AERO(THERMO)DYNAMIC CFD ANALYSES OF THE PARES RE-ENTRY CAPSULE SHAPE IN COMPARISON TO RECENT TEST RESULTS

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OVERVIEW

Capsules and other space vehicles designed for non-destructive re-entry from outside the earth's atmosphere must exhibit acceptable aerodynamic/aerothermodynamic qualities (flight stability, atmospheric braking capability, aerokinetic heating issues) through an extremely wide flight regime encompassing high hypersonic Mach numbers down to transonic and subsonic flight.
In order to improve the aerodynamic/aerothermodynamic analysis tools, to reduce the safety margins required and to allow for a true optimization of hypersonic flight vehicles and re-entry systems further empirical knowledge is desirable.
The detailed identification of the aerodynamic and aerothermal features of the vehicles through numerical and experimental activities is therefore mandatory. for the aforementioned optimization tasks.

One such vehicle configuration recently analyzed not only by CFD but also by intensive wind tunnel testing (involving two versions of the capsule shape) has been the PARES (Payload Return System) capsule: The announced retirement of the US Shuttle in 2010 prompts the need for an European download capability from the ISS, in order to preserve the attractiveness of the ISS as research facility. The capability to download processed or collected samples has to be guaranteed to that end. As Soyuz does not offer sufficient capability, ESA decided to investigate complementary systems for ISS logistics which can perform essential tasks, taking advantage of existing or planned infrastructure. The PARES definition study has been conducted in that frame, as a potential enhancement to the ATV, Progress and HTV systems.
If realized, PARES can provide a frequent download capability for small and medium sized samples and equipment from ISS in the time frame 2008 to 2016.
A description of the overall PARES system concept can be found in [1].

In addition to CFD analyses utilizing state-of-the-art Navier-Stokes methods (TAU-Code), ESA and EADS Astrium initiated a wind tunnel campaign (using facilities of DLR, Cologne and VKI, Brussels) to address the following issues:

1) Provision of static aerodynamic coefficients (axial force coefficients, normal force coefficients, pitching moment coefficients) for subsonic, transonic and supersonic/hypersonic Mach numbers

2) Determination of heat flux distribution on the PARES configuration at hypersonic Mach Numbers (“cold” hypersonic flow only) for laminar and turbulent flow conditions

3) Determination of dynamic stability characteristics of PARES prior to activation of the descent and landing parachute system (still in progress)

The paper focuses on relevant CFD analysis results of PARES in comparison to related wind tunnel results.

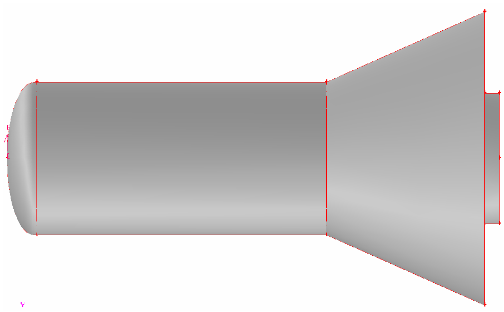

FIG 1. Overall Layout of PARES Capsule

1. WIND TUNNEL FACILITIES AND TEST RESULTS

1.1 Introduction

Wind Tunnel testing within the PARES study consisted of the following elements using appropriate wind tunnel facilities:

- Determination of static aerodynamic force and moment coefficients in subsonic, supersonic and transonic Mach numbers was performed at **DLR's *TMK***-Wind Tunnel at Cologne

- For the determination of the aerodynamic coefficients at hypersonic Mach numbers **DLR's the *H2K***-Wind Tunnel (also at Cologne) was used. The same facility was employed for the determination of heat flux distributions on the PARES surface at flight relevant Reynolds numbers at hypersonic Mach Numbers

- Finally, a still ongoing dynamic stability investigation (dynamic stability characteristics of PARES prior to activation of the descent and landing parachute system) is being performed at **VKI's *S1*** Wind Tunnel Facility in Brussels

1.2 Wind Tunnel Tests for the Determination of Static Aerodynamic Coefficients

1.2.1 Test Objectives

The test objective was the determination of the longitudinal aerodynamic coefficients (axial force, normal force and pitching moment coefficients) at subsonic, supersonic and transonic Mach numbers.

The Wind Tunnel Test data served to validate the findings of previous CFD calculations (and also broadened the database considerably by providing numerous data points for the subsonic through hypersonic regime not available from the CFD investigations).

1.2.2 Test Facilities

For transonic and supersonic flow conditions the tests were performed in the subsonic/supersonic (closed) and transonic (perforated) test sections of the **TMK** Wind Tunnel of DLR – Cologne.
The size of the TMK test section is: 0.60 x 0.60 m².
This allowed for a model scale of **1:18.5**
FIG 2 contains a comparison of PARES flight data to the maximum achievable Reynolds numbers vs. Mach in the TMK wind tunnel with the 1:18.5 model.
It is evident from FIG 3 that over most of the Mach range the related flight Reynolds numbers can be provided in the wind tunnel

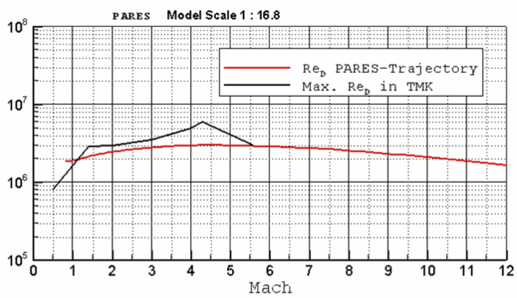

FIG 2. Reynolds Number vs. Mach / Wind Tunnel Data and PARES Flight Data

In order to complete the wind tunnel data towards higher Mach numbers, two additional test runs for Hypersonic Flow conditions (Mach > 5) were performed at the **H2K** Wind Tunnel (H2K test section Ø 0.60 m).

1.2.3 Wind Tunnel Models

Wind tunnel models for the current baseline PARES configuration and of a modified geometry (variation of stabilizer deflection angle) were employed so as to validate the CFD data obtained before the tests and to consolidate the PARES baseline shape selection.
The retained PARES configuration is an axisymmetric shape. consisting of a blunt nosed cylindrical payload container and a (deployable) flare at the rear end serving as aerodynamic stabilizer (FIG 1).

FIG 3 shows the wind tunnel model of the baseline configuration on the left side. On the right side of FIG 3 the variation of the baseline configuration employing a stabilizer deflection angle reduced by ~4° is shown.
This model variation allows for an experimental assessment of the relation between Drag Coefficient/Center-of-Pressure Position and varying stabilizer deflection angles. The models are manufactured in Aluminium, with a Nickel coating to prevent any damage on the model surface due to particle impingement.
The reference quantities used in the definition of the aerodynamic coefficients are related to the capsule geometry as follows:

Reference Length **:**
Capsule Forebody Diameter D

Reference Area:
based on forebody diameter D, $A_{ref} = \pi \cdot D^2/4$

Moment Reference Center:
$\mathbf{X_{MRC}/L = 0.439}$ (Relates to the most forward CoG position considered for PARES)
$\mathbf{Y_{MRC}/L = 0.0}$ in vertical symmetry plane
$\mathbf{Z_{MRC}/L = 0.0}$ on axisymmetry axis

Model Mounting:
A conventional sting mounting was used. FIG 4 shows the model installed in the TMK wind tunnel.

FIG 3. PARES Wind Tunnel Models - *Left*: Baseline Configuration, *Right:* Reduced Stabilizer Deflection Angle

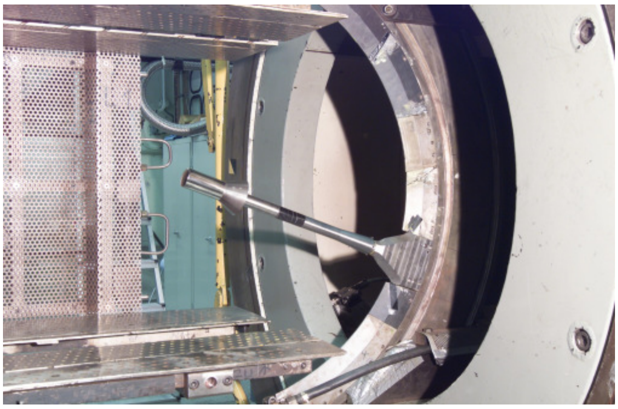

FIG 4. PARES Model in TMK Wind Tunnel

1.2.4 Test Matrix

For the baseline configuration (FIG 3, left) 12 Polars (force and moment coefficients vs. angle-of-attack) covering a Mach range between **0.7** and **8.8** were determined during the test campaign:

10 Polars in TMK: Ma=0.7, 1.4, 2.0, 3.0 and 4.0 in the closed test section and Ma= 0.7, 0.8, 0.95, 1.1 and 1.2 in the transonic test section (perforated walls). The Angle of Attack range is between ~ -2° and 35°.

2 Polars in H2K: Hypersonic Mach numbers 6 and 8.8. Angle-of-Attack range ~ -2…15°

In addition to the polars determined for the baseline configuration, a restricted number of tests were performed using the model variation with reduced stabilizer deflection angle (FIG 4, right), consisting of:

5 Polars in TMK: Ma=0.7, 1.4, 2.0, 3.0 and 4.0 in the closed test section. The Angle of Attack range lies between ~ -2° and 35°.

Schlieren visualization was performed during the tests with the closed test section.

1.2.5 Test Results

Schlieren pictures taken during the wind tunnel tests under typical supersonic flow conditions are provided in FIG 5. The characteristic shock patterns associated to the various flow conditions are clearly evident in the figures.

FIG 5. Schlieren Optics at Varying Mach Numbers (M=1.4, 2.0, 4.0), AoA ~ 5°

A compact overview covering measured aerodynamic coefficients (axial force, normal force, pitching moment) over the relevant range of Mach numbers and Angles-of-Attack is provided below in figures 6 through 8.

FIG 6 shows the axial force coefficients vs. angle-of-attack, FIG 7 and FIG 8 contain the normal force coefficients and the pitching moment coefficients. On the upper diagram of each figure we find the wind tunnel data of the valid PARES baseline configuration, whereas the lower diagram allows for a comparison to the corresponding data of the PARES modification using the reduced stabilizer deflection angle.

In full agreement to theoretical considerations, evidently the reduction of the deflection angle leads not only to reduced axial and normal force coefficients but also to a significant reduction in magnitude of the pitching moment coefficients.

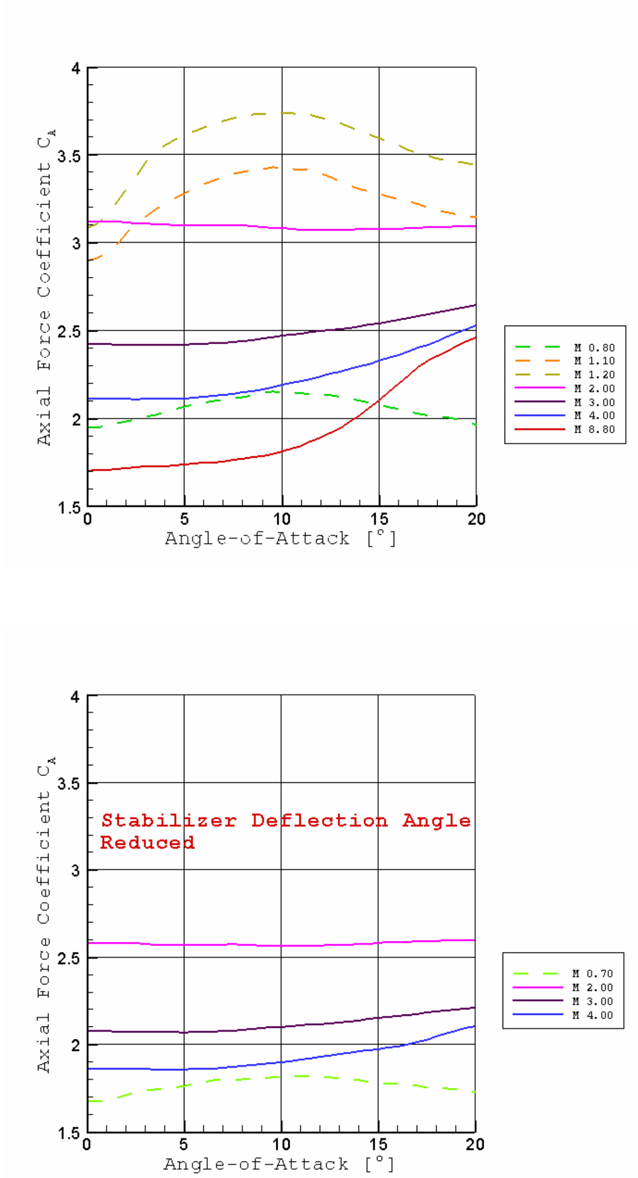

FIG 6. PARES Axial Force Coefficient vs. Angle-of-Attack

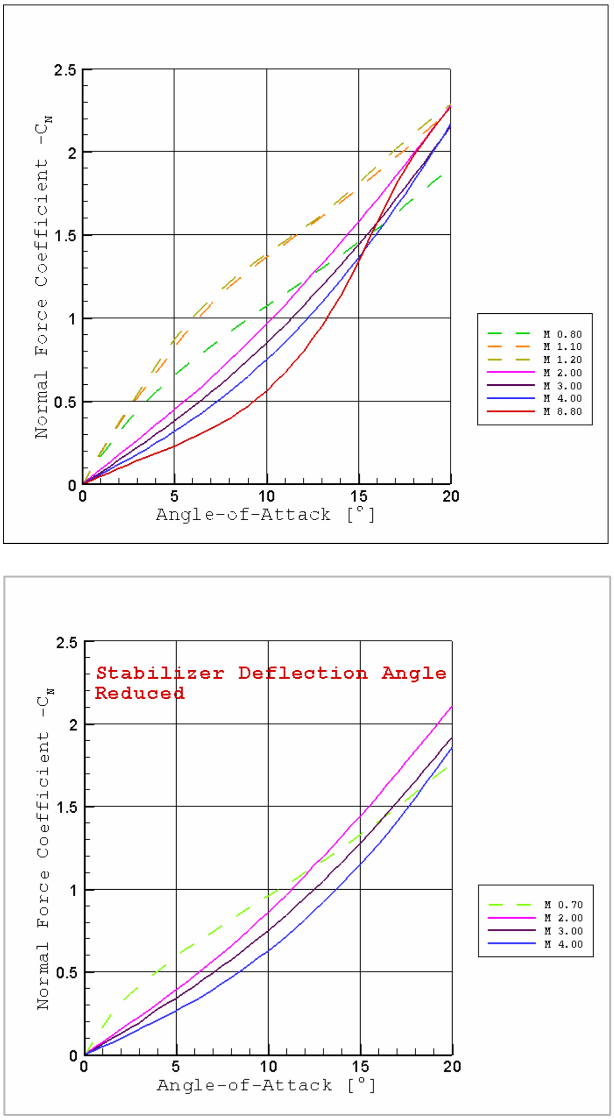

FIG 7. PARES Normal Force Coefficient vs. Angle-of-Attack

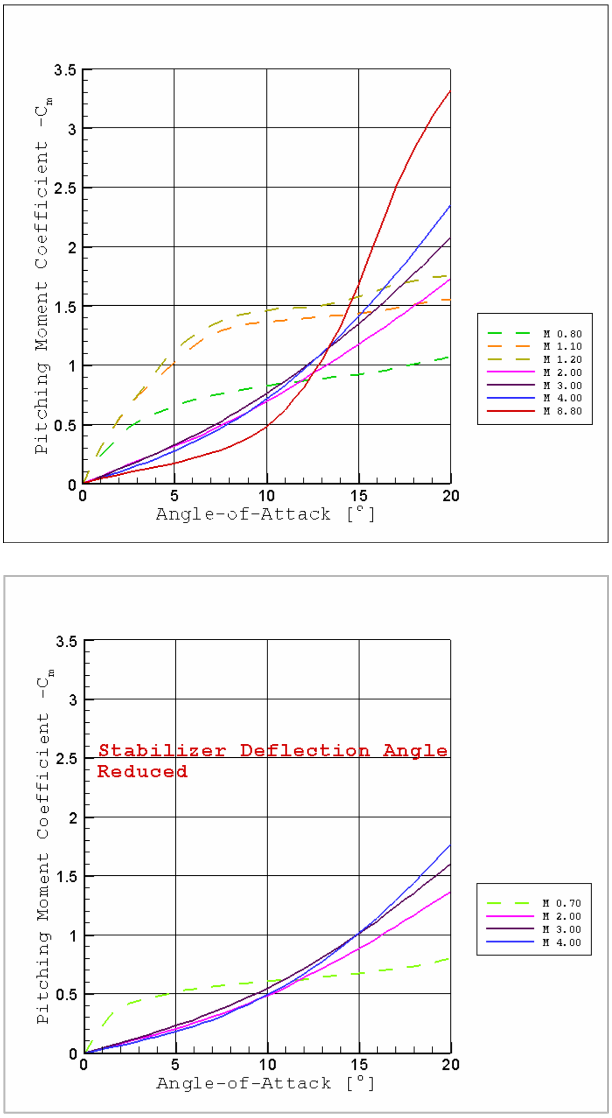

FIG 8. PARES Pitching Moment Coefficient vs. Angle-of-Attack

1.3 Wind Tunnel Tests using IR Thermography

1.3.1 Test Objectives:

Determination of heat flux distributions on the PARES configuration for laminar and turbulent Reynolds number conditions at hypersonic Mach numbers in the "cold" hypersonic H2K wind tunnel.

1.3.2 Test Facility

DLR's **H2K** Facility was used for the tests using IR Thermography.

1.3.3 Wind Tunnel Model

A solid plastic model (with known material properties) of PARES (scale 1:11.2, FIG 9) is employed to derive the heat flux rate from measured surface temperatures (5 seconds after test start), using an IR camera.

The measurement technique used is outlined in detail in [6].

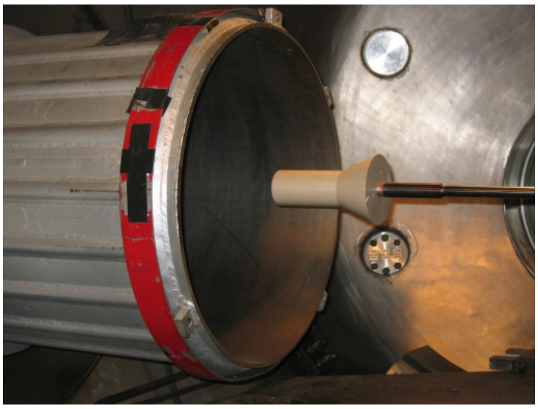

FIG 9. Solid Plastic Model Used for the IR Tests (Scale **1:11.2**) .

1.3.4 Test Conditions

Provided was the determination of Heat fluxes for "cold" hypersonic flow conditions at 2 Mach numbers (Mach 6.0 and Mach 11.2)

Reynolds numbers leading to laminar (Re ≈ 3 Mio.) as well as turbulent (Re ≈ 20 Mio.) flow conditions at the stabilizer skirt were used.

A table defining the actual test conditions is shown below:

TAB 1. ***PARES Test Conditions IR-Thermography:***

Ma	T_0 [K]	p_0 [bar]	α [°]	Re [Mio]
6.05	468.2	24.190	0	20.98
11.2	723.0	35.120	0	3.02

1.3.5 Results

FIG 10 shows thermography images obtained on the PARES model flow condition Mach 6 (turbulent Reynolds Number). Fig 11 contains the corresponding temperature/heat flux curves along the PARES wall contour.

FIGS 12 and 13 illustrate analogous test results for different flow conditions leading to laminar heat fluxes on the model surface, corresponding to the Mach 11.2 case.

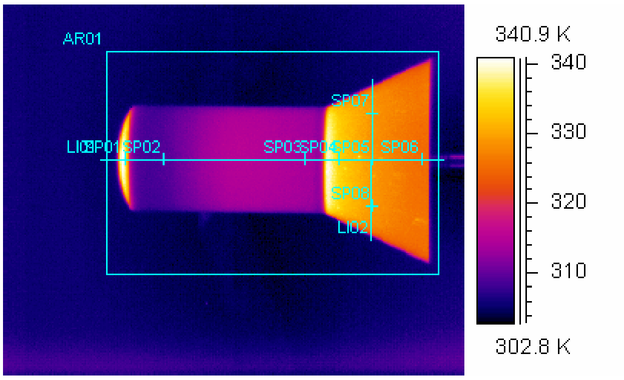

FIG 10. Thermography Image for Mach 6, turbulent Reynolds Number

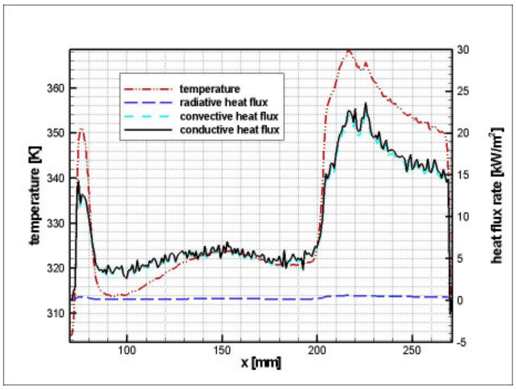

FIG 11. Surface Heat Flux (Black Curves) along Model Contour (Plane of Symmetry) Mach 6, AoA 0°

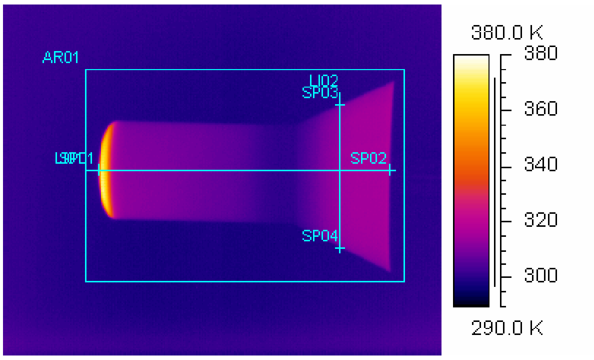

FIG 12. Thermography Images for Mach 11.2, AoA 0°, Laminar Reynolds Number

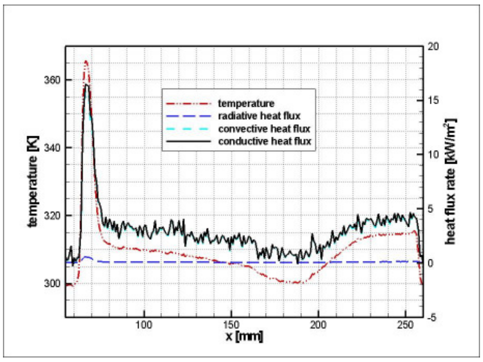

FIG 13. Surface Heat Flux (Black Curves) along Model Contour (Plane of Symmetry) Mach 11.2, AoA 0°, Laminar Reynolds Number

The heat flux densities (determined from the thermography images 5 seconds after test start) along the model surface (in the plane of symmetry) are shown as black curves in diagrams FIG 11 and 13 (x-coordinate starts at nose tip of model). The corresponding surface temperature distribution is also shown in the diagrams (red curves), as well as the radiative (dark blue) and convective (light blue) parts of the surface heat fluxes. It is evident that radiative part of the heat fluxes bears practically no significance in the tests.

The expected decrease of the heat flux levels at laminar vs. turbulent flow conditions is well represented in the corresponding test results.

Due to the unfavourable view angle of the IR camera (the view angle is perpendicular to the longitudinal axis of PARES) from the tests no usable heat flux data are available for the nose region.

However along the cylindrical part and the stabilizer skirt, the curve shapes obtained experimentally for laminar vs. turbulent flow conditions correlate reasonably well to heat flux distributions determined by theoretical analysis (Chapter 2).

1.4 Wind Tunnel Testing Concerning Dynamic Stability Investigations

Dynamic stability investigations are being conducted at **VKI's S1** Wind Tunnel Facility in Brussels.

The objective of these tests is the determination of dynamic stability characteristics of the PARES capsule prior to activation of the parachute system (Mach range considered M = 0.8…2.0), in order to assess the possibility to use a conventional subsonic pilot chute. If confirmed, such a possibility would result in significant development cost reductions and a robust operational system

A Free-to-Tumble mounting system is used to that end, whereby the wind tunnel model is free to rotate about its pitch axis using a low-friction mounting through the model CoG. During the tests the model is initially locked at a pre-selected Angle-of-Attack. After the desired flow conditions are established in the wind tunnel, the model is released so that the developing dynamic behavior of the model about its pitch axis can be observed.

The facility also allows for the identification of the static coefficients (as part as the normal procedure for obtaining the dynamic derivatives), which can be compared to those obtained in DLR's TMK for validation purposes These wind tunnel investigations are not yet finished and will be included in a future paper.

2. CFD CALCULATIONS

2.1 CFD-Code:

For theoretical aerodynamic/aerothermodynamic analysis of the PARES configuration, the DLR Navier-Stokes- and Euler-Solver TAU-Code [2] has been used at EADS Astrium Bremen. The code has been extensively validated against test results and other CFD Codes in the past, see e.g. [3]

The three-dimensional TAU-Code CFD program was developed by the German Aerospace Center DLR for unstructured and structured grids (under participation of several branches of EADS Germany).

The TAU flow solver represents a three-dimensional parallel hybrid multigrid code employing a finite volume scheme for solving the Reynolds-averaged Navier-Stokes equations. The inviscid fluxes are calculated using an AUSM or a Roe type 2nd-order upwind scheme. The gradients of the flow variables are determined by employing a Green-Gauss formula. Central differences are used to discretize the viscous fluxes.

Treatment of viscous walls within the TAU-Code allows for *adiabatic*, *constant wall temperature* or *radiation equilibrium* conditions.

Turbulence modeling:

The TAU Code offers a choice of different one- and two-equation turbulence models (Spalart-Allmaras-model, various versions of the k-ω-model).

For PARES, the Spalart-Allmaras model was used to cover turbulent flow situations.

Air Chemistry:

Regarding the available thermo-chemical models for hypersonic flows, the following options are incorporated into the TAU-Code:

a) Equilibrium chemistry:

Air is considered as a 5 species ideal gas mixture. The temperature and pressure dependent equilibrium gas properties are modeled via appropriate fit functions.

A temperature range between 50K and 20000K and a density range between 10^{-12} kg/m^3 and 10 kg/m^3 is covered by the fits currently in use.

b) Chemical nonequilibrium:

The nonequilibrium model currently implemented in the TAU-Code consists of a five species and seventeen reactions air model employing the finite reaction rates according to Gupta et al. This can be easily replaced by more detailed models (Ref. [7]).

The diffusion is modeled according to Fick's law by a single diffusion coefficient for all species. The diffusion coefficient is connected to the local viscosity via a user-specified constant Schmidt number.

Within PARES flow simulations, the air was treated as perfect gas for flow conditions below Mach 10; above Mach 10 thermo-chemical equilibrium was assumed.

Grid Generation:

The CENTAUR [4] grid generator software was used to model the CFD grids. The TAU CFD meshes for the PARES analyses employed a hybrid grid approach consisting of structured prismatic grid layers in the wall regions to resolve the boundary layers as well as tetrahedral cells covering the rest of the computational domain.

In order to limit the impact of the grid density on the computed flowfield, the solution dependant grid adaptation features of the TAU Code were used. A total of 2 to 3 grid adaptation cycles were performed to improve the solutions

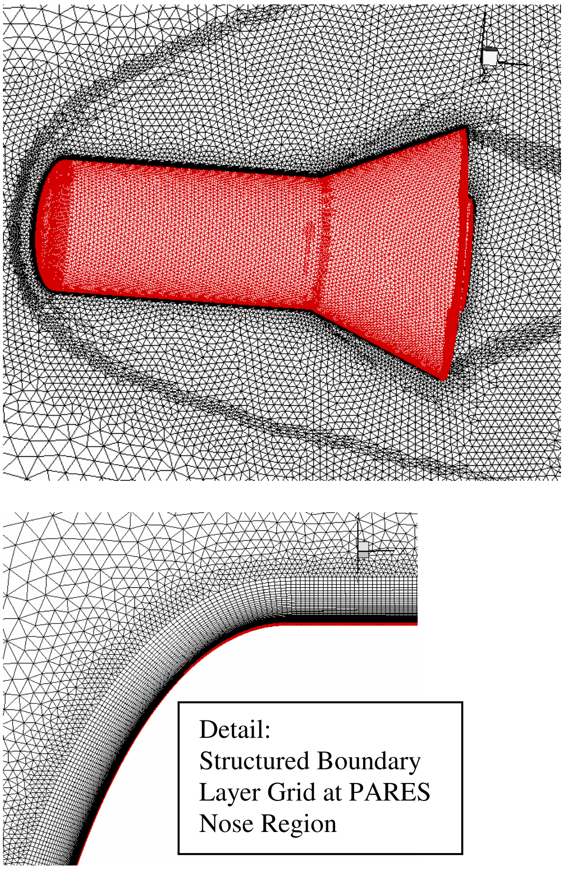

FIG 14. Hybrid PARES CFD Mesh for Flight Condition Mach 10, Angle-of-Attack 5° after One Adaptation Cycle

Typically about 3 Million grid cells where employed after the final grid adaptation for three-dimensional CFD runs, considering one half of the PARES capsule geometry.

FIG 14 exemplifies a hybrid PARES CFD mesh for flight condition Mach 10, angle-of-attack 5° after one adaptation cycle. FIG 15 shows the calculated pressure field for the same freestream condition

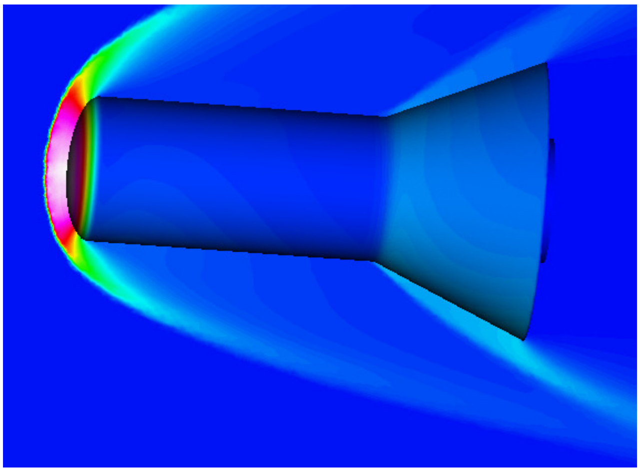

FIG 15. CFD Result: Color Coded Pressure Field Around PARES Capsule, Mach 10, AoA 5°

2.2 CFD data versus Wind Tunnel Results comparison

2.2.1 Static Aerodynamic Coefficients

Quite numerous variations of PARES had to be considered in the course of the work leading to the current baseline configuration. Therefore, in order to prevent the number of CFD calculations from becoming unmanageable within the given time constraints, an engineering approach was used while CFD Calculations were performed for only a reduced set of freestream conditions for each of the most promising configurations.
To enable 6DoF trajectory simulations of selected capsule variations, typically about 5 Mach Numbers for angles-of-attack 5 or 10 degrees were analyzed by CFD.

Based on the assumption (confirmed by trajectory analyses) that no extreme angle-of-attack variations should occur during the ballistic reentry, the derivatives $dC_N/d\alpha$ and $dC_m/d\alpha$ were determined from the CFD values for each Mach number considered, thereby assuming linear variation of the aerodynamic coefficients with α for the excursions from "zero" angle-of-attack α.
Linear interpolation was also used between the coefficients at different Mach numbers.
The respective set of CFD calculations for the definitive (baseline) PARES configuration (TAB 2) was basically verified through the wind tunnel tests as shown in the diagrams below.

TAB 2. Calculated Aerodynamic Coefficients PARES baseline configuration

Mach	α	C_A	C_N	C_m
10.0	5	1.689	0.2000	0.1437
5.00	5	1.917	0.3225	0.2589
2.00	10	3.158	0.9705	0.7848
1.20	5	3.999	0.8261	0.8688
0.85	10	2.190	1.0720	1.0630

The reference quantities for these aerodynamic coefficients are consistent to those used for the diagrams in FIG 6 through 8.

The Graphs below show the relevant wind tunnel data together with the CFD values:

FIGS 16 through 18 contain Axial Force Coefficient CA, Normal Force Coefficient CN and Pitching Moment Coefficient Cm vs. Mach number from wind tunnel tests as well as CFD.

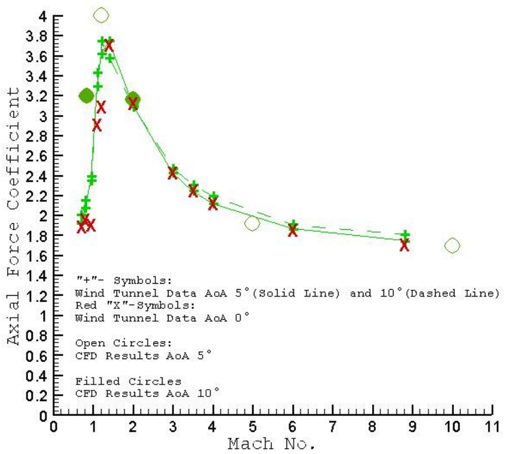

FIG 16. Axial Force Cofficient C_A vs. Mach

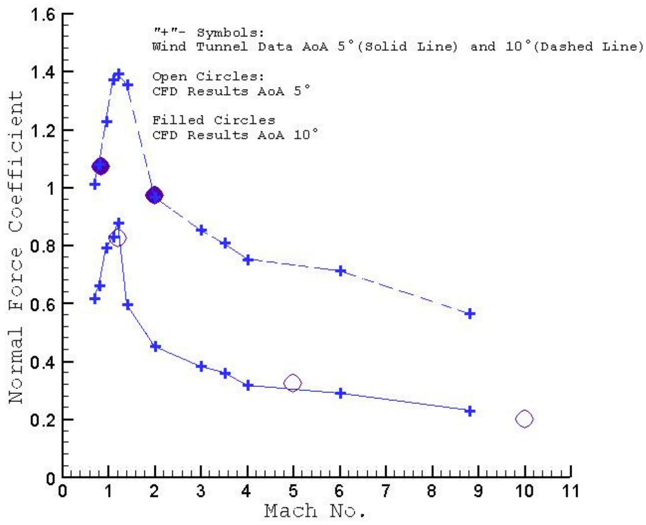

FIG 17. Normal Force Coefficient C_N vs. Mach

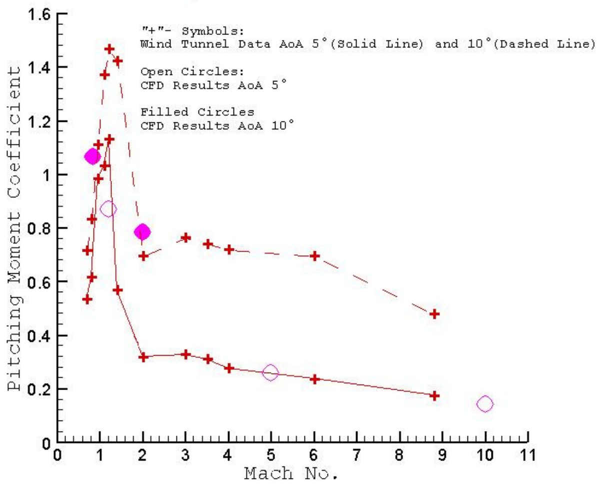

FIG 18. Pitching Moment Coefficient C_m vs. Mach

The CoP (Center of Pressure) Range of the PARES Capsule vs. Mach Number is shown in FIG 19. The Data shown are derived from Wind tunnel tests and also CFD results, which correlate well to the Test Data.

As can be seen from the CoG (Center of Gravity) range included in the same diagram, a certain static margin exists throughout the whole Mach no. range down to subsonic speeds, even for the most rearward CoG position.

As illustrated in FIG 19, for moderate angles of attack the CoP is located well behind the most rearward Center of Gravity position in most flight regimes from hypersonic through supersonic flight conditions and moves even further backwards at transonic flow conditions.

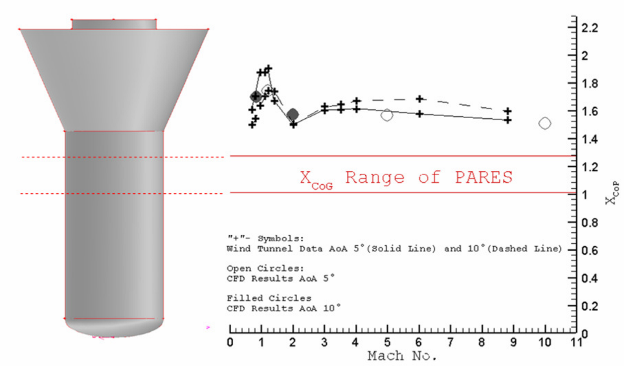

FIG 19. PARES Center of Pressure (CoP) Range vs. Mach Number

Also, the overall correlation between wind tunnel tests and CFD appears quite acceptable, in both qualitative and quantitative terms, as illustrated by Figures 16 through 19.

2.2.2 Aerokinetic Heat Fluxes at the Capsule Surface

The heat flux measurements described in chapter 1.3.5 enabled a first validation of heat flux data otherwise derived completely from CFD throughout the PARES study.
In spite of the fact that the PARES flight conditions are of course different to the “cold” hypersonic flow conditions that can be provided in the H2K Wind tunnel, the wind tunnel data provide nonetheless an important indication of the quality and reliability of heat flux calculations obtainable via CFD.

As evident from FIG 20 and 21, the Stanton numbers (based on freestream total temperature) obtained by CFD calculation (TAU-Code) compare reasonably well to the corresponding experimental results for both the laminar Mach 11.2 case and the turbulent Mach 6 calculation.

Interestingly, the deviations observed for the laminar case are somewhat larger especially in the stabilizer area (within about max. 20% deviation, which might reflect on the level of experimental accuracy) than for the turbulent case, despite of the additional uncertainties introduced by the turbulence model (Spalart-Allmaras-Model).

In any case the CFD heat flux values deviate somewhat above the experimental values, therefore it can be argued that the CFD results are slightly on the safe side for the conditions considered.

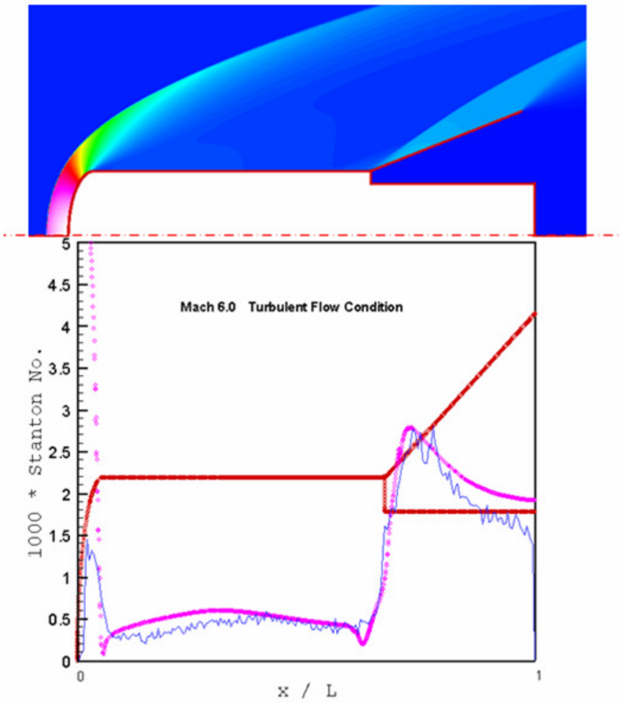

FIG 20. Comparison of CFD derived (Magenta Curve) and experimentally determined(Blue Curve) Stanton numbers for the turbulent Mach 6 Wind tunnel Condition (AoA 0°)

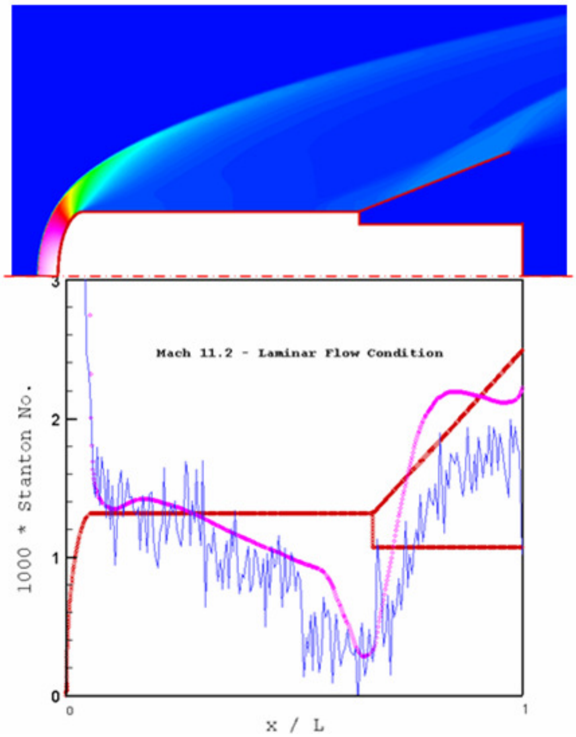

FIG 21. Comparison of CFD derived (Magenta Curve) and experimentally determined (Blue Curve) Stanton numbers for the laminar Mach 11.2 Wind tunnel Condition (AoA 0°)

3. CONCLUSIONS AND FUTURE WORK:

A large amount of aerodynamic and aerothermodynamic test data has been generated within the framework of the PARES programme (aerodynamic forces and moments for full Mach number range covering subsonic, transonic and supersonic/hypersonic regime, hypersonic heat flux measurements, ongoing dynamic stability investigations).

It can be concluded that the Wind tunnel Test Results basically support the findings of the CFD calculations performed earlier and also broadened the aerodynamic database by providing more numerous data points for the subsonic through hypersonic regime than were available from purely theoretical analysis.

Therefore, the valid baseline of the PARES aeroshape is experimentally confirmed regarding all flight characteristics driven by static aerodynamic coefficients, as far as the expected operating range of PARES is concerned

However, the extensive experimental aerodynamic/ aerothermodynamic data provided through the test campaign forms a valuable basis for future CFD validation activities going beyond purely project related tasks within the PARES study, e.g.:

- Influence of different turbulence modelling on heat flux as well as aerodynamic forces/ moments.
- CFD calculations covering the static coefficients over the full AoA range (up to 35°) as tested in the wind tunnel, encompassing both stabilizer angles tested (AoA's beyond 5 to10° were not considered theoretically within the PARES project since they lie outside the normal operating range of the re-entry capsule).
- Theoretical investigation of dynamic stability issues in conjunction to the currently running test activities at VKI

4. ACKKNOWLEDGEMENTS

The Work presented in this paper was sponsored by the European Space Agency (ESA) within the frame of the PARES programme.

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