LEA FLIGHT TEST PROGRAM – STATUS IN 2005

F.Falempin
MBDA–France, 2 rue Béranger - BP 84 - 92323 CHATILLON Cedex - France

L. Serre
ONERA, 29 av. Div. Leclerc – BP72 – 92322 CHATILLON Cedex - France

MBDA and ONERA are leading a specific scientific program, called LEA, aiming at demonstrating their ability to predict the aeropropulsive balance of a hypersonic vehicle, ensuring sufficient margins to undertake a costly full scale development program, by :

- Defining a methodology for the development of a hypersonic vehicle using ground tests and numerical simulation
- Developing the required tools (experimental or numerical) for this purpose
- Applying this methodology to the development of a simplified, low cost experimental vehicle
- Validating this methodology through a series of flight tests.

Started in January 2003, this program is planned to end in 2012 after 6 autonomous flights of the experimental vehicle in the Mach number range from 4 to 8.

Introduction

During the two past decades, a lot of system studies, generally based on large technology development efforts, have been performed in France to assess the interest of high-speed airbreathing propulsion for both military and civilian application ([1] to [10]).

The development of such operational application depends of two key points :

- development of needed technologies for the propulsion system as a low weight, high robustness fuel-cooled structure for the combustor,
- capability to predict with a reasonnable accuracy and to optimise the aero-propulsive balance (or generalized thrust-minus-drag).

Technology development effort

Even if technologies will finally need to be flight proven, a large part of the technology development effort can be led with available ground test facilities [11] and classical numerical simulation (thermics, mechanics…).

In that field, the effort started during the PREPHA Program has being continued last years through several initiatives taken by ONERA and MBDA France to maintain and develop knowledge and preserve human and material investments in spite of the lack of new National or European R&T program [12] :

- JAPHAR program (ONERA and DLR) ([13] to[18]),
- WRR program (MBDA France and MAI) ([19] to[23]),
- PROMETHEE program (ONERA and MBDA France) ([24] to [27]),
- A3CP (ONERA/SNECMA/Pratt & Whitney)
- PTAH-SOCAR (MBDA France and EADS Space Transportation),
- Other cooperation with research laboratories ([28] to [36]).

Today, the technology development effort is pursued on different aspects which contribute to ensure the performance and safe operation of the combustion chamber :

- variable geometry needed to optimize the performance on the overall flight Mach number range,
- fuel used as coolant for combustion chamber structure ([37] to [41]),
- fuel-cooled structure itself ([42] to [51]).

Beyond the works already in progress, the test facility, developed by MBDA France and ROXEL in their Bourges Subdray test center in the framework of PREPHA program [49], is under upgrading. The new test facility, called METHYLE, will allow to perform long endurance test in representative conditions to pursue and reinforce technology development by using a modular water-cooled dual mode ramjet combustion chamber able to integrate different kind of testing parts as for :

- element of variable geometry,
- sealing system,
- fuel-cooled structure,
- measurement techniques,
- engine control system…

LEA flight test program

Aero-propulsive balance sensitivity

For an airbreathing propulsion system, the net thrust (e.g. the thrust which can effectively be used for compensating the drag and accelerating the considered vehicle) is the difference between the thrust provided by the exit nozzle (momentum of accelerated hot gas coming from the combustion chamber) and the drag due to air capture by the inlet. Indeed, atmospheric air has initially no speed. During capturing process, some energy has first to be paid to accelerate the incoming air in the upstream direction up to 40 to 75 % of the vehicle speed. On the contrary, hot exhaust gas must be ejected through the nozzle in the rear direction at a speed exceeding flight speed (in vehicle reference).

This fact can be illustrated as follows :

- at flight Mach number 2, a net thrust of 1 is obtained by producing a thrust of 2 by the nozzle which compensates an air capture drag of 1,
- at Mach 8, a net thrust of 1 is obtained by a nozzle thrust of 7 while air capture drag is 6,
- at Mach 12, a net thrust of 1 is obtained by a nozzle thrust of 12 while air capture drag is 11.

Then, the higher the flight Mach number, the more sensitive the net thrust. At Mach 8, for example, an error of 5 % on nozzle performance leads to a reduction of 35 % in net thrust.

Moreover, it is more and more mandatory to optimize the integration of the propulsion system into the vehicle airframe. Then, vehicle and propulsion system components are operating in a very coupled way which would require to test the overall system to determine the global performance.

But, the higher the flight Mach number, the more it becomes difficult to simulate right flight conditions with on-ground test facilities. Generally, in such test facilities, air is heated up to total temperature before being accelerated through a nozzle to enter the test section at the right Mach number. Whatever the heating process may be, that generally leads to the creation of radicals, and very often some pollution, into the air which can change combustion process.

By another way, some scaling effect to be addressed for large aircraft or space launcher stage are difficult (or impossible) to solve with similarity rules. Then, the overall system should be tested at full scale that implies very large, and extremely expensive if feasible, test facilities.

Development methodology

The here above described extreme sensitivity of the aero-propulsive balance on one hand, and the corresponding limited capability of ground test facilities to represent right flight conditions on the other hand make mandatory the definition of a specific on-ground development methodology coupling very closely experimental and numerical approaches.

In such a methodology, the in-flight performance can be predicted only by a nose-to-tail numerical simulation. Then on-ground test facilities will be used to performed partial test of vehicle and propulsion system components separated or coupled two by two.

These tests have two goals :

- to allow components design tuning and verify a minimum performance,
- to verify, step by step, the ability of numerical simulation to predict accurately performance in conditions as close as possible to the actual flight.

Obviously, such methodology is very challenging. So, before starting any operational development, it must be demonstrated that applying this approach will give an accurate value of the performance, allowing to guarantee design margins and to identify properly right directions for optimizing system design. That is why, a flight experimental program is a mandatory step towards future operational developments.

Beyond all current technology development works mentioned here above, and on the base of previous acquired results, MBDA France and ONERA started a flight test program, called LEA, in January 2003 with the support of French Administration.

In order to limit the cost, this flight test program will be realized with a minimum experimental vehicle without any technology demonstration purpose (use of existing technologies as often as possible) (Fig. 1). In the same view this vehicle will be non-recoverable, then non-reusable.

The test principle consists in accelerating the flight experimental vehicle specimen thanks to an air-launched booster up to the given test Mach number, chosen in the range 4 to 8. Then, after booster separation and stabilization, the experimental vehicle will fly autonomously during 20 to 30 seconds (Fig. 2).

During this flight, the airbreathing propulsion system will be ignited during approximatively 5 seconds with a fuel-to-air equivalence ratio variation.

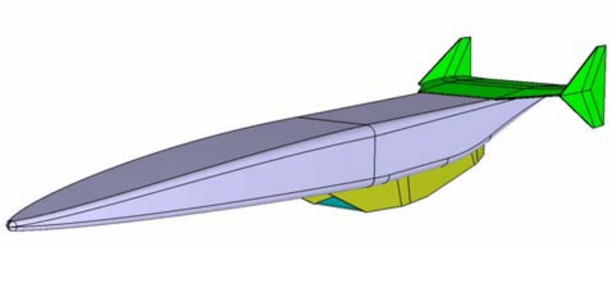


Fig.1 – CAD view of LEA vehicle

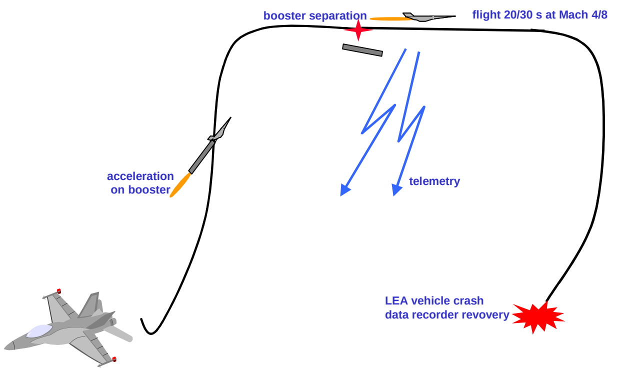


Fig.2 –LEA flight testing sequence

The vehicle would be specifically instrumented to give a precise evaluation of the aero-propulsive balance with and without combustion and to determine the contribution of each propulsion system component to this balance. All measured parameters will be transmited to ground by telemetry and recorded with an on-board data recorder which will be recovered after the crash of the vehicle.

The program is divided into 4 phases, as described by Fig. 3, and should be achieved after 6 flight tests, planned between 2010 and 2012 for exploring Mach 4 to Mach 8 range.

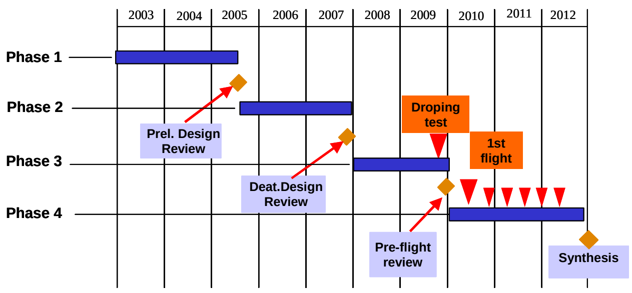


Fig.3 –general time schedule

As explained previously, and beyond a detailed understanding of the aero-propulsive balance constitution, such a flight test program will give the opportunity to define, implement and validate a development methodology which will be available for the design of any future operational vehicle.

Since the beginning of 2003, first steps of the preliminary design phase have been performed.

A parametric study has been performing regarding the size of the vehicle and its propulsion system in order to limit the corresponding development and production costs while ensuring the compliance with the technical requirement of the flight test program. The total length of the vehicle has then been reduced below 4.5 m. and the entrance area of the combustion chamber has been chosen to allow performing full scale direct connected pipe test in ONERA ATD 5 test facility.

Moreover, the general airframe configuration have been defined in order to ease the refinement of airframe and engine thermo-mechanical design.

For the experimental vehicle, the airbreathing propulsion system concept has been chosen by taking into account all results acquired during engines developments performed these last years.

The considered propulsion system concepts were mainly a fixed geometry one, derived from the PREPHA/JAPHAR engine (which needs a variable geometry inlet) (Fig.4), a variable geometry one, derived from the PROMETHEE engine (Fig.5) and an other variable geometry one derived from the PIAF engine (Fig.6).
The finally selected concept is a variable geometry one directly derived from the PIAF engine but will use a thermal throttling. Nevertheless, as each flight test will be performed at a nearby constant Mach number, a fixed geometry engine will be used for each LEA test vehicle, this engine configuration being representative of the selected variable geometry concept at the tested flight Mach number.

A large parametric study has been performed on the possible technology for the combustion chamber. The goal of such a study was to identify the best trade-off between several requirements as :

- limited structural mass,
- limited alteration of combustion chamber geometry due to mechanical and thermal loading,
- representative wall temperature limiting the heat losses and then optimizing performances,
- limitation of development and production costs.

The finally selected solution is based on metallic heat sink solution with a deposit of high temperature low thermal conductivity layer.

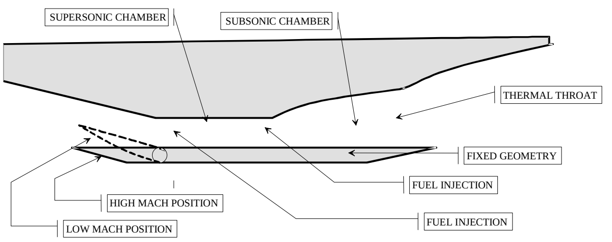


Fig.4 – fixed geometry JAPHAR engine

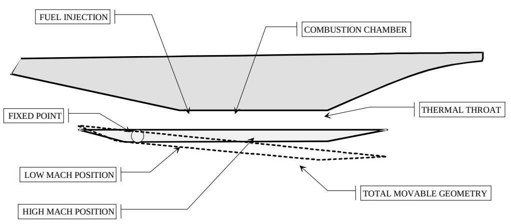


Fig.5 – variable geometry PROMETHEE engine

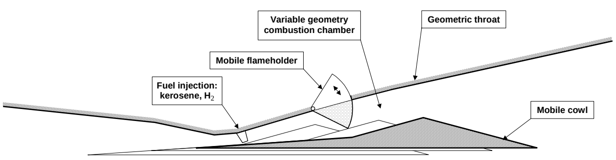


Fig.6 – variable geometry PIAF engine

The fuel has also been chosen. The most part of French experience in supersonic combustion is related to Hydrogen. But, considering the very low density of Hydrogen, it is preferable to avoid this fuel in order to limit the size of the tank, then the size of the vehicle and consecutive difficulties to find a possible acceleration system complying with the needs (integration constraints, needed total energy release…).

On the other hand, liquid hydrocarbon fuel could be considered. But, our experience is very limited with such a fuel and it would be difficult to ensure a robust ignition and a good combustion efficiency without previous reforming in a regenerative cooling system (simplest technology used on board of the experimental vehicle).

Finally, a mixture of gaseous Methane and gaseous Hydrogen has been selected. By using this mixture, it is possible to increase the fuel density then limit the fuel tank size. It will be also possible to vary the H2/CH4 ratio during the flight to ensure a robust ignition and control the heat release along the combustor.

Some specific works have been performed to adapt our computation codes to this particular fuel ([52] to [54]). These codes have been validated thanks to basic experiments led in updated ONERA LAERTE test facility.

Moreover, ONERA ATD 5 test facility has been updated to allow future CH4/H2 tests for the LEA engine. By waiting, a first test series has been performed with already existing JAPHAR combustion chamber to acquire a first experience with such a fuel [55].

The forebody has been specifically studied. Some parametric studies have been carried out in order to determine a set of design parameters allowing a satisfactory pre-compression while complying with technology constraints (Fig. 7).

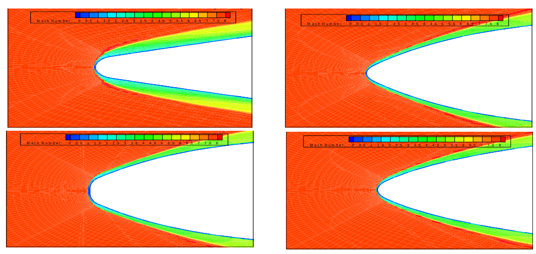


Fig.7 – Example of parametric results obtained on forebody

On the base of an air inlet design and corresponding performances, a first design of the combustion chamber has been realized thanks to 1D, then 2 and 3D computation. On this basis, a full scale mock-up is under manufacturing for future test in ATD 5 ONERA test facility.

The afterbody/nozzle has been also studied. Due to its particular configuration (Fig.8), a specific effort is under progress to well understand the interaction between the propulsive jet and the external flow to accurately determine the effect of propulsion on external aerodynamics.

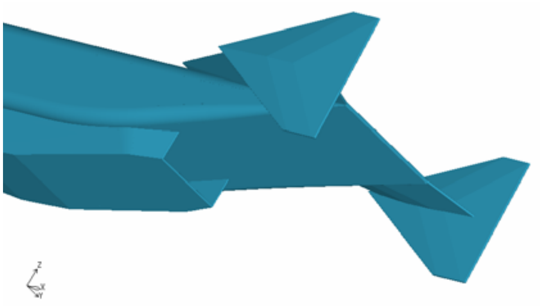


Fig.8 – Afterbody/nozzle configuration

Aerodynamic behaviors of the LEA vehicle and of the Flight Experimental Composite constituted by LEA and its booster have been evaluated by computation for preparing future aerodynamic tests.

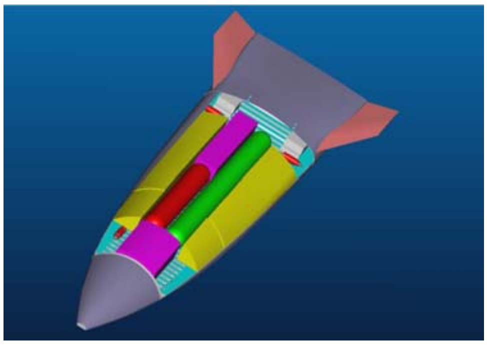
Finally, this configuration is under detailed evaluation, including Nose-to-Tail computation, and will be improved step by step.

All the previous elements have been used in a detailed flight simulation in order to obtain a first evaluation of reachable maximum LEA/booster separation conditions. This flight simulation allows simulating a complete flight test sequence including LEA/booster dropping from air carrier, acceleration on booster, separation, descent trajectory of booster, LEA autonomous flight up to final crash.

Other activities have also been undertaken in order to chose the basic technologies used for the LEA vehicle and its propulsion system and to perform a preliminary design (Fig. 9).

By another way, a general approach for on-ground testing has been defined but still remain to be refined and confirmed.

Indeed, as Fig. 10 shows and on the base of previous studies [56], a large part of the on-ground testing program should be realized in the S4Ma windtunnel located in ONERA Modane test Center in the French Alps. It is intended to upgrade this test facility in order to take advantage of the existing alumina peeble bed heater which allows to perform test with air non vitiated by water vapor up to Mach 6.5 conditions (1800 K). Thanks to a complementary pre-burner or to an upgrading of the peeble bed heater, tests in conditions corresponding to flight at Mach 7.5/8 should be also feasible [57].



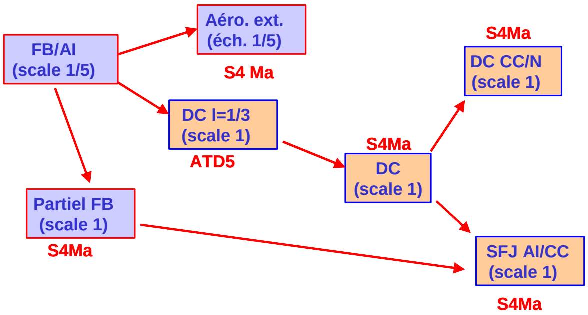


Fig. 9 – Preliminary internal lay-out of LEA vehicle

Fig. 10 – general approach for on-ground testing

Detailed design studies, as for example free jet test configuration (Fig.11), are under progress to verify the feasibility of such an upgrading and evaluate precisely the corresponding cost.

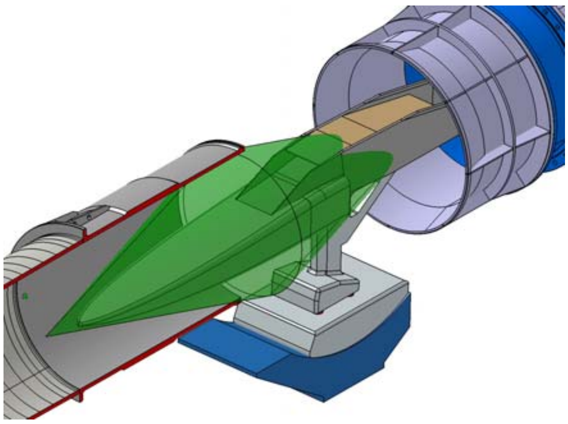


Fig. 11 – Study of LEA free-jet testinstallation in S4Ma ONERA test facility

Conclusion

Since more than ten years, ONERA and MBDA France are leading a large technology development effort for high-speed airbreathing propulsion and particularly for dual mode ramjet.

Beside these technology activities, which can be pursued on ground, and considering the extreme sensitivity of the aero-propulsive balance and the limitation of on-ground test facilities, MBDA France and ONERA are now leading the minimum flight experimental program, called LEA.

This program will demonstrate the feasibility of a positive aero-propulsive balance and, moreover, it will also allow to define, implement and flight validate an on-ground development methodology able to provide a good prediction of the aero-propulsive balance and to guarantee required design margins : feasibility of such development methodology remaining a preliminary but mandatory condition before considering operational applications for high-speed airbreathing propulsion.

A preliminary design phase has been started in January 2003. Step by step, the main design guidelines of the LEA experimental vehicle are defined and will be confirmed by a Preliminary Design Review planned by the end of 2005.

References

[1] F. FALEMPIN, D. SCHERRER, G. LARUELLE, Ph. ROSTAND, G. FRATACCI. French Hypersonic Propulsion programme PREPHA - Results, Lessons and Perspectives - AIAA - 98 – 1565 - Norfolk

[2] C. ROTHMUND, D. SCHERRER, F. LEVY, M. BOUCHEZ Propulsion system for airbreathing launcher in the French PREPHA program - AIAA – 96 – 4498 – Norfolk

[3] T. BONNEFOND, F. FALEMPIN, P. VIALA - Study of a generic SSTO vehicle using airbreathing propulsion - AIAA – 96 – 4490 – Norfolk

[4] F. FALEMPIN - French hypersonic program PREPHA - System studies synthesis - XIII ISABE - Chattanooga - 1997

[5] M.BOUCHEZ, V.LEVINE, V. AVRASHKOV, D.DAVIDENKO, P. GENEVIEVE - Airbreathing space launcher interest of a fully variable propulsion system - AIAA–2000 – 3340

[6] M. BOUCHEZ - Dual-mode ramjet thermo-mechanical design and associated performance - AIAA-2001- - Kyoto

[7] F. FALMEPIN - The fully reusable launcher – a new concept asking for new visions - AIAA – 2003 - 6994 - Norfolk

[8] L. SERRE - Hypersonic UAV for reconnaissance in the depth - AGARD 594 - Athens – 1997

[9] L. SERRE, F. FALEMPIN - High altitude high-speed UAV for reconnaissance operations - Projection of forces int. symposium -AAAF – Paris – Dec. 99

[10] F. FALEMPIN - Possible military application of high-speed airbreathing propulsion in the XXIst Century – an European vision - AIAA-2003–2733 - Dayton

[11] F. FALEMPIN - Ramjet/Scramjet technology – French capabilities - AIAA - 99 – 2377 – Los Angeles

[12] F. FALEMPIN, Ph. NOVELLI, P. HENDRICK, A. SOUCHIER Airbreathing/rocket combined cycle propulsion efforts in Europe - AAAF – 2002 – 268 - Versailles

[13] Ph. NOVELLI, W. KOSCHEL - JAPHAR : a joint ONERA-DLR research project for high-speed airbreathing propulsion XIV ISABE - Florence - IS 7091 - 1999

[14] Ph. NOVELLI - Progress of the JAPHAR cooperation between ONERA and DLR on hypersonic airbreathing prop. - AIAA-2001- - Kyoto

[15] Th. EGGERS, Ph. NOVELLI - Design studies for a M 8 dual mode ramjet flight test vehicle - AIAA – 99 - 4877 - Norfolk

[16] Ph. DUVEAU, R. HALLARD, Ph. NOVELLI, Th. EGGERS Aerodynamic performance analysis of the hypersonic airbreathing vehicle JAPHAR-XIV ISABE -Florence-IS 7286–99

[17] O. DESSORNES -Tests of the JAPHAR dual-mode ramjet engine -AIAA-2001- - Kyoto

[18] O. DESSORNES -Weighing of the JAPHAR dual mode ramjet engine -AIAA – 2002 – 5187 – Orléans

[19] M. BOUCHEZ, V. LEVINE, V. AVRASHKOV,D. DAVIDENKO, F. FALEMPIN -France-Russia partnership on hypersonic Wide Range Ramjet : status in 1999 -AIAA – 99 – 4845

[20] M. BOUCHEZ, F. FALEMPIN, V. LEVINE, V. AVRASHKOV, D. DAVIDENKO -French-Russian partnership on hypersonic Wide Range Ramjet : status in 2001 - AIAA-2001-1872

[21] F. FALEMPIN, V. LEVINE, V. AVRASHKOV,D. DAVIDENKO, M. BOUCHEZ - MAI/AEROSPATIALE Cooperation on a hypersonic WRR: evaluation of thermal protection systems - XIV ISABE - Florence - IS 7140 – 1999

[22] 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

[23] 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.

[24] F. FALEMPIN, L. SERRE - The French PROMETHEE Program – status in 2000 - AIAA – 2000 – 3341

[25] L.SERRE, F. FALEMPIN - The French PROMETHEE Program on hydrocarbon fueled dual-mode ramjet – status in 2001 - AIAA-2001-1871

[26] L. SERRE, F. FALEMPIN - PROMETHEE : The French military hypersonic propulsion Program - AIAA – 2002 – 5141

[27] L. SERRE, F. FALEMPIN - Promethee - The French Military Hypersonic Propulsion Program - AIAA-2003-6950

[28] U. BRUMMUND, B. MESNIER - Flow field visualisation of non-reacting and reacting supersonic flows in a scramjet model combustor using non-intrusive optical diagnostic - 8th Int. Symp.of Flow Visualisation, Sorrento, 1998

[29] F. FALEMPIN, M. GOLDFELD - Design and experimental evaluation of a M 2– M 8 Inlet - AIAA-2001-1890 – Kyoto

[30] F. FALEMPIN, M. GOLDFELD, R. NESTOULIA, A. STAROV. Evaluation of a variable geometry inlet for dual mode ramjet - AIAA-2002-5232 - Orléans
[31] M. BOUCHEZ - Status of measurement techniques for supersonic and hypersonic ramjets in industrial facilities XIV ISABE - Florence - IS 7168 – 1999
[32] M.BOUCHEZ, JP.MINARD, O.LEGRAS, I.VALLET, J.VALLY, I.GÖKALP,C.DeIZARRA,O.VALLEE, Ph.HERVE, B.SARH, V.AVRASHKOV - RAPIERE : An innovative industrial optical measurement system for scramjet flows - AIAA- 2001 – 1861
[33] J-P. MINARD -RAPIERE : An innovative industrial optical measurement system for scramjet flows - AIAA – 2002 - 5156
[34] O. LEGRAS -Ramjet application of industrial equipment to measure flame radiation for temperature profile retrieval AIAA – 2002 - 5157 - Orléans
[35] M. GOLDELF,V. PETROCHENKO, R.NESTOULIA, V.SHISHOV, F. FALEMPIN The Direct measurement of friction in the boundary layer at supersonic flow velocities - AIAA – 2001 – 1769 – Kyoto
[36] M. GOLDELF, R. NESTOULIA, F. FALEMPIN -The Direct measurement of friction in the boundary layer at supersonic flow velocities - AIAA – 2002 – 5199 – Orléans
[37] E.DANIAU, M. BOUCHEZ, R. BOUNACEUR, F. BATTIN-LECLERC, P.-M. MARQUAIRE, R. FOURNET. Contribution to Scramjet active cooling analysis using n-dodecane decomposition model as a generic endothermic fuel - AIAA-2003-6920, Norfolk
[38] N.GASCOIN, Ph.GILLARD, Y.TOURE, S.BERNARD, E.DANIAU, M.BOUCHEZ. Transferts couplés dans un statomixte en composite thermostructural refroidi par transpiration - Congrès Français de Thermique, SFT 2004, Presqu'île de Giens, France, 25-28 mai 2004.
[39] M. SICARD, F. SER, B. RAEPSAET, C. MASSON. Kinetic study and decomposition products determination of a N-Alkane endothermic fuel - AIAA – 2005 – 3402
[40] E. DANIAU, M. BOUCHEZ, O. HERBINET, P. MARQUAIRE, F. BATTIN-LECLERC, R. FOURNET, R. BOUNACEUR. Fuel reforming for scramjet thermal management and combustion optimization -AIAA–2005– 3403
[41] E. DANIAU, M. SICARD. Experimental and numerical investigations of an endothermic fuel cooling capacity AIAA – 2005 – 3404
[42] D.MEDWICK, J.CASTRO, D.SOBEL, G.BOYET, JP. VIDAL-Direct fuel composite structure - AIAA SL-233/USA-54
[43] C. BOUQUET, A. LUC-BOUHALI, B. HAUBER, J. THEBAULT Validation of a leak-free C/SiC heat exchanger technology AIAA-2003-6918, 2003.
[44] C. BOUQUET, J. THEBAULT, P.SOYRIS, R. FISCHER. Fully ceramic composite heat exchanger qualification for advanced combustion chambers – AIAA – 2005 - 3433
[45] E. DUFOUR, M. BOUCHEZ - Semi-emperical and CFD analysis of actively cooled dual mode ramjets - AIAA – 2002 – 5126
[46] M.BOUCHEZ, E.SAUNIER, P. PERES, J.LANSALOT-Advanced carbon/carbon injection strut for actual scramjet - AIAA – 96 – 4567
[47] F. FALEMPIN, T. SALMON, V. AVRASHKOV Fuel-cooled composite materials structures - status at AEROSPATIALE MATRA - AIAA - 2000 - 3343 - Huntsville
[48] F. FALEMPIN, M. BOUCHEZ, T. SALMON, P. LESPADE, V. AVRASHKOV - An innovative technology for fuel-cooled composite materials structures - AIAA -2001- 1880 - Kyoto
[49] M. BOUCHEZ, F. FALEMPIN - PTAH-SOCAR Fuel-cooled composite materials structure - AIAA – 2002 – 5135 – Orléans
[50] M. BOUCHEZ, G. CAHUZAC, S. BEYER - PTAH-SOCAR Fuel-cooled composite material structure for dual-mode ramjet and liquid rocket engine - AIAA – 2004 – JPC Fort Lauderdale
[51] M. BOUCHEZ, S. BEYER. PTAH-SOCAR fuel-cooled composite materials structure for dual-mode ramjet and liquid rocket engines – 2005 status – AIAA – 2005 – 3434 - Capua
[52] D. DAVIDENKO, I. GOKALP, E. DUFOUR, D. GAFFIE - Kinetic mechanism validation and numerical simulations of supersonic combustion of methane-hydrogen fuel - AIAA – 2002 - 5207 - Orléans
[53] D. DAVIDENKO, I. GOKALP, E. DUFOUR, D. GAFFIE - Numerical simulation of supersonic combustion of methane-hydrogen fuel in an experimental combustion chamber - Moscow – July 2003
[54] D. DAVIDENKO, I. GOKALP, E. DUFOUR. Numerical modeling of inert and reacting compressible turbulent jets - AIAA – 2005 – 3237
[55] O.DESSORNES, M. BOUCHEZ. Combustion experiments of liquid kerosene and hydrogen/methane mixing in a dual-mode ramjet - AIAA – 2005 – 3400
[56] J-P. MINARD - French potential for semi-free jet test of an experimental dual mode ramjet in Mach 4-8 conditions - AIAA – 2002 – 5241
[57] L. SERRE. New ONERA capabilities for scramjet ground testing up to Mach 12 - AIAA – 2005 – 3330 - Capua