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Numerical and experimental scientific investigation of combustion in a translating cowl dual-mode ramjet

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Design of a wide range dual-mode ramjet

To sustain high speed flight in the atmosphere, American, European and Russian institutes or companies have studied scramjet-powered hypersonic vehicles for over 40 years, and some other countries worldwide.
Many applications can use such an airbreathing engine, theoretically from flight Mach number Mf= 2 (or less, in some extent) up to Mf=12 (or more, according to some studies and shock tunnel experiments).
In a large part of the flight regime, the air-breathing mode appears to be a possible good solution for future Reusable Space Launchers (RSL).
Achieving efficient supersonic combustion is not so challenging compared to be able to design a ramjet able to operate from subsonic to supersonic combustion in the same engine, for example on a flight envelope from 2 < Mf < 8 (or 10 or 12 with pure hydrogen): this engine is called dual-mode ramjet.
Dual-mode ramjets have been studied to propel such TSTO (Two Stage To Orbit) or Single Stage To Orbit (SSTO) vehicles, or other kind of hypersonic vehicles.
For example, in the scope of the French PREPHA program, the study of a generic SSTO vehicle led to conclusion that the best type of airbreathing engine could be the dual-mode ramjet (subsonic then supersonic combustion).
Two main ways of approach are possible for the DMR: a fixed or a highly variable geometry. The propulsive performance (thrust, consumption) of the DMR have to be optimised, computed and at-best demonstrated.
For a wide range, a variable geometry appears mandatory. The concept studied here is a good trade-off between complexity and performance.

Engine concept : translating cowl dual-mode ramjet (DMR)

The airbreathing propulsion system concept has been chosen by taking into account all results acquired during engines developments performed in France these last 15 years [1][2]. Some of the corresponding scientific investigation has been made in cooperation with Russian institutes [1][4][5].
The currently studied concept is a variable geometry one using a simple translation movement of the engine cowl and a thermal throttling.

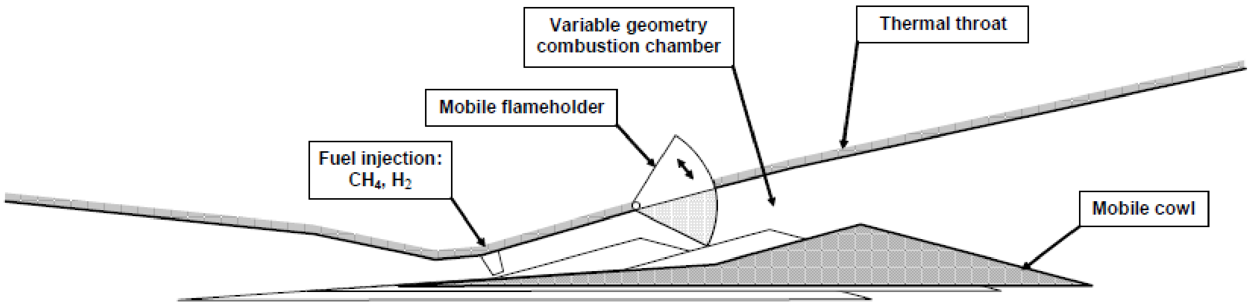

Figure 1 : concept of translating cowl dual-mode ramjet

This concept is used for the LEA experimental flight vehicle[15][20], but also for other studies such as one of the LAPCAT high speed aircraft projects [17][18][19] or the nano-launcher project [16].

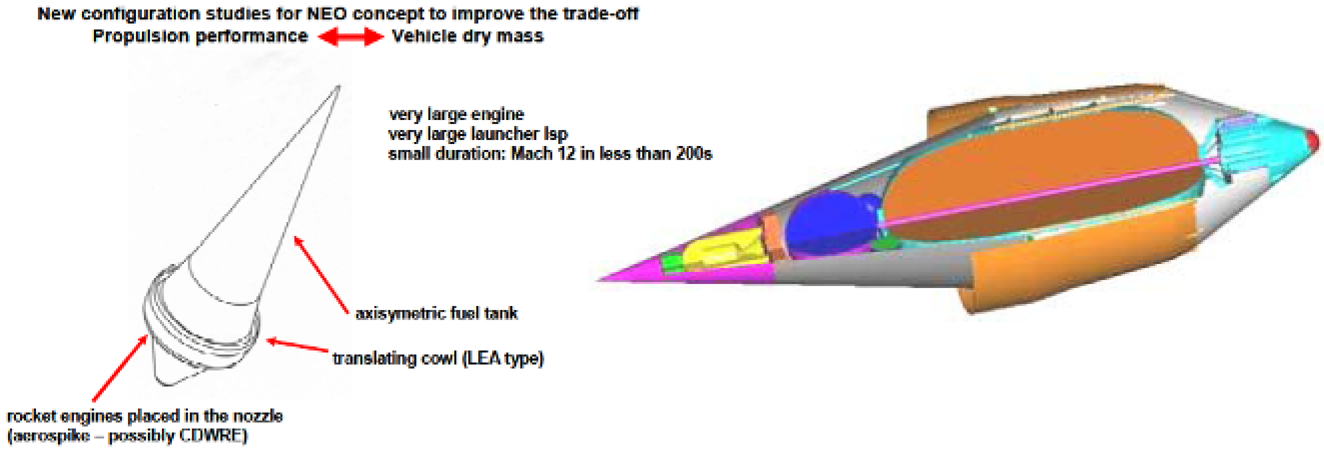

Figure 2 : space nano-launcher project with translating cowl DMR

The combustion investigation presented here contributes to the general know-how on the scientific process of these kind of engines and.

The combustion investigation presented here contributes to the general know-how on the scientific process of these kind of engines, constitutes a good opportunity to study different regimes of combustion operation, by playing on the fuel injected as well as the position of the cowl. But the main focus is the preparation of the LEA flight experiment, planned before 2015 up to Mach 8.

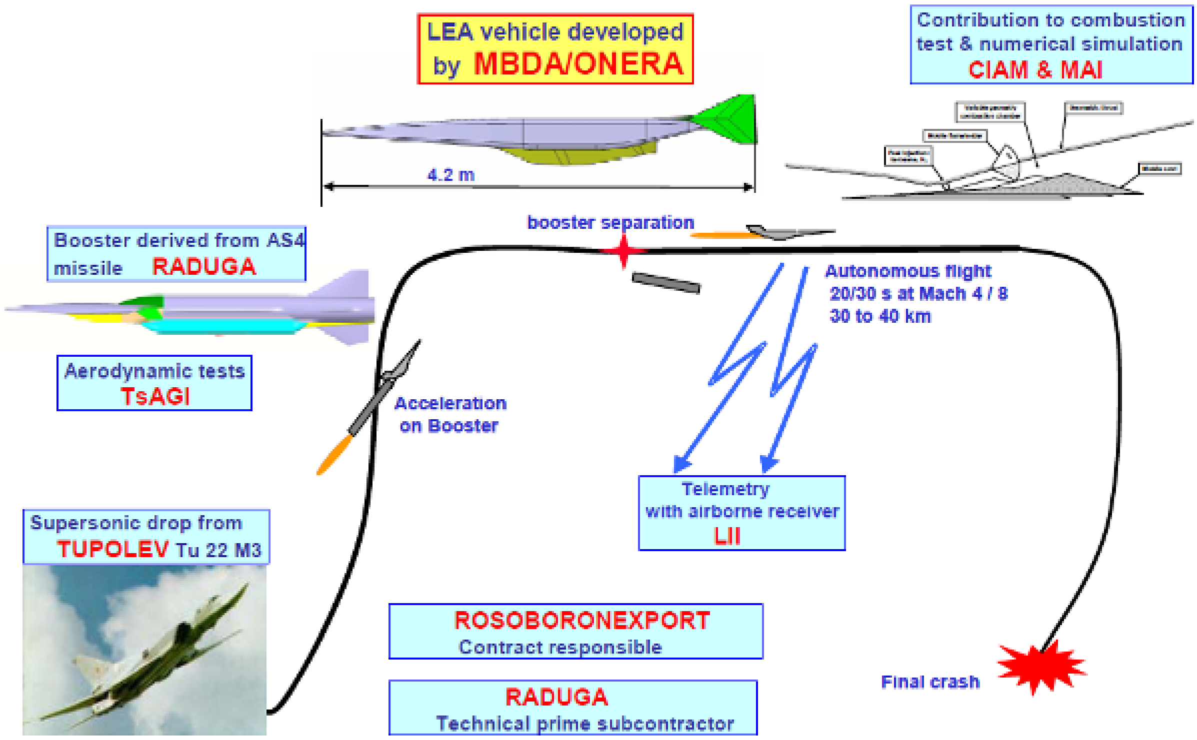

Figure 3 : LEA flight experiment sequence and corresponding France/Russia cooperation

Fuel

In addition with this DMR concept, different fuels are considered by MBDA : pure gaseous hydrogen, pure methane, a mixture of CH_4 and H_2, regular or endothermal kerosene, H_2-bubbled kerosene, [5][11][12][1][2] …

The most part of French experience in supersonic combustion is then related to hydrogen. But, considering the very low density of hydrogen, liquid or gaseous hydrocarbon fuel could be considered. The use of liquid hydrocarbon adds complexity. Finally, a mixture of gaseous methane and gaseous hydrogen was chosen for LEA. By using this mixture, it is also possible to vary the H2/CH4 ratio to ensure a robust ignition and control the heat release along the combustor, to study different regimes of combustion.

Some specific works have been performed to adapt numerical simulation codes to the particular CH4/H2 fuel. These models have been validated thanks to basic experiments from the literature or led in updated ONERA LAERTE test facility. The kinetic model proposed by Davidenko (21 species, 79 reactions) and implemented in CEDRE is used by MBDA and ONERA for computations of CH4/H2 combustion in the LEA DMR as well as by CNRS ICARE laboratory for more academic investigations [7][8][9][10]. Moreover, ONERA ATD 5 test facility has been updated to allow CH4/H2 tests to test the same kind of combustor [11].

DMR combustor design and validation

Different injection systems and flame-holding systems have been designed and investigated.
For one of the configuration, the pressure computed in 3D by MBDA with the CEDRE code and reacting models is given below for the flight range expected for the LEA experimental vehicle

Wall pressure computed on DMR upper wall in flight (symetry plane)

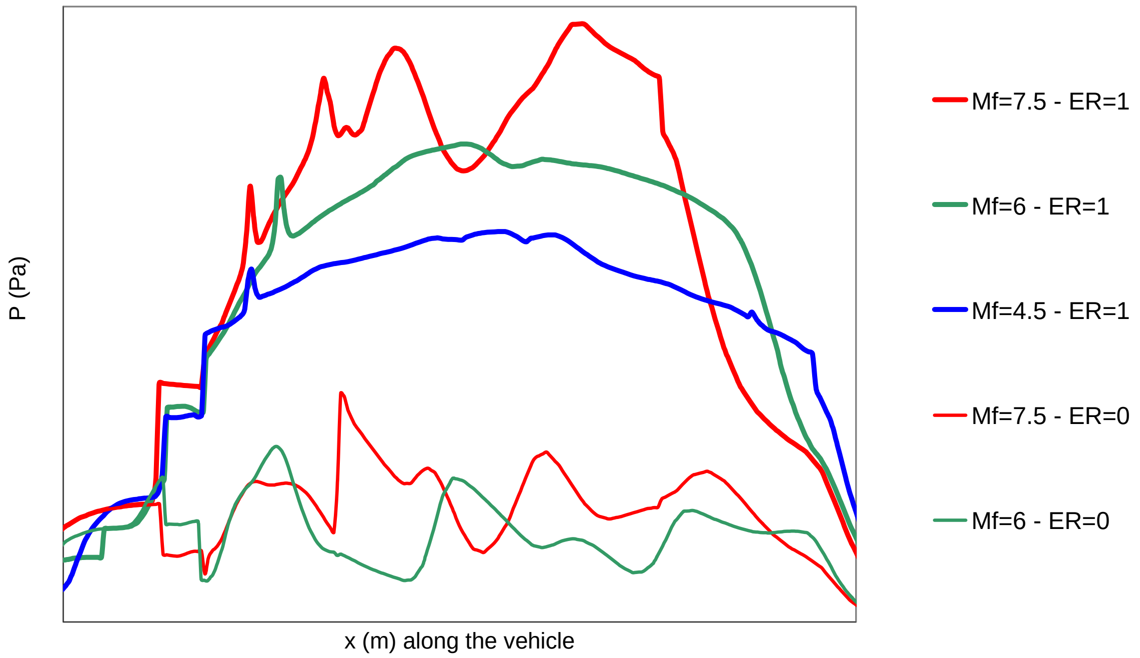

Figure 4 : example of expected pressure along the LEA vehicle - upper wall (MBDA computations)

The design is made with the conjunction of experimental and numerical tools.

For such a DMR, the regime moves from 'subsonic combustion around Mach 4 to 'fully supersonic' combustion close to Mf=8.
Intermediate combustion regime ('sometimes called 'trans-sonic' combustion) is for example expected at Mf=6 conditions.

Depending on the injection system, on the chosen geometry for the intake and the combustor, the DMR has to operate in a wide range of contradictory regimes.

The current paper presents some experimental and computational results of this DMR concept used in LEA, as it was tested at Moscow Aviation Institute.
In parallel, other combustion test series are realized in other test facilities : in ATD5 and at METHYLE in connected pipe and at S4 Modane in free-jet testing [6][13][14].

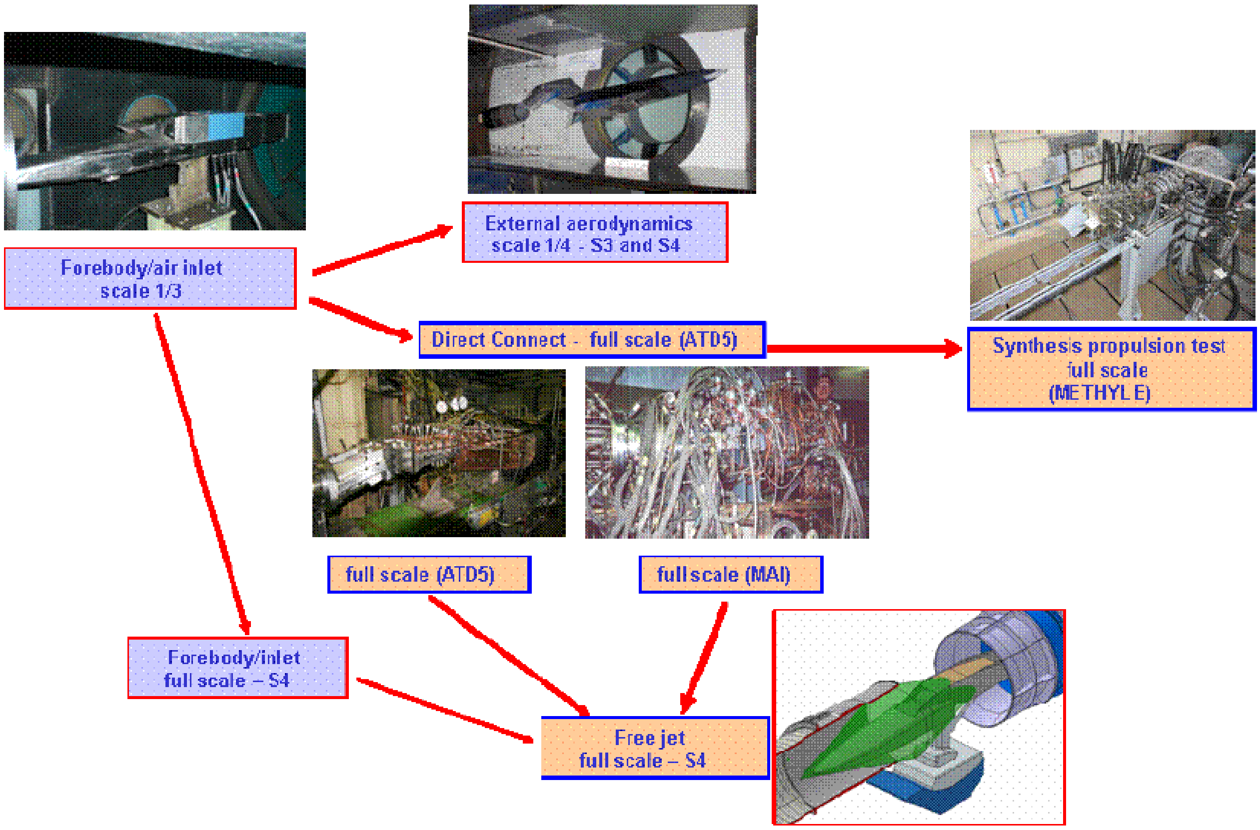

Figure 5 : aeropropulsive ground testing in the LEA program

An example of two different test series performed on one hand in METHYLE at Bourges with the SMR modular combustion model and at MAI at Moscow is given below (Figure 6).
The DMR concept and overall size in the same in the two configurations, the incoming parameters are roughly the same (except that incoming air is preheated with H2 and O2 at METHYLE for this test and with kerosene and O2 for MAI). But the internal geometry and injection system is different between the two test. Here the divergence of the combustor (Aexit/Aentry) was 25% bigger at METHYLE than at MAI.
For these test no exhaust ejector was set, leading to separation at the exit of the duct because of the 1 bar back pressure effect.

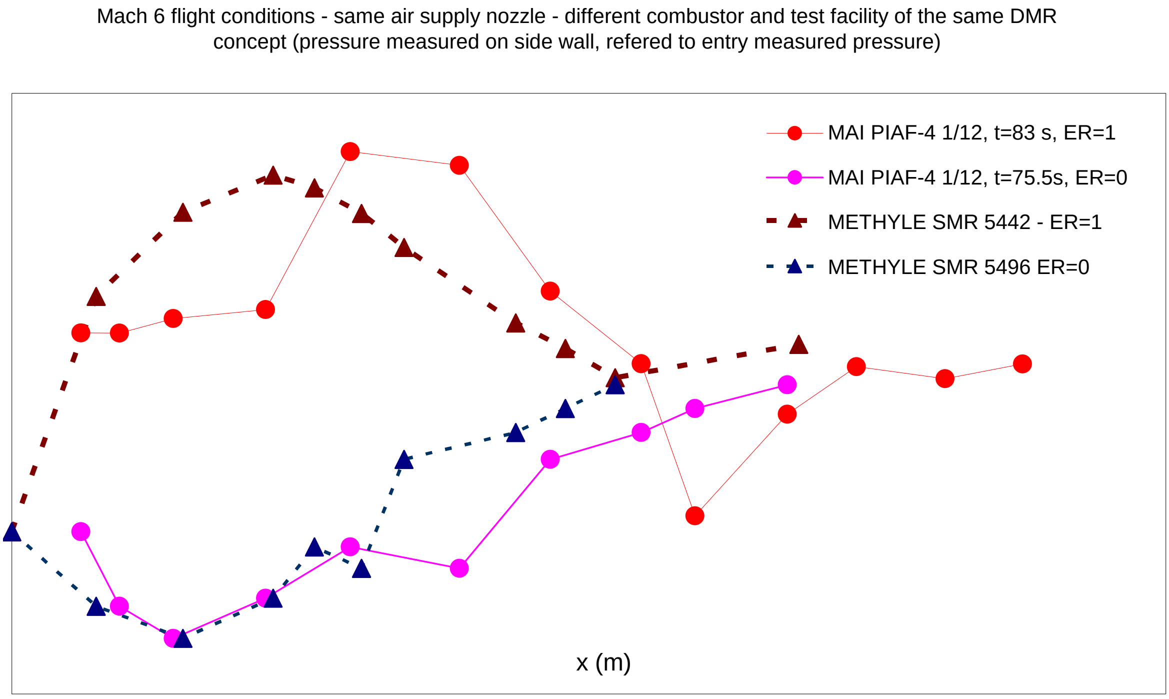

Figure 6 : measured pressure contours of translating cowl DMR concept (Mach 6 flight conditions)

Combustion test at Moscow Aviation Institute

At MAI, after the development of a new preheater (vitiator), a full scale water-cooled model has already been tested in the flight Mach number range 2 to 7+, first with H2 and kerosene as fuels, then with CH4/H2 mixture .

A new full scale model was manufactured and new test have been undertaken in Fall 2009 up to first quarter of 2010 (referred as PIAF4 test series).

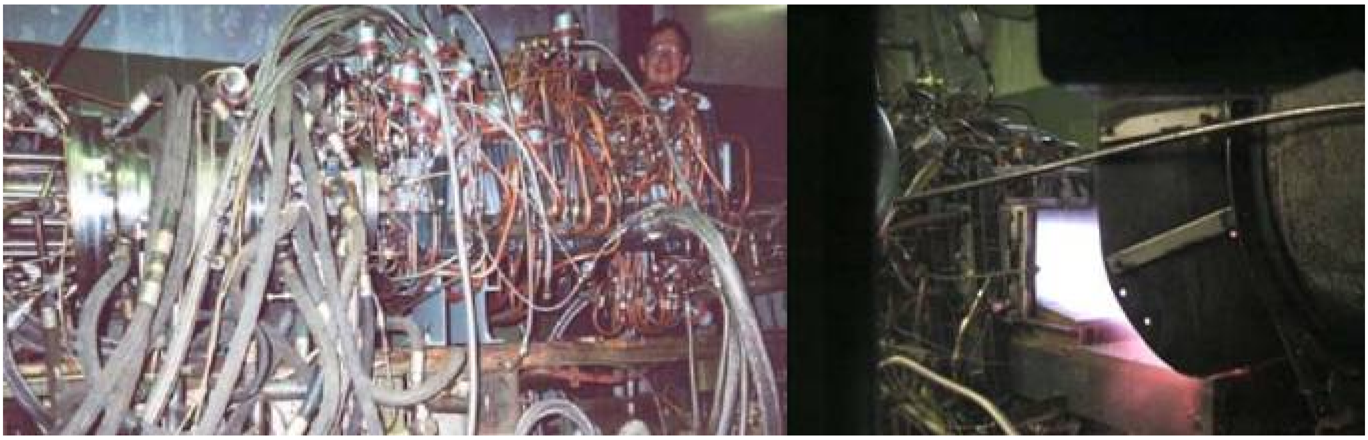

Figure 7 : combustion mock-up of translating cowl DMR at MAI

This combustion model is cooled by water. Wall temperature is assumed to be uniformly Tw=400K for 'case A' and Tw=800K for 'case B'.

One example for moderate flight Mach number operation of this DMR concept is referred here as "case A". The figure gives the contour pressure along the combustor length measured at MAI.

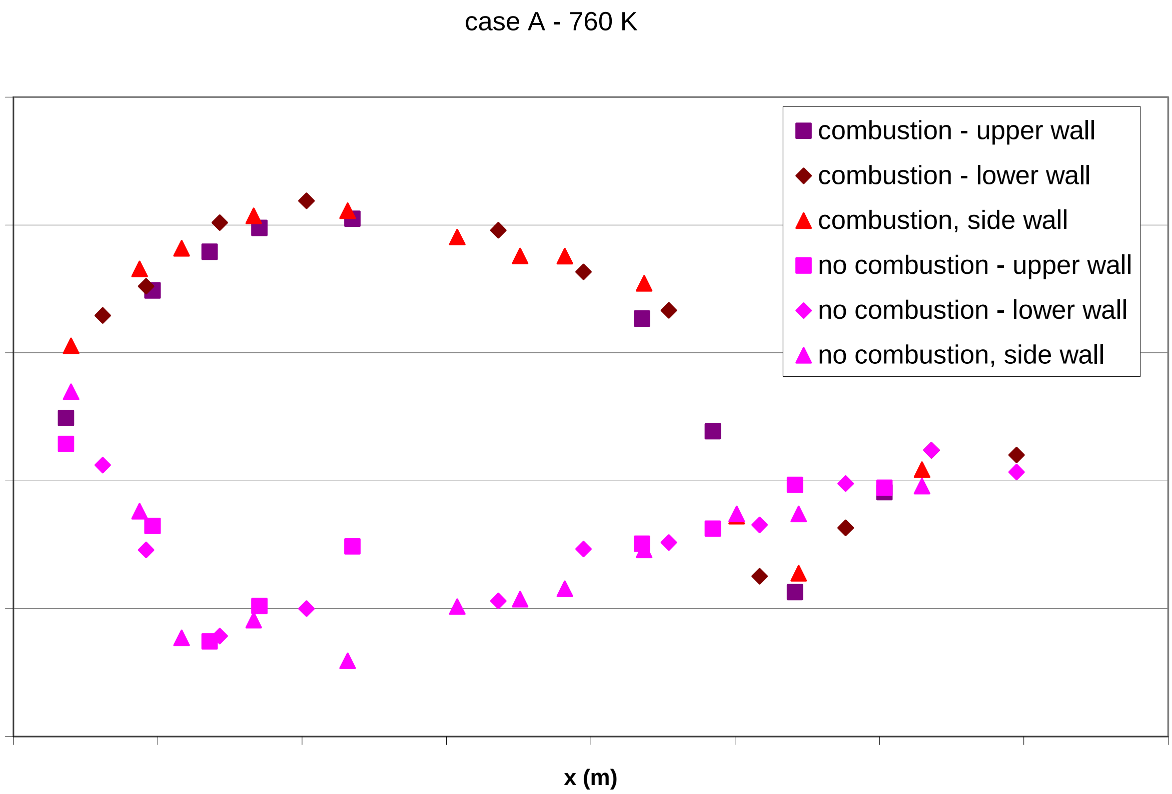

Figure 8 : measured contour pressure of case A at MAI (Mach 4 flight conditions)

Case A corresponds to a LEA type injection system studied under flight test conditions of Mf=4.
The incoming vitiated air flow has nominal stagnation temperature of Ti2=760K
The air supply nozzle accelerates the flow to the combustor with average M2=1.5.

Another example, referred here as "case B", is the Mach 6 operation of the same DMR combustion chamber, with another cowl position (moved upstream from case A to case B) The figure below gives the corresponding contour pressure along the combustor length as measured at MAI.

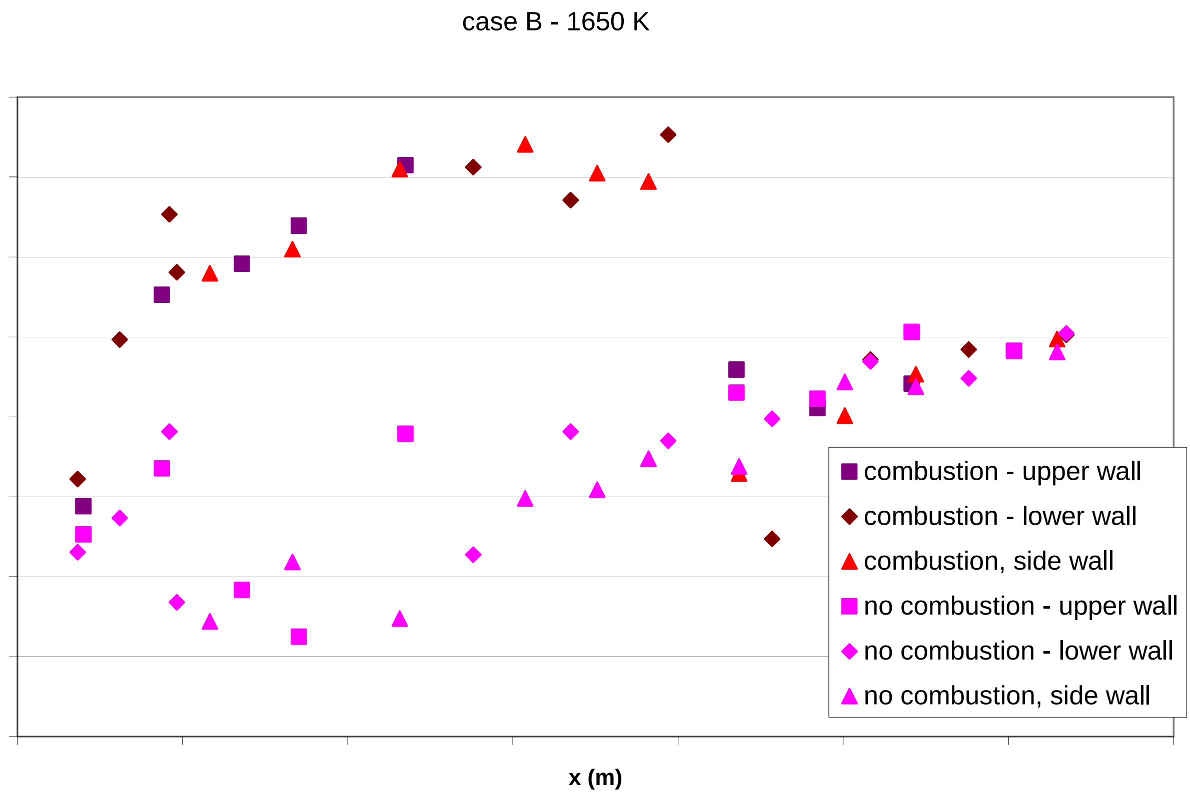

Figure 9 : measured contour pressure of case B at MAI (Mach 6 flight conditions)

Computational analysis in France and in Russia

1D test preparation and analysis is made by MBDA using 1D aerothermochemistry code PUMA.
3D computations are realized before and after the test by MBDA and ONERA using the code CEDRE.
In addition, 3D computations were realized at CIAM with complementary approach.
For the 3D computations, different model are used, as well for turbulence modelling and for combustion modelling (kinetics …).

As an example of this work, the current paper compares on the same DMR operation the experimental results with different numerical approaches. The first case (called 'case A') presented corresponds to a flight at Mach 4 (subsonic regime) , the second (called 'case B') is one of the scramjet regimes expected at Mach 6. The DMR combustor and its injection system are the same in the two presented cases, but the incoming flows and the cowl position correspond to the expected ones in flight.
The capability of taking into account the back pressure effect for ground testing without exhaust system is also investigated on the 'case A'.

With regard to presence of vertical plane of symmetry, only one half of the combustor is considered in all the presented computations. For the case presented here the MBDA computational domain is meshed in about 2 million of elements and the CIAM one about 800 000 cells.

Results for Mach 4 flight DMR operation

MBDA computed the case A with effect of turbulence modelling (k-l or k-omega), of combustion model (Eddy Break Up with 5 species and two tuned reactions or Davidenko with 16 species and 79 reactions).
CIAM used in the present 3D computations a particular one-equation turbulence model [21] and a kinetic model that includes neutral nitrogen and 25 reacting species involved in 162 reactions [22][23].

The entry flow generated by the air supply nozzle was computed in 3D and the corresponding flowfield was used as incoming boundary condition for the 3D combustion test.

MBDA computations (effect of turbulence and combustion modelling)

The Mach number flow-field of the case A is shown below for CEDRE computations.

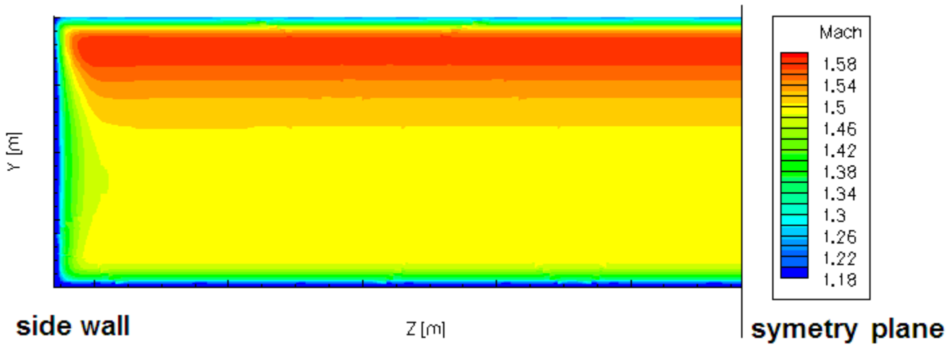

Figure 10: Mach 1.5 entry flowfield for case A in MBDA computations

The temperature regime after 3D analysis can be seen below for the two different combustion models used in this work with CEDRE. As expected, the dissociation effect remains relatively limited, leading to similar temperatures for the EBU and the kinetic computations. But some differences can still be seen.

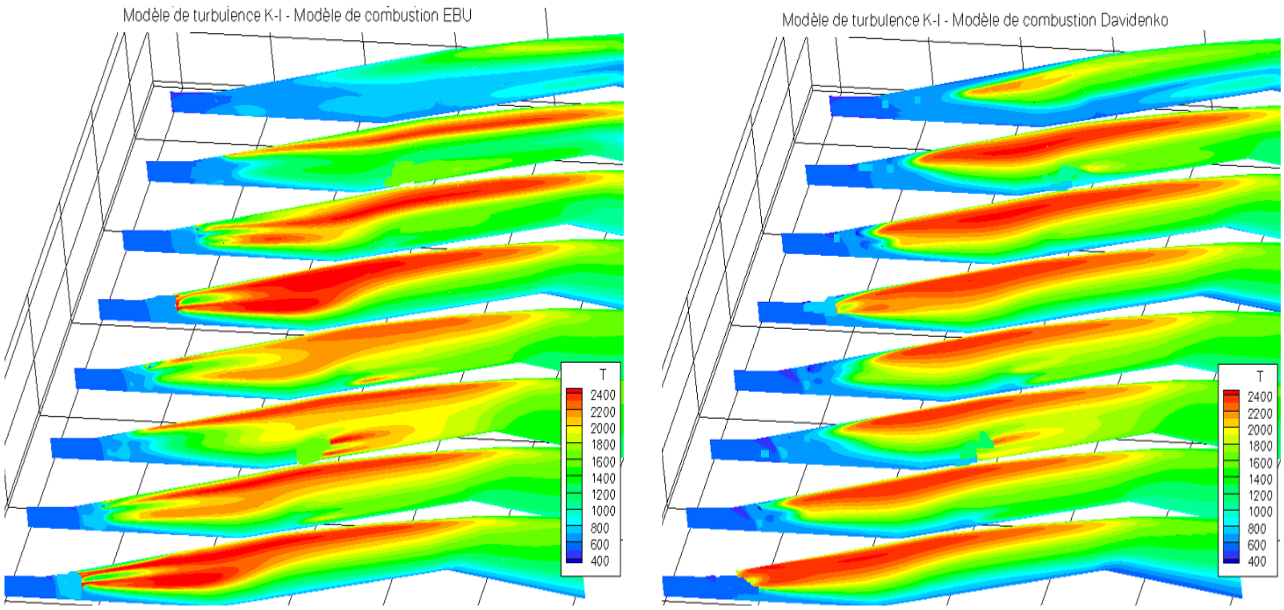

Figure 11 : computed temperature fields of case A with combustion : Eddy Break Up – left / kinetic model – right (MBDA computations)

The pressure contour appears to be very similar for case A between the different 3D computations -all refered as 'calcul' in the figure- and with the experimental results, referred as 'essais' in the figure (except in the nozzle where the back pressure effect was not computed here).

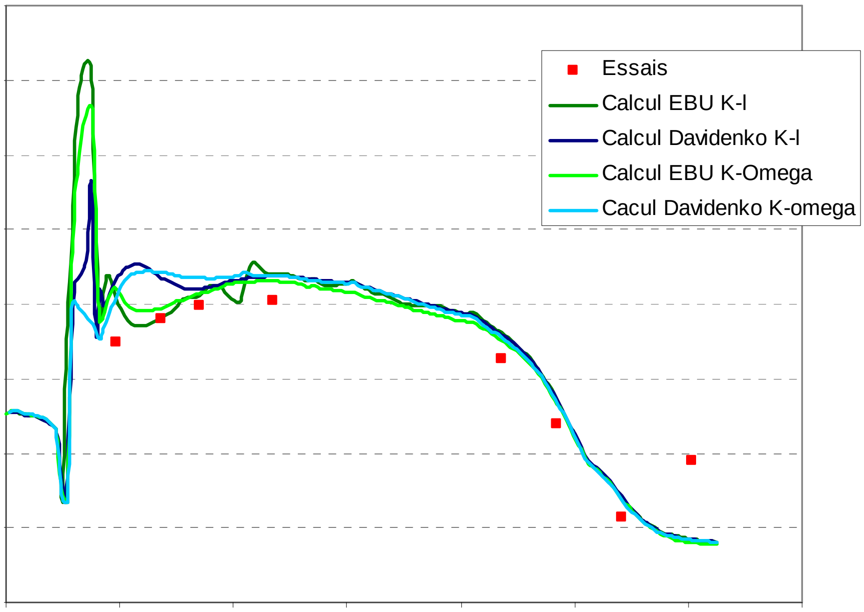

Figure 12: computed and measured pressure along the duct for case A in combustion - upper wall (MBDA computations)

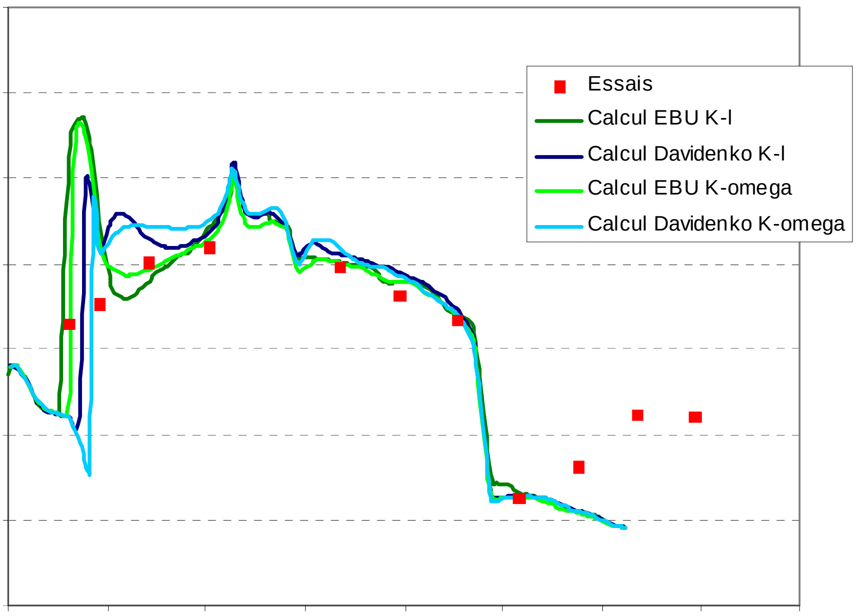

Figure 13 : computed and measured pressure along the duct for case A in combustion - lower wall (MBDA computations)

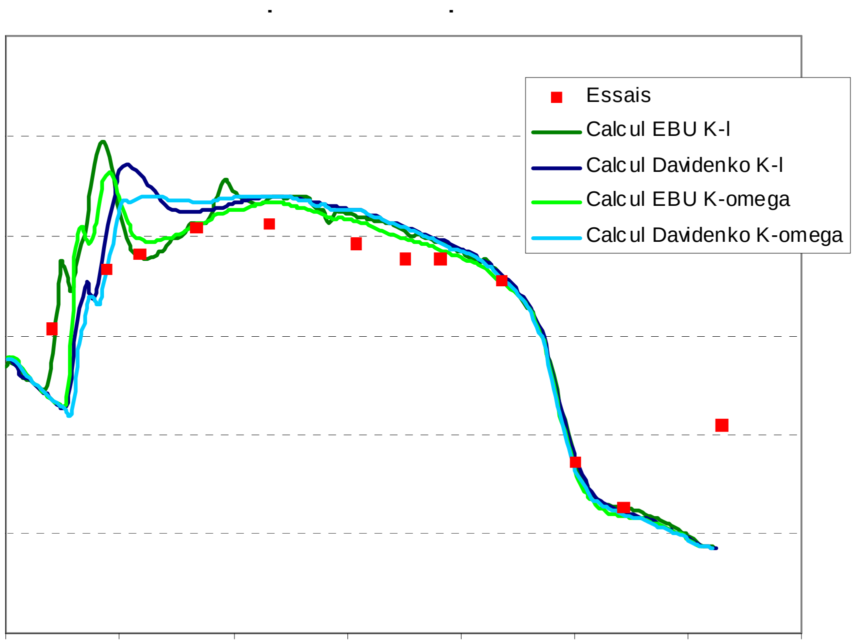

Figure 14 : computed and measured pressure along the duct for case A in combustion - side wall (MBDA computations)

The difference in the first part of the chamber, where the main phenomena takes place, is illustrative f the difficulty to correctly predict the local interactions between combustion, shocks, boundary layer, between turbulence and chemistry.
The fact that EBU and kinetic model gives similar results after combustion stabilizing was expected for this moderate flight velocity regime.

CIAM computations (effect of incoming total temperature of air)

CIAM computations were used to investigate the effect of Ti2 (nominal value of 760K, but know with 40K uncertainty) on the combustion initiating and stabilizing. The "cold" test regime A1 was simulated without back pressure influence (as probably in flight, but not in the real test at MAI, at ambient pressure without ejector exhaust system). The computation A2 corresponds to the nominal Ti2=760K. The computation A3 corresponds to the lower estimation of the incoming temperature (Ti2=720K).

The computed temperature flow-field of case A is given below as an illustrative example.

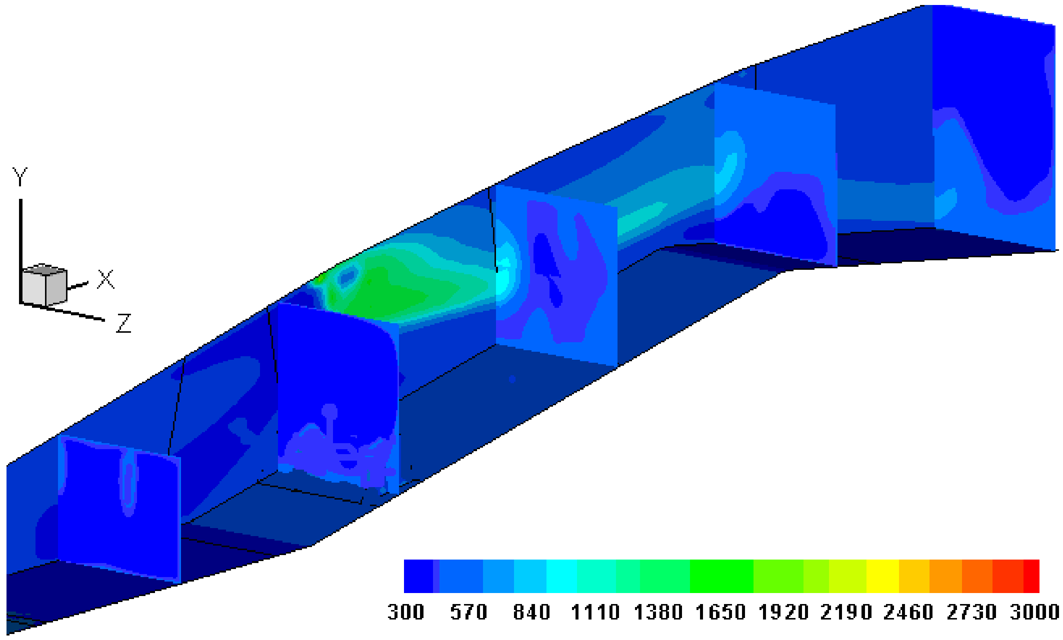

Figure 15 : computed temperature field for case A - no combustion (CIAM)

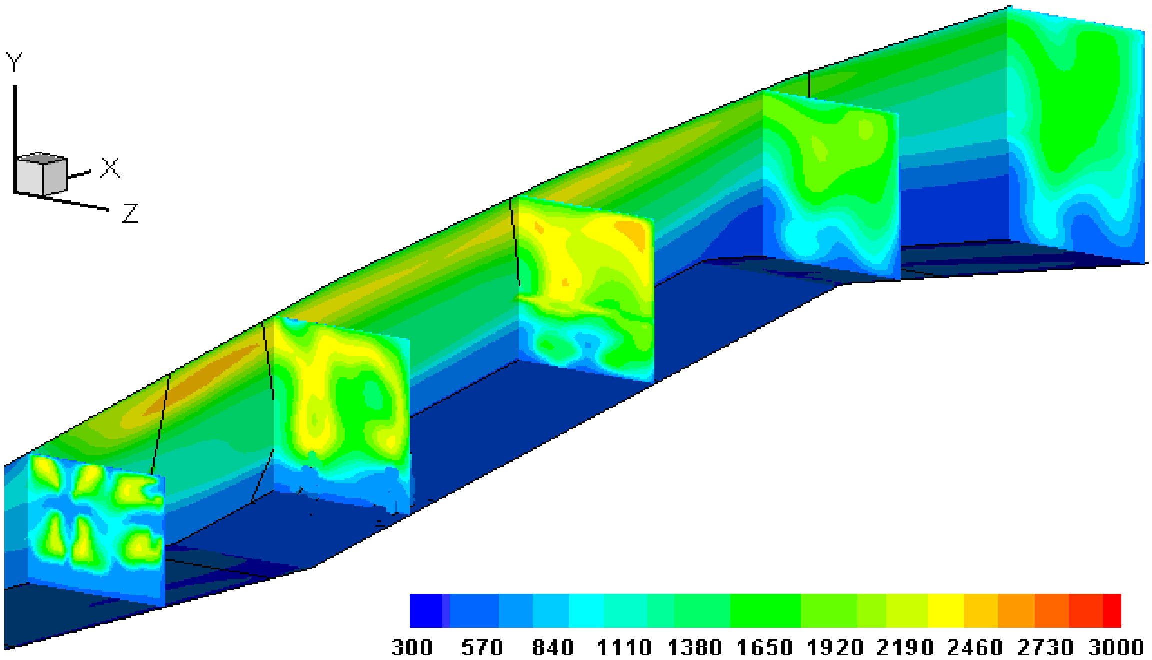

Figure 16 : computed temperature field for case A with combustion at Ti2=760 K (CIAM)

The computed Mach number is in average subsonic for the combustion test case A.

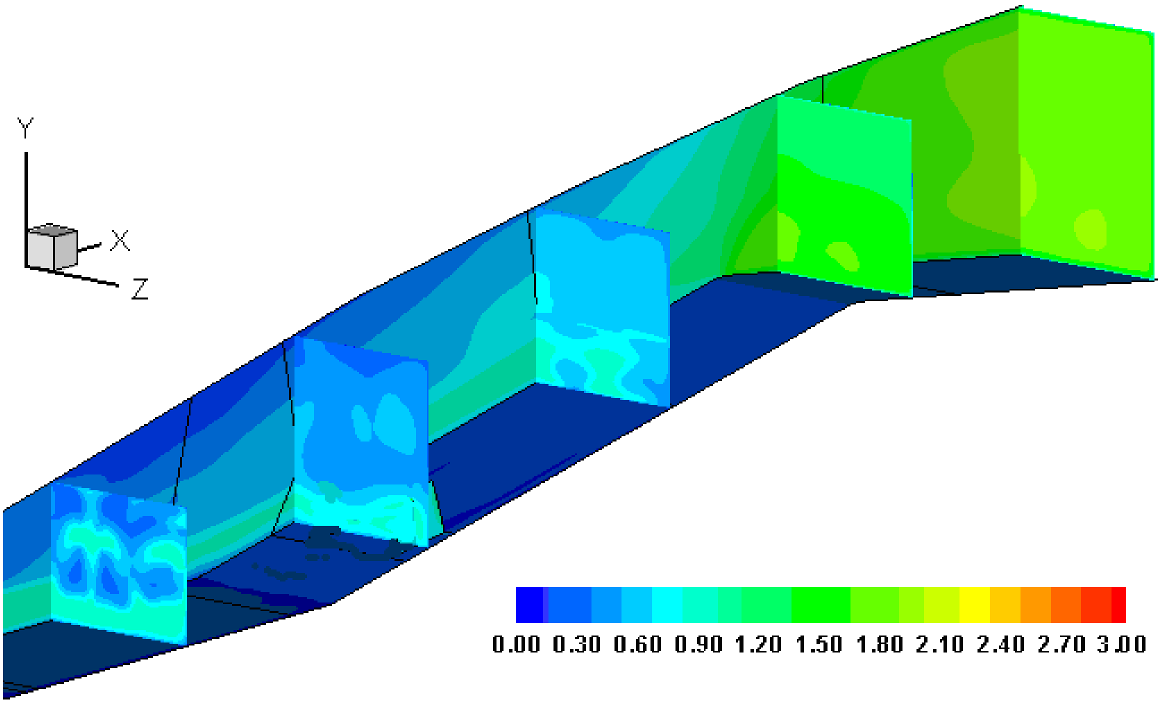

Figure 17: computed Mach number field for case A with combustion at Ti2=760 K (CIAM)

The 3D Mach number fields computed by CIAM or MBDA as well as the 1D analysis of experimental pressure contour confirm the DMR operates with subsonic combustion for 'case A'.

The computed wall pressure are quite consistent with the measured ones, and the uncertainty on the incoming air temperature (Ti2=760K for A2, Ti2=720K for A3) conduct to conclude on the overall capability of the Navier-Stokes models to compute the case A for this DMR Mach 4 flight regime.

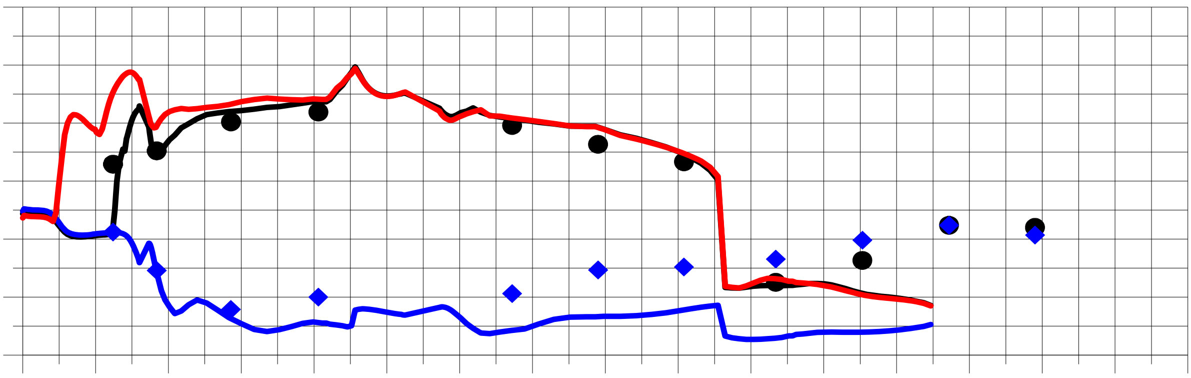

Figure 18 : computed and measured pressure along the duct for case A - upper wall (CIAM computations)

◆ A1 (experiment); A1 (calculation); ● A2 (experiment); A2 (calculation Ti2=760K); A3 (calculation Ti2=720K)

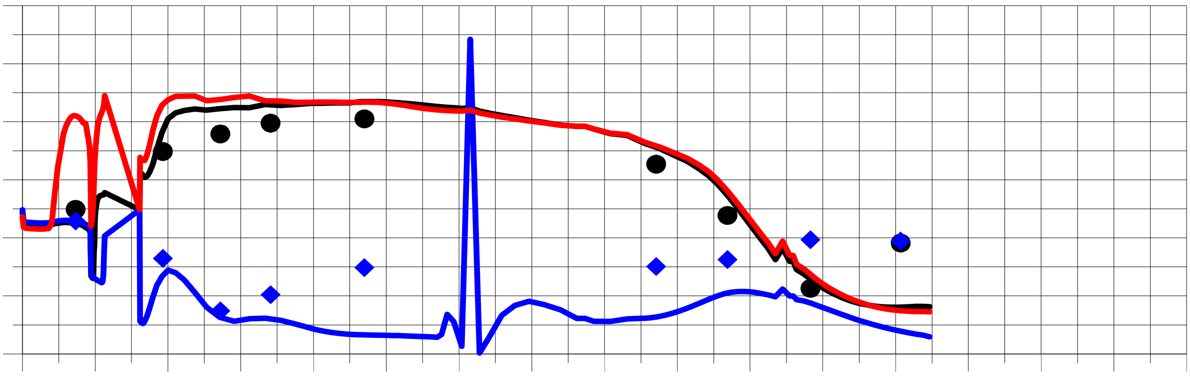

Figure 19 : computed and measured pressure along the duct for case A - side wall (CIAM computations)

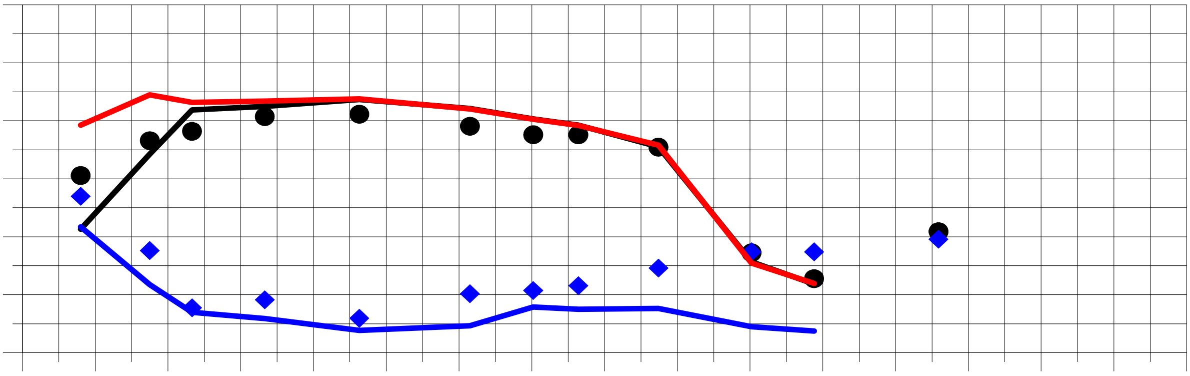

Figure 20 : computed and measured pressure along the duct for case A - lower wall (CIAM computations)

Effect of back pressure and associated 3D computation before combustion

Computations of the case A without combustion (no fuel injection) were made with two options of the CEDRE code : the one assuming a supersonic condition downstream (as expected in flight, referred in the figure as 'sortie supersonique') and the one considering a downstream static pressure of 1 bar (as during this test at MAI, referred in the figure as 'calcul avec réactualisation'). For the "case A" test conditions, the supersonic back pressure procedure of CEDRE was able to correctly compute the 3D flow, as it is shown with the pressure measured at MAI (referred in the figure as' essais').

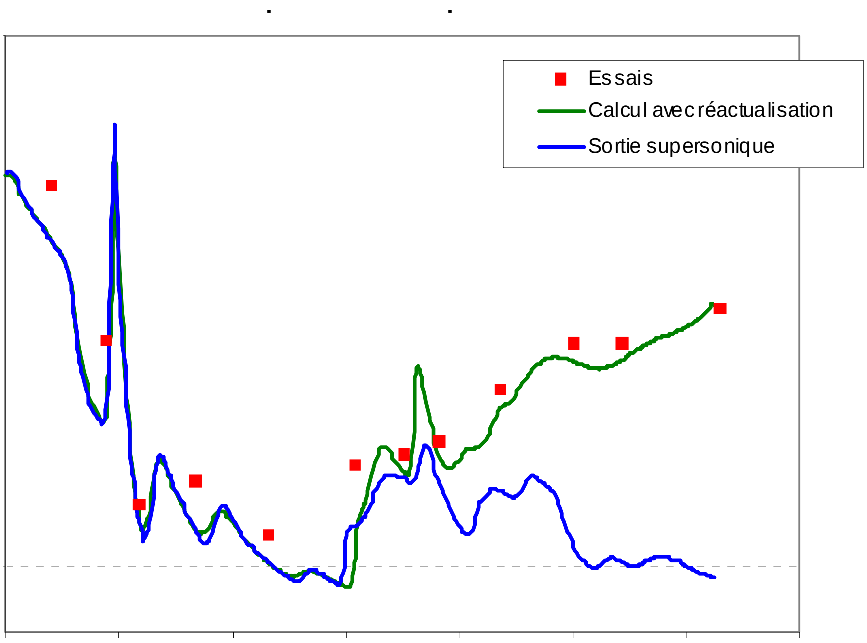

Figure 21 : computed and measured pressure along the duct for case A without fuel injection - side wall (MBDA computations with back pressure treatment or supersonic exit flow assumption)

Conclusion

The current paper illustrates performed to investigate experimentally and numerically the phenomena that contributes to the design of a movable geometry dual-mode ramjet such as the one that is planned to be flight-testing on the LEA vehicle.

Different regimes and configurations have been demonstrated during ground testing and corresponding 3D Navier-Stokes computations have been done with different models and codes. The agreement between the pressure contour in combustion is quite good for the cases presented here. As already published, overall prediction of our computational methods is also correct for fully supersonic combustion of gaseous fuel.

The effect of back pressure in case of ground testing before ignition was found able to be correctly treated for the case A without combustion, but it is not always so easy to obtain such a result (accurate separation prediction requires specific numerical methods).

Even if the overall capability of 3D reactive CFD is sufficient for industrial use on DMR design, work on numerical modelling is still in process, especially to compute ignition process, accurate interaction between the different phenomena.

Experimental work is also going on, in order to optimize and to characterize on ground the expected behaviour of the translating cowl dual-mode ramjet chosen for forthcoming LEA hypersonic flight experiments.

References

[1] F.Falempin, French hypersonic program PREPHA - System studies synthesis, XIII ISABE - 1997

[2] F.Falempin, M.Bouchez, L.Serre, C.Bruno, P.Hendrick, Airbreathing Propulsion for Future Space Launchers – Proposal for a Minimum R&T Program for Europe, AIAA – 2005 – 3362 – Capua

[3] M.Bouchez, F.Falempin, V.Levine, V.Avrashkov, D.Davidenko, French-Russian partnership on hypersonic Wide Range Ramjet: status in 2001, AIAA-2001-1872

[4] M.Bouchez, J-P.Minard, V.Levine, V.Avrashkov, D.Davidenko, French-Russian partnership on hypersonic Wide Range Ramjet: status in 2002, AIAA-2002 - 5254

[5] M.Bouchez, V.Levine, V.Avrashkov, French-Russian Cooperation on Dual-Mode Ramjet : significant step passed for technology and combustion processes mastering, AIAA-2003-7004.

[6] F Falempin, JP. Minard, B. Le Naour, METHYLE : Long endurance test facility for dual-mode ramjet combustor technologies - AIAA-2009-7378

[7] D.Davidenko, I.Gokalp, E.Dufour, D.Gaffié, Kinetic mechanism validation and numerical simulations of supersonic combustion of methane-hydrogen fuel, AIAA – 2002 - 5207 - Orléans

[8] D.Davidenko, I.Gokalp, E.Dufour, D.Gaffié, Numerical simulation of supersonic combustion of methane-hydrogen fuel in an experimental combustion chamber Moscow – July 2003

[9] D.Davidenko, I.Gokalp, E.Dufour, Numerical modelling of inert and reacting compressible turbulent jets, AIAA – 2005 –3237

[10] D.Davidenko, I.Gokalp, E.Dufour, Ph.Magre, Systematic study of the supersonic combustion in an experimental combustion chamber, AIAA – 2006 - Canberra

[11] O.Dessornes, M.Bouchez, Combustion experiments of liquid kerosene and H2/CH4 mixing in a dual-mode ramjet, AIAA–2005–3400

[12] M.Bouchez, D.Scherrer, Combustion investigation for dual-mode ramjet for the LEA program, AIAA–2008–2648

[13] L.Serre, F.Falempin, Development of a Free Jet Test Facility for the French LEA flight test program, AIAA–2008–2651

[14] L. Serre, ONERA S4 Free Jet Facility Development - Status for LEA Flight Test Program-AIAA-2009-7358

[15] F.Falempin, L.Serre, LEA flight test program - Status in 2006, AIAA – 2006 - 7925

[16] F.Falempin, M.Bouchez, Fully axisymmetric airbreather concept for space launcher – first application to a micro space launcher, IAC-08-C4.5.6

[17] J.Steelant, EU Program overview – LAPCAT and ATTLAS, plenary session, 15th AIAA international space planes and hypersonic systems and technologies – 2008 – Dayton (OH)

[18] F. Falempin, M. Bouchez, LAPCAT 2 –Axisymmetric Concept for a Mach 8 Cruiser Preliminary Design and Performance Assessment - AIAA-2009-7437

[19] S. Defoort, L. Serre, LAPCAT II: Towards a Mach 8 Civil Aircraft Concept Using Advanced Rocket/Dual-Mode Ramjet Propulsion System - AIAA-2009-7328

[20] F. Falempin, L. Serre, French Flight Testing Program LEA, Status in 2009, AIAA 2009-7227, 16th AIAA/DLR/DGLR International Space Planes and Hypersonic Systems and Technologies Conference.

[21] Gulyaev A.N., Kozlov V.E., Secundov A.N. A Universal One-Equation Model for Turbulent Viscosity. Fluid Dynamics, 1993, V.28, No.4, p.485-494.

[22] Dautov N. G., Starik A. M. On the Problem of Choosing a Kinetic Scheme for the Homogeneous Reaction of Methane with Air. Kinetics and Catalysis, 1997, V.38, No.2, p.185 -208.

[23] Starik A.M., Titova N.S. Intensification of the Oxidation of Rich Methane/Air Mixtures by O2 Molecules Excited to the a1□g State. Kinetics and Catalysis, 2006, Vol. 47, No. 4, pp. 487–496.