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# LAPCAT: A TECHNICAL FEASIBILITY STUDY ON SUSTAINED HYPERSONIC FLIGHT

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**Abstract**

In spring 2005, the EC kicked-off a 3 years long project called LAPCAT: Long-Term Advanced Propulsion Concepts and Technologies to initiate research on propulsion concepts for sustained hypersonic flight. The ambitious mission goal is to reduce travelling time of long-distance flights, e.g. Brussels to Sydney, to about 2 to 4 hours. The project, composed of a consortium of 12 partners from industry, research institutions and universities, is coordinated by ESA-ESTEC.

## Introduction

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 configurations and related propulsion engines presently studied for classical flight Mach numbers around M=0.9 look into e.g. blended wing-body configuration for aerodynamic performance and multiple engines mounted on top of the wings close to its trailing edges to improve propulsion efficiency. These interesting developments will decrease further fuel consumption up to 30% but will not enable the shortening of travel times.

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…

## 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 [1] 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

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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 interaction 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).

## Turbine Based Combined Cycles

The project objective was 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.

### Hydrogen Precooled Turbo-Ramjet

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 [2].

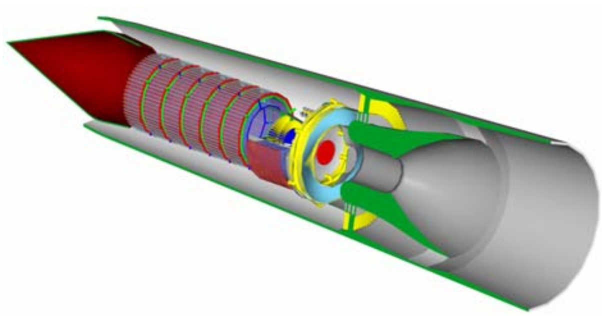

**Fig. 1: Precooled Turbofan-Ramjet Scimitar engine for LAPCAT A2 cruiser.**

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 [3] are feasible for applications in hypersonic aerospace 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.

### Hydrogen Mach 5 Cruiser

*a. Vehicle*

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 configuretion A2 is shown in Figure 2. 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. A leading edge sweep angle of 55 deg was chosen as roughly equivalent to the Concorde value and known to be the minimum necessary to generate a stable separated vortex at high AOA. A thickness-chord of 3% was selected as typical of supersonic cruise vehicles. An achievable takeoff wing CL of 0.59 gives a minimum wing area of 900m$^2$ for a takeoff mass of 400tons. A fuselage diameter of 7.5m was chosen to trade a small increase in drag for a saving in fuselage mass. The resulting fuselage is much longer than existing aircraft at 139m.

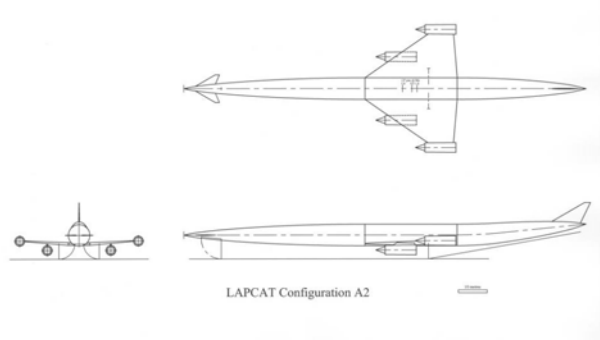


**Fig. 2: LAPCAT A2: Mach 5 TBCC vehicle based on hydrogen**

The flight deck and passenger compartment (arranged in two decks) occupies a length of about 32 m and is located over the wings on the vehicle centre of gravity. Unlike conventional airliners hydrogen storage within the wings is not feasible since the wing volume is too small. Consequently the liquid hydrogen occupies the remainder of the fuselage volume and is split into two large pressurised tanks either side of the passenger compartment. This permits circular cross section tankage which minimises insulation and pressure vessel mass.

The vehicle has 4 engines (for redundancy), which are mounted in separate axisymmetric nacelles on the wing. Carrying the engines on the wing gives good CP/CG matching and is structurally efficient, whilst the alternative option of mounting the engines on the fuselage incurs the penalty of a large boundary layer diverter and acoustic fatigue of the fuselage skins. As for Mach 5 the wing shock wave is at an angle of only 8.9 deg relative to the wing lower surface, an engine mounted underneath a wing would necessitate moving the nacelle aft until the intake face was behind the wing trailing edge. Therefore this approach is structurally impractical and would scrape the nacelles on the runway during takeoff rotation. Consequently the nacelles are positioned with the intake face ahead of the wing shock wave in relatively freestream conditions, which has the added advantage that no wing boundary layer has to be dealt with. The inboard nacelles are mounted underneath the wing to reduce wing skin acoustic fatigue damage. The main disadvantage of the inboard nacelle location is that the nacelle cross section is introduced ahead of the wing maximum thickness which is counter to normal area ruling practice and will increase transonic wave drag.

*b. Routes*

Commercial civil transport aircraft, flying subsonically, normally follow a “great circle” route between the airports of departure and arrival, once they are clear of local traffic. However in the case of supersonic aircraft there is the complication of the “sonic boom”, or ground overpressure produced by supersonic flight. Various tests show broad agreement that an overpressure below 50 Pa is tolerable for regular overflights of populated areas.

Current overpressure estimates for the LAPCAT configura-tion A2 vehicle suggest that at the start of Mach 5 cruise the over-pressure will be about 85 Pa under the ground track, reducing to about 70 Pa at mid cruise. Therefore preliminary route planning for the LAPCAT vehicle has assumed “worst case scenario” that supersonic flight is only possible over regions of very low population density.

The Brussels to Sydney route was adopted as the baseline mission. This was seen as a sensible starting point in that it requires extreme range and would greatly benefit from hypersonic speeds in significantly reducing flight times. Nevertheless, other potential routes of interest have been evaluated.

*c. Development plan and economics*

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 hydro-gen 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.

**Kerosene Mach 4.5 Cruiser**

An 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 the wing size is 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 inboard wing panel, and a moderately swept outboard wing panel. The inboard wing panel is swept 78°, allowing the flow component normal to its leading edge to remain subsonic even at the Mach 4.5 cruise condition. The outboard wing panel is swept 55° but its exact, possibly curved form has not been defined yet. The total wing is inclined with a positive angle of attack of approximately 2.75°.

The forebody of the concept is slender and elliptical in cross section. The wing-mounted struts of the main landing gear should retract into the engine nacelles and are housed between the inlet ducts. The two-wheeled nose gear is mounted on the bulkhead forward of the crew station and retracts forward. The four advanced turbo-RAM-jet engines 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.

## 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.

**Hydrogen RBCC engine for M=8 cruiser**

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.

A basic concept for the SERN nozzle and the contouring criteria was defined such that the concept was valid for both the subscale experiments and the fullscale M8 vehicle design. The same applied for the definition of a flexible intake geometry for parametric testing but still representative for the fullscale M8 vehicle. Both intake and nozzle work logic is described below.

The TRL of RBCC propulsion is low and a high degree of uncertainty exists on its actually achievable performance in ejector-rocket and SCRAM-mode. Therefore, an iterative approach in defining the thrust requirements and subsequent calculation of the mission performance has been chosen. All variants studied are based on LH2 propellant and on LOX as the oxidizer in rocket mode.

**Hydrogen Mach 8 Cruiser**

The dimensioning of the propulsion system components allowed DLR-Sart to define the lower part of the latest generic LAPCAT-M8 airplane 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.

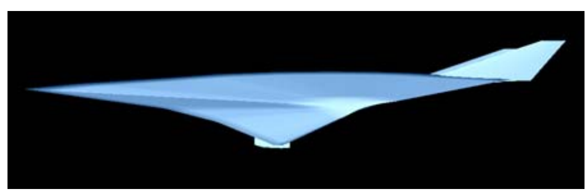

**Fig. 3: Preliminary design of a Mach 8 cruiser based on a H2 RBCC**

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 aerodynamic trim and control.

The engine operational sequence supposes ejector-rocket mode up to

M= 2.5, a pure RAM operation up to M= 5, and subsequently a transition to SCRAM-jet. In its current configuration based on the best available consistent data the airbreathing hypersonic airliner is not able to reach or come any close the LAPCAT mission requirement. The total amount of required LH2 and LOX-propellant is 669ton. 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 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.

**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, to evaluate the performance and achievements for potential fuels, either hydrogen or hydrocarbons (HC) and potential oxidizers (air or liquid oxygen), including the investigation of reaction products and hence the impact on emission requirements, to evaluate the chemical kinetics and its interaction with the flow-field turbulence, its impact on ignition delay and flame stabilization, to evaluate potential injection systems with emphasis on mixing and combustion efficiencies and to set-up a database for modelling and validation purposes in these areas where detailed and dedicated experiments are lacking.

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 (fig. 4).

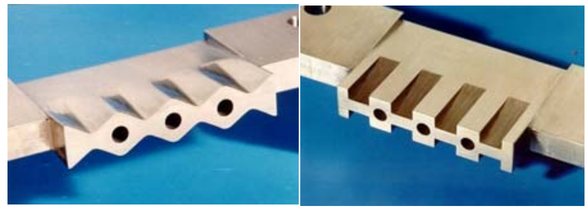

**Fig. 4: Different strut injectors tested in M11-facility: left WAVE and right USCER injector**

The campaign of testing a complete airbreathing engine in the High Enthalpy Shock Tunnel Göttingen (HEG) has started with promising results. Two generic scramjet configurations were selected for the ground based testing in HEG. These two configurations allow comparing the efficiency of two types of fuel injector configurations (perpendicular porthole injection and wall injection using vortex generators). Further, a flexible wind tunnel model with detailed surface instrumentation and optical access was designed and built (fig. 5).

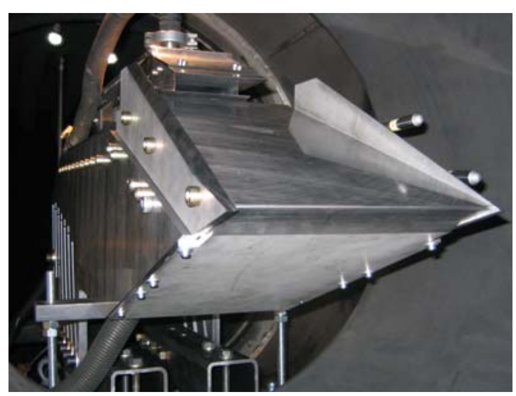

**Fig. 5: Full M=8 engine model mounted in the HEG shock tunnel with optical access.**

In the framework of high pressure combustion experiments with focus on the HC disintegration processes, the ITLR shock tube at the University of Stuttgart (fig. 6) has been equipped with a fast-response fuel injector [6]. Experiments were performed for purpose of validating the spray injection technique with respect to reproducibility of the spray, timing of the experiments, and the achievement of steady-state firing conditions. Currently, fluid disintegration experiments are being performed under supercritical and subcritical conditions, employing dodecane (as exemplary hydrocarbon fuel) in argon. The results are visualised by means of flashlight shadowgraphy.

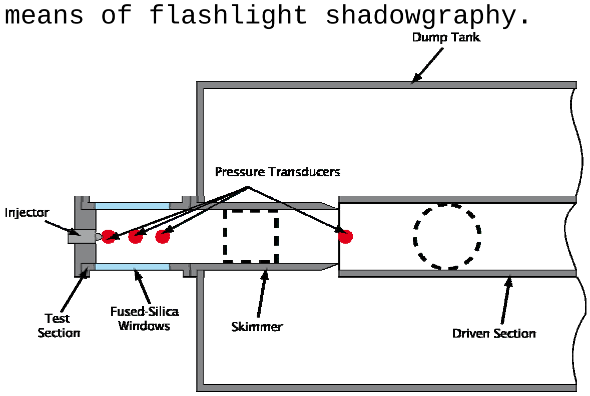


**Fig. 6: Shock tube test set-up for investigation of HC disintegration in sub-, trans- and supercritical conditions.**

The objective of these experiments is twofold:

- to provide quantitative data on binary fluid disintegration;
- to relate the experimental results to literature data in order to assess the differences between one-component and binary systems.

The M3 test facility (fig. 7) at the German Aerospace Center, DLR in Lampoldshausen, designed for the operation with H2/O2 (cryogenic or ambient) has been refurbished to allow the use.

Spectroscopy of the flame's emission due to chemi-luminescence and thermal radiation has been analyzed for pressures up to 1 MPa. Quantitative thermometry of the hot gases using CARS-spectroscopy has been started in the CH4/O2-flames. Based on the CARS-spectra obtained in the laboratory flames a decision on probe molecules was achieved. 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.

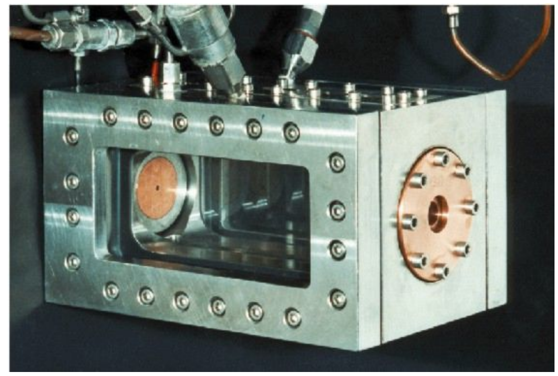

**Fig. 7: M3 test facility with optical access**

The intensive literature study and the validation predictions yielded the Leeds mechanism as the most promising candidate mechanism for $O_2/CH_4$ combustion for further reductions towards a kinetic scheme short enough to become applicable in 3D CFD tools. First attempts towards a skeletal mechanism have been performed and the validation predictions are underway but not yet finished.

**Combustion Modelling and validation**

The goal is to investigate physics of supersonic combustion and to develop new tools to enhance numerical simulations. In fact, numerical simulations performed by means of RANS (Reynolds Averaged Numerical Simulations) or LES (Large Eddy Simulations) are fundamental in designing SCRJ 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.

The extension and validation of the Astrium's axisymmetrical code Rocflam-II towards Kerosene and Methane chemistries has been finished. The necessary fluid data and reaction schemes have been selected and implemented. The reaction model in Rocflam-II consists of a tabulated equilibrium chemistry with a PPDF (*presumed probability density function*) approach to model turbulent combustion. The code has been further adapted and applied to an Air/Kerosene Ramjet engine.

CIRA's code C3NS-PB consists of two different modules: a pressure-based (C3NS-PB) and a density-based (C3NS-DB) module. The pressure-based module is able to describe the flow of a 3D, unsteady, turbulent, chemically reacting mixture of ideal gases. A thermodynamic model able to properly describe propellants injection in high pressure LOx/HC rocket thrust chambers has been developed and implemented.

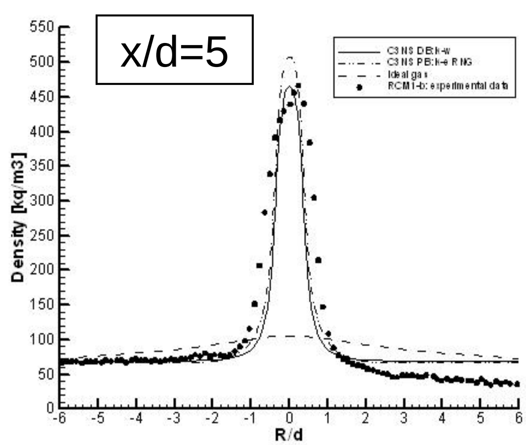


**Fig. 8: Influence of real gas EOS and turbulence modelling: Radial density profiles**

The compressibility factor formulation has been implemented in the flow solver and a suitable test case has been selected to test the capabilities of the model in typical rocket operating conditions (super-critical in pressure, trans-critical in temperature) (fig. 8). In order to simulate supersonic combustion processes in scramjet engines, both parallel and normal injection are under investigation.

The DLR Tau code has been further extended with an assumed PDF method to account for the influence of the turbulent flow in Scramjet combustors on the chemical production rates. The assumed PDF approach has been chosen from many available turbulent combustion models for the following reasons:

- Wide range of applicability for premixed, non-premixed and partially premixed combustion and different Damköhler numbers,
- Limited computational cost, high robustness and straightforward implementation,
- Convergence acceleration techniques can be used because the PDEs for the needed temperature and concentration variances have the same form as the Navier-Stokes equations (contrary to e.g. multi-dimensional PDEs used for transport PDF methods that need to be solved with particle methods),

The complete supersonic combustion model in TAU was validated and tested using experimental benchmark results for a supersonic coaxial burner which produces a lifted flame at typical scramjet flow conditions (fig. 9). The flame lift-off distance and flame structure could be well reproduced by the numerical investigation of this test case using the DLR Tau-Code. Application to a full-engine scramjet simulation can be found in [7].

The study concerning the applicability of several hydrogen-air reaction mechanisms for scramjet applications has been completed.

Different lobed strut injector concepts have been investigated. In case of axial fuel injection methods for mixing enhancement are required to enable a short combustor length and to reduce the skin friction drag. Possibilities for mixing enhancement may be based on the use of shock waves or on the production of strong streamwise vorticity. The last concept has been investigated numerically using the TASCOM3D code.

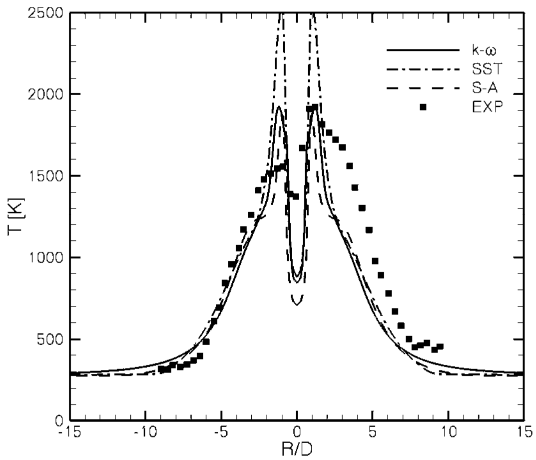


**Fig. 9: Radial distribution of temperature 50 mm downstream of the nozzle exit (middle).**

The strength and size of the vortices induced may be modified by changing the strut geometry. Different lobed strut injectors are compared in a cold non-reacting mixing study with respect to their mixing efficiencies and losses in total pressure. Aim is to produce vortices which cover large parts of the combustor cross section. A comparison with experimental data for one strut geometry has demonstrated the numerical accuracy of the code. At low flight Mach numbers of a scramjet (7 to 8 as in LAPCAT) detached flames are possible in case of axial fuel injection. Thus the degree and speed of mixing has a strong influence on the ignition delay too. The next step in this investigation has extended the studies to hot reactive flows with combustor inlet conditions, corresponding to the LAPCAT flight Mach number [8].

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 [9].

**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. Along the last 40 years, almost all attempts to fly a scram-jet propelled vehicle have failed due to largely underestimation of the vehicle total drag with respect to the allocated thrust. One of the lessons learned of such experiences 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. To accomplish with that mission CFD tools require dedicate validation experiments, hence specific tasks focus on the carefully design and experimental testing of intakes, nozzles and the interaction with the external flow to be used for CFD validation. Furthermore, being the loss of thrust due to earlier nozzle flow separations and the vehicle total drag the main issues required to be predicted, important efforts are assigned to test advanced turbulence models. Finally, since one of the major potential show-stoppers of intakes is the transition of the incoming boundary layer from laminar to turbulent, specific efforts are allocated to fix from the very beginning of the intake operation turbulent flow.

For the definition of the required experimental models it was decided not to use any generic intake or nozzle / base flow but those resulting from the vehicle system parameters studies. Accordingly, two highly flexible wind tunnel models, allowing many configurative variations have been designed and are today under construction: one for the intake (fig. 10) and one for the nozzle flow/external flow interaction problematic (fig. 11). 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.

**Fig. 10: Intake model without forebody for M8 vehicle.**

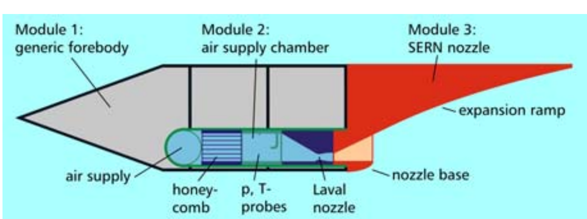


**Fig. 11: Concept of a Single Expansion Ramp Nozzle and Base Flow experimental model**

**S**everal types of CFD turbulence model have been evaluated with respect to geometrical configuretion constraints and numerical dissipation. It turns out a clear advantage for the highly developed models even they require large computational resources. The capabilities of different turbulence models for the simulation of unsteady turbulent phenomena have been investigated. 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 signifycantly higher complexity of the computation.

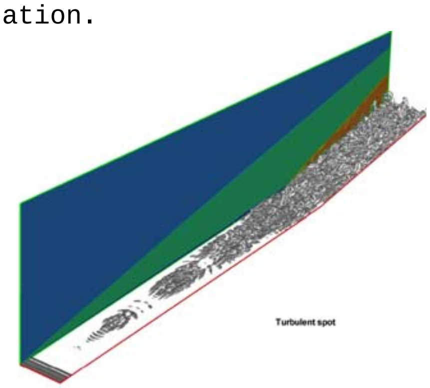


**Fig. 12: passing turbulent spot on an intake ramp by LES for a flight Mach=6;**

Furthermore, large eddy simulation models have been found by comparison with direct numerical simulation, to be accurately enough tools for the prediction of supersonic 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 (fig. 12)[10]. The design of turbulence devices for forcing turbulent flow is underway.

## Conclusions

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. 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. Preliminary parametric studies within the Lapcat project have shown so far that Mach 4-5 is achievable and not marginal. However, for the M=8 RBCC propelled vehicle more detailed investigations are needed and ongoing to ascertain its performance.

These vehicle system studies allowed the definition of operational conditions of interest for detailed experimental and numerical work. Windtunnel models are in preparation and will try to reveal or justify some of the used parameters. Also numerical work is well underway and will be soon validated with the newly generated experimental database.

**Acknowledgement**

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