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Heat Transfer Measurements in a Water-Cooled Rocket Combustion Chamber Operated with Oxygen/Methane Mixtures at the Mascotte Test Facility.

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A test series aimed at investigating wall temperatures and heat fluxes in a subscale rocket engine combustion chamber operated with oxygen and methane was achieved at the Mascotte test facility. A total of nearly one hundred and fifty stabilized operating points were reached, enabling to cover a wide operating domain, ranging from subcritical to supercritical chamber pressures (2 to 7 MPa) and mixture ratios from 1 to 3.5, firstly in gas/gas and then in liquid/gas injection conditions. The influences of geometrical parameters like the injectors diameters governing the momentum flux ratio and the distance between the injectors and the wall were also investigated. Some unexpected behaviors were observed for the liquid/gas cases at subcritical pressures, which are still under investigation and deserve further testing.

Key Words: Oxygen/Methane, Liquid Rocket Engine, Heat Transfer

Nomenclature

J	: momentum flux ratio
M	: mixture ratio (O/F)
P	: pressure, MPa
H_2	: hydrogen
CH_4	: methane
GOX	: gaseous oxygen
LOX	: liquid oxygen
BHM	: high pressure high mixture ratio water-cooled combustion chamber
\emptyset	: diameter, mm

1. Introduction

The recent start of the PROMETHEUS LOX/CH₄ engine development by ArianeGroup, within ESA's FLPP NEO program, brings new needs for characterization of LOX/CH₄ combustion in operating conditions of rocket-engine combustion devices. In the framework of CNES-ONERA R&D activities, experiments were recently achieved in liquid rocket engine – like conditions at the Mascotte test facility of ONERA, operated with oxygen/methane mixtures.

The test series aimed at measuring wall heat fluxes and wall temperatures in a water-cooled cylindrical chamber that was previously operated with oxygen/hydrogen mixtures.¹⁻⁴⁾

The correct prediction of heat load on the chamber walls is indeed a major topic in the design process of a rocket engine. A small mistake of the wall temperature can induce a 50% reduction of the engine's lifetime.⁵⁾ Several research groups all over the world have tackled this topic using small-scale

experiments. Marshall et al. studied the single injector configuration,⁶⁾ whereas DeRidder and Anderson focused on multi-injector configurations.⁴⁾ They have shown how the global flux scales with pressure but also that its longitudinal distribution depends on the injector arrangement and the mixture ratio. Similar studies have been conducted by Conley et al.⁸⁾ By varying independently the chamber pressure and the fuel mass flow rate, they questioned the direct pressure dependence and proposed a square root of the fuel mass flux law instead. The influence of the geometry (chamber length) was also highlighted. Cai et al. studied experimentally and numerically the influence of the injector design on the heat fluxes,⁹⁾ whereas Silvestri et al. measured the influence of the coaxial injector recess length on heat transfer.¹⁰⁾ Celano et al. also experimented with single and multi injector configurations using methane as the fuel.¹¹⁾ However, most of these configurations used capacitive combustion chambers, i.e. uncooled chamber walls for which the temperature increases over the duration of the hot-fire test. Cooled configurations able to reach a steady state are rarer. They are mainly based on calorimeter cooled segments in which the heat fluxes are deduced from enthalpy difference measurements of the cooling channels. Such a setup was operated with methane and used for direct comparison with numerical simulations,¹²⁾ with both methane and hydrogen, with a specific focus on film cooling.^{13,14)} Ahn et al. also used a calorimeter cooled combustion chamber to study the influence of the biswirl injector recess length on the heat transfer at the wall for a multi-injector oxygen-kerosene configuration.¹⁵⁾ They proposed a correlation of the heat transfer with the main characteristics being the combustion chamber pressure, the oxygen-to-fuel ratio, and the recess length.

2. Experimental set-up

Common CNES-ONERA experimental investigations of wall heat fluxes on Mascotte started in 2010.¹⁾ The bench itself, as well as the BHM, the high pressure high mixture ratio water-cooled combustion chamber used for these tests, were described in several previous papers,¹⁻⁴⁾ and will not be described here again. Let us just recall that several versions of the hardware were developed and manufactured for the different items of interest in experimental research. The “thermal” version (Fig. 1) used in the present study consists of an injection head with an interchangeable face plate, two cylindrical segments and an axisymmetrical nozzle. The cylindrical segments are equipped with fifty-one pairs of thermocouples along three generatrices referenced A, B and C. The thermocouples are brazed on both the hot gas side and the water-cooled side of the wall, at a depth of 1 mm from the interface on the hot side and 0.5 mm from the cold side, enabling the possibility to measure the wall temperatures and to derive the heat fluxes.

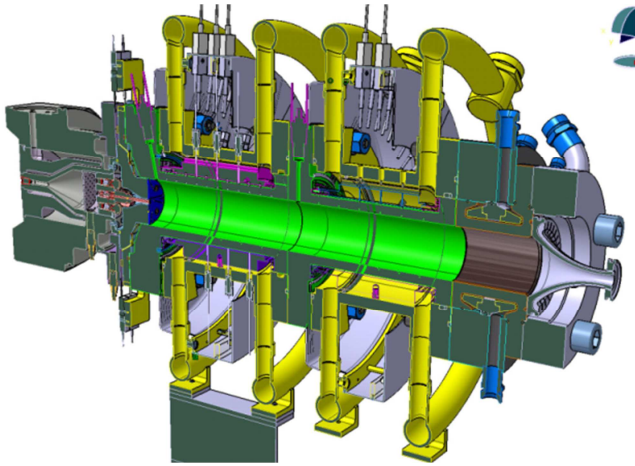


Fig. 1. The water-cooled BHM combustion chamber.

The BHM is fed by five shear coaxial injectors, a central one on the axis of the chamber and four more arranged on a circle of diameter either $\varnothing = 30$ mm or $\varnothing = 40$ mm. The diameter of the chamber itself is 56 mm. In the first case (Fig. 2 left) the upper injector is in front of generatrix A, in the second case (Fig. 2 right) the bottom right injector is in front of generatrix C.

The methane was always injected gaseous at ambient temperature in these experiments, while the oxygen was either gaseous at room temperature or liquid (or transcritical) at approximately 100 K.

The operational domain covered a large range of pressures, from subcritical to supercritical (1 to 7 MPa), as well as a large variety of mixture ratios from 1 to 3.5, allowing investigations of both gas generator and thrust chamber applications.

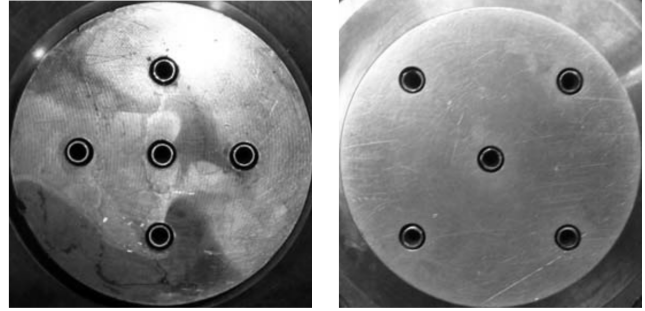


Fig. 2. Injector elements arrangements ($\varnothing 30$ left, $\varnothing 40$ right).

2.3. Operating points, experimental conditions and measurements

The objectives of this oxygen/methane campaign were to get a first evaluation of the wall temperatures and heat fluxes in our subscale combustion chamber, with various parameters, mainly for model validation.

Among the different parameters investigated during the campaign, let us focus on the following:

- the injection conditions for oxygen (i.e. gaseous at room temperature or liquid or transcritical at approximately 100 K),
- the distance between the outer row of injectors and the combustion chamber walls,
- the oxygen injector diameters that influence the momentum flux ratio J (only for LOX injection cases).

For each combination of the above mentioned parameters, a large domain of mixture ratios M and chamber pressures P was explored, with the goal to draw a heat flux map.

Thirty-two runs of 120 s average duration were realized during the test campaign between January and March 2018, including twelve runs in the GOX/CH₄ configuration and twenty in the LOX/CH₄ configuration. In the same way as in the oxygen/hydrogen tests series completed in 2016,¹⁶⁾ several operating points were targeted successively during each Mascotte run. In addition, two different cooling water mass flow rates were tested for each stabilized chamber pressure, with the objective to estimate the heat exchange coefficients on the hot gas side. Nearly one hundred and fifty stabilized conditions were reached for the nominal cooling water mass flow rate. Figure 3 shows these points in the (M, P) plane. The different symbols in this figure correspond to the different combinations of injection parameters. The first letter L or G means LOX or GOX; the second letter H or L corresponds to the diameter of the LOX post, H meaning the element initially designed for high mixture ratios and L the one foreseen for low mixture ratios; the number 30 or 40 is the diameter of the outer row of injectors shown in Fig. 2. More than half of these operating points were also realized with a lower cooling, enabling the estimation of the heat transfer coefficient.

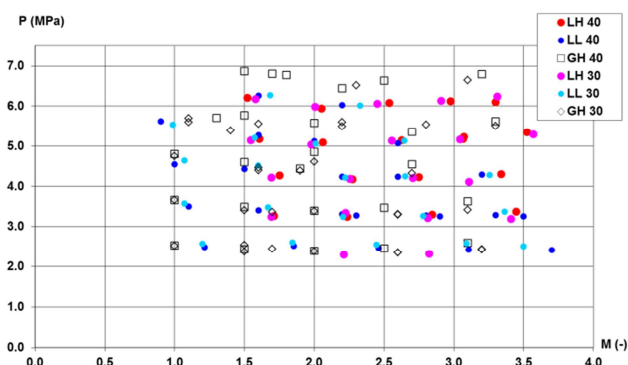


Fig. 3. Achieved operating points in the (Mixture ratio, Chamber pressure) plane for different combination of injection parameters.

For all these stabilized conditions, the wall temperatures were measured on both the hot and cold sides, and the wall heat flux densities were derived using a 1D unsteady approach, based on an analytical solution developed in 2016.¹⁶⁾ The basic assumption is that the heat diffuses only in the radial direction because of the axisymmetric geometry. The heat equation is then solved along a radial line which contains the two thermocouples of the same pair (the PG and PE). The boundary conditions are the time dependent measured temperatures. This solution is almost the exact solution, and thus it represents the best way to model the unsteady heat diffusion in the cylindrical wall, in one dimension along a radial line. As the analytical solution is valid only between two points within the chamber wall, an extrapolation is required to get the temperatures and the heat flux densities at both surfaces of the wall (hot gas and cooling water). Several intermediate points are defined along the segment between the two points of measurement, and they are used to build two third degree interpolation polynomials, which vary in time, and which lead to the temperature and the heat flux density at the adjacent surfaces by extrapolating each polynomial and its derivative.

To face the great amount of information to process and the great amount of mean values to calculate, it was necessary to develop and implement a quasi-automatic method to detect the heat flux levels and to calculate the means values.

3. Results and discussion

3.1. Temperature and heat fluxes profiles

For the gas/gas runs, the temperature profiles are similar to the H_2/O_2 case, with a quite high value on the first segment and a lower stabilized profile on the second segment where the combustion is complete and the gaseous mixture more homogenous. These temperatures increase with both pressure and mixture ratio.

Nevertheless, for LOX/ CH_4 conditions, the profiles evolution strongly differs from the LOX/ H_2 case. While the LOX/ H_2 profiles resemble GOX/ H_2 ones, the behavior with CH_4 changes drastically. The observed temperature profiles are very flat, with relatively low heat fluxes at the walls, and some levels show almost monotonous increase in temperature, as if the combustion was not finished, or as if there was a high

thermal resistance between the combustion zone and the temperature sensors. Only a few operating points exhibit temperature profiles similar to the gas/gas cases, and most of them seem to be at high pressure (above the oxygen supercritical pressure $P=5.04$ MPa). One hundred and twenty operating points, with LOX injection, show unexplained features that deserve further investigation to try to understand the underlying physical phenomena.

Several hypotheses have been proposed:

- presence of a water film at the wall surface,
- slow, possibly incomplete combustion process,
- bad flame anchoring.

The combustion efficiency estimated from the experimental combustion chamber pressure does not highlight any suspicious values, but this has to be checked more precisely. Indeed, the helium film injected at the nozzle inlet may introduce a bias. It has been taken into account as an additional mass flow rate but its possible influence on the chamber temperatures was neglected, based on the assumption that it remains a film along the nozzle walls with no exchange with the main flow. On the other hand, the energy loss through the walls has not been considered either.

Figure 4 presents typical temperature profiles along the three instrumented generatrices of the combustion chamber walls, along with the heat flux profiles. PE stands for the water-cooled side and PG for the hot gas side. The calculated temperatures (black curves) are the values extrapolated at the interface with the hot gases, using the model and the measurements of the thermocouples located at a depth of 1 mm.

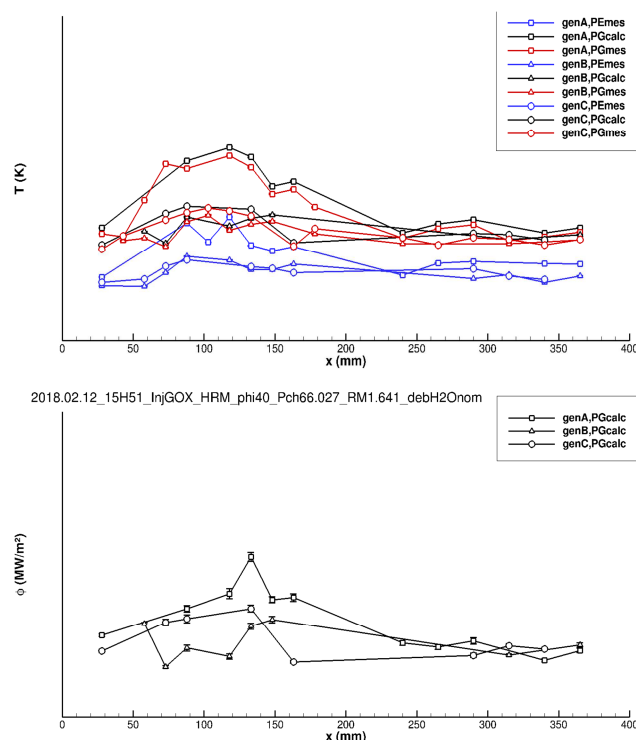


Fig. 4. Typical temperatures (top) and heat fluxes (bottom) for gas-gas case ($M=1.6$, $P=6.6$ MPa).

Figure 5 shows the evolution of the temperature and heat flux profiles with decreasing pressure and increasing mixture ratio at LOX conditions injections (with quasi similar momentum ratios J). As expected, the heat fluxes decrease with the pressure, however the levels of heat fluxes are quite low for LOX injections.

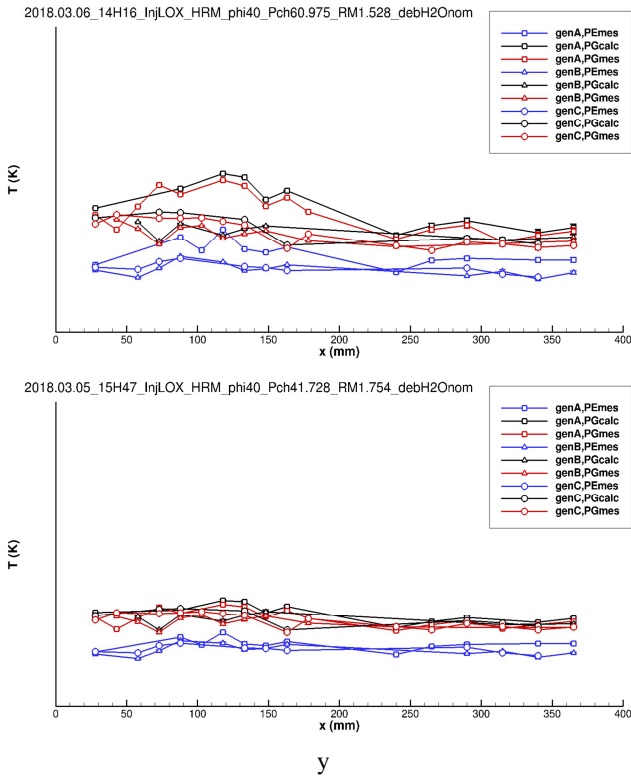


Fig. 5. Evolution of temperature and heat flux profiles for LOX injection for a quasi constant J factor.

Even with nearly stoichiometric mixture ratio ($M=3.3$), as plotted in Fig. 6, temperature profiles are very flat and heat fluxes profiles exhibit quasi constant and low value, whereas for gaseous similar conditions, the temperature and heat fluxes profiles are really different (Fig. 7).

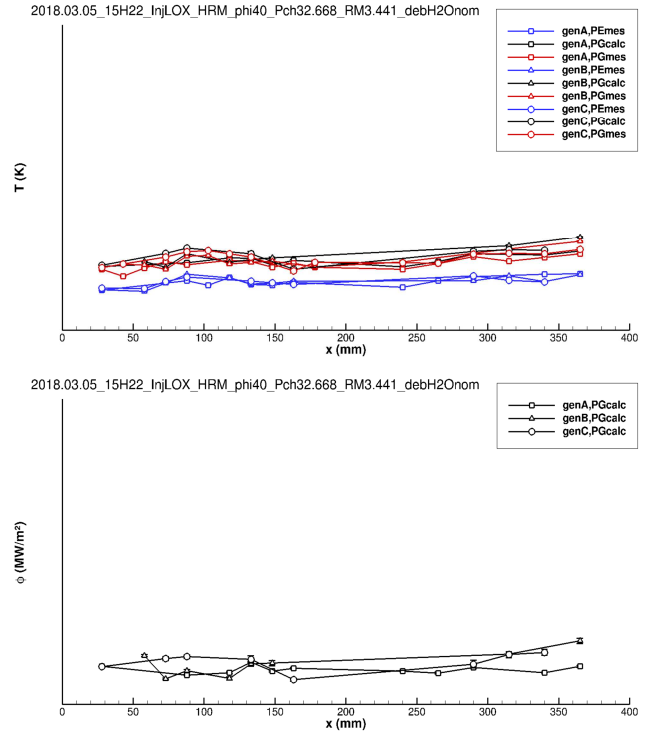


Fig. 6. Temperature and heat flux profiles for LOX injection. High mixture ratio case ($M=3.4$) and moderate pressure ($P=3.3$ MPa).

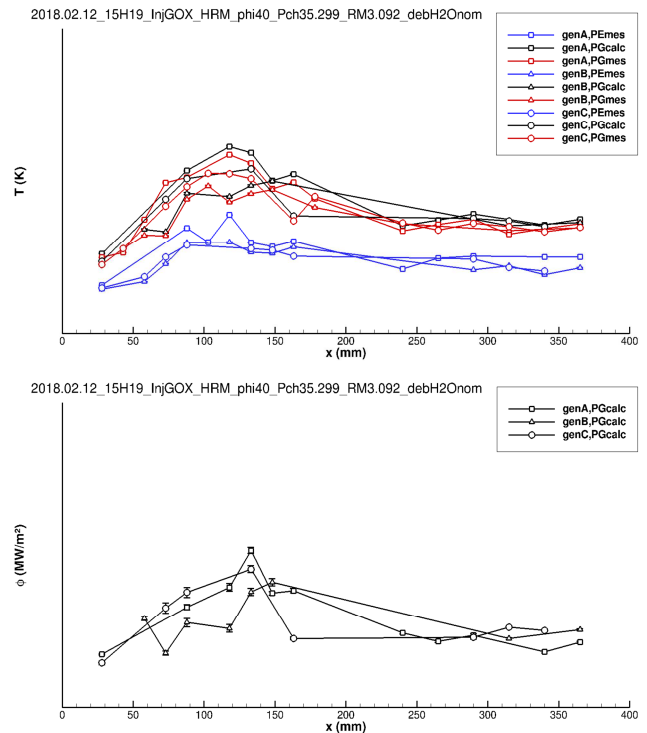


Fig. 7. Temperature and heat flux profiles for GOX injection. High mixture ratio ($M=3.1$) and moderate pressure ($P=3.5$ MPa) case.

3.2. Heat fluxes maps

The maximum and averaged heat fluxes along the combustion chamber were also extracted from these data for the whole set of conditions.

Figure 8 shows the heat flux maps for GOX injection, with two wall to injector distances. The outer injectors are on the diameter 30 (configuration GH 30) for the top part of Fig. 8, i.e. at 13 mm from the wall, and they are on the diameter 40 (configuration GH 40), i.e. at 8 mm from the wall for the bottom part of the figure.

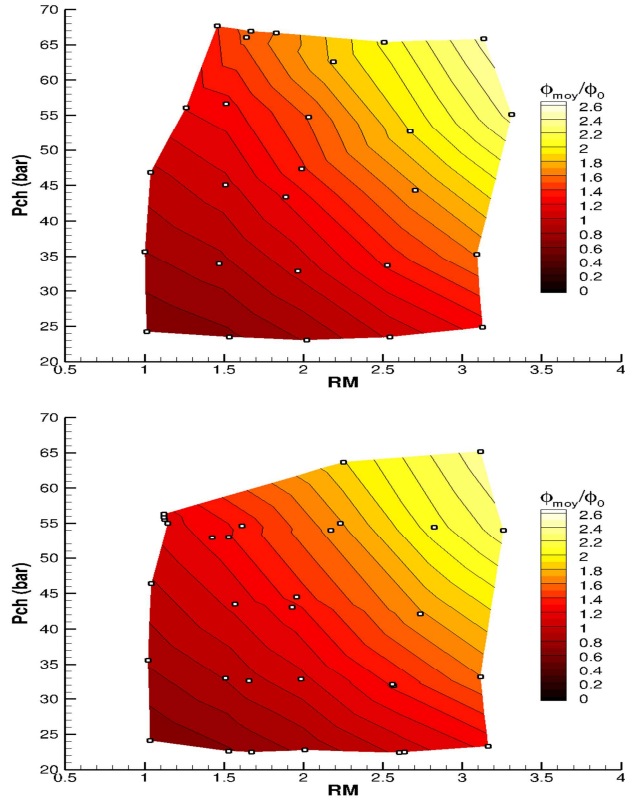


Fig. 8. Non dimensional heat flux map for gaseous conditions, lateral injectors 13 mm from the chamber walls (top) and 8 mm from the chamber wall (bottom).

Both levels and iso-contours are similar for these two cases. Iso values of mean heat fluxes show a monotonic increase with both pressure and mixture ratio, which is quite classical. Indeed, the heat exchange coefficient at the wall is known to vary with $P^{0.8}$ and the gas temperature is higher with a higher mixture ratio.

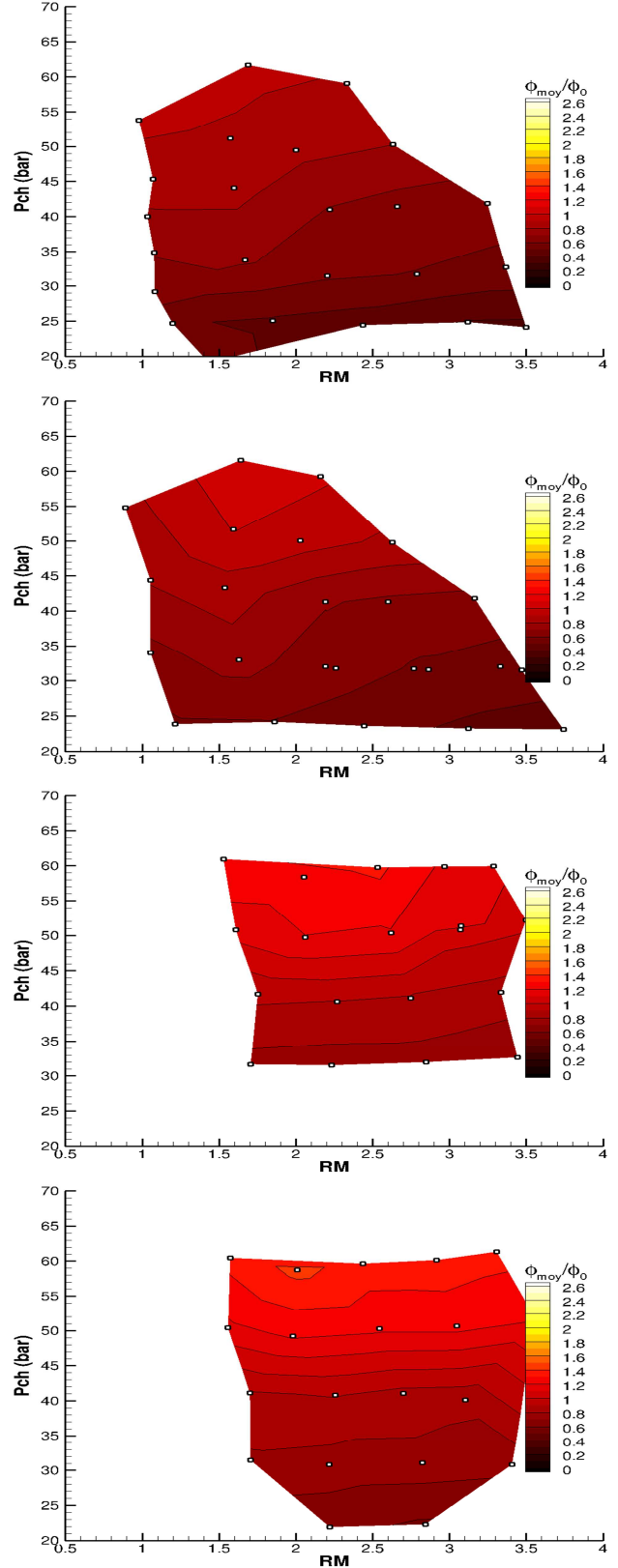


Fig. 9. Non dimensional heat flux maps for LOX injection in the (M, P) plane. Two lateral injectors positions and two injectors diameters in the following order LL 30, LL 40, LH 30, LH 40.

Figure 9 shows the same type of non-dimensional heat flux maps. As previously observed in gaseous conditions, the distance of the outer row of injectors to the combustion chamber walls (comparison between LL 30 and LL 40 on one hand and between LH 30 and LH 40 on the other hand) seems to have nearly no effects on the averaged heat flux. The shape of the injectors, which changes the momentum flux ratio J (comparison LL 30 to LH 30 and LL 40 to LH 40) exhibits much more differences and higher heat fluxes with the H injectors, dedicated to high mixture ratio cases. J is significantly higher for H injectors than for L injectors for two similar operating points.

This figure also highlights a quite surprising fact: although the mean heat flux (closely related to the quantity of heat extracted from the combustion chamber) increases with the combustion chamber pressure, the iso-contours are nearly horizontal, which indicates that there is nearly no influence of the mean mixture ratio on the heat quantity evacuated through the combustion chamber walls. Moreover, for the L injector cases (low J), this behavior is worse: with higher mixture ratios, the mean heat flux through the combustion chamber walls is lower. No satisfactory explanations were found to address this behavior so far, it is still under investigation and new tests are foreseen in the near future, possibly with a windowed chamber, to address this unexpected observation.

On H injectors cases, we can see that the iso-contours of mean heat fluxes seem to be closer to each other, meaning a higher mean heat flux gradient vs pressure, between 4 and 5 MPa, which could indicate that the behavior changes near the LOX critical pressure. This effect, if present, is not that clear for the L injector case. The evaluation of this potential transition effect is also an objective of the test series planned this year.

The same maps are presented with J dependency instead of M , as J is the key factor of the atomization process when the oxygen is injected in liquid phase. Once again, similarly to M , there is no evident correlation between J and the mean values of heat fluxes on the combustion chamber walls. Almost only the dependency on the chamber pressure appears on the iso-contours of Fig. 10.

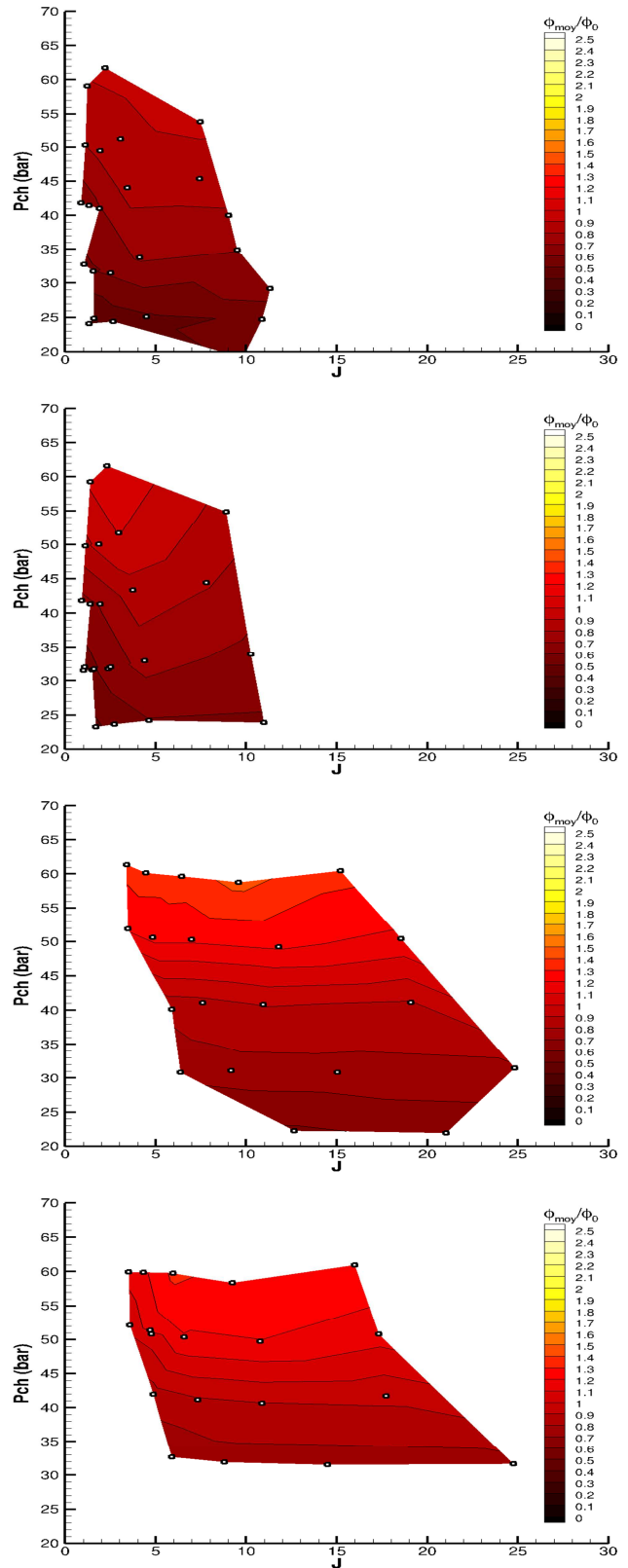


Fig. 10. Non dimensional heat flux maps for LOX injection in the (J, P) plane. Two lateral injectors positions and two injectors diameters in the following order LL 30, LL 40, LH 30, LH 40.

7. Conclusion

A test series aimed at investigating wall temperatures and heat fluxes in a subscale rocket engine combustion chamber operated with oxygen and methane was achieved at the Mascotte test facility. A total of nearly one hundred fifty stabilized operating points were reached, enabling to cover a wide operating domain, ranging from subcritical to supercritical chamber pressures (2 to 7 MPa) and mixture ratios from 1 to 3.5, firstly in gas/gas and then in liquid/gas injection conditions. The influences of geometrical parameters like the injectors diameters governing the momentum flux ratio and the distance between the injectors and the wall were also investigated.

When comparing the results to oxygen/hydrogen cases, it appears that for gas/gas injection, it looks very similar, with maximal heat fluxes between 4.5 and 9 MW/m², but for liquid/gas and subcritical pressures, the behavior seems to change drastically. Further investigations are foreseen to try to clarify this unexpected observation.

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