A European Project on Advanced Propulsion Concepts for Sustained Hypersonic Flight

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Abstract

The ambitious mission goal is to reduce travelling time of long-distance flights, e.g. Brussels to Sydney, to about 2 to 4 hours. Therefore advanced propulsion concepts and technologies need to be developed. This requires a new flight regime with Mach numbers ranging from 4 to 8. At these high speeds, classical turbo-jet engines need to be replaced by advanced airbreathing engines. Different combined cycles, i.e. TBCC and RBCC, are evaluated both on system and fundamental research level in combination with a corresponding vehicle system study.

A three years long project called LAPCAT: Long-Term Advanced Propulsion Concepts and Technologies was launched in spring 2005, partially financed by the European Commission, to initiate research on propulsion concepts for sustained hypersonic flight. The project, composed of a consortium of 12 partners from industry, research institutions and universities, is coordinated by ESA-ESTEC.

1. Introduction

Tendencies in aeronautics clearly show a continuous increase in air traffic. Based on IATA statistics the international passenger traffic growth increased with 6.8% in February 2006 over 2005 which continues on pace with forecast. Even for long-distance flight such as from Europe to Asia Pacific, IATA's five year forecast shows an annual average growth of 5.9% between 2005 and 2009. This is primarily due to the explosive economic growth in Asia and in particular in China. These long-distance flight taking easily flight times of 16 hours or more to connect two major intercontinental cities, would become more attractive when travel-time would be reduced drastically such that a final destination can be reached within 4 hours or less.

However, with present aircraft and propulsion designs, we're getting close to the optimal design and margins for further improvement are getting smaller. Only drastic changes in aircraft configuration, propulsion concepts and flight velocities are able to achieve these goals. New aircraft development seems to be stalled with respect to flight speed, despite the proven technical possibility shown by the supersonic Concorde. Opponents to supersonic transport development always point to the large specific fuel consumption of Concorde which undeniable is roughly twice the value of present commercial aircraft. However, one should not forget that the specific fuel consumption, sfc, obtained for the first turbojet driven aircraft, e.g. Comet in 1951 were only 20% lower. Since then fuel consumption reduction for aero-engines has been drastically driven throughout time by technology e.g. cooling techniques, new alloys, improved thermodynamic cycles by increased pressure ratios and TIT, etc… As the Olympus 593 engine was based on the Olympus design of the early 50's, it is hence impossible to compare its sfc with e.g. the latest Trent's of R&R or the GE90-family when half a century of technology development has not been implemented in these Olympus engines.

Before given an overview of the LAPCAT goals, some basic considerations about supersonic vs. subsonic flight and its potential for evolution will be discussed. Finally some first results obtained so far within the LAPCAT project will be discussed.

2. Motivation

Reducing travel times by going supersonic has only sense on long-distance flights. Range is hence an important figure of merit to evaluate high-speed aircraft concepts. It is strongly dependent on total available fuel mass and its consumption throughout the itinerary, i.e. from taxiing, speed-up cruise and final descent manoeuvres. Among these different parts, cruise represents a major portion of the needed fuel. The range achieved during cruise can be easily derived from the Bréguet range equation:

$$R = \frac{H}{g}\eta\frac{L}{D}\ln\left[\frac{1}{1-W_F/W}\right] = \frac{V_\infty}{g\,sfc}\frac{L}{D}\ln\left[\frac{1}{1-W_F/W}\right] \qquad (1)$$

where R is the Range [m], H the fuel energy content [J/kg], g the gravity constant [m/s^2], η the overall installed engine efficiency, sfc the specific fuel consumption [kg/s/N], V the flight velocity [m/s], W the total take-off mass [kg] and W_F the fuel mass [kg].

The range depends linearly on the energy content H in the fuel which can be increased with a factor of 2.7 by switching e.g. from kerosene to hydrogen. The aerodynamic performance given by L/D in eq. (1) depends primarily on the Mach number. Optimized waverider designs taken into account viscous effects results in a L/D barrier (Anderson[1]):

$$\left(L/D\right)_{\max,viscous} = 6(M_\infty + 2)/M_\infty \qquad (2)$$

For an increasing Mach range the value are decreasing asymptotically to a value of 6. This decrease of aerodynamic performance with increasing Mach number would inherently exclude long-range supersonic flight as it would be economically not viable. However, the overall propulsion efficiency increases with Mach number for turbojets and ramjets suggested by R.G. Thorne according to[2]:

$$\eta = \frac{T\cdot V_\infty}{m_f{}'H} = \frac{V_\infty}{sfc\,H} \approx \frac{M_0}{M_0+3} \qquad (3)$$

In [2], a weight breakdown analysis is described for which the total take-off weight W is split into different parts. Items including wings, undercarriage, services and equipment are proportional to the overall weight, i.e. c_1W. Other items are proportional to payload c_2W_p including fuselage weight, furnishings and the payload itself, hence $c_2 > 1$. Finally we have the engine and fuel weight W_E and W_F. This results into the left eq. (4). Combined with eq. (1) one can obtain the right expression of eq. (4).

$$W = c_1W + c_2W_p + W_E + W_F \qquad \frac{W_p}{W} = \frac{1}{c_2}\left[\exp\left(-R\frac{H}{g}\eta\frac{L}{D}\right) - c_1 - \frac{W_E}{W}\right] \qquad (4)$$

Evaluating W_E/W from a large range of data a value of 0.05 seems to be a good average. The factors c_1 and c_2 largely depend on the use of state-of-the-art structural materials and are retained here as variable parameters. In fig. 1, the payload fraction W_p/W, i.e. passengers or cargo, for multiple existing aircraft is plotted against the non-dimensional range. These data have been fitted by adapting the structural parameters c_1 and c_2, along with the propulsion and aerodynamic performance parameter $\eta L/D$ of eq. (1) according to the values given in table 1.

Generally speaking, the payload fraction increases from A to D due to the improved structural and propulsive parameters and demonstrate the technological evolution introduced into the newer airplanes. The line E is definitely lower for the supersonic aircraft which is due to the lower $\eta L/D=3$ versus 4 for the subsonic ones achieved in the same era. Small changes on the aerodynamics, as proposed for Concorde B in 1976, combined with efficiencies of recent engines developed for supersonic fighters, indicate that a recent SST might achieve a performance which lies in between lines A and B.

The still remaining parameter to be discussed is the use of hydrogen as fuel. Studies have been performed in Europe (e.g. Cryoplane) and Russia, but little information is available on the aircraft performance. However, making use of the suggested correlations, the influence of hydrogen as a fuel can be easily assessed.

Table 1: Parameter sets used for evaluation of future trends

	A	B	C	D	E
$\eta L/D$	4	5	5.5	6	3
c_1	0.3	0.25	0.2	0.15	0.35
c_2	2.25	2.00	1.90	1.75	2.75

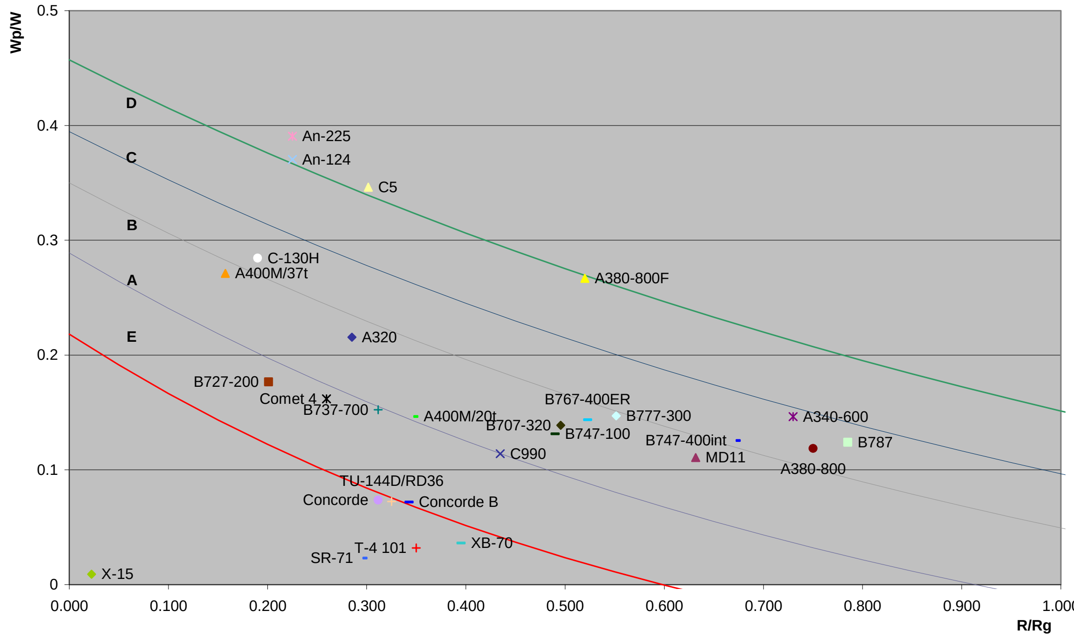

Fig. 1: Indicative payload fraction in function of non-dimensional range for various aircraft. Full lines A to E are based on eq. (4) for structural, propulsion & aerodynamic parameter variation.

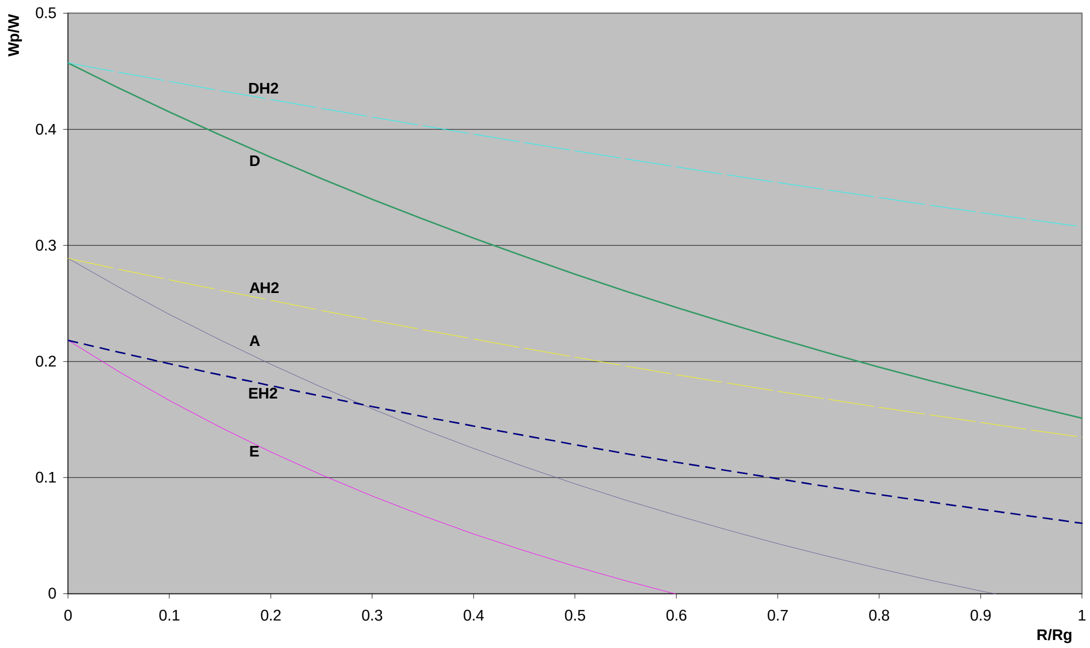

Fig. 2: Payload fraction dependence on fuel type: kerosene (full), hydrogen (dashed).

In fig. 2, the previous parameter settings A, D and E have been applied for a hydrogen aircraft, denoted respectively AH2, DH2, and EH2. This is a first approximation as the larger required volume for hydrogen storage will induce a higher drag which is not accounted for. The dashed lines clearly indicate that aircraft have a larger potential in range with still an interesting payload capacity, including SST. Aircraft of lower performance, according to A, have now a potential equivalent for the ultimate range to aircraft of type D by switching to hydrogen. This opens up the potential to reach anti-nodal destination with optimum seat-km already for conservatively designed aircraft. This motivated the LAPCAT-team to tackle the final technological challenge within aviation: can man travel to the other side of the world within a relatively short time of two to four hours?

3. Objectives

In Europe, continuous effort for basic high-speed airbreathing propulsion research has been made at many institutions. However, these efforts are scattered and strongly specialized. The LAPCAT project offers the opportunity to practice the indispensable cooperation on European level and to integrate specialized findings into a system to assess the overall relevance and benefits. During the project, system design tools are developed as well as rules and guidelines for conceptual development of system which have not been in place before. The capability to systematically guide a system development process through interface management and to assess its output will be enhanced.

The baseline mission requirement is to reduce travelling time of long-distance flights, e.g. Brussels to Sydney, in about 2 to 4 hours. This requires a new flight regime with Mach numbers ranging from 4 to 8. At these high speeds, classical turbo-jet engines need to be replaced by advanced airbreathing propulsion concepts and hence related technologies need to be developed. As objectives, two major directions at conceptual and technological level are considered: ram-compression and active compression. The latter has an upper Mach number limitation but can accelerate a vehicle up to its cruise speed. Ram-compression engines need an additional propulsion system to achieve their minimum working speed. Key objectives are the definition and evaluation of:

- different propulsion cycles and concepts for high-speed flight at Mach 4 to 8 in terms of turbine-based (TBCC) and rocket-based combined cycles (RBCC)
- critical technologies for integrated engine/aircraft performance, mass-efficient turbines and heat exchangers, high-pressure & supersonic combustion experiments and modelling.

A sound technological basis will be determined for long-term (20-25 years) to advance innovative propulsion concepts. The most critical RTD-building blocks will be identified employing analytical, numerical and experimental tools to address issues of the following road-map:

- two airbreathing engines for selected reference vehicle(s) and trajectory point(s),
- dedicated combustion experiments for supersonic and high-pressure combustion,
- modelling and validation of combustion physics,
- aerodynamic experiments for major engine components and for inter-action of vehicle and propulsion aerodynamics.
- evaluation and validation of advanced turbulence and transition modelling for unsteady and separated flow regimes,
- performance prediction of contra-rotating turbines and light cryogenic fuel heat exchangers.

The team consists of 12 partners out of 6 European countries and is coordinated by the European Space Research and Technology Centre ESTEC-ESA in the Netherlands. This involves four industries EADS-Astrium (D), Reaction Engines (UK), Snecma (F) and Cenaero (B); four research institutions being ESA-ESTEC (NL), DLR (D), CIRA (I) and VKI (B) and finally the universities of Rome (I), Stuttgart (D), Southampton (UK) and Oxford (UK).

4. Turbine Based Combined Cycles

The project objective is to examine two turbine based cycle (TBCC) engine concepts for high Mach number (4 – 5) flight in the context of future civilian transportation. The experience accumulated from turbojet design and operation is huge and this should obviously form the basis of the next generation of engines if at all possible.

4.1 Hydrogen Mach 5 Cruiser

The LAPCAT A2 vehicle flying at Mach 5 was carried out by Reaction Engines. The preliminary results of this analysis are encouraging. The vehicle study is complete at initial project study level and indicates that a 400ton, 300 passenger vehicle could achieve antipodal range without marginality. The concept is particularly interesting for this mission requirements as a trajectory optimization allowed to fly almost continuously over sea and avoiding sonic boom impact when flying over land.
The proposed aircraft configuration A2 is shown in Figure 1. The vehicle consists of a slender fuselage with a delta wing carrying 4 engine nacelles positioned at roughly mid length. The vehicle is controlled by active foreplanes in pitch, an all moving fin in yaw and ailerons in roll. This configuration is designed to have good supersonic and subsonic lift/drag ratio and acceptable low speed handling qualities for takeoff and landing.

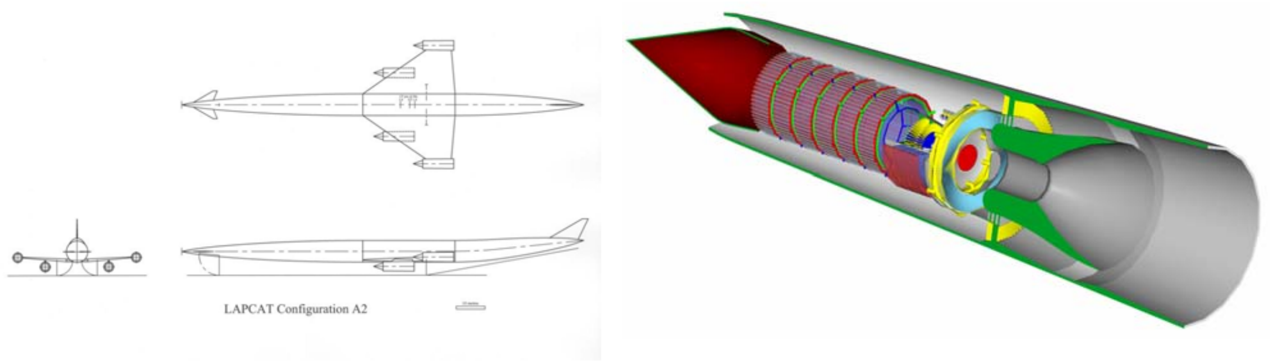

Fig. 1: LAPCAT A2: Mach 5 hydrogen based vehicle (left) with precooled turbofan-ramjet Scimitar engine (right)

The first study focused on a precooled Mach 5 engine, named Scimitar, employing a cycle based on the Reaction Engines SABRE spaceplane engine and fuelled by liquid hydrogen. The Scimitar engine must have good subsonic and supersonic performance if it is to be a practical engine for a new generation of hypersonic aircraft. This would allow it to operate from normal airports and over-fly inhabited regions without the nuisance and political problems which limited Concorde's effectiveness. These characteristics have been successfully incorporated into the Scimitar design (fig. 1) by incorporating a high bypass fan into the bypass duct which encloses the core engine and is otherwise needed to match the intake air capture flow to the engine demanded flow over the supersonic Mach number range. The bypass fan is driven by a hub turbine using flow diverted from the core engine nozzle. The flow then discharges into the bypass and mixes with the bypass flow. More details on the engine and its thermodynamic cycle are given by A. Bond[3].

Due to their central role to the concept of the precooled engine two technologies are being addressed at experimental level: a lightweight heat exchanger and contra-rotating turbine. The test program will start soon and demonstrate that very efficient ultra-compact heat exchangers and turbines are feasible for applications in hypersonic aero-space engines. The Scimitar engine analysis suggests that it can produce efficient supersonic and subsonic flight and meet the anticipated noise regulations for normal airport operation. An important side result is the critical role of environmental impacts, specifically NOx, contrails and Ozone damage. Future studies need to include these problems.

To address the relatively high technical risk of this project it is proposed that the development program proceed in a step by step basis in 3 phases, namely Concept Validation (2 years), Technology Demonstration (3 years) and System Development (8 years). At the end of each program stage the project would be reviewed before deciding whether to proceed with the next stage. An arbitrary start date of 2010 has been assumed which implies an Entry Into Service date at the beginning of 2023. The predicted engine development cost in 2006 prices is 8,147M€ and vehicle development cost 14,454M€ to give a total development cost of 22,601M€. The first vehicle production cost is 979M€. Assuming an 85% learning factor and a total production run of 100 vehicles implies an average vehicle sale price of 639M€ (including full development cost recovery). The estimated annual operating cost per vehicle is 553,8M€ of which the liquid hydrogen fuel comprises 83%. This assumes hydrogen derived from electrolysis of water however hydrogen derived from steam reforming of hydrocarbons would be about a third of the cost which would roughly halve the annual operating cost.

4.2 Kerosene Mach 4.5 Cruiser

A parallel study carried out by DLR-Sart[4] focuses kerosene as a fuel in order to explore the performance of this fuel in preference to hydrogen since its supply infrastructure is well established. In order to keep the wing loading in an acceptable range, the new supersonic cruise airplane has a wing size of 1600m2. The total length reaches 102.78m which is only slightly longer. The LAPCAT-M4 employs a blended wing-body with a modified nose, a highly swept in-board wing panel, and a moderately swept outboard wing panel. The four advanced turbo-RAM-jet Variable Cycle Engines (VCE) are mounted in two nacelles on the wing lower surface adjacent to the fuselage. The location of the engine and nacelles is still open for adaptation if required by trim as long as they remain under the wing. The total take-off mass of the supersonic cruise airplane has been iterated in the first loop to the huge value of 720ton, which is well beyond any supersonic passenger aircraft built to date. The dry mass is estimated at 184.5ton and the structural index is at a for airplanes low 36.8%. According to current data the HSCT would be able to transport about 200 passengers with their luggage.

4. Rocket Based Combined Cycles

In parallel to TBCC propelled vehicles, Rocket Based Combined Cycles are evaluated for the two vehicle concepts. As the thrust to weight ratios for rockets are far higher (~60-100) than turbojets (~3), they might be a good alternative for the acceleration phase despite their higher sfc. The preliminary design and dimensioning of RBCC engines coupled with vehicle and a reference trajectory was addressed after the first vehicle designs for M4 (kerosene) and M8 (hydrogen) became available. For each of the vehicles, a basic RBCC concept was derived, and tools and rules for dimensioning the RBCC were developed. The evaluation showed that for the given mission kerosene as fuel was unfeasible, but that the mission can theoretically be achieved using a hydrogen-fuelled RBCC. Also, the performance-sensitive factors have been highlighted and their influence on the net I_{sp} of the RBCC was shown.

The hydrogen-fuelled RBCC for Mach 8.0 is a planar design with a sophisticated intake system, and rockets integrated into struts. The nozzle consists of a single expansion ramp nozzle of the Sänger type and was tentatively demonstrated to be efficient for the proposed vehicle type. Currently, the RBCC engine model for the M8 vehicle is extended to include ramjet combustion and thermal choking to enable the examination of a mixed ramjet-scramjet configuration with different fuel injection positions and side wall struts in the remainder of the system.
From practical gas dynamic and manufacturing considerations, the scramjet combustion chamber should not exceed a maximum length allowing for a slight divergence to give margin for design issues other than the mixing process. By cooperation with specialized CFD analyses, the assumed model input parameters could be refined in a series of parametric studies to represent more realistic values.

The dimensioning of the propulsion system components allowed DLR-Sart to define the lower part of the latest generic LAPCAT-M8 air-plane geometry as illustrated in fig. 3. The upper section of the vehicle is dependent on the necessary volume for fuel tanks and the SERN expansion ratio intended to be as far adapted as possible. LAPCAT-M8 as a generic airplane is designed as a lifting body with a simple 2D-geometry in the central air-intake part, easing not only the conceptual lay-out but also CFD and experimental investigations.

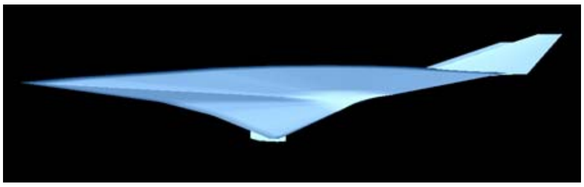

Fig. 3: Preliminary design of a Mach 8 cruiser based on a H2 RBCC

The total length is 101.2m with a total span of 41.58m. Its height mounts up to 19.5m. The outboard region converges rapidly to the "wingtips", so that the leading edge sweep angle is about 82°. The stabilizer located in the tail part of the lifting body and two vertical fins, slightly inclined outboards, are to be used for aero-dynamic trim and control.Though using ultra light-weight structural design in high load and very high temperature environment, its empty weight mounted still to 267ton with an incredibly large take-off mass of 944ton.
As the RBCC requires a rocket ejector operation at low Mach number flight, its low performance along with the non-availability of reliable data, results in a very high fuel consumption during the acceleration phase. Its performance is highly critical to overall feasibility. This version of a Mach 8 hypersonic RBCC airliner could reach intercontinental

range of up to 9500km. LAPCAT-M8 flight performance calculation should not be interpreted as a proof of its feasibility. Intention is to show “best case” performance and identify critical points.

5. Combustion Experiments

Dedicated combustion experiments are clearly needed for both TBCC & RBCC concepts in order to evaluate and check the performance and characteristics at specific conditions for supersonic combustion and high-pressure combustion. So far, experimental data obtained in supersonic combustion experiments performed in the M11 connected tube facility at DLR Lampoldshausen have been evaluated for differently shaped strut injectors. The campaign of testing a complete airbreathing engine in the High Enthalpy Shock Tunnel Göttingen (HEG) has started with promising results[5].

In the framework of high pressure combustion experiments with focus on the HC disintegration processes, the ITLR shock tube at the University of Stuttgart has been equipped with a fast-response fuel injector[6]. Currently, fluid disintegration experiments are being performed under supercritical and subcritical conditions, employing dodecane (as exemplary hydrocarbon fuel) in argon. The M3 test facility at the German Aerospace Centre, DLR in Lampoldshausen, has been refurbished to allow the use of hydrocarbon fuel such as methane. Quantitative thermometry of the hot gases using CARS-spectroscopy has been started in the CH4/O2-flames. For the characterization of the ignition transient and stationary spray combustion software tools are developed to analyze shadowgraphs and high speed recordings of the flame emission.

6. Combustion Modelling and Validation

The goal is to investigate physics of high-pressure and supersonic combustion requiring the development of new tool. In fact, numerical simulations performed by means of RANS (Reynolds Averaged Numerical Simulations) or LES (Large Eddy Simulations) are fundamental in designing rocket combined cycles and scramjet combustors; in particular, by focusing on the unsteadiness of the flow, Large Eddy Simulations (LES) can help in understanding how to improve mixing, flame anchoring and combustion efficiency in supersonic reacting flows.

For high-pressure combustion a compressibility factor formulation has been implemented and validated for typical rocket combined cycle operating conditions (super-critical in pressure, trans-critical in temperature). Extension and validation toward kerosene and methane consists of a tabulated equilibrium chemistry with a PPDF (*presumed probability density function*) approach to model turbulent combustion.

For supersonic combustion, finite rate combustion with appropriate turbulent mixing is used as a start[7] extended further with an eddy-dissipation concept to account for turbulence dominated combustion. A more complex extension towards turbulent combustion is based on an assumed PDF method to account for a wide range of applicability for premixed, non-premixed, partially premixed combustion and different Damköhler numbers. Whereas the assumed PDF approach suffers from simplifications due to the chosen shape of the joint PDF, a transported PDF models require tremendous CPU times. Nevertheless a multi-variate-β-PDF for species distributions seems to be a good compromise between accuracy and CPU time, necessary for complex 3D simulations. A major drawback of this approach is the required statistical independence of species and temperature fluctuations. At this point further investigations and improvements are in progress. Results obtained by LES simulation indicate combustion may be made to take place in a short distance by supersonic injection of hydrogen inside the supersonic airstream. The ISCM LES SGS is under validation[8].

7. Design and Aerodynamics of Propulsion Components

For high-speed transportation vehicles powered by air-breathing engines achieving a positive aero-propulsive balance is crucial for the success of the whole system. One of the lessons learned is that the vehicle design requires an optimized propulsion airframe integration resulting in an extremely coupled development procedure of the system components, namely the intake, combustion chamber, thrust nozzle and air-frame. However, this last statement is not easy to realize since there is no ground facility in the world which allow testing a real sized vehicle under flight conditions including operating engines and furthermore, till today no scaling rules are available at all. Accordingly, the only successful flight of a vehicle propelled with a scram-jet, e.g. the X-43, has been done with a vehicle sized to a scale compatible with the size of the ground based facilities used for its design. As like other areas of the hypersonic technology, here the potential of the CFD tools for ground to flight extrapolations is coming on request. Two highly flexible wind tunnel models, allowing many configurative variations have been designed and are today under construction: one for the intake and one for the nozzle flow/external flow interaction problematic. Both models have been designed taking into account the nominal flight conditions resulting from the project system study but also accounting for the facilities capabilities.

Several types of CFD turbulence model have been evaluated with respect to geometrical configuration constraints and numerical dissipation. The study has shown that the superior results of Detached Eddy Simulation models against Unsteady Reynolds Averaged Navier-Stokes models and the deep insight into the unsteady flow physics are purchased by a significantly higher complexity of the computation. Large eddy simulation models have been found by comparison with direct numerical simulation, to be accurately enough tools for the prediction of super-sonic shock induced laminar-turbulent boundary layer transition. It has been shown that it is possible to have self-sustained transition to turbulence in a shock-induced separation bubble provided the pressure rise over the bubble is high enough. The design of turbulence devices for forcing turbulent flow is underway.

8. Conclusions

LAPCAT wants to (re)-evaluate SST and to go beyond the material's limit imposed for Concorde by integrating light-weight advanced materials allowing speeds 4 to 8 times the speed of sound. Based on general trends in the evolution of aircraft performance and the possible aerodynamic and propulsive achievable efficiencies for high-speed vehicles, there's a potential to achieve antipodal range. Preliminary parametric studies within the project have shown so far that Mach 4-5 is achievable and not marginal. However, for the Mach 8 RBCC propelled vehicle dedicated investigations are required to ascertain its performance.
The vehicle systems defined during the project allowed the setting of working conditions of interest for detailed experimental and numerical work. Windtunnel models are presently in use to reveal particular physical phenomena and to justify the use of some parameters. Also numerical work is well underway and will be soon validated with the newly generated experimental database.

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