Aerothermodynamic Analysis of Space-Vehicle Phenomena

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Aerothermodynamics is a key technology for the design and optimisation of space vehicles because it provides the necessary databases for, for example, the choice of trajectory, for guidance, navigation and control, as well as for the thermal-protection and propulsion systems. Computational aerothermodynamics, in particular, has become a powerful tool for improving our understanding of the physical phenomena that are at work. This article presents its current capabilities with respect to flow phenomena. Examples are presented of external flows past re-entry-vehicle demonstrators and launchers. Internal flow problems associated with propulsion and the interactions with external flow are also presented.

The future work requirements for further strengthening the computational and testing capabilities in Europe are identified. These objectives would be facilitated by bringing together a European network of industry, research organisations and universities. The need to verify ground-based tests with in-flight experiments, i.e. vehicle demonstrators, is also addressed.

Introduction

By adding thermodynamics to aerodynamics, one arrives at the notion of 'aerothermodynamics', in which those flow fields are considered, the analysis of which requires - beyond its use in classical aerodynamics - the consideration of special thermodynamic relations. Well-known examples are the high-temperature flows past re-entry vehicles, and flows in combustion chambers and in the nozzles of propulsion systems.

The development of aerothermodynamics in Europe experienced a substantial boost in the mid-eighties within the framework of ESA's development efforts for the Manned Spaceflight Programmes, such as Hermes, and later in the framework of the follow-up Technology Programmes. This was especially true of the development of the hypersonic high-enthalpy facilities, as well as for computational aerothermodynamics. Since then, aerothermodynamics has evolved to cover a wide field of applications and its use is becoming increasingly multidisciplinary.

The design of space vehicles depends crucially upon databases providing the forces, moments, temperatures and heat fluxes along the chosen trajectories. These databases can be established for given shape and control surfaces, for an assumed centre of gravity, where the shape and control surfaces of the space vehicle need to be determined in an iterative manner until stable and controllable flight is achieved. If the thermal-protection system chosen does not tolerate the loads encountered along the trajectory, the latter has to be adapted such that the flight remains controllable, by changing the space vehicle's shape and/or its control surfaces. In such multidisciplinary iterations, the available databases play a key role. The problem becomes more complex if the aeroelastic effects are considered and integration of the propulsion system is required, the latter being most important for future launchers. Figure 1 indicates the strong interaction between aerothermodynamics and other disciplines.

Aerothermodynamic tools for design purposes

Aerothermodynamic design issues can be addressed using advanced analysis methods, ground-based facilities, and flight testing. In a classical approach, the design of space vehicles (e.g. the Space Shuttle) depends heavily on experimental data. Owing to the inherent limitations of similarity laws, ground-based facilities cannot simulate fully the physical flows around space vehicles during reentry. In the USA, therefore, data obtained from in-flight experiments, particularly with the X-vehicles, have been used to complement the test data obtained from ground-based facilities. The latter contribute to the data required for design work up to Mach 10. These so-called 'cold' wind-tunnel data provide the 'anchor' points for the extrapolation to flight conditions. In the Hermes era, Europe chose to complement the knowledge available from the cold wind tunnels, which are not able to model

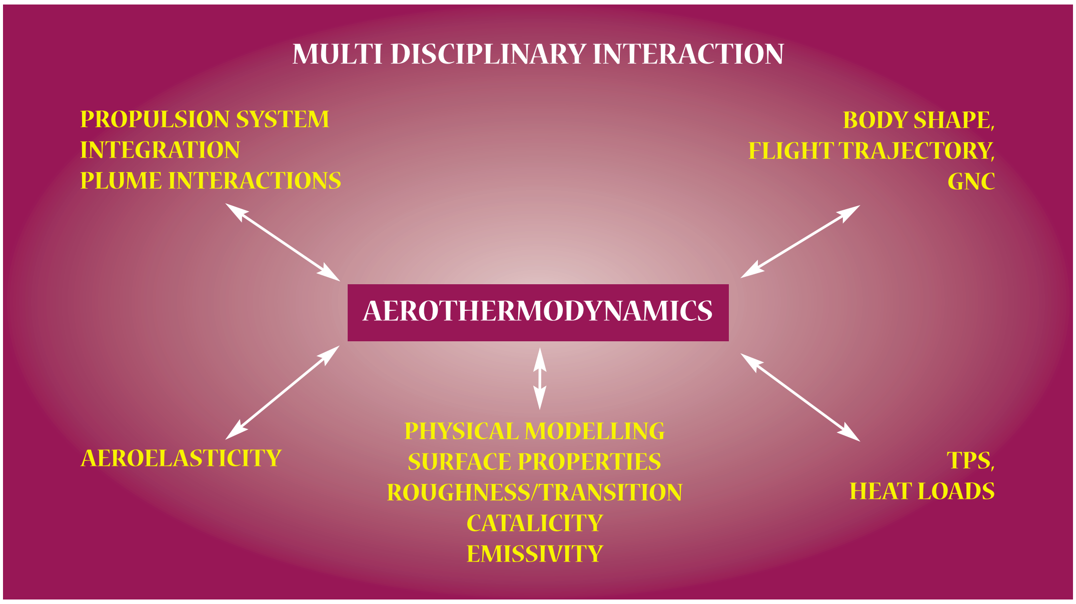


Figure 1. Interactions between aerothermodynamics and other disciplines

the high-temperature effects typical for higher speeds and altitudes, by means of high-enthalpy or hot-flow facilities. ESA has supported the modernisation of existing cold wind tunnels, and also the construction of facilities with new capabilities.

Facilities that were initiated during the Hermes Programme and completed or upgraded during the follow-up Manned Spaceflight and Technology Programmes include:
– Two high-enthalpy facilities, which are mutually complementary, for the study of high-temperature effects on controllability and heating: the 'hot shot' facility F4 at ONERA Le Fauga, and the piston-driven 'shock tube' HEG at DLR Goettingen.
– Three plasma facilities, also mutually complementary, to investigate the heat load and gas surface interaction on materials and structures: the segmented arc-jet-heated L3K facility at DLR Cologne (max. power 6 MW), more recently the larger Scirocco facility at CIRA Capua (max. power 70 MW), as well as the recently commissioned plasmatron facility at VKI Brussels (max. power 1.2 MW).

The Scirocco facility is still in the commissioning phase, but should be operational in 2001; the other facilities are already in full operation.

In 1997, Europe decided to carry out full-scale free-flight experiments and embarked on the Atmospheric Re-entry Demonstrator (ARD) capsule. The corresponding post-flight analysis has recently been completed. A lifting-body re-entry demonstrator (X-38) will be flown in 2002 based on a close partnership with NASA, where ESA's and the German TETRA programme have joined forces. In February 2000, a low-cost flight experiment based on Inflatable Re-entry and Descent Technology (IRDT) from Russia, initially foreseen for a Mars lander, was carried out. This flight experiment is being repeated in 2001 to evaluate its potential as an independent, low-cost Space-Station payload return vehicle in greater detail. In addition to ground-based facilities and the little available flight testing so far, the tool that has been developed most since the Hermes era is Computational Fluid Dynamics (CFD). CFD is being used to gain greater insight into the physical phenomena and to help to accelerate and improve the design processes.

CFD has become a powerful tool in classical aerodynamics, but its usefulness relies on input from appropriate physical modelling, for example transition and turbulence for the numerical integration of the flow governing Reynolds averaged Navier-Stokes equations. Hence, measurements in ground-based facilities provide the skeleton or anchor points for the database below Mach 10. The corresponding 'interpolation' is performed with the results of validated CFD solvers. Above Mach 10, where in particular high-temperature effects dominate the flow, CFD must be used. The appropriate validation of CFD is therefore of great concern. It is achieved by comparing data measured in, for example, the above-mentioned high-temperature facilities with those obtained by numerical prediction. In many cases the use of CFD goes hand in hand with the definition of the test cases and interpretation of the data. In this context, ESA/ESTEC and others have organised a number of workshops in the past. CFD is subsequently being used for flight simulations above Mach 10. This 'extrapolation method' assumes, however, that the physical models that enable good results for the simulation of the experimental test case, will provide good results also for free flight. Therefore, free-flight data are urgently required to remove any doubts about the validity and accuracy of the CFD predictions and to confirm the extrapolation methodology. This is particularly important for man-rated vehicles.

Today's aerothermodynamic issues are discussed below in the context of examples from the different ESA Directorates.

Aerothermodynamic applications in the ESA Manned Spaceflight and Microgravity Programme

Thanks to ESA's Manned Space and Technology Research Programmes, European expertise in aerothermodynamics has been advanced considerably in recent years. The flight of the Atmospheric Re-entry Demonstrator (ARD), and the challenging participation in NASA's Crew Return Vehicle (X-38/CRV) programme with substantial European hardware and software contributions, represent major steps in this respect.

ARD

ARD was flown successfully on Ariane-503 in October 1998. The objective was to test and qualify re-entry technologies and flight-control algorithms under real flight conditions, to achieve in-flight validation of design concepts, hardware and system capability, to validate aerothermodynamic prediction tools, to qualify the thermal-protection system, to assess guidance, navigation and control laws, to assess parachute and recovery-system performance, and to study radio-communication links during re-entry.

The ARD flight was a major achievement for Europe. It provided real flight data and enabled comparison with experimental and numerical design tools used for all flight phases. Data were recorded from the de-orbiting, throughout the high-speed portion of the flight, until parachute deployment and splashdown. Reaction and control system efficiencies, local heating, blackout, transition phenomena and dynamic and static stability data were all measured. The splashdown in the Pacific occurred less than 5 km from the expected position. The ARD's angle of attack and flight-path angle differed only slightly from the prediction (around 2 deg for trim and 0.5 deg for side-slip angle). Four angle-of-attack manoeuvres were successfully executed to study pitch damping. A detailed post-flight analysis has just been completed with new experiments and computations to check the databases. Figure 2 shows an example of a Schlieren picture in the S4 ONERA Modane facility at Mach 10, together with corresponding predictions using the in-house-developed Lore code. Figure 3 compares experimentally obtained oil-flow patterns with predicted skin friction lines for the study of the local heating, using the same facility.

The ARD flight not only allowed the verification of the use of ground-based facilities and the use of CFD for databasing and design, but also highlighted some critical issues requiring further study and improvement, such as flight heat-flux gauge integration and high-enthalpy wind-tunnel pressure and heat-flux data accuracy improvement.

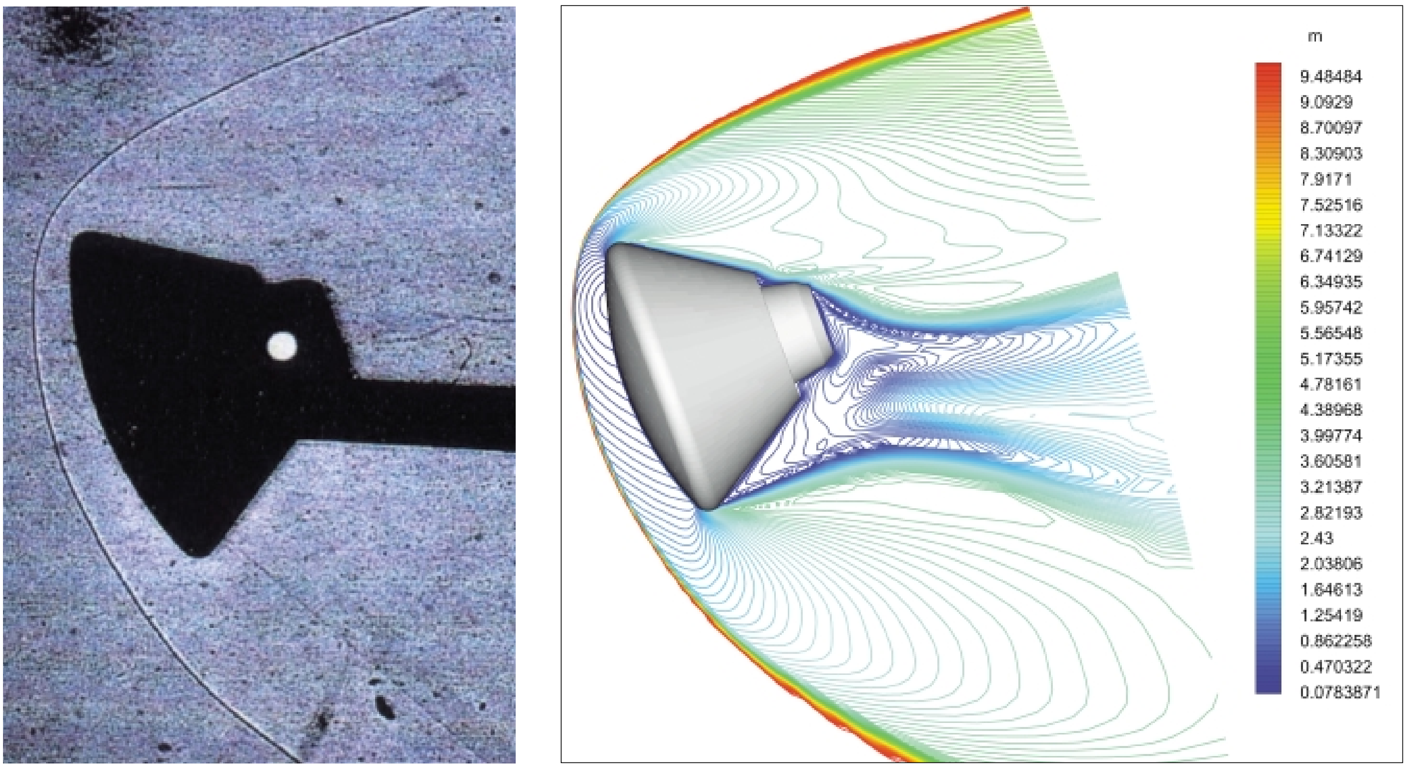


Figure 2. ARD Schlieren photograph taken in the ONERA S4 facility at Mach 10 (incidence angle 20 deg) and the corresponding computed iso Mach lines

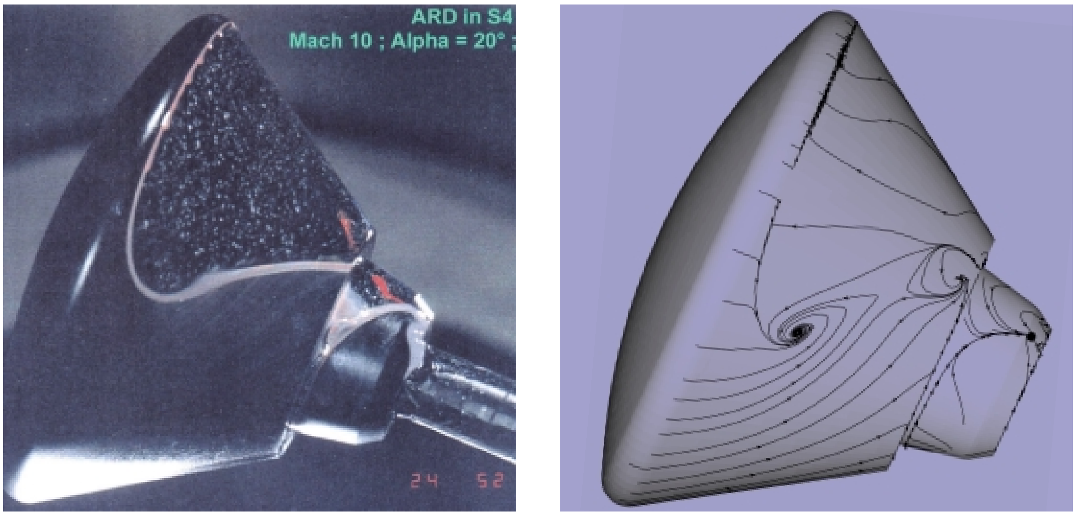


Figure 3. ARD oil flow patterns in the ONERA S4 facility at Mach 10 (incidence angle 20 deg) and the corresponding computed skin friction lines

X-38/CRV

The joint NASA/ESA/DLR X-38 project includes the demonstrator V201 being assembled for a Shuttle-carried hypersonic re-entry flight planned for 2002. This partnership with NASA will be carried over to the production of the operational man-rated Crew Return Vehicle (CRV) for the International Space Station in collaboration with American industry as prime.

Some of the aerothermodynamic issues for the X-38 design are:

- Stability and trimming: the influence of real gas and viscous interaction effects on control-flap efficiency and heating.
- Roughness-induced boundary-layer transition, flap shear-layer transition and its influence on local heating.
- Micro-aerothermodynamic effects due to flow through hinges and gaps in rudders and flaps.
- Qualification testing of the thermal-protection system in ground-based facilities and extra-polation to flight.
- Wall catalysis and radiation influencing heating rates.
- Transonic dynamic derivatives for stability control.
- Flight measurement techniques, including air data system.
- Reaction and control system efficiencies.

To assess these issues, CFD is being heavily used in defining wind-tunnel test conditions, in interpreting the measured data, and finally for the flight extrapolation.

Figure 4 shows some interesting flow patterns on the windward and lee sides of the X-38 vehicle at Mach 17.5 and 40 deg incidence. It confirms the predicted (Lore) increased radiation equilibrium temperatures at the leading edges and at the flap corners, especially between the body flaps and at the base end behind the control flaps. Figure 5 shows the effect that the boundary layer has when it transitions from laminar to turbulent

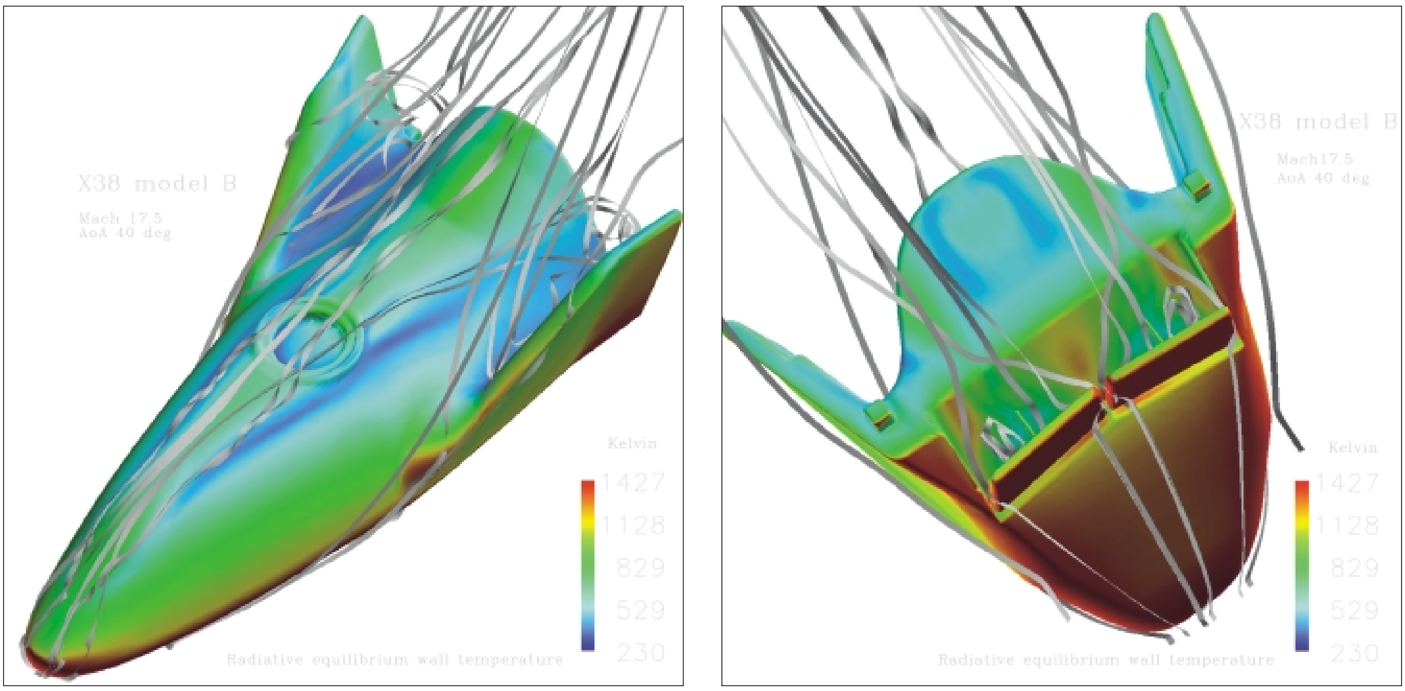


Figure 4. Predicted X-38 flow streamlines at Mach 17.5 (incidence angle 40 deg) combined with the equilibrium radiative wall-temperature distribution

flow on the flap. A comparison is presented with experiments performed in the NASA LARC 20-inch Mach 6 facility. The complexity and multidisciplinary nature of the interactions involved in the body-flap design are shown in Figure 6. Extensive testing is being conducted within the German TETRA programme using the L3K plasma facility at DLR in Cologne. Figure 7 shows a model set-up as tested under high-enthalpy conditions. Here again CFD is required for flight extrapolation, as the local conditions in the wind tunnel only partially duplicate those in flight.

The collaboration with NASA's Johnson Space Center has helped Europe to improve the understanding of such phenomena as windward roughness-induced transition, based on Shuttle lessons-learnt and extensive testing in NASA's LARC Mach 6 facility. Roughness-induced transition correlations were developed and validated by properly designing these roughness distributions on the windward side such that the transition encountered in the wind tunnel corresponds to that in flight. This European collaboration with NASA is unique and all partners are looking forward to strengthening the relationship through the

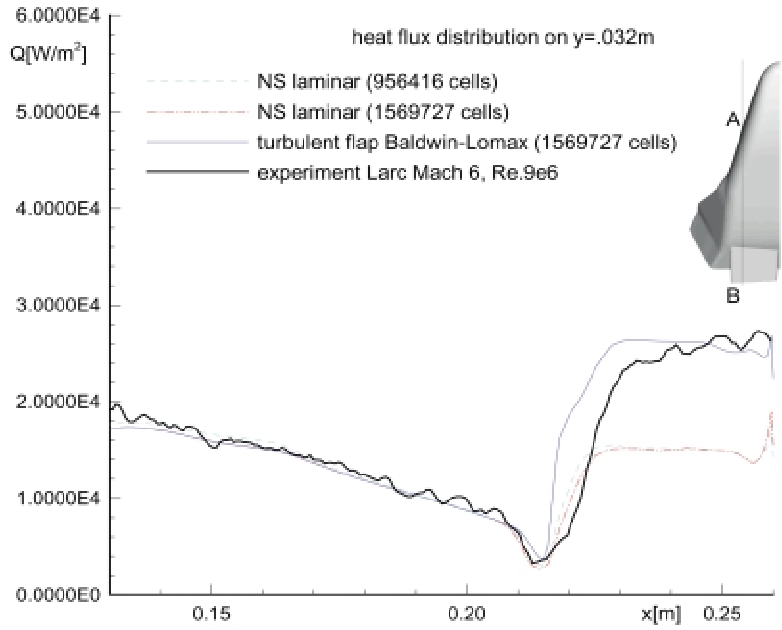


Figure 5. Predicted laminar and turbulent heat-flux distribution along the X-38's deflected body flap and a comparison with NASA LARC Mach 6 experiments

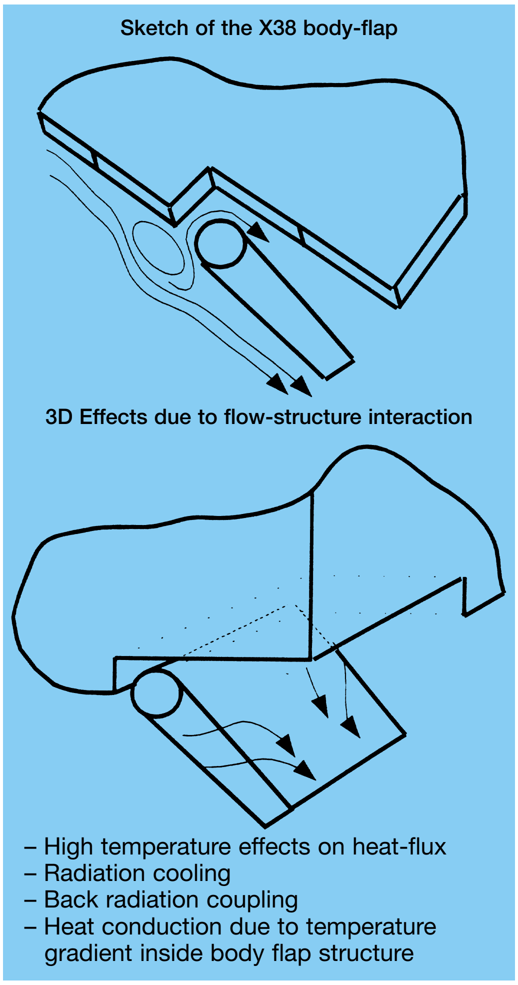


Figure 6. Sketch of complex flow-structure interaction on the X-38 body flap

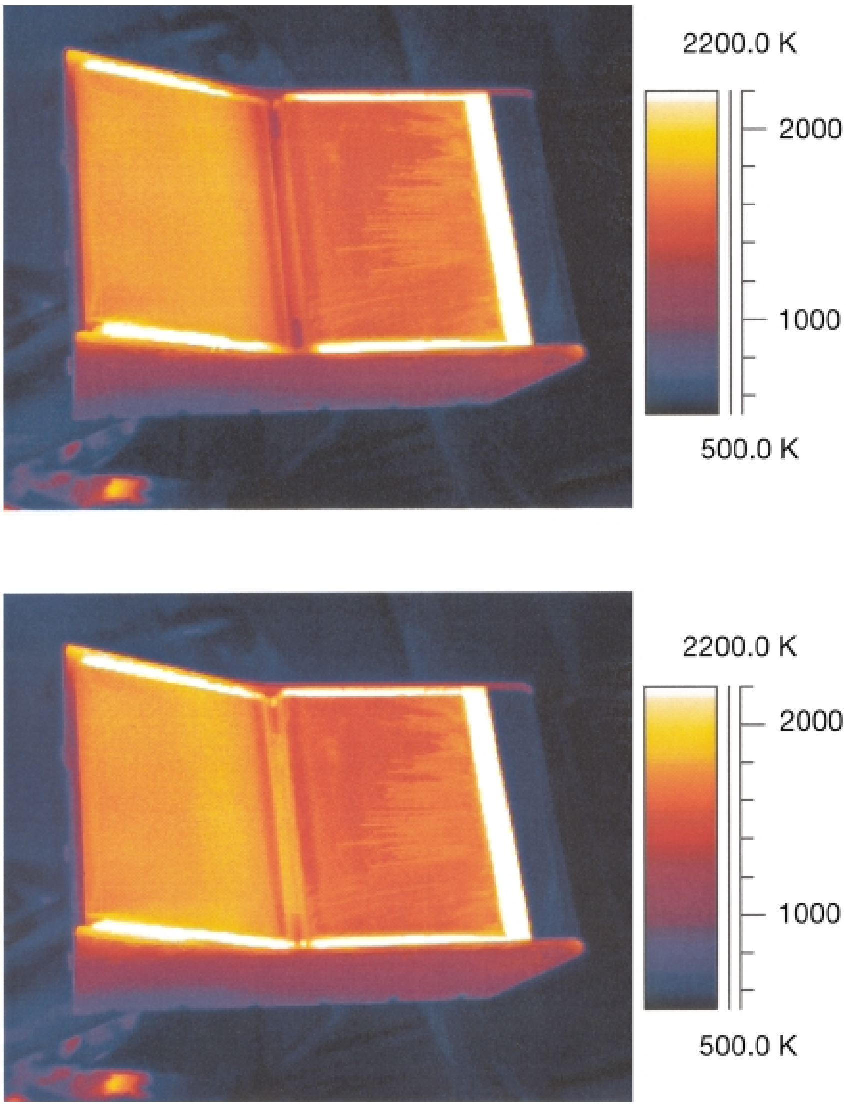


Figure 7. Surface-temperature distributions in the TETRA X-38 body-flap model with closed and open gaps in the L3K facility at DLR in Cologne

upcoming X-38/V201 hypersonic flight and the CRV programme.

Aerothermodynamic applications in ESA Science Programmes
One of the aerothermodynamic issues associated with satellites is plume impingement due to the interaction of the propulsion system with the spacecraft's surfaces. Improperly engineered plumes not only produce pressure and frictional forces, but may also cause contamination or unacceptable heat loads. To assess this computationally, a combination of different numerical methods is used: Navier-Stokes solvers for the continuum flow in the thruster nozzle, a Monte-Carlo direct simulation method for the near-transitional flow field, and free-molecular-flow tools for the far field. For routine project design work, industry uses quick empirical models. Such models for plume/surface interaction are currently being improved using data obtained in the unique, ESTEC-supported STG simulation facility at DLR in Goettingen, which produces roughly 10 m^3 of 'real space conditions'. The interaction of the rarefied flow with the surfaces requires separate modelling.

Planetary-science missions with capsule planetary entry or Earth sample-return scenarios involve critical aerothermodynamic phenomena:
- Direct entry using aerocapturing or aerobraking techniques involves improved knowledge of the reaction and control system interactions with the flow in transitional and continuum regimes.
- Thermochemical effects and radiation play a dominant role in the shock layer and in the wake of capsules for TPS design. Entering atmospheres of which the composition is not well known makes the assessment even more complex.
- Wake-flow stability and wake-flow transition effects influence the payload shield design for the capsule.
- For the higher capsule entry speeds, more complex phenomena have to be considered in the layer between the bow-shock wave and thermal-protection system, such as radiation and ionisation including gas/surface interactions, requiring knowledge of the appropriate material properties.
- The qualification of thermal-protection systems in plasma facilities using gases other than air is non-trivial. In addition, in many cases the thermodynamic and chemistry databases are incomplete or even non-existant.

Here also, CFD plays a major role in the design process. The validation is complex and requires dedicated tests in shock tubes, shock tunnels and plasma facilities using sophisticated instrumentation. These only provide the database for partial validation, because the facilities cannot completely simulate the free-flight flow field around the capsules. Again, the validity of the CFD-based extrapolation needs to be checked against actual in-flight measured data.

Aerothermodynamic applications in ESA Launcher Programmes
The aerothermodynamic issues for launchers differ significantly from those for blunt-body re-entry vehicles. In general, Mach number (compressibility) and Reynolds number effects (viscous forces) are important parameters for ascent-type vehicles, whereas high-temperature effects and pressure forces are dominant for re-entry vehicles.

Ariane-5
The aerothermodynamic activities involved in designing a launcher like Ariane-5 touch upon many areas: overall drag assessment during take-off, unsteady buffeting loads assessment at transonic speed, maximum steady-state load estimations around Mach 2, booster separation and jet impact during staging, solid booster radiation, local aerothermodynamics such as local heating at high Mach number around the booster attachment bars, attitude-control-system plume contamination and performance, nozzle-induced side loads at start-up and sloshing in tanks during staging or payload separation.

Only a limited subset of the many interesting fluid-dynamics issues will be touched upon here:
- *Performance of the attitude control system:* Its qualification involved hydrazine tests at ONERA Le Fauga for the verification of possible vaporisation inside the pipes. Because the test could not simulate vacuum conditions, CFD was used to extrapolate to flight conditions.
- *Explaining peculiar measurements with the help of computational simulations:* An overshoot in heat flux measured in flight proved to be due to the sharp drop in the wall temperature at the locations of the heat sensors. Figure 8 shows the locations of the thermocouples on the Ariane-5 fairing, and the temperature and corresponding heat flux distributions at those locations for two sets of flight conditions during ascent: those corresponding to Mach 3.7 and an altitude of 29 km, and those for Mach 5.8 at an altitude of 49 km. The predictions were made using the in-house-developed Sesmans code.
- *The magnitudes of the buffeting loads in the base region of the cryogenic tank (EPC) and on the Vulcain nozzle are a major concern.* Unsteady, separated flow emanating from

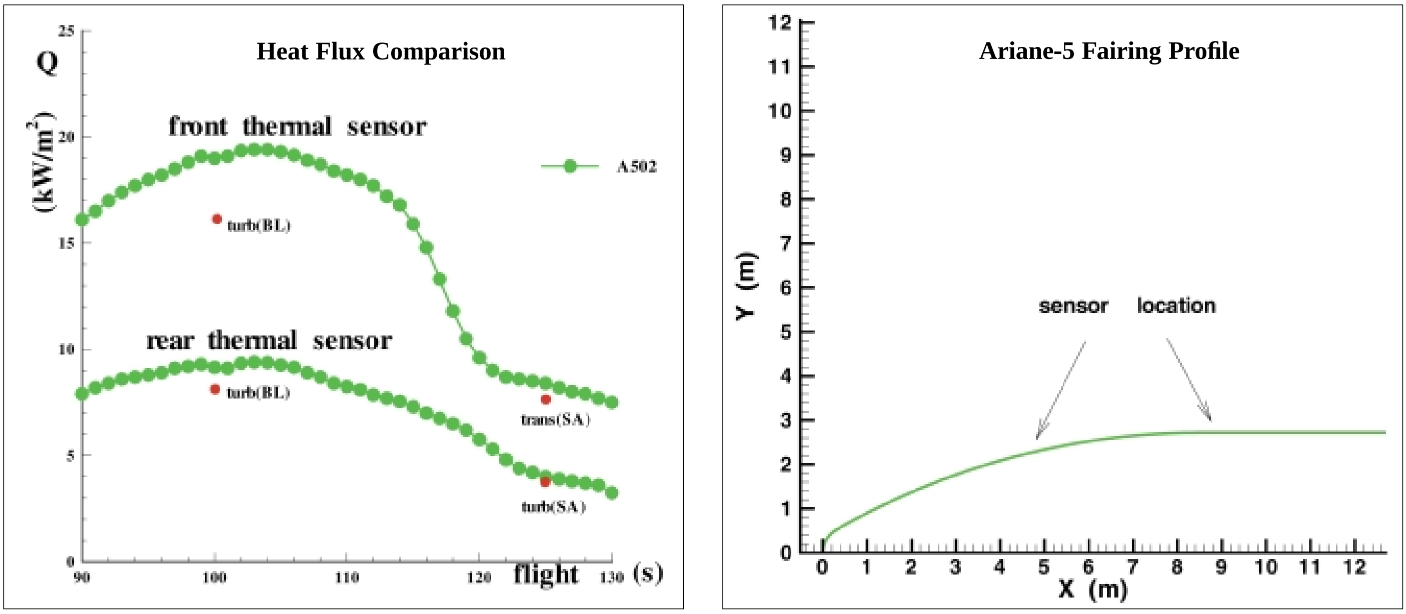


Figure 8. Comparison of computed and in-flight-measured heat flux on the Ariane-502 nose cone

the central core creates unsteady forces on the Vulcain nozzle. The magnitude and direction of these forces are influenced by 3D effects originating from the protuberances, as well as from the solid boosters. Extensive experimental campaigns involving large-model testing in transonic facilities with and without plume simulation were carried out. The analysis has recently been augmented with experimental activities for the study of possible coupling between external flow and shock-separated flow in the nozzle (all experiments in the transonic facilities are carried out with cold jets, and extrapolation to flight involves an assessment of the influence of hot jets on the buffeting interaction). Figure 9 shows the predicted unsteady velocity vectors using the ESA-funded Euranus code, highlighting the complexity of the flow. Figure 10 shows the Ariane-5 model in the FFA transonic/supersonic facility (S4). It is believed that the use of Large Eddy Simulations (LES) or eventually of Direct Numerical Simulation (DNS) will improve our understanding by enhancing the analysis of the influence of the hot plumes.

– *Ariane-5 loads:* CFD can be used to assess the pressure and heat loads and to update the launcher specification to reduce the structural and thermal-protection-system mass. To this end, CFD wind-tunnel flow simulations are carried out to build up confidence for flight computations. In-flight results from several sensors at specific locations provide the real flight data which, when used in combination with CFD results, allow the assessment of pressure and heat load. Figure 11 shows a typical 3D grid and preliminary computational results (Lore) for Mach 0.7 conditions in NLR's transonic facility (HST). The distribution of 3D pressure load in the base region is shown.

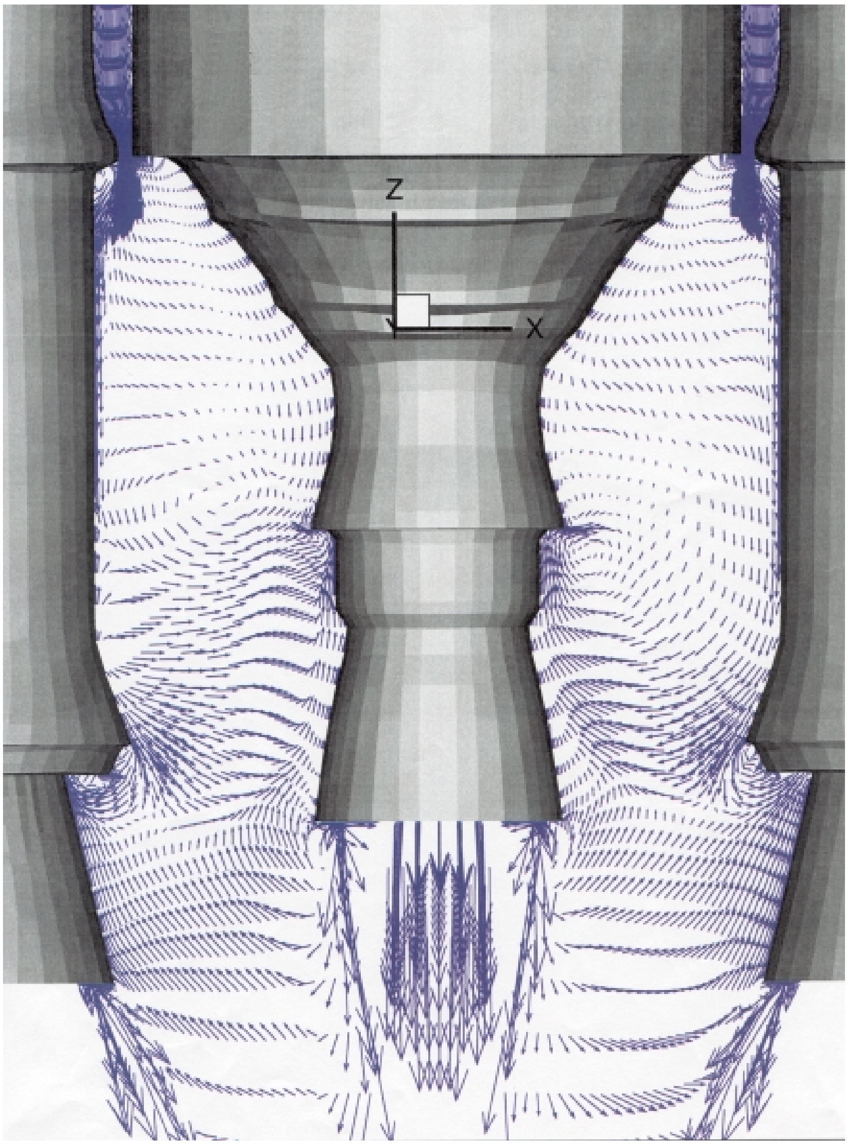


Figure 9. Predicted unsteady velocity vectors in the base region of the Ariane-5 model at Mach 0.7

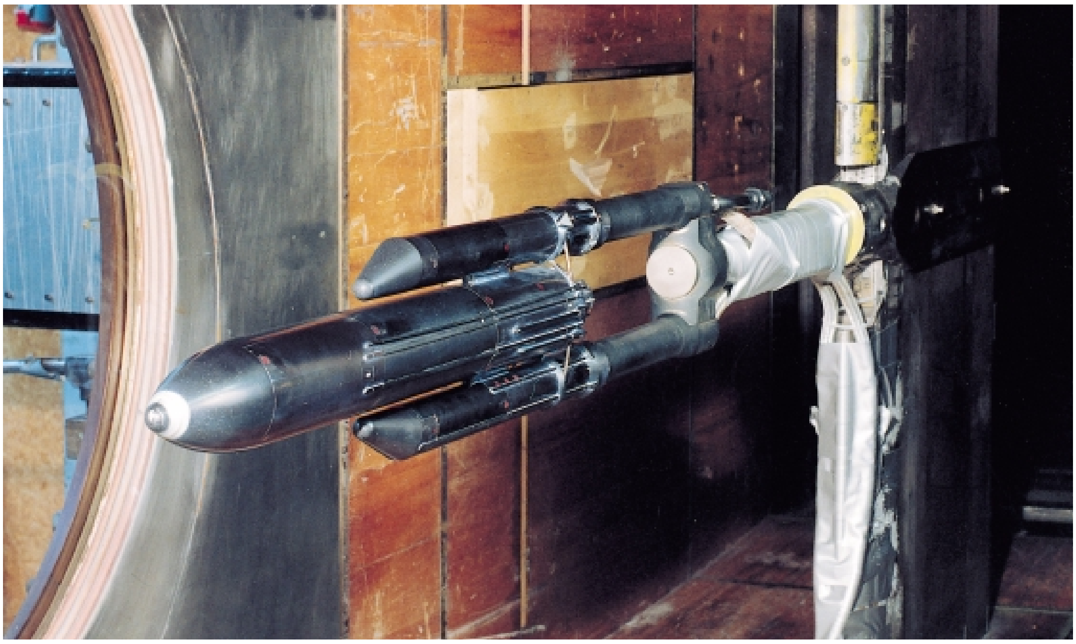


Figure 10. The Ariane-5 model in the supersonic S4 tunnel at FFA

– *Vulcain-2 performance analysis:* CFD was used to analyse the boundary-layer separation and shock pattern during the flow start-up process in the nozzle. The challenge here is to include in the simulation the correct representation of turbine exhaust gas (TEG) re-injection and the hydrogen dump cooling. The results explained the 3D heating patterns observed in a series of hot-flow experiments conducted at DLR in Lampoldshausen. Figure 12 shows the iso Mach contours (Lore) in the Vulcain-2 nozzle, the details of the flow structure near TEG injection and the H_2 dump location, and the shock-induced boundary-layer separation at the nozzle exit.

FESTIP

Within ESA's FESTIP Technology Programme, aerothermodynamic research has been performed in three main areas:

– *Configuration analysis:* Analysis of aerodynamic coefficients was carried out on generic shapes using numerical tools with different levels of sophistication, taking the Experimental Test Vehicle (EXTV) as the reference configuration. Force and moment bookkeeping data in the S4 FFA for the low-attack-angle ascent phase, with and without twin plume interaction, were analysed. Pressure-Sensitive Paint (PSP) data were recorded for comparison with CFD. Figures 13 and 14 show some typical experimental results with jets. The oil-flow picture shows the complex interactions to the lee side of the body flaps induced by the jets. The Schlieren photograph shows the embedded shock patterns at the location of the flap hinge influencing the overall trimming of the vehicle.

– *Critical-point analysis:* Roughness-induced-transition experiments were conducted on a

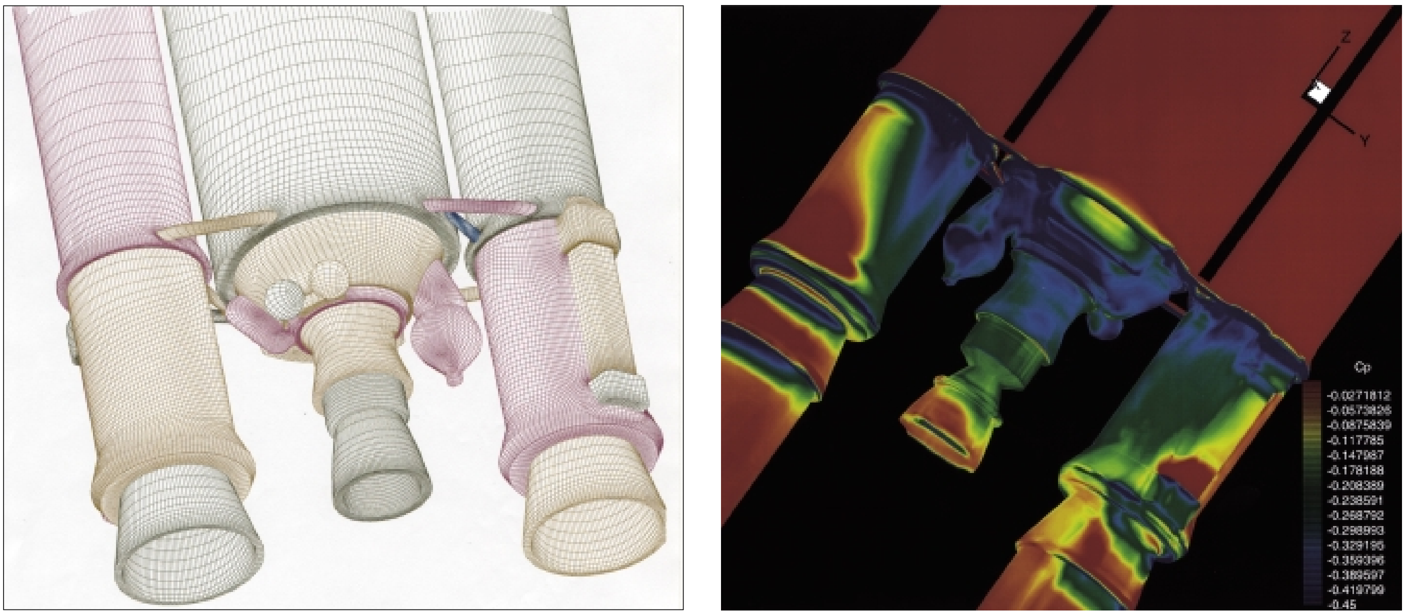


Figure 11. Surface mesh and preliminary predicted pressure distributions around an Ariane-5 model in NLR's HST facility for Mach 0.7 conditions

generic configuration and compared with existing correlations. Shock-wave boundary-layer interactions were studied for ramp flows, and CFD was used to study scaling effects, where in particular wall-temperature effects were addressed. As part of this programme, base flow plume-interaction experiments were also conducted at TU Delft and FFA for validation purposes. The importance of strut effects and the need for improved, time-accurate turbulence models were stressed.

– *Flight measurement techniques and flight-test analysis:* The activities here focussed on the definition of requirements for air data systems for the Raduga D2 configuration and on the MIRKA flight analysis. New experiments in the plasma facilities at IRS (Univ. of Stuttgart) as well as in the Ludwieg Tube at HTG (Hypersonic Technology Goettingen) were performed with a MIRKA configuration for the study of catalycity and of the influence of real gas on shock stand-off distance. Numerical results in the wind tunnel as well as under flight conditions were derived for MIRKA. These confirmed that in-flight catalytic experiments are feasible on simple ballistic configurations.

FLTP

To improve understanding of the issues related to launch-vehicle reusability and to enhance European technology in this field, the Future Launchers Technologies Programme (FLTP) was initiated as an ESA optional programme. Here we are focussing on the critical points from previous programmes that have not yet been completely solved:

– Increased heating due to roughness-induced boundary-layer transition will be investigated and shear-layer transition validation experiments will be carried out. CFD will be used to study scaling issues and hot-wall effects.
– Plasmatron experiments will be carried out to study the catalycity and compared with laboratory-obtained O_2, NO and N_2 catalytic recombination reactions. CFD will be used to bridge the gap and to report on the accuracy of the semi-numerical methods as presently used in the plasmatron.

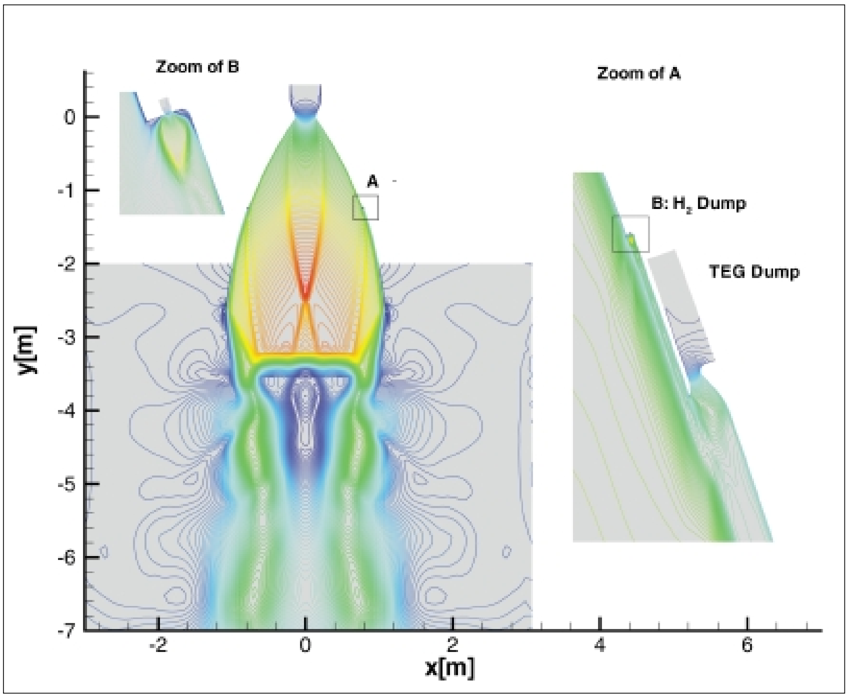


Figure 12. Predicted iso Mach lines for Vulcain 2 at design point at 115 bar with zoom of turbine exhaust gas section and hydrogen dump slot

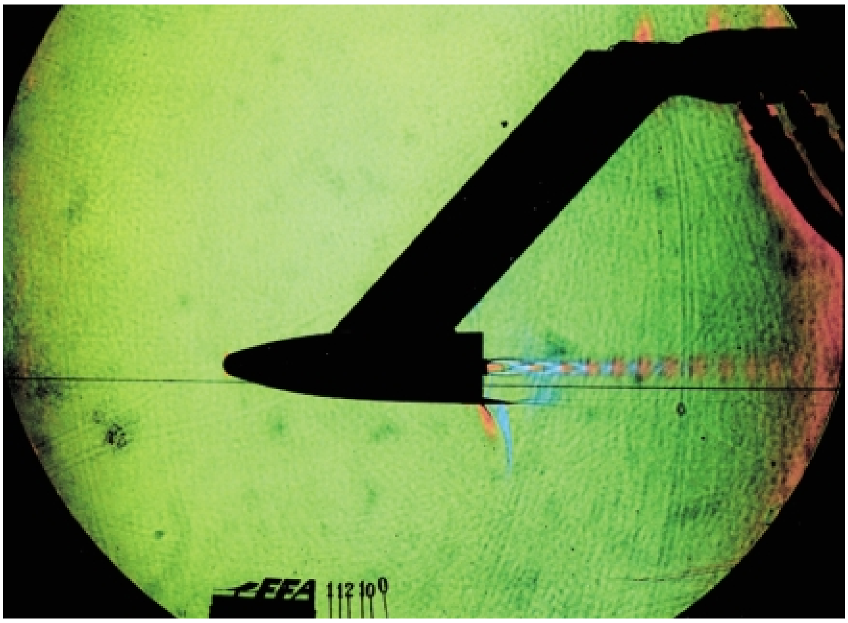


Figure 13. Schlieren picture of EXTV in the S4 FFA facility at Mach 0.9, incidence angle 0 deg, nozzle pressure ratio 10

Figure 14. Oil-flow visualisation on EXTV in the S4 FFA facility at Mach 0.9, incidence angle 10 deg, nozzle pressure ratio 10

– Local aerothermodynamics effects will be investigated such as flap/gap flow, with the emphasis on scaling.
– Base flow experiments, with and without jet interaction, will be performed, with the emphasis on hot-plume effects. Understanding hot-plume effects is crucial not only for base flow pressure recovery and heating, but also for unsteady buffeting effects and nozzle flow separation/external flow interaction assessment.

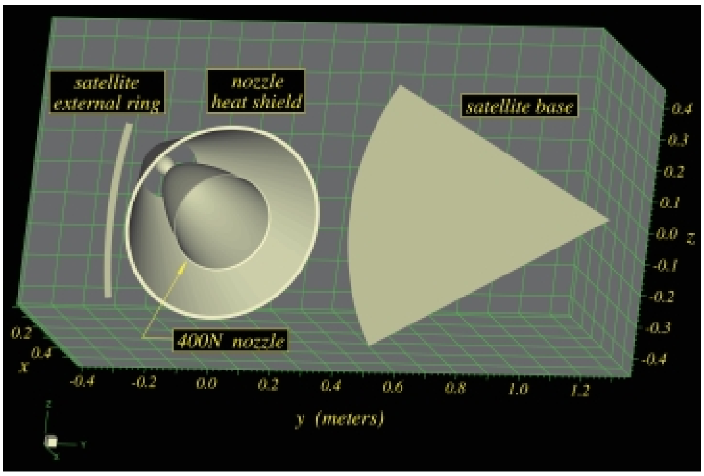
Aerothermodynamics in ESA Application Programmes

A typical example of plume-impingement analysis for an Application Programme is shown in Figure 15, for the MSG mission. The back flow emanating from the main 400 N rocket-engine nozzles impinges on the satellite's external ring and on its base. The heat shields around each of the two nozzles protect the satellite base region against radiation and against convective heating. A coupled Navier-Stokes (in-house-developed YPANS code) and Direct Simulation Monte Carlo solver (ITAM/ Smile code) has been used to compute the total energy flux at critical locations. This analysis involved axisymmetric computations; 3D computations are planned to predict the heat flux to be measured in flight.

Aerothermodynamic research activities in ESA

The Agency has set up Technology Programmes (GSP, TRP, GSTP) in order to initiate novel developments and to assure knowhow continuity, and to advance analysis and experimental capabilities. These activities are intended to prepare to meet the technology needs for future programmes and advance our capabilities to allow industry to stay at the cutting edge of technology. The (non-exhaustive) list of aerothermodynamic research activities includes:

– *Gap heating, using data from the Japanese suborbital re-entry demonstrator Hyflex:* A combined numerical and experimental activity has been set up using the DLR L3K facility, where a set of instrumented tiles are being tested which are identical to those used in flight (Fig. 16). The objective is to achieve wind-tunnel conditions such that the local convective and radiative heat fluxes in the gaps are as close as possible to those in flight. Wind-tunnel and flight flow fields are being predicted with CFD, taking into account the 3D effects in the gaps as well as the heat conduction into the material. The results obtained from the analyses will identify where further investigations in the flow /material-interaction area are needed.
– *Plasmatron measurement techniques:* Non-intrusive measurements will be developed and calibrated to provide a direct means of measuring the species concentrations in the boundary layer in front of a model. This method will be compared with the semi-numerical methods currently being used in plasmatron applications to assess recombination coefficients.
– *Hot-plume testing:* Retrofitting of an existing H_2/O_2 propulsion stand is planned to study the influence of hot plumes on the base pressure and heating of launchers.
– *Buffeting:* Experimental and numerical studies of base-flow buffeting on simple and complex Ariane-5 models are planned, including cold-jet effects.
– *Nozzle flow-separation control device:* Experimental and numerical flow-separation studies will be conducted on different nozzle



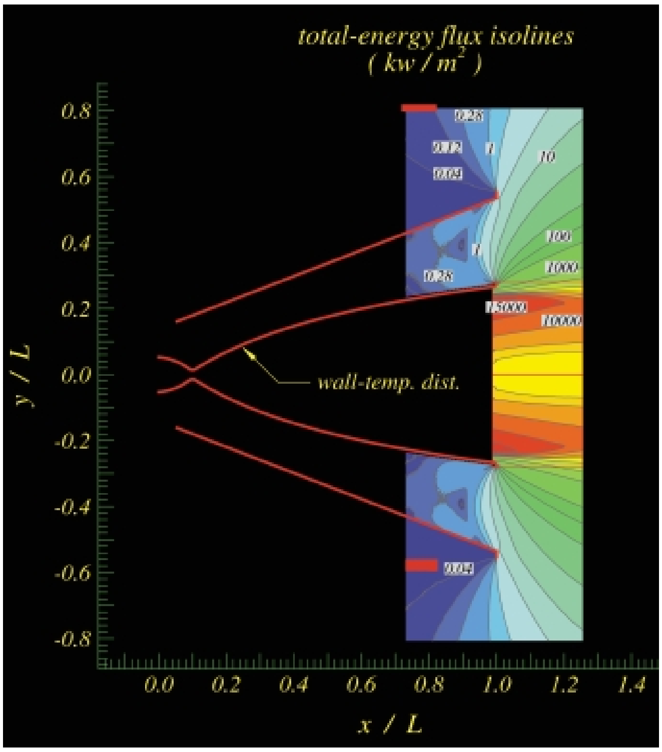


Figure 15. Meteosat Second Generation (MSG) plume-impingement numerical analysis using Navier Stokes predictions for the nozzle and Monte Carlo simulations for the plume flow

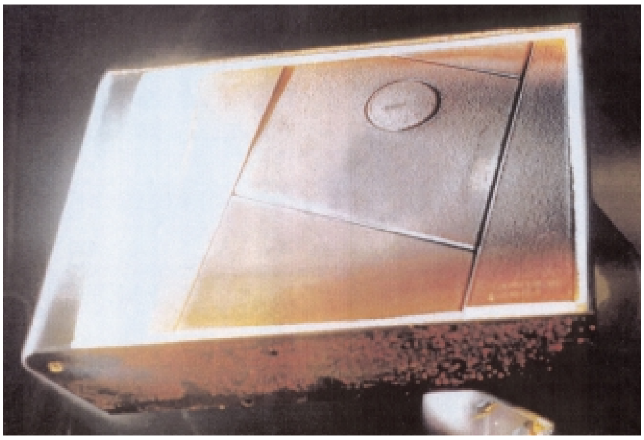


Figure 16. Hyflex tiles instrumented with as-flown sensors tested in the L3K DLR facility in Cologne

shapes such as the classical bell-type, dual-bell, extendable and external-expansion nozzles in order to understand and control nozzle flow separation.
– *In-flight research:* The objective is to perform a feasibility study for in-flight research using generic configurations to study transition, catalycity and shock boundary-layer interaction. The study will also focus on the corresponding wind-tunnel tests to represent flight, and on improvement of the accuracy of flight measurement techniques and their integration into the thermal-protection system.
– *Inflatable Re-entry and Descent Technology (IRDT):* A flight experiment was performed in 2000, which was supported by the European Commission through the ISTC programme. Astrium carried out this programme in close collaboration with Babakin Space Centre (Lavochkin). One of the objectives was to evaluate IRDT's potential as an independent, low-cost payload-return capability for experiments conducted on the International Space Station (ISS). The successful suborbital flight in February 2000 confirmed the technology's potential (Fig. 17; see also ESA Bulletin No. 103, August 2000). Another flight, initiated by the Directorate of Manned Spaceflight and Microgravity, and a precursor flight are planned for March and August 2001, respectively. Near-orbital entry conditions will be achieved for full validation of the concept.

Conclusions

This article has discussed some of the critical aerothermodynamic issues inherent in the design of re-entry space vehicles and launchers, as well as reviewing the analysis and test results obtained to date. The importance of flight-testing for the validation of methods and procedures for the extrapolation of results obtained from ground-based facilities has been highlighted. In particular, such flight data are needed to establish real confidence both in the computational fluid dynamics and the underlying physical modelling.

Aerothermodynamics has emerged as a key discipline for the design and qualification of advanced launchers, re-entry vehicles, and planetary probes. It requires enhancements in multidisciplinary techniques which, thanks to the rapid growth in computing power, will be increasingly used in the future. The Agency is working towards continued and well-directed research with flight demonstrators to advance Europe's computational and experimental capabilities for future space programmes. Continuation of such activities in Europe is essential to remain at the cutting edge of technology for space transportation.

Figure 17. The IRDT reentry configuration

These efforts will be supported by co-ordinating European activities and promoting closer collaboration between universities, research establishments and industry. The success of this challenging undertaking depends upon support from all of the nations involved. Continued international cooperation, such as the partnership with NASA in the CRV Programme, will only be possible if Europe continues to enhance its aerothermodynamic knowhow and expertise, which includes the availability of verification facilities and flight demonstrators.

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