Aerothermodynamics for Space Vehicles – ESA's Activities and the Challenges

J. Muylaert and W. Berry
Propulsion and Aerothermodynamics Division, ESA Directorate for Technical and Operational Support, ESTEC, Noordwijk, The Netherlands

In August 1988, ESA implemented a specialist section for aerothermodynamics within the Propulsion and Aerothermodynamics Division at ESTEC in the Netherlands. This capability was created to provide a competence in ESA for a new generation of space vehicles requiring aerothermodynamics expertise to enable their design: the Hermes Space Plane, planetary missions within the Agency's Space Science Programme and the Ariane-5 launcher. The Section was to be the focal point for this new discipline within ESA in addition to coordinating European activities in aerothermodynamics and providing technical support to the Agency's programmes. The Aerothermodynamics Section is now exactly 10 years old, making it timely to review the achievements, to elaborate on the importance of aerothermodynamics for space vehicles, and to present the challenges for current and future ESA space vehicles.

Introduction

Aerothermodynamics for space vehicles embraces the science and technology of classical aerodynamics extended to cover hypersonic speeds, and includes the physics and chemistry of chemically reacting and dissociated flows. The field covers external flows around aerospace vehicles and internal flows through vehicle propulsion systems. The activities cover theoretical aerothermodynamics, including computational fluid dynamics (CFD), experimental aerothermodynamics, flight testing and operations.

Over this ten-year period, as the technical capabilities of the Section have increased, more demanding space missions have inevitably emerged comprising launchers, reentry vehicles, planetary landers, and space station crew transfer and rescue vehicles. These new missions have imposed demanding aerothermodynamic requirements and challenges, which are reviewed in this article.

Aerothermodynamics at ESTEC has now evolved into a wide field of applications encompassing all of the major fluid dynamic aspects:

- External aerodynamics of aerospace vehicles covering their complete flight regime: subsonic, transonic, supersonic and hypersonic speed. The outputs of this work are aerodynamic loads and kinetic heating rates, used for the structural, thermal and flight-control design of the vehicles.
- External aerodynamics of aerospace vehicles to cover the transition from high-altitude free molecular flow to continuum flow as vehicles enter planetary atmospheres. Flight control of vehicles during this phase requires a combination of reaction control from small rocket engines and aerodynamic control from vehicle control surfaces.
- Aerodynamics of parachute and parafoil landing systems.
- Internal aerodynamics of aerospace vehicles covering the design of propulsion engine inlets, propulsive exhaust nozzles, engine flow control valves, manifolds and vents.
- Micro-aerodynamics which encompasses the assessment of local flow effects in gaps between thermal-protection tiles, and at steps between structural elements and at corners, such as those occurring at aerodynamic control surface hinges.
- Unsteady flow effects due to aerodynamic buffeting and flutter of structural elements.
- Chemically-reacting flows in combustion chambers and in the shock layer of aerospace vehicles during entry into planetary atmospheres.
- Two- and three-phase flows in non-equilibium, chemically frozen or equilibrium conditions where contamination or debris are concerns.
- Rocket-engine exhaust-plume flow impingement effects on spacecraft surfaces: forces moments, heating and contamination.
- Flow analysis of liquid-in-tube nutation dampers.

Aerothermodynamic facilities and tools for design

The means to address aerodynamic design issues, to quantify their effects and to qualify the vehicle are:

- ground-based facilities such as classical wind tunnels, shock tunnels, plasma facilities and their instrumentation

- numerical analysis codes, ranging from simple and fast engineering tools to complex CFD codes combined with their pre- and post-processing routines. CFD is essential in the design process for the definition of the experiments, the interpretation of data, the validation of the physical modelling (for example, for transition and turbulence) and the subsequent extrapolation to flight conditions

- flight testing, ranging from simple generic configurations such as capsules, to complex vehicles for design validation and technology qualification in realistic environments, including their associated flight measurement techniques and air data systems.

To strengthen European capabilities for the design and qualification of space vehicles, the improvement of the three interdependent tools – wind tunnels, CFD and flight testing – has received top priority in ESA's Technology Research Programme (TRP) and General Support Technology Programme (GSTP). Furthermore, numerous workshops and symposia have been organised by the Aerothermodynamics Section to promote cooperation and interaction between universities, research establishments and industry.

The Manned Spaceflight Programme

Over the last ten years, this programme has been the main initiator and stimulus for a large number of aerothermodynamic activities. Its needs have resulted in the current high level of European technical expertise in experimental facilities and techniques, and CFD codes for space vehicle design. The current programmes are:

ARD

The Atmospheric Reentry Demonstrator (ARD) is a guided reentry vehicle of the Apollo type, (Fig. 1) which was launched on the third Ariane-5 test flight in October 1998. This mission was a major achievement for Europe as the ARD was the first ESA vehicle to perform a complete reentry. Throughout its reentry and descent, flight measurements were taken to evaluate heating, transition, reaction control system interaction, ionisation (black out) and parachute deployment. The post-flight analysis will give industry invaluable experience, allowing them to validate and improve their design tools.

XCRV

The Experimental Crew Rescue Vehicle (XCRV), also called the X38, is being designed as an experimental vehicle for the emergency return of crew from the International Space Station (ISS). It is a joint ESA/NASA project scheduled to have its maiden flight in late 2000. Europe plays an important role in the aerodynamic design of this vehicle. The aerothermodynamic challenges are:

- control and stability of the vehicle throughout its complete reentry flight regime
- efficiency estimates of the body flap and rudder effects of boundary-layer transition
- micro-aerothermodynamic effects like local heating in hinges and gaps
- heating rates on the nose and heating effects of windward boundary-layer transition
- integration of flight instrumentation into the vehicle in a non-obtrusive manner.

Figures 2 to 5 show some models of the XCRV vehicle and example CFD calculation results using Navier-Stokes codes.

ATV

The Automated Transfer Vehicle (ATV) is an expendable supply vehicle for the transport of equipment and propellant to the ISS. During rendezvous and docking operations using small rocket engines on the vehicle, exhaust-plume interaction effects will arise. These must be well understood and quantified during the design of the vehicle. The ATV must be destroyed during reentry. Aerothermodynamic calculations must guarantee that the burn-up of the vehicle in the atmosphere takes place

Figure 1. Artist's impression of the Atmospheric Reentry Demonstrator (ARD)

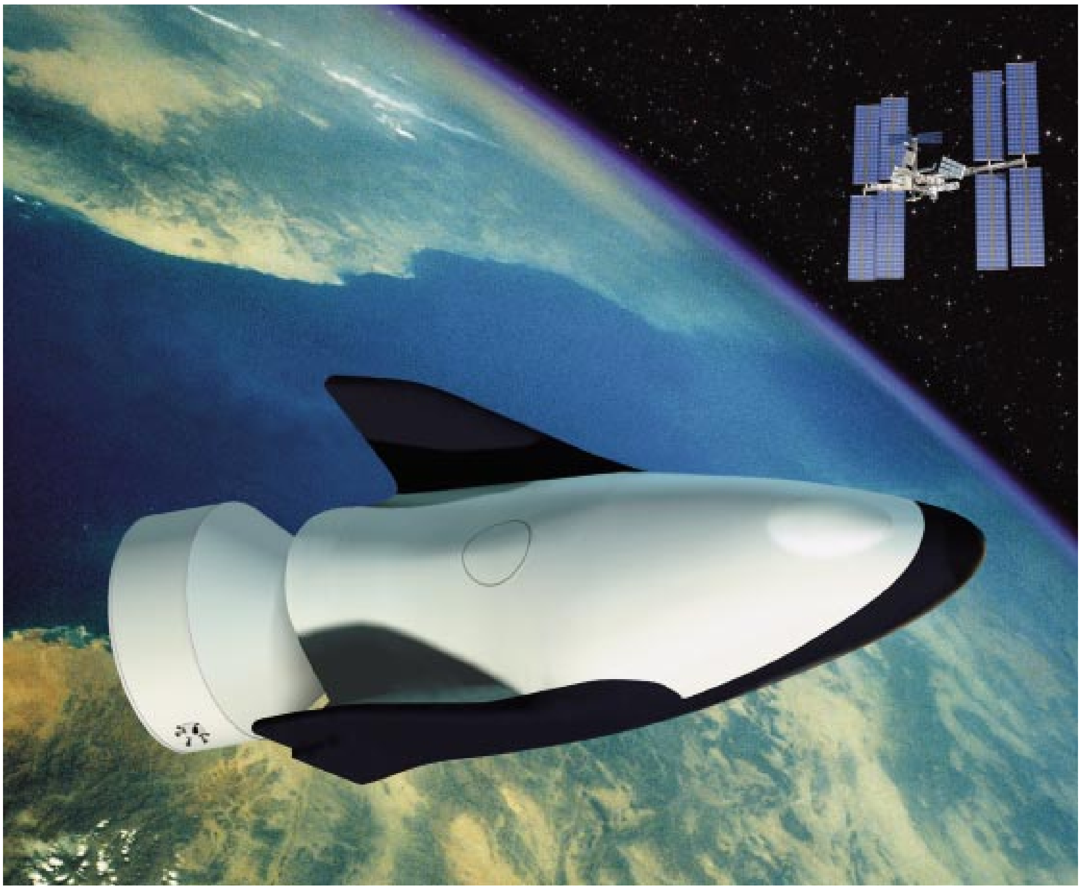


Figure 2. Artist's impression of the ESA/NASA X38 Crew Rescue Vehicle (CRV)

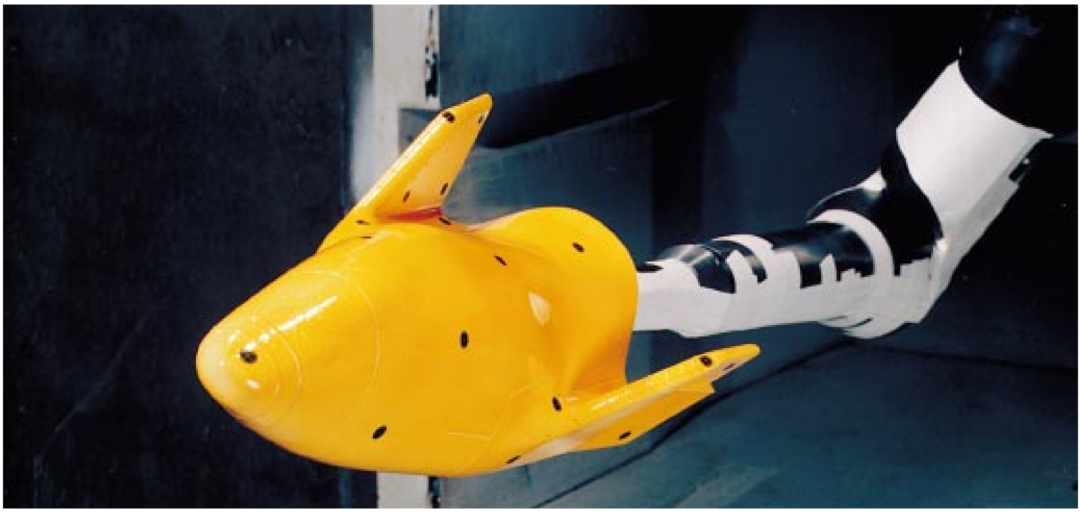


Figure 3. Aerodynamic tests of an X38 model at FFA in Sweden

Figure 4. Schlieren photograph of an X38 flow field during testing at FFA in Sweden

completely so that no parts of this large vehicle fall to Earth.

MSTP Technology Programme

The Manned Space Technology Programme was created to continue the development of technologies in reentry aerothermodynamics after the cancellation of the Hermes Space Plane Programme. The emphasis was on ground test facilities, reentry capsule critical issues, industrial CFD code improvements including code validation workshops, a parafoil technology programme and the creation of an engineering database for design. This work was completed by the end of 1997 when the programme was terminated. Figure 6 shows the test cases for CFD validation used for the aerothermodynamic workshops and the extrapolation-to-flight approach used for design.

Plasmatron

An induction heated plasma facility (plasmatron), was designed and developed at the Von Karman Institute (VKI) in Belgium, for the study of gas surface interactions such as catalycity and ablation in a contaminant-free environment.

Scirocco

The 70 MW Scirocco arc-heated plasma facility is under design and construction at CIRA in Capua, Italy. It will be used for materials testing under the high-temperature conditions experienced by reentry vehicles. It will be ready for operational use by the end of 1999.

The Science Programme

Spacecraft for science programmes have to deal with plume impingement problems caused by the exhaust gases from attitude and orbit control rocket engines. Additionally, those spacecraft which must enter planetary atmospheres face critical aerothermodynamic problems.

Intermarsnet and Venus Return Mission

The ESA-NASA Intermarsnet mission will place three instrumentation stations on the surface of Mars and an Orbiter around Mars for data-relay purposes. The launch is scheduled for 2003 using an Ariane-5 launcher. The stack of three stations must perform a ballistic entry into the Martian atmosphere using a heat shield to progressively reduce the vehicle's speed by aerodynamic drag. A parachute landing system will then be used to place the vehicle on the Mars surface. The configuration of the vehicle is shown in Figure 7. The aerothermodynamic issues are entry heating and vehicle stability, heat-shield separation, and parachute deployment.

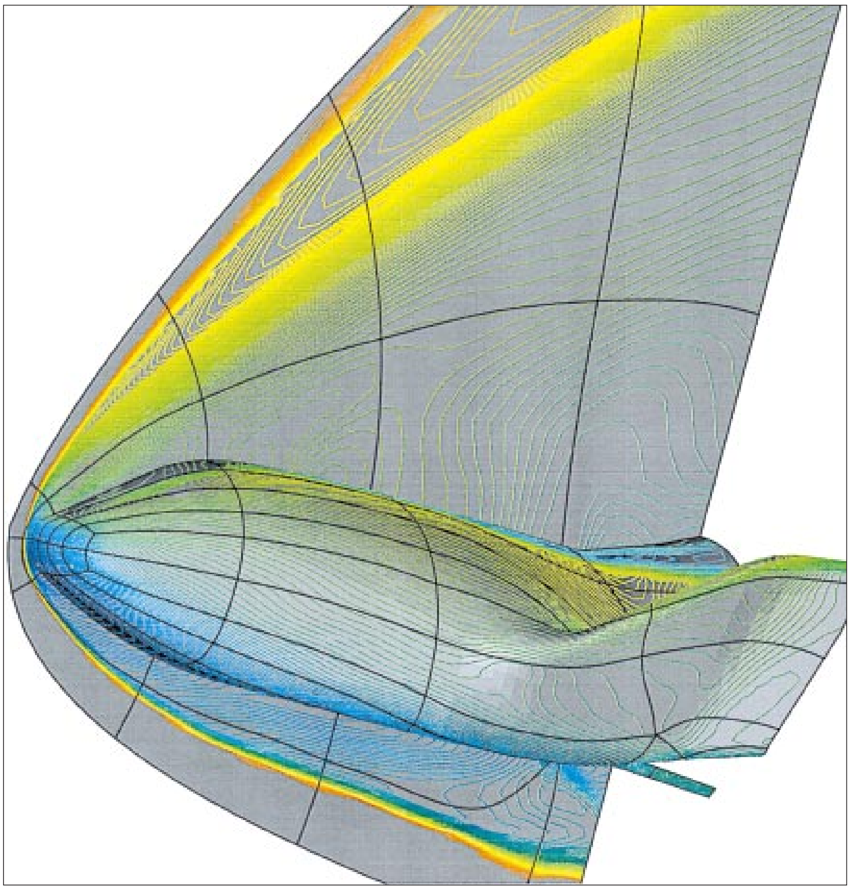


Figure 5. Mach number contours around the X38 (ESTEC)

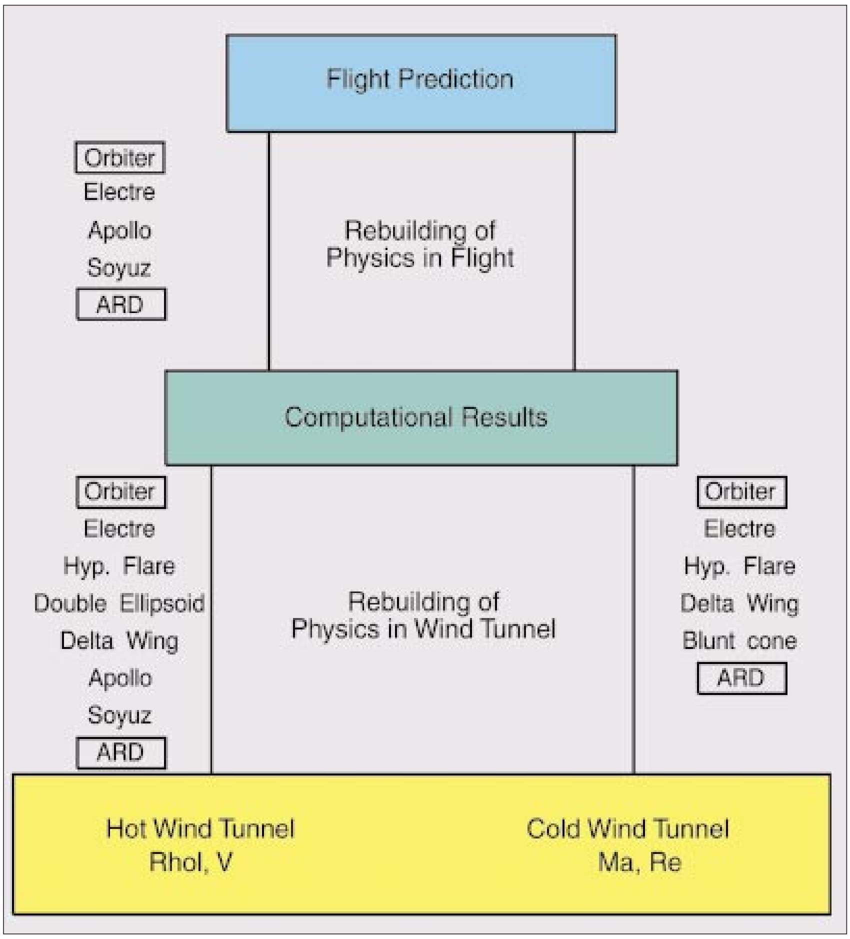


Figure 6. Test cases for CFD validation used in ESTEC workshops

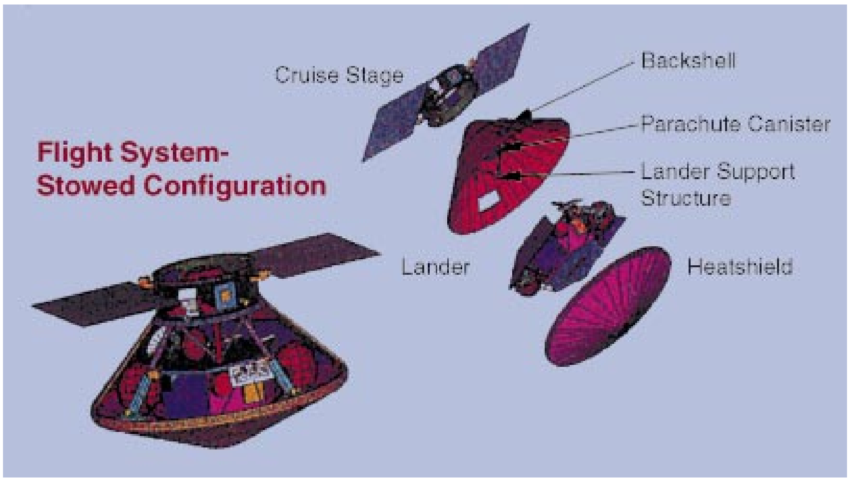


Figure 7. Intermarsnet vehicle configuration

One of the most challenging ESA scientific missions under study is the Venus Sample Return. It aims to return soil and atmospheric samples from Venus. Two Ariane-5 launchers will be required; one to launch an Orbiter composed of the Venus Orbital Module and Earth Return Module and the other to launch a Lander which will enter the Venusian atmosphere and descend using aerodynamic braking and parachute landing systems. For the return to Earth of rock and soil samples, the Lander will use a balloon to lift the vehicle off Venus' surface. A multistage solid-rocket system will then propel the vehicle to a Venus parking orbit to rendezvous and dock with the Orbiter vehicle. The Earth Return Module will then be propelled back to Earth and will enter the Earth's atmosphere and descend to a soft landing using aerobraking and parachute descent systems.

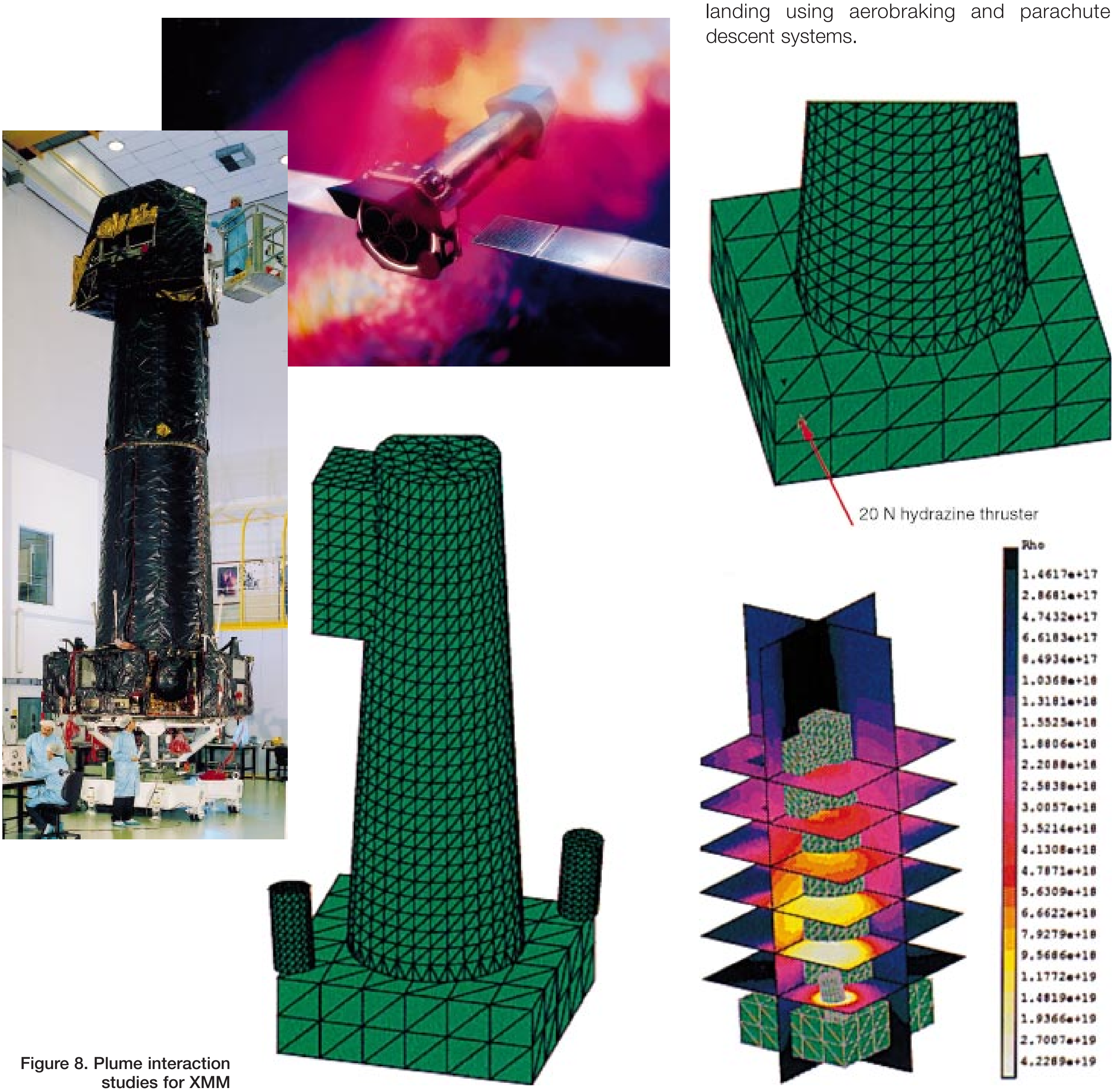


Figure 8. Plume interaction studies for XMM

The critical aerothermo-dynamics issues are:
– Venus aerocapture and aerobraking
– Venus and Earth atmospheric entry and descent
– ascent of the balloon
– ascent of the solid-rocket-propelled stage.

XMM

XMM is a large spacecraft, which makes plume-impingement effects from the attitude control rocket engines a critical issue. To illustrate the work that has been done to minimise such effects, Figure 8 shows the thruster nozzle pressure contours, the location of the thruster, the numerical calculation grids used and the resulting impinged gas pressure contours around the satellite. A combination of Navier-Stokes codes for the nozzle flow field calculation, with a Monte Carlo analysis for the plume near-field in combination with free molecular flow calculations for the thruster far field were used to address this problem.

The Telecommunications and Earth Observation Programmes

The major aerothermodynamic problem for these spacecraft is plume-impingement effects from rocket engines used for attitude and orbit control. The impingement effects from chemical rocket engines are now well understood and advanced analysis tools are available. Electric propulsion is now being introduced on these spacecraft for orbit-control purposes. This will pose a new problem of impingement of ionised propellant species, which is now being addressed at the level of the basic physics of the phenomena. An example is shown in Figure 9 for the Meteosat Second Generation (MSG) spacecraft. This shows the plume heating on the edge of the central plate of the structure caused by the exhaust plume from the 400N apogee engine. Navier-Stokes codes for nozzle flow calculations, in combination with Monte Carlo analysis, have been used to study this complex plume flow interaction.

The Launchers Programme

The aerothermodynamic challenges within the launcher Directorate are multiple and several types of support are therefore provided by the Aerothermodynamics Section.

Ariane-5

On behalf of CNES (the French Space Agency) and in close collaboration with industry, experimental and numerical studies have been carried out to assess the contamination from unused propellant as it is vented to space from the Second Stage Propulsion System (EPS) and the Attitude Control System (SCA). Another major activity was the design, construction and transonic wind-tunnel testing of the unsteady base flow buffeting loads on the Ariane-5 vehicle. Figure 10 show the details of an

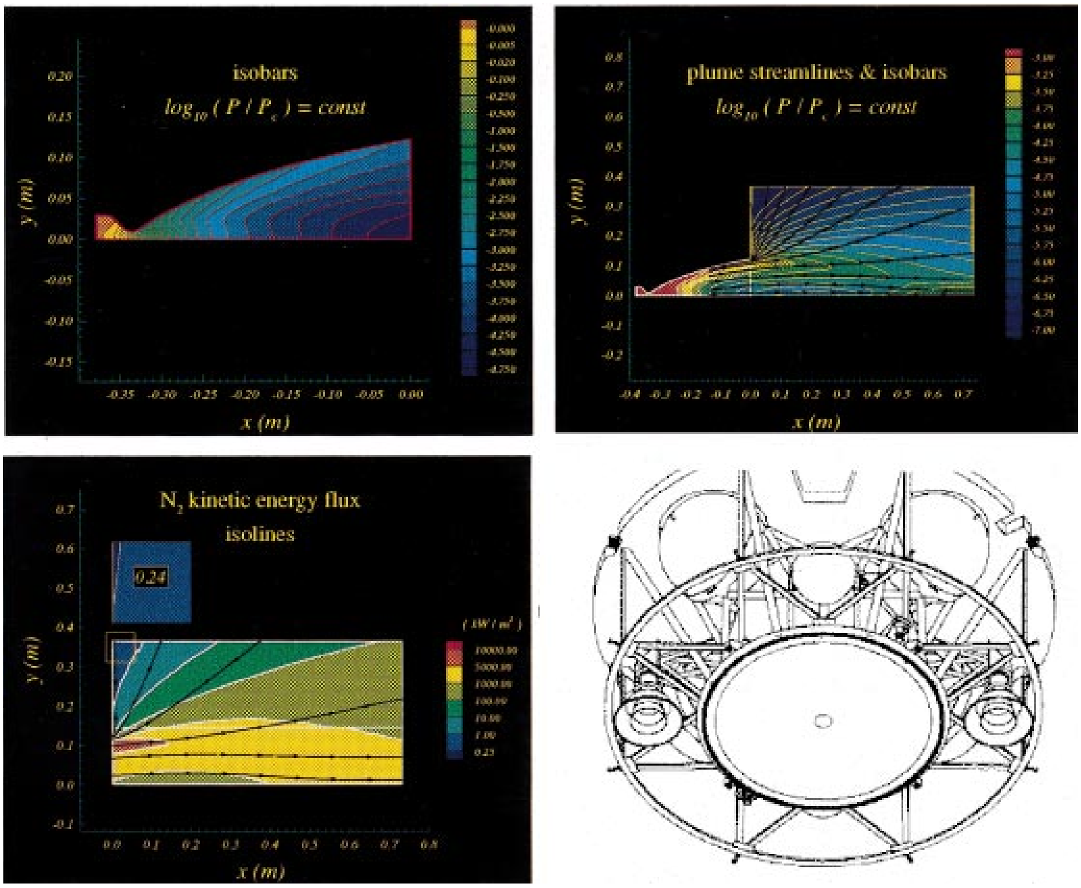


Figure 9. Plume interaction studies for MSG

Figure 10. Ariane-5 model for buffeting studies at FFA in Sweden

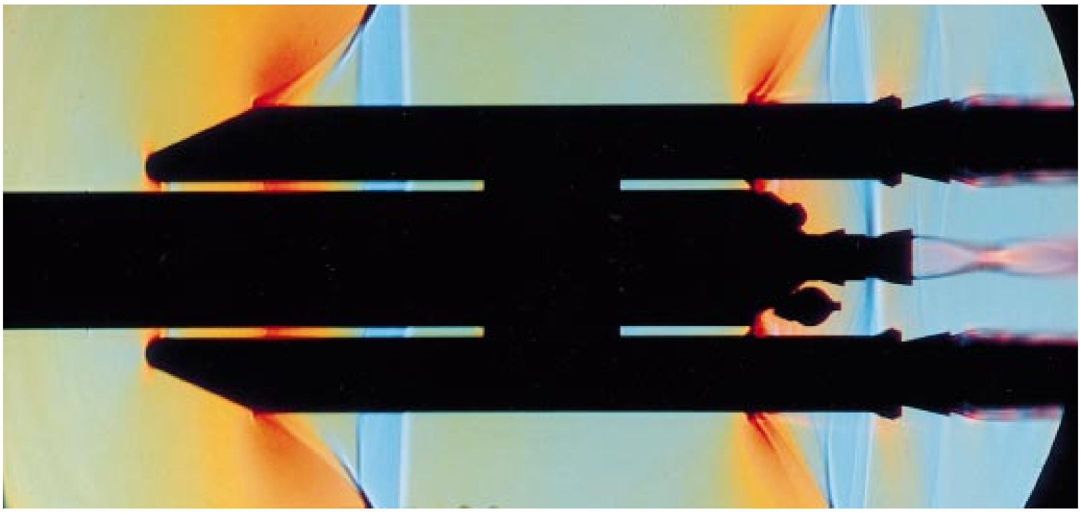
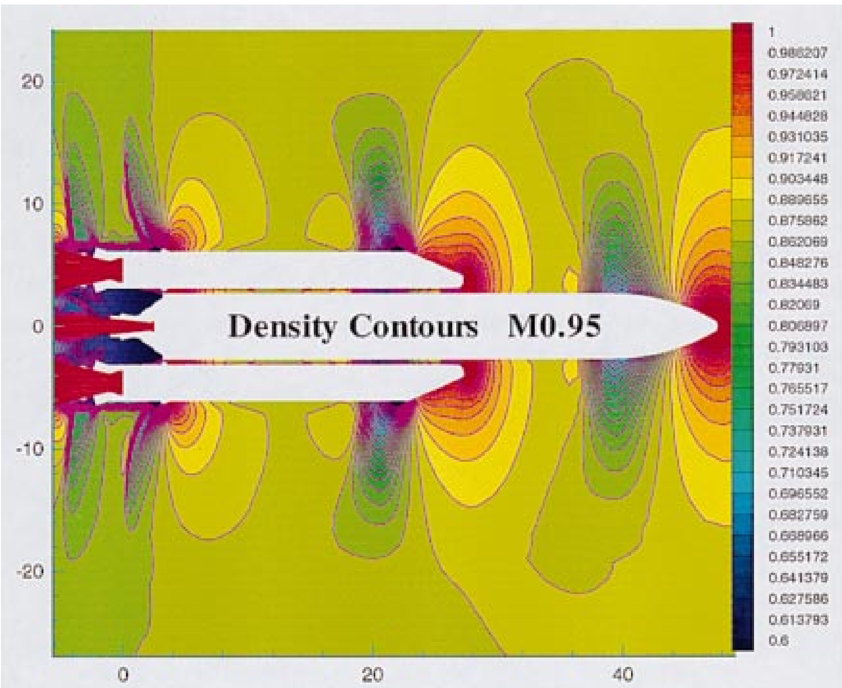


Figure 11. Schlieren photograph of an Ariane-5 flow field during testing at FFA in Sweden

Figure 12. Density contours around the Ariane-5 launcher



Ariane-5 wind-tunnel model for the measurement of the unsteady buffeting loads using sensitive pressure transducers. The particularity of this model is that it also simulates the plume flow, using cold nitrogen gas, from the Vulcain main engine and from the Solid Rocket Boosters. Figure 11 shows a Schlieren photograph of the flow. The compression and expansion waves are clearly visible. Figure 12 shows three-dimensional Navier-Stokes unsteady flow computations at Mach 0.95.

FESTIP

ESA's Future Space Transportation Investigation Programme (FESTIP) has been implemented to examine future reusable launcher concepts that could be of interest for Europe. For FESTIP, aerodynamic activities were concentrated on generating aerodynamic and aerothermodynamic databases for each of the single-stage-to-orbit (SSTO) and two-stage-to-orbit (TSTO) configurations and on the definition and follow up of the FESTIP technology programme in aerothermodynamics. The technology programme focussed mainly on the following critical points:

- roughness-induced boundary-layer transition
- turbulence modelling for shock-wave boundary-layer interactions
- flap efficiencies and heating
- base flow plume interaction
- flight measurement techniques
- air data systems.

As an example of this work, Figure 13 shows the computational grid of the FSS 5 configuration, which is an SSTO lifting body.

FLTP Programme

ESA's Future Launcher Technology Programme (FLTP) is now being prepared to continue the work undertaken within the FESTIP Technology Programme and is expected to start in 1999. Major aerothermodynamic activities which need to be pursued within the FLTP are:

- Improvement of measurement techniques such as:
  - pressure sensitive paint, infrared and phosphor paint techniques for heating analysis
  - stereo lithography for rapid model prototyping
  - standardised force balances for rapid testing in transonic, supersonic and hypersonic facilities.
- Simulation of hot plumes for base plume interaction for steady and unsteady loads.
- Stage separation loads, plume interaction loads, local micro-aerothermodynamic loads, buffeting on protuberances and base flows.
- Transition and turbulence modelling for shock/boundary-layer interactions.
- Interaction effects between aerothermodynamics, propulsion, structures and thermal protection.
- Propulsion system improvements: nozzle flow separation control, advanced nozzle concepts and integration.

During the FLTP it will be mandatory to maintain the following European aerothermodynamic facilities:

- the high enthalpy facilities: F4 at ONERA, HEG at DLR
- the plasma facilities: LBK at DLR, Simoun at Aerospatiale, Scirocco at CIRA, the plasmatron at VKI and the arc-heated facilities at IRS (Stuttgart University).

ESA's aerothermodynamic R&D activities

A series of TRP and GSTP activities have been initiated to prepare the technology needs for Europe's space programmes, including:

- Development and validation of three-dimensional nonequilibium Navier-Stokes codes combined with research on parallel processing to investigate the cost and time savings of executing aerodynamic codes on massively parallel computers.
- Validation experiments in hypersonic wind tunnels for the study of different types of boundary-layer transition mechanisms and turbulence modelling improvements for shock/boundary-layer interactions including the influence of hot wall effects.
- Scaling and extrapolation to flight conditions using NASA Shuttle Orbiter data for the study of the influence of real gas effects on trimming and flap efficiency. Testing in the F4 facility at ONERA and the shock tube HEG at DLR, to allow the comparison of wind-tunnel data with flight data using CFD.
- Testing instrumented tiles as flown on Japan's Hyflex reentry vehicle in the DLR plasma facilities for the study of micro-aero-thermodynamic phenomena such as tile gap filler heating and local boundary-layer transition.
- Improving Direct Simulation Monte Carlo codes for the study of satellite thruster plume interactions which cause forces, moments, heating and contamination.

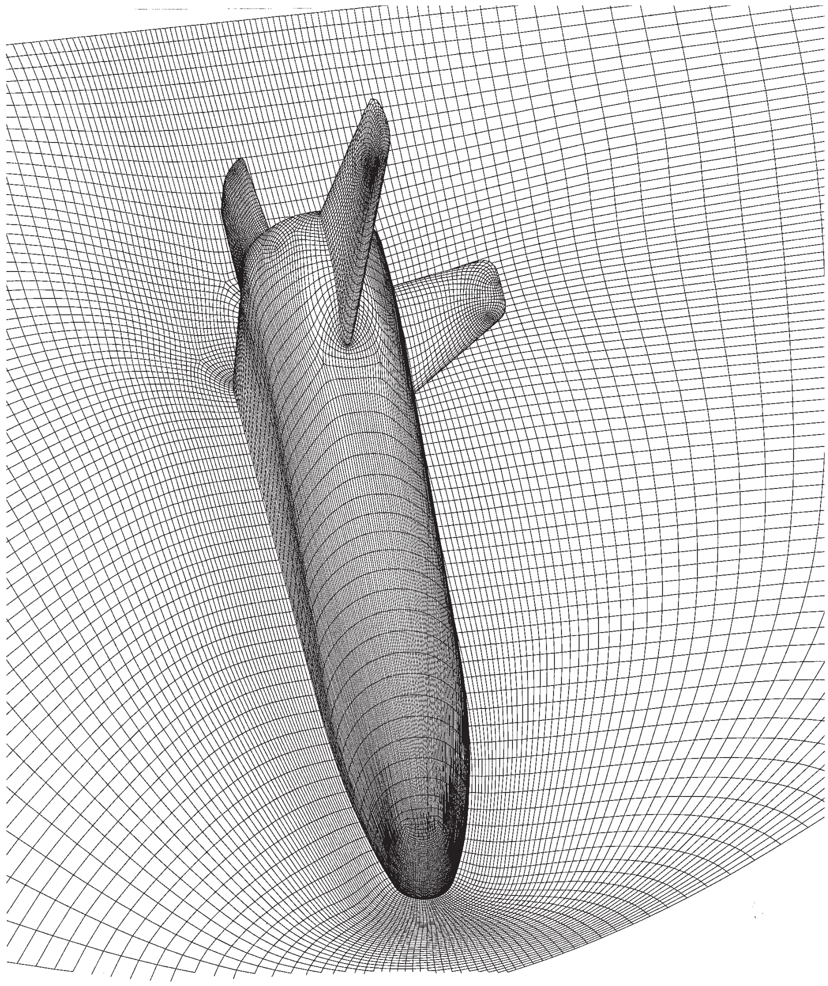


Fig. 13. Flow field computational surface grid around the FESTIP FSS 5 reusable launcher (ESTEC)

– Optimising force balances for dynamic-derivative testing using free and forced oscillation techniques for blunt body configurations such as the Huygens Probe, the ARD and the X38.
– Experimental study of base flow buffeting on simple and complex configurations such as the Ariane-5 launcher, including cold plume effects at transonic flow.
– Experimental and numerical studies of external expansion nozzles (plug nozzles) (Figs. 14, 15 & 16a,b) and nozzle flow separation control mechanisms for improved propulsion performance at sea level.
– Aero-thermochemistry database creation and standardisation including multi-phase flows.
– Aerodynamic analysis tool development for preliminary design.

International collaboration
Collaboration with partners outside Europe on specific items such as the Shuttle Orbiter and X38 with the USA, the Hyflex reentry vehicle with Japan and plasmatron test facilities with Russia have been very useful. An improved understanding has been obtained on critical hypersonic design problems such as the influence of real gas effects on vehicle pitch trim and flap efficiency, and tile gap heating and determination of the catalytic effects of thermal-protection-system tile coatings.

– In cooperation with the USA, NASA Shuttle Orbiter models were tested in the ONERA and DLR High Enthalpy facilities in exchange for NASA Langley wind-tunnel and flight data. This resulted in a good understanding of the use of these real gas facilities in the design process (Fig. 17).

– In cooperation with Japan – as part of an ESA/Japan Exchange Agreement – a combined experimental and numerical

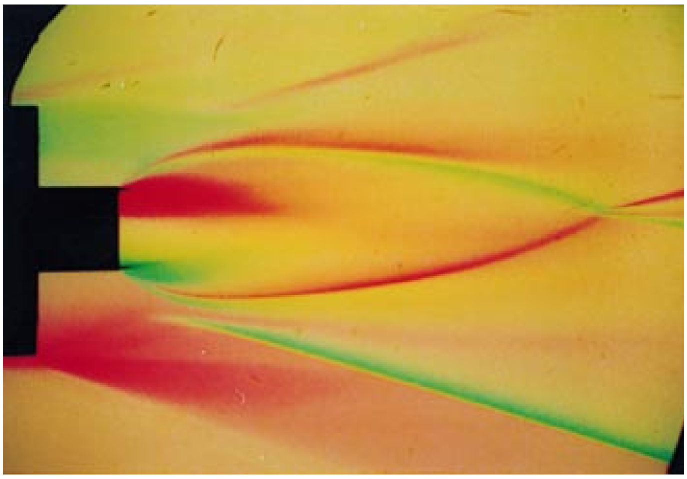


Figure 14. Schlieren photograph of the flow field from a plug nozzle (Technical University Delft)

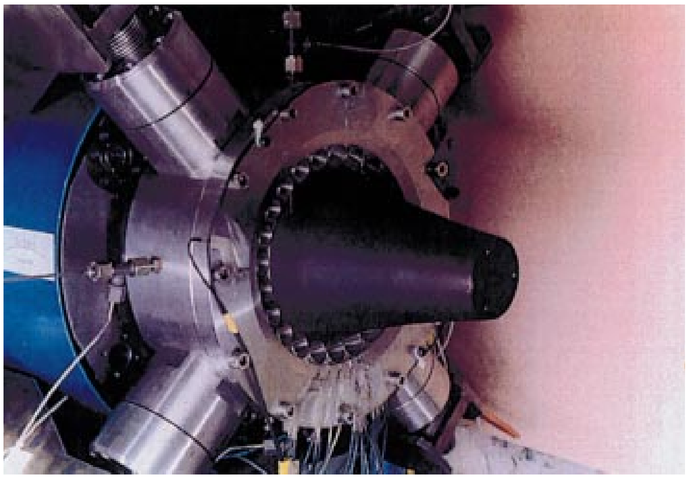


Figure 15. A clustered plug nozzle in the ONERA Ch4 test facility

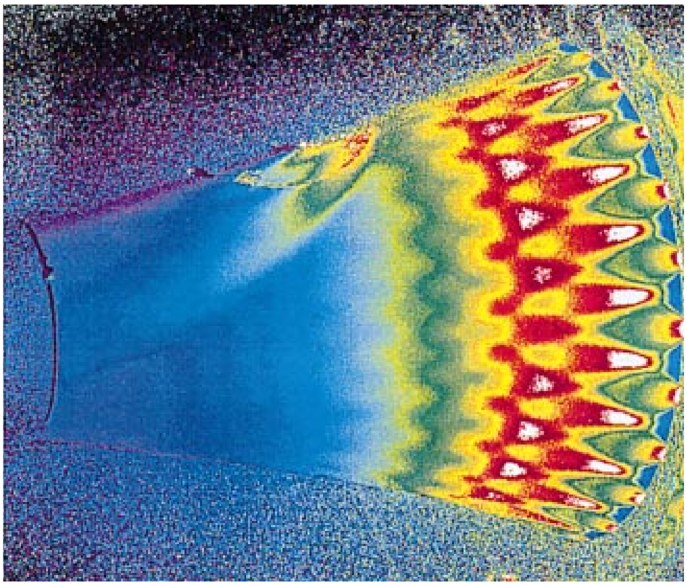


Figure 16a. Temperature field on a clustered plug nozzle using pressure-sensitive-paint techniques (ONERA)

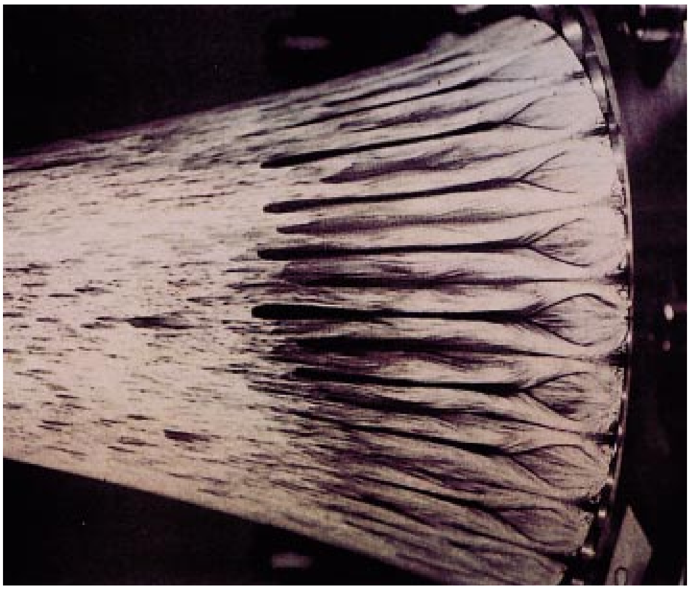


Figure 16b. Oil-film technique measurements (SEP)

activity is underway in the DLR LBK facility to study the heating between tiles flown on Japan's Hyflex reentry vehicle. The objective is to compare plasma wind-tunnel data with flight data and to analyse scaling and wind-tunnel-to-flight extrapolation issues. CFD plays an important role in these wind-tunnel and flight rebuilding activities (Fig. 18).

– In cooperation with Russia, a series of very useful activities have been performed including the examination of lessons learned from the Russian reentry vehicles Bor and Buran and the use of Russian facilities for database creation for validation, especially for thermal-protection-system testing. Of particular importance is the Russian expertise in plasmatron design, manufacture and testing for gas surface interaction effects: ablation, oxidation, ageing and coating catalytic behaviour. A strong collaboration has been embarked upon with VKI (B) for which the Agency has funded a completely new 2 MW plasmatron – the world's largest (Fig. 19).

Conclusion

This article has presented the wide scope of aerothermodynamics for aerospace vehicles and has traced ESA's activities in this field over the last 10 years – since August 1988 – when the Aerothermodynamics Section was first implemented at ESTEC. Aerothermodynamics has emerged as an important discipline, which is essential to enable the design of advanced launchers, reentry vehicles and advanced propulsion systems.

The Agency is sponsoring European industry and research laboratories in developing efficient numerical and improved experimental tools for aerothermodynamic design and verification. ESA's technology research programmes in aerothermodynamics have already helped European industry to increase its competence in this field. ESA has set up a coherent research programme to meet the needs of space projects. However, in order to maintain European expertise in CFD and experimental techniques, a continuing investment is essential. For the future, ESA will continue to pursue its objective of strengthening European aerothermodynamic capabilities by coordinating European efforts and by promoting close collaboration between universities, research establishments and industries. esa

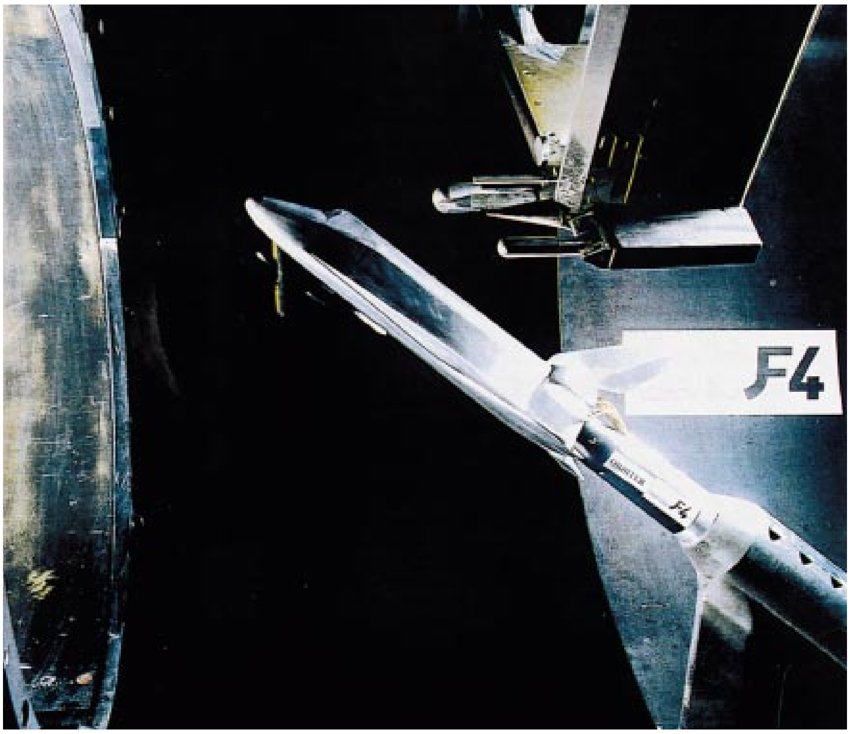


Figure 17. NASA orbiter model in the ONERA F4 High Enthalpy wind-tunnel

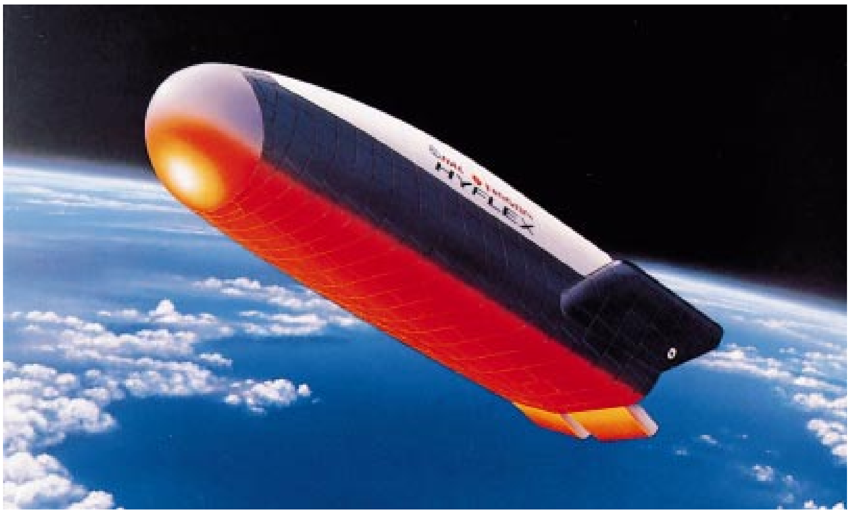


Figure 18. Artist's impression of Japan's Hyflex Reentry Demonstrator (NAL Japan)

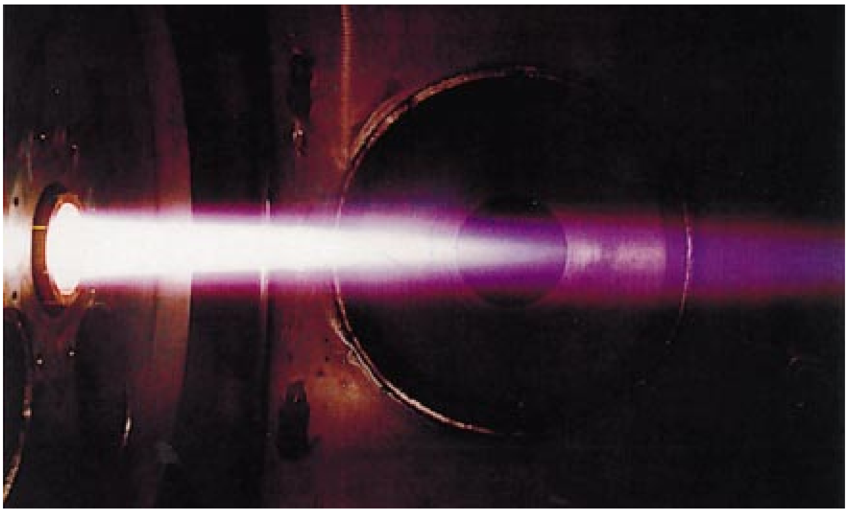


Figure 19. The new 2 MW plasmatron in operation at VKI in Belgium