

ATOMIZATION AND COMBUSTION IN LOX/H₂- AND LOX/CH₄-SPRAY FLAMES

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ABSTRACT. Propellant injectors are for several reasons of central importance for the performance of rocket combustors. Existing correlations used to guide the design of injectors are mainly based on experimental and theoretical investigations of non-reacting sprays. Furthermore most of the experiments have been done with substitute fluids of significantly different properties as compared to liquid oxygen. Experimental investigations of reactive sprays with original propellants, liquid oxygen as oxidizer and hydrogen and methane as fuels, are presented and the influence of the injection conditions and of the fuel on the atomization and spray flame is discussed.

INTRODUCTION

In liquid rocket propulsion H₂/O₂-combustion delivers the highest specific impulse, i.e. momentum per mass of propellant. Hydrogen and oxygen are therefore the propellants of choice in terms of thrust performance. Especially for high power booster engines however other performance characteristics have to be considered as well, as for example mass of tank structures for cryogenic propellants and evaporation losses of liquid hydrogen in the run-tanks. Furthermore the toxic potential of storable propellants like the hypergolic MMH/NTO or solid propellants is motivation to look for non-toxic propellant substitutes. For this reason in the last few years hydrocarbons have been taken into focus in Europe as fuels for rocket propulsion. Among these, CH₄ and Kerosene are particularly of interest. The main expected advantages using hydrocarbons are the high propellant density, reduced handling effort, and reduced safety precautions.

The technology of propellant injection is central for optimal rocket combustor performance due to its effect on liquid fuel atomization, mixing, combustion, and thermal and chemical load on combustor walls. Propellant injectors are key components controlling by a major part efficiency and stability of combustion. In main combustion chambers oxygen is injected in its liquid state, whereas the fuel - used for regeneratively cooling the combustor walls - is injected in the gaseous state. The standard injection element is the shear co-axial injector with the liquid injected through the central tube and the gaseous fuel through the annular slit.

For cold flow coaxial injection there are numerous experimental and theoretical investigations ([1-7]). Not very much data with systematic parameter variation for reactive sprays are available. Therefore there is need for proven injector design rules to minimize costs for expensive manufacturing and qualification tests during a development program. Unfortunately the predictivity of models for liquid fuel atomization, droplet evaporation, mixing and turbulent combustion are far from reliable outside the range of injection and combustion chamber conditions where these models have been adjusted and qualified. Thus despite the prominent role of the injection process, the complexity of atomization and spray combustion does not allow to predict injector performance from basic principles, injector design is based on empirical correlations.

At DLR Lampoldshausen work has been initiated to improve the knowledge and understanding of propellant injection and spray combustion for LOX/hydrocarbon fuels. The focus today is on methane. Although the trade off between methane and kerosene in respect to the overall system

performance is not straight forward, methane is chosen for the basic investigations due to its relatively simple kinetics and well defined composition as compared to kerosene.

There is a huge data base on LOX/H₂-combustion in Europe. It is worthwhile then to compare LOX/CH₄ to LOX/H₂. One objective of the investigations is to prove whether concepts from LOX/H₂-injector design can be transferred to LOX/HC injection. That there may be limitations can be supposed when comparing the thermo-physical properties. Assuming a chamber pressure of 6MPa and H₂-injection temperatures of 120K and 280 K for hydrogen and methane respectively some properties are listed in Table 1. It can be seen, that at typical injection conditions H₂ is far in the supercritical region and shows in a good approximation ideal gas behaviour. Methane however is near critical and some properties will show significant deviations from ideal gas behaviour. The density of methane is about 4 times, the thermal conductivity about 0.3 times that of H₂ at typical injection conditions. The laminar flame speed for CH₄/O₂ is about a factor of 2.5 below the value for H₂/O₂, which may be of importance for flame propagation and stabilization during the ignition transient and flame anchoring phenomenology at stationary conditions. Furthermore the remarkable difference in ignitability in the fuel rich limit has to be pointed out in this context. Especially the difference in these properties characterizing the combustion behaviour motivates to assume differences in the ignition characteristics of methane and H₂.

Table 1
Thermo-physical properties of propellants
(injector exit conditions: P=6MPa, T=120K for H₂, T=280K for CH₄)

	O ₂	CH ₄	H ₂	
critical temperature	154.6	190.5	32.9	[K]
critical pressure	5.04	4.60	1.28	[MPa]
reduced pressure P/P_{crit}	1.19	1.30	4.69	
reduced pressure T/T_{crit}	0.65	1.47	3.65	
density @ injector exit conditions		47.3	11.7	[kg/m ³]
viscosity @ injector exit conditions		12.0	4.94	[μPa·s]
specific heat @ injector exit conditions		43,89	32.3	[J/mol·K]
thermal conductivity @ injector exit conditions		0.038	0.113	[W/m·K]
laminar flame velocity @ ambient		3.93	10.7	[m/s]
ignitability limits		5.1-61	4-94	[Vol %]

CO-AXIAL INJECTION IN ROCKET ENGINES

Co-axial injectors The commonly used injector type for the injection of a gaseous and a liquid propellant component is the co-axial injector as shown in Fig .1. The liquid component is injected through the central post. Near the exit the post may be tapered to reduce the flow velocity of the liquid at the injector exit. The gaseous component is injected through the annular slit. The gas velocity is typically an order of magnitude above that of the liquid.

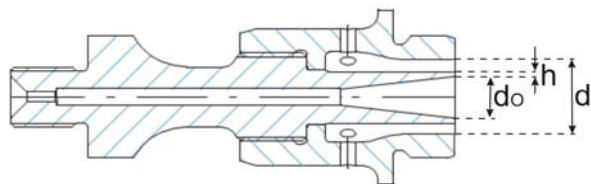


Figure 1: Sketch of a coaxial injector

Atomization process in cold flow sprays The atomization process is a complex interaction of several forces. The shear between the high speed gaseous co-flow and the liquid central jet induces surface instabilities. The surface tension leads to the formation of liquid sheets and ligaments which then disintegrates in droplets. The viscosity and the inertia of the liquid have a damping effect on the disintegration dynamics. The relative relevance of these forces are expressed by non dimensional numbers:

$$We = \frac{\rho_{fuel} (v_{fuel} - v_{ox})^2 d_{ox}}{\sigma} \quad J = \frac{(\rho v^2)_{fuel}}{(\rho v^2)_{ox}} \quad R_V = \frac{v_{fuel}}{v_{ox}} \quad Oh = \frac{\sqrt{We}}{Re}$$

Commonly the Weber-number We and the momentum flux ratio J [6, 7] are assumed to be important control parameters, however also the Ohnesorge-number Oh is applied to classify the atomization regime in cold flows [9] and the velocity ratio R_V is a parameter used to scale injector performance.

The relative importance of these forces is strongly depending on injection conditions, physical properties of the propellants and the local flow field in the spray. This is the reason why even in non-reacting sprays correlations derived from experimental results do only show a rough agreement in what property increases or decreases e.g. droplet size [8]. An extrapolation of correlations obtained in cold-flow tests with water to cryogenic conditions with the low level of surface tension and viscosity of liquid oxygen is therefore highly unreliable. Due to the properties of liquid oxygen liquid Reynolds-numbers

$$Re_l = \frac{\rho_{ox} v_{ox} d_{ox}}{\mu_{ox}}$$

are generally one order of magnitude below representative conditions ($Re \approx 10^5 - 10^6$) when using substitute fluids like water. To be closer to representative conditions test have to be done with liquid oxygen or substitute fluids of similar properties, e.g. liquid nitrogen.

Interaction of combustion with spray formation The major question however is whether and how results from cold flow tests can be transferred to hot fire conditions. In fig. 2 an image of the emission of the OH-radical in the flame of coaxial LOX/H₂-spray at 6 MPa is shown. It is clearly seen that the flame anchors in the recirculation zone at the lip of LOX-post. As a consequence the LOX-jet is separated from the annular high speed gas flow by a turbulent mixing layer of hot reaction products and reactants.

Combustion in hot fire tests has therefore several consequences for the atomization process. The liquid oxygen jet is not directly exposed to the aerodynamic forces of the annular gaseous flow, but these forces have to be transmitted by the turbulent mixing layer of reaction products and evaporated oxygen to the liquid surface. As a consequence the spray formation may happen under the conditions of a different atomization regime as compared to cold flow conditions.

In hot fire tests the evaporation rate of liquid oxygen is increased as compared to cold flow tests. Visualization of LOX-sprays at identical injection conditions in cold flow and hot fire tests for instance clearly shows the fast evaporation of the small LOX-droplets in the reactive flow.

Flame anchoring at the LOX-post as shown in fig. 2 has been consistently observed for LOX/H₂ injection. However with a different fuel type a lifted flame, anchoring in the turbulent mixing layer of evaporated LOX and gaseous fuel is also a possible flame anchoring mechanism (see fig. 3). In this case the interaction of combustion with the spray formation process starts downstream the flame anchoring position.

From this discussion the limitations of cold flow tests in predicting hot fire atomization becomes evident. When discussing the role of the fuel properties on the atomization process it is not enough to focus on the physical properties of the fuel like its density, injection velocity etc., but the kinetic

properties of the reaction partners, and the turbulent transport properties of the reactants and products have to be taken into regard as well. Juniper and Candel [2] e.g. derived from numerical investigations that the non-dimensional quantity $\psi=h/\delta_F$, the ratio of LOX-post thickness h and the flame thickness δ_F is a control parameter for the flame stabilization behaviour.

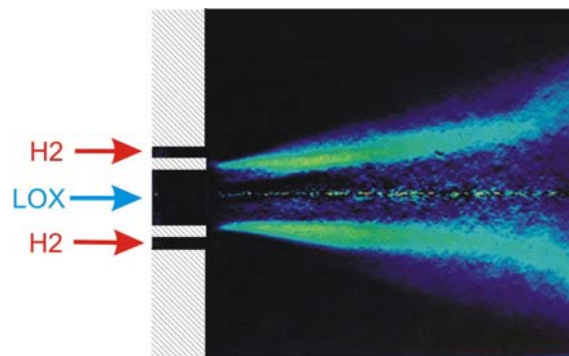


Figure 2: Cross sectional distribution of the OH-chemiluminescence of a burning LOX/H₂ spray

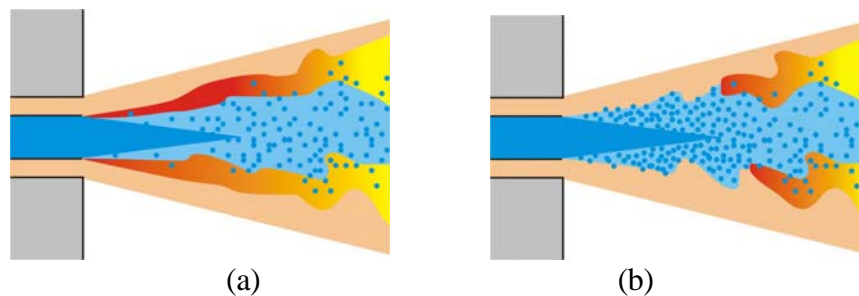


Figure 3: Flame anchoring mechanisms: (a) flame anchored at LOX-post (b) lifted flame

EXPERIMENTAL APPROACH

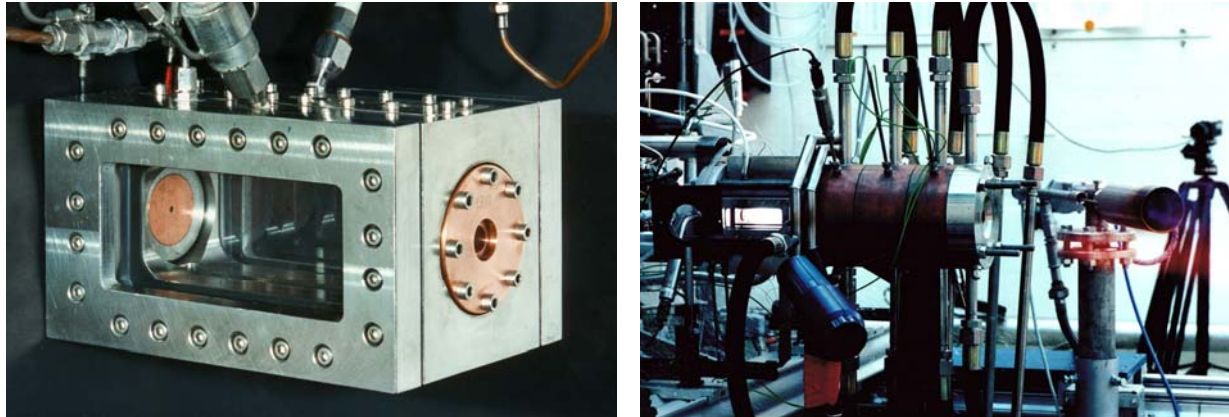
To investigate the influence of the physical properties of the fuel and the kinetics of the propellants on the atomization and combustion process tests are done with the two propellant combinations LOX/H₂ and LOX/methane. The general strategy is to investigate the spray and the flame in model combustors operated at similar injection conditions as characterized by non-dimensional numbers like We , Re , J etc. for both propellant combinations.

LOX-spray combustion is investigated at DLR Lampoldshausen using several model combustors. The micro-combustion chamber (see fig. 4a) can be operated at pressures up to 1.5 MPa and has full optical access to the combustor volume. The combustor can be operated with LOX/CH₄ as well as with LOX/H₂. A blown down vacuum system can be connected to the test facility to allow ignition tests under high-altitude conditions. Details of the hardware can be found in [10]. The high pressure combustor "C" (see fig. 4b) allows to investigate the spray flame at representative pressures conditions of up to 10 MPa. Today only a feed system for H₂ is available, a CH₄-supply is in preparation.

Validation of model predictions requires quantitative experimental data obtained at well known boundary conditions. Quantitative measurements at representative combustion chamber conditions are challenging, modelling of the full complexity of rocket combustor phenomena is ambitious. Thus experiments of reduced complexity are performed to obtain data that can be used to validate models and simulation codes. For this reason the main results concerning LOX/CH₄-combustion have been obtained at the micro-combustor up to now at subcritical pressure.

A variety of injection conditions can be adjusted by varying the injector dimensions and the combustion chamber pressure. The test matrix has been chosen to guarantee an independent variation of Weber-number and momentum flux ratio (see fig. 5).

The spray is visualized with Schlieren photography, the flame by imaging the chemiluminescence of the OH-radical. Both visualization methods can be applied at frame rates up to several 10KHz to resolve dynamic phenomena, especially during the ignition transient.



(a) (b)
Figure 4: (a) micro combustion chamber (b) combustor "C"

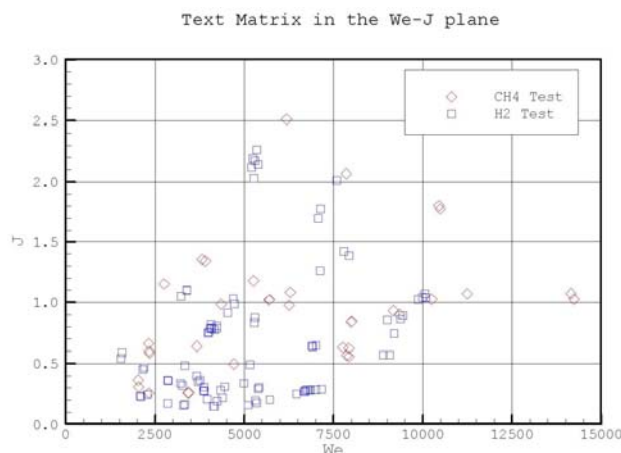


Figure 5: Test conditions in terms of Weber-number and momentum flux ratio J for LOX/H₂ and LOX/CH₄-tests at the micro-combustor facility

RESULTS

Stationary Combustion

Spray pattern. The effect of momentum flux ratio J and Weber-number for a burning LOX/CH₄-spray is shown in fig. 6. Increasing J results in a higher dispersion of the liquid phase, the visible break-up length is decreasing with increasing momentum flux ratio. This trend is in accordance with predictions of Villermaux [1] for cold flow. However the visible break-up length in our hot fire tests is much larger than the predicted values. The images recorded at high Weber-number show a LOX-jet disintegrated in significantly smaller droplets.

For high Weber-numbers a sudden change in the atomization behaviour can be seen in fig. 6 at the locations marked with an arrow. As will be shown below, at this injection conditions the LOX/CH₄-flame is not attached to the injector, the flame is stabilized in the mixing layer at the positions marked by arrows. The change of the atomization behaviour downstream the flame anchoring position clearly demonstrates the interaction of the combustion with the atomization process.

To identify the influence of fuel on the atomization in the reactive spray visualizations of LOX/H₂- and LOX/CH₄-spray flames are compared in fig. 7. The injection conditions in terms of Weber-number and momentum flux ratio have been chosen to be similar for both propellant combinations. As may be expected for LOX/H₂ increasing We and J results in a more efficient atomization similar to the LOX/CH₄ case. However atomization is significantly more efficient in the case of CH₄ at all injection conditions. The visible break-up length is much larger for LOX/H₂ as compared to LOX/CH₄. The comparison of the results for hydrogen and methane shows that Weber-number and momentum flux ratio - characterizing the cold flow injection conditions - do not reflect the major controlling mechanisms of spray formation in hot fire tests.

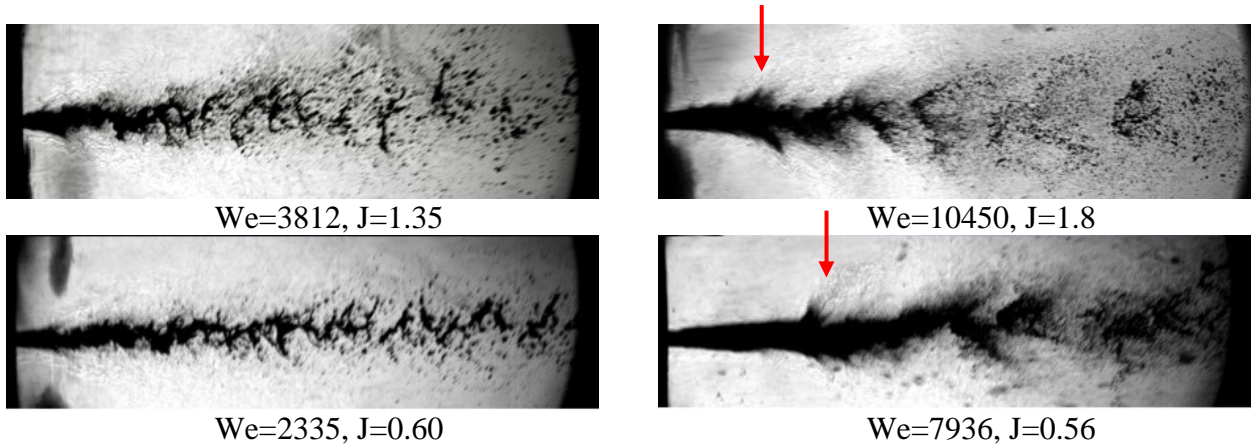


Figure 6. LOX spray pattern for CH₄/LOX sprax flames ($P_c=1.5ba$)

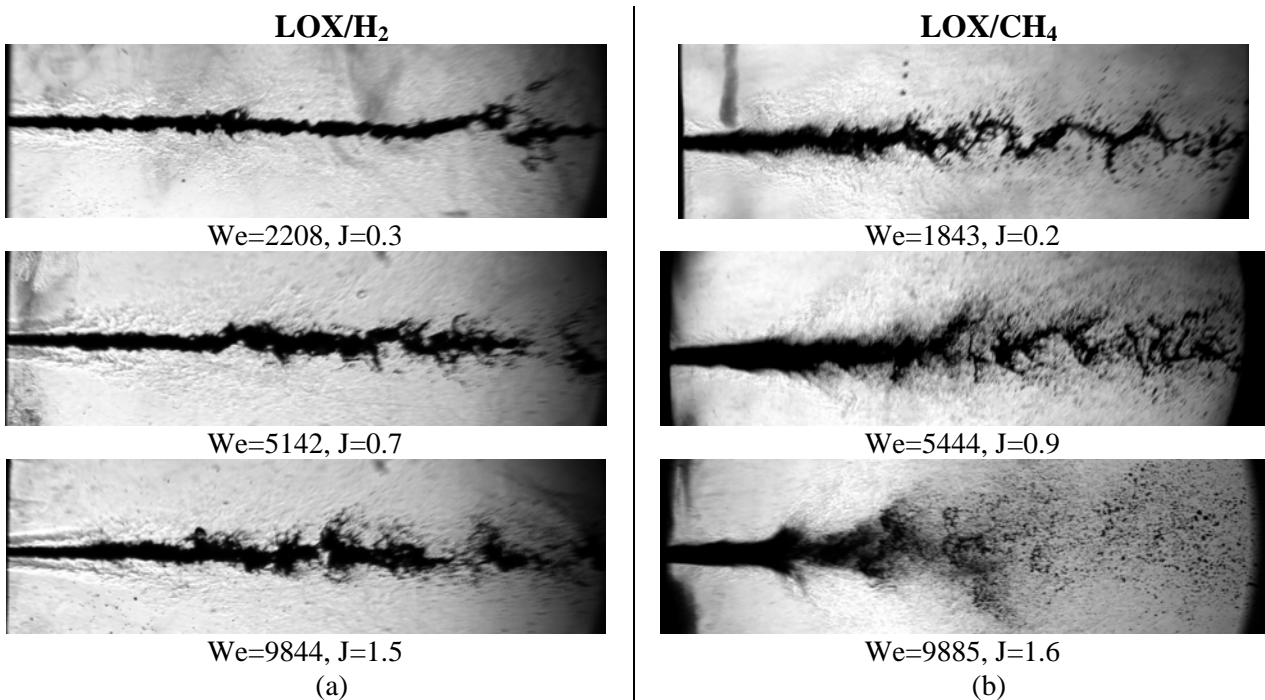


Figure 7: LOX spray pattern for (a) LOX/H₂ and (b) LOX/CH₄ spray-flames ($P_c=1.5bar$)

Flame pattern. Spray visualizations together with flame images for burning LOX/H₂- and LOX/CH₄-sprays are shown in fig. 8. Two main differences are observed: the spreading angle of the LOX/CH₄ flame appears to be significantly larger as compared to the LOX/H₂-test case. The spreading angle of the flame has been evaluated quantitatively for both propellant pairs and the results are shown in figure 9. The data correlate best with the Weber-number (fig. 9a), no other non-dimensional number like momentum flux ratio, liquid Reynolds number, Ohnesorge number or

velocity ratio (fig. 9b) exhibits a similar level of correlation. The increase of flame angle with Weber-number supports the interpretation that the increased surface due to more efficient atomization with increasing We results in a higher evaporation rate of oxidizer and thus in an increase of reaction products and heat release.

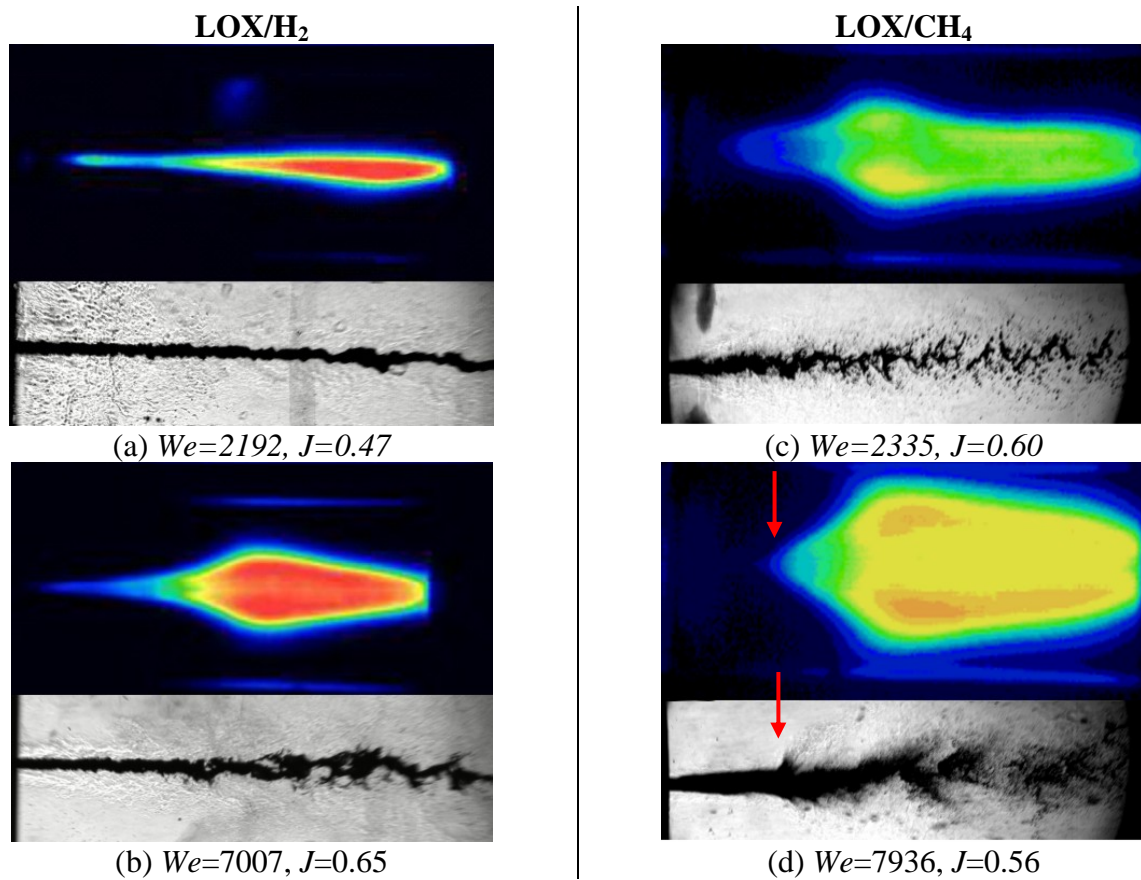


Figure 8. Flame and LOX spray pattern for (a, b) LOX/H₂ and (c, d) LOX/CH₄ spray-flames ($P_c=1.5$ ba)

The huge majority of LOX/CH₄-tests at 1.5 bar show lifted flames whereas all flames with LOX/H₂-injection have been observed to be anchored at the LOX-post. The large values of flame spreading angles have only been observed for lifted LOX/CH₄-flames. LOX/CH₄-flames anchored at the injector show spreading angles of similar size as in the LOX/H₂-test cases (see fig. 9a). The high spreading angles for LOX/methane flames have therefore to be attributed to the difference in the flame anchoring mechanism for both fuels. A lifted flame stabilized in the shear layer between evaporated oxygen the gaseous co-flow seems to change essentially the atomization process as compared to flames anchored at the injector.

No systematic dependence of lift-off distance x on one of the non-dimensional numbers have been found. As an example the dependence of x on We and J is shown in fig. 10.

It has been found that the lift-off phenomenon is very sensitive to combustion chamber pressure P_c . Whereas at $P_c = 1.5$ bar in rather all test cases the LOX/CH₄-flame was stabilized in a lift-off position, in tests at 3 bar the flame was anchored at the LOX-post. In fig. 11 the spray images of two test cases are shown with identical injection conditions concerning Weber-number and J . The position and spreading angle of the flame front is indicated by the dashed red lines. In the 1.5bar case shown in fig. 11a the flame is lifted off. In the 3bar test case shown in fig. 11b the flame is anchored at the injector exit and the flame spreading angle is significantly smaller. For the lifted flame the atomization process looks significantly more violent downstream the flame anchoring position.

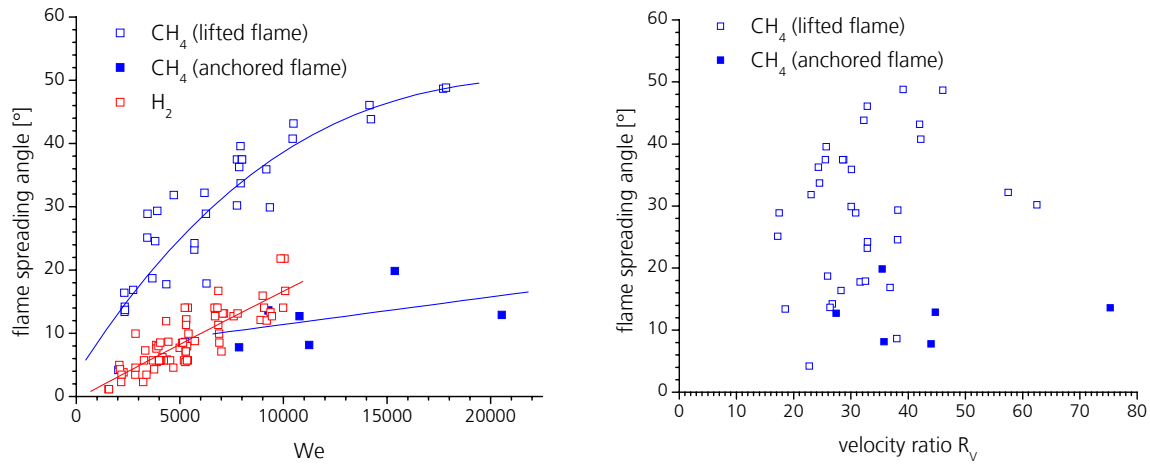


Figure 9. Flame spreading angle for LOX/CH₄- and LOX/H₂-spray flames as function of (a) Weber-number and (b) velocity ratio

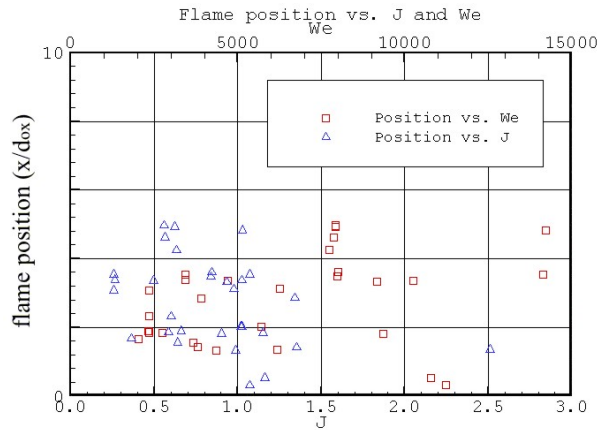


Figure 10. Lift-off distance of LOX/CH₄-flames as function of We and J .

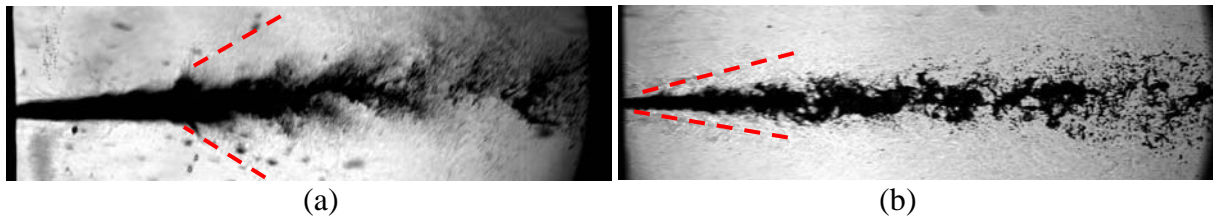


Figure 11. Effect of combustion chamber pressure on atomization and flame pattern for LOX/CH₄-spray flame. (a) $P_c=1.5\text{bar}$, $We=7260$, $J=0.5$, (b) $P_c=3.0\text{bar}$, $We=8417$, $J=0.5$

Spray Ignition

Ignition characteristics has been investigated by igniting the LOX/fuel-spray by laser-induced gas-break down. The laser was focused into the mixing layer of evaporated oxygen and the annular flow of gaseous fuel some distance downstream the injector exit. The evolution of the flame kernel in the early time after ignition was detected with a high-speed intensified CCD-camera. From these images the velocity with which the flame front moves through the turbulent mixing layer has been extracted [11, 12]. The flame front velocity shows with none of the investigated non-dimensional numbers a strong correlation. Only a weak correlation with the Weber-number for both propellant systems (see Figure 12) is found. The trends shown in both plots have only a weak confidence level. However the difference in the level of velocities is significant: at similar Weber-number the

flame front velocity of the H_2/O_2 -system is about 3-5 times that of the CH_4/O_2 -system, the ratio is near to that of the laminar burning velocities which is about 2.7.

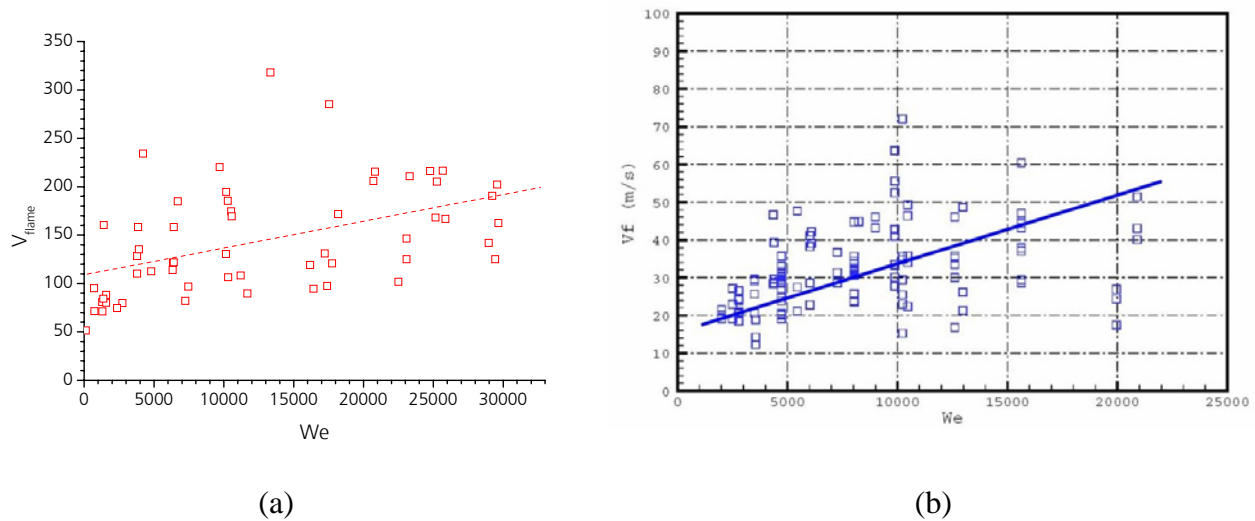


Figure 12: flame velocity as function of Weber-number for (a) LOX/ H_2 - and (b) LOX/ CH_4 -ignition

CONCLUSIONS AND OUTLOOK

From the results obtained up to now it obvious that non-dimensional numbers characterising the fluid-dynamical interaction of the two fluids at the injector exit are not sufficient to scale co-axial injector performance from one fuel to another. At identical injection conditions in terms of Weber-number and momentum flux ratio especially flame stabilization mechanisms may be different for different fuels. As has been shown in the experiments the flame stabilization process has strong influence on the atomization and flame characteristics. Scaling of injector designs for different type of fuels has therefore to take into account kinetic and transport properties associated with combustion.

The tests presented in this paper have been done at subcritical pressure conditions for oxygen. Pressures representative for rocket combustors are in the supercritical pressure range. Co-axial injection of LOX/ H_2 in the near critical region has been analyzed by various diagnostic tools at the P8 test facility during the last years [13]. Tests are currently in preparation using LOX/ CH_4 as propellant. At representative pressures O_2 as well CH_4 are in the trans- and supercritical thermodynamic state. Real gas behaviour has to be taken into account and the specific characteristics of transport phenomena at these thermodynamic conditions have to be considered. As an example the specific heat of methane and the thermal diffusivity of oxygen is shown in fig. 13. In the near critical region the specific heat exhibits a pronounced maximum, another fingerprint of the near critical property is the minimum in the thermal diffusivity $\kappa = \lambda / (\rho c_p)$. The experiments will show how the trans-critical behaviour of methane will influence the atomization, mixing and flame stabilization process.

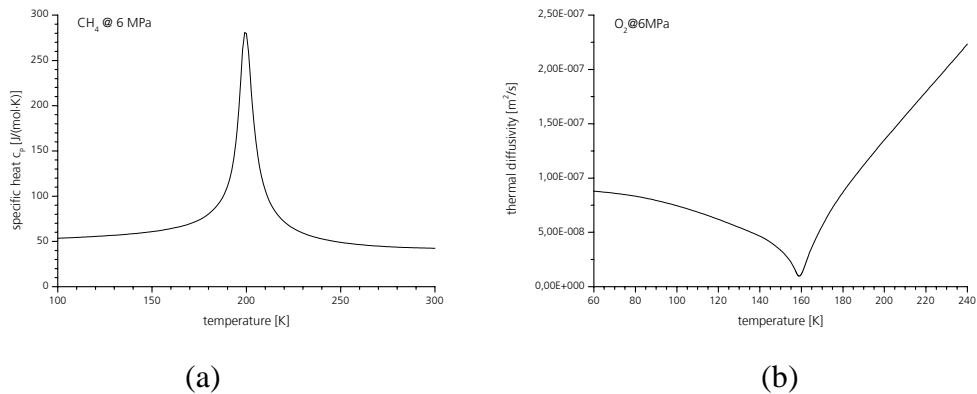


Figure 13: (a) specific heat of CH₄ and (b) thermal diffusivity of O₂ at 6 MPa

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