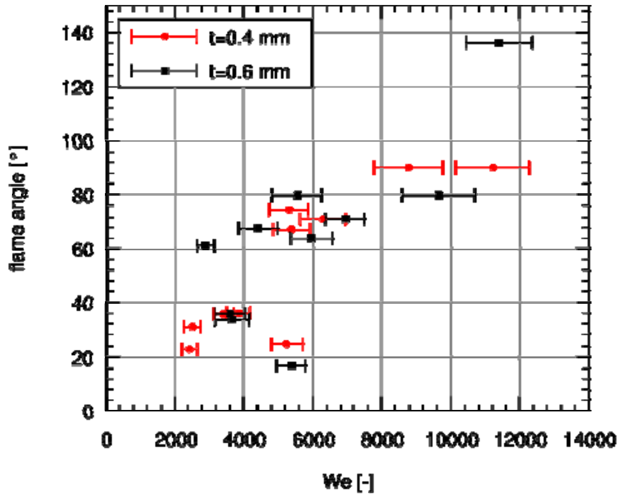

Fig. 14: flame angle vs. Weber number

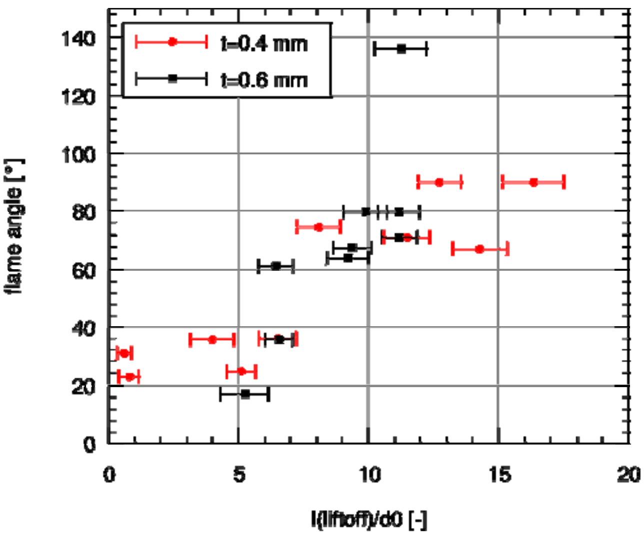

Fig. 15: flame angle vs. lift-off distance

Moreover, a linear relation is found between the flame angle and the lift-off distance (Fig. 15): this means that we cannot obtain in the same moment a good anchoring of the flame near the injector and an effective spreading of propellants in the combustion chamber.

Eventually, as expected, if the flame angle increases the combustion chamber wall temperature increases due to the higher heat transfer from the reaction zone to the wall.

The last important parameter examined in the present work was the characteristic velocity $c*$:

$$c* = \frac{p_c A_t}{\dot{m}} \quad (2)$$

In particular following quality factor was considered:

$$\xi_{c*} = \frac{c*}{c*_{id}} \quad (3)$$

the ratio between the actual $c*$, obtained with the data from the tests, and an ideal $c*$ ($c*_{id}$) computed by Gordon-McBride chemical equilibrium software CEA [8] considering the measured mass flows of propellants. This factor is a measure of combustion efficiency.

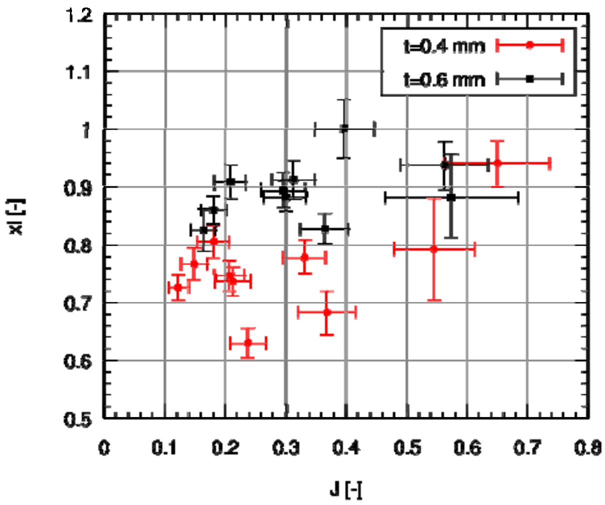

Fig. 16: ξ_{c*} vs. J

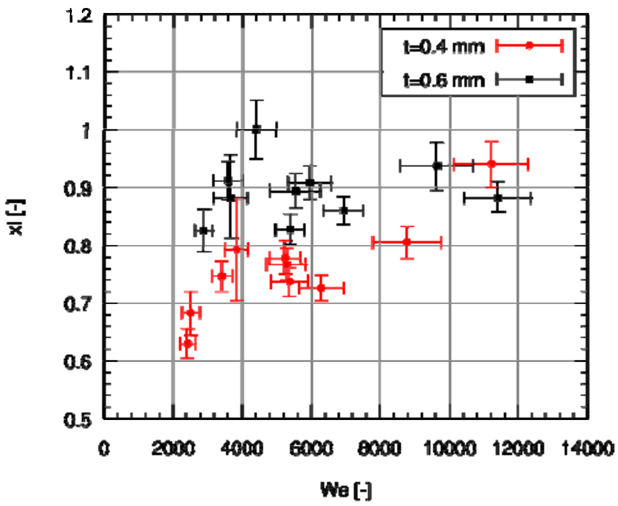

Fig. 17: ξ_{c*} vs. Weber number

It is interesting to observe that, considering any parameter, this ratio is higher in all cases (except one) with the thicker post (Fig. 16 and 17): the combustion process is more effective if the thicker post is used.

This can be due to the better atomization (at high Weber and low J) but actually no relation is found between ξ_{c*} and the liquid length. Another possible explanation is the better mixing of fresh propellants due to the wider shear layer generated by the thicker post: in this case the geometry of the injector plays an important role.

No relation is found between the combustion efficiency ξ_{c*} and the combustion chamber pressure (increasing pressure means increasing the reaction velocity): this tells us that in such tests, the combustion processes are more affected by the big recirculation zone of combustion products than by other typical parameters, i.e. pressure and ROF.

6. CONCLUSIONS

Experimental results of LOX/CH_4 spray combustion have been shown. The aim of this test campaign was the study of the influence that the LOX post thickness may have on atomization and combustion processes. Two different thicknesses (0.4 mm and 0.6 mm) were used. The results are summarized here:

- Using the thicker post, atomization is quite independent from typical parameters like J and Weber; with the thinner post, the liquid length increases at low J numbers and high Weber numbers. We can conclude that for these conditions, atomization is more effective if the thicker post is used;
- There is not a clear relation between the flame lift-off distance and J and Weber, when the thicker post is used; with the thinner post, the lift-off distance increases when the liquid length increases, too.
- The flame intensity center lies nearer to the injector and is more stable for the thicker post, for the whole test matrix investigated.
- Considering all tests, we could see that flame attaches in a region where the liquid length is still intact: therefore other processes (i.e. evaporation, recirculation zone) must be considered in the anchoring of the flame.
- No particular dependence on LOX post thickness was found for the flame angle: similar values were obtained for both the injectors and a good linear relation between flame angle and Weber was found. The same linear relation is found between the flame angle and the lift-off distance: therefore we cannot obtain at the same time a good anchoring of the flame and a good spreading of propellants in the combustion chamber.
- Considering the combustion efficiency, with the thicker post higher values in terms of characteristic velocity ratio were always obtained. No relation was found between this ratio and the studied parameters. ξ_{c*} seems to be unrelated with the atomization efficiency, i.e. liquid length. Therefore one possible explanation of the higher combustion efficiency with the thicker post is the bigger recirculation zone behind the LOX post lip: it can favor a more effective mixing of fresh propellants reducing the characteristic time of reaction.

7. ACKNOWLEDGMENTS

The support of Dr. Liu Hong (Northwestern Polytechnic of China) to the campaign and of Prof. Luigi DeLuca to Andrea Fusetti is gratefully acknowledged here.

8. NOMENCLATURE

A_t	area of exit nozzle	[m^2]
$c*$	characteristic velocity	[m/s]
d_0	inner LOX post diameter	[m]
$J = \dfrac{\rho_{CH4} u_{CH4}^2}{\rho_{LOx} u_{LOx}^2}$	fuel to oxygen momentum ratio	
L	liquid length	[m]
$\dot{m}$	propellant mass flow	[kg/s]
p_c	combustion chamber pressure	[MPa]
ROF	fuel to oxygen mass flow ratio	
u	velocity of propellants	[m/s]
$We = \dfrac{\rho_{CH4}(u_{CH4} - u_{LOX})^2 d_0}{\sigma}$	Weber number	
x	lift-off distance	[mm]
ρ	density of propellants	[kg/m^3]
σ	surface tension of LOX	[N/m]

9. REFERENCES

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