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INTERMEDIATE EXPERIMENTAL VEHICLE

EXTRAPOLATION GROUND TO FLIGHT WIND TUNNEL AND CFD APPROACH

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With the aim of placing Europe among the world's space players in the strategic area of atmospheric re-entry, several studies on experimental vehicle concepts and improvements of critical re-entry technologies have paved the way for the flight of an experimental spacecraft. The Intermediate eXperimental Vehicle (IXV), under ESA's Future Launchers Preparatory Programme (FLPP), is the step forward from the successful Atmospheric Re-entry Demonstrator flight in 1998, establishing Europe's role in this field.
The IXV project objectives are the design, development, manufacture and ground and flight verification of an autonomous European lifting and aerodynamically controlled re-entry system.
The design of re-entry spacecraft requires the prediction of the aerthermodynamic characteristics for high altitude / high velocity conditions which cannot be duplicated in ground facilities.
A strategy based on wind tunnel testing and CFD simulations is used to reduce uncertainties related to the extrapolation of on wind tunnel and CFD data to flight conditions.
This paper presents the general strategy used, based on the ONERA S4ma (cold flow), F4 high enthalpy facilities as well as CFD code from RTECH, CFSe and Dassault Aviation. The main results are discussed with emphasis on the pre-flight uncertainties for IXV application.

I GENERAL STRATEGY

The design of any kind of re-entry aircraft requires the prediction of its aerothermodynamics characteristics for high altitude / high velocity conditions which cannot be duplicated in ground facilities. Consequently, the concept of ground-to-flight extrapolation has been introduced for the design of such aircrafts. The process of ground to flight extrapolation is as follows:

1) Definition of reference conditions, as close as possible to the actual flight conditions, but for which testing of a reasonably and scaled model of the designed vehicle can be performed
2) Reduction to a minimum of the uncertainties in the prediction of the aerodynamic characteristics of the aircraft for these reference conditions
3) Extrapolation to flight: utilization of the same methods for the reference and the flight conditions and identification of the deviation between predictions for flight and reference conditions
4) Analysis of the differences, in terms of flow physics between the reference and the flight conditions and derivation of the uncertainties.
5) Uncertainties in the predictions for flight conditions, as the sum on the uncertainties for the reference conditions and of those due to he extrapolation process

The aerothermodynamics of re-entry can be primarily divided in a main inviscid perfect gas aerodynamics, modified by viscous effects, which will define friction and heat fluxes and modify the pressure field when so-called viscous interactions are present, and modified again by the real gas effects (chemistry effects due to the dissociation of air at high temperature which modify both pressure and skin friction).

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The inviscid perfect gas and viscous interaction parts depend on Mach and Reynolds number and can be modelized using 3D RANS (Reynolds Averaged Navier Stokes) solver and reproduce in large scale ground facilities.

Real gas effects depend primarily on enthalpy and secondarily on pressure. Currently, those parameters are extremely difficult to match simultaneously, for hypersonic flight, in ground facilities.

The decomposition inviscid-viscous interaction-real gas effects is very interesting to clearly identified physics making easier the quantification of the uncertainties of each component.

II GROUND FACILITIES

The wind tunnel choice, based on past experience, includes the ONERA S4ma for the reference perfect gas conditions for which a good flow quality and accurate measurement techniques are available and the ONERA F4 high enthalpy wind tunnel for which real gas effect has been already demonstrated by addressing in the past the US Shuttle “pitch up anomaly” [1].

II I ONERA S4ma

The ONERA S4ma facility is a hypersonic Blow down wind tunnel with a nozzle diameter ranging from Ø 0.68 to 1 m (see fig 1). The Modane S4 wind tunnel produces an airflow at a maximum stagnation pressure of 120 bar and a maximum stagnation temperature of 1,800 K .

Axisymetric nozzles are available for respectively Mach 6.4; 10 and 12.
Run duration is up to 90 seconds (with 8,000 m^3 vacuum downstream tank at 10 mbar).

- Compressed air: 270 bar, 29 m^3 upstream storage tanks, repressurized by a 5.7 kg/s mass airflow compressor.
- Vacuum: 0.010 bar minimum pressure, 4,000 or 8,000 m^3 storage tanks, sucking in air at up to 15 m^3/s.

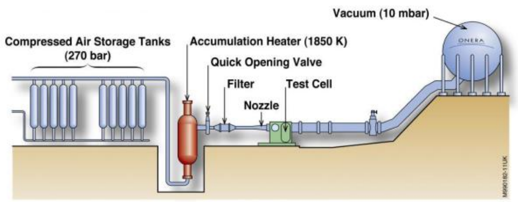

Fig 1: ONERA S4ma, general overview

Fig 2: IXV model in the test section

II II ONERA F4 [2]

The ONERA F4 represents an intermediate step between the ONERA S4 perfect gas and the flight conditions, on which CFD results can be crosschecked in the extrapolation ground to flight process.

Total enthalpy is the first key flow parameter to be duplicated as far as real gas effects are concerned since it is related to Air dissociation.

The obtained total enthalpy in F4 corresponds to a trajectory Mach number of about M= 15.5 in flight at which real gas effect are expected to be present. As far as the binary factor is concerned, due to the scale of the model, this parameter is below the flight trajectory value leading in F4 to have high degree of non-equilibrium flow compared to the flight one (see Fig 3).

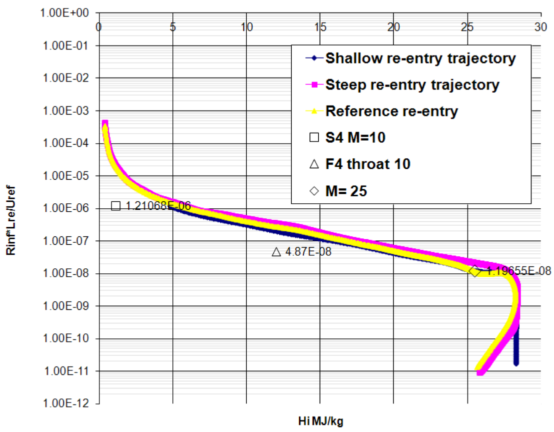

Fig 3 : Binary factor evolution versus enthalpy

The ONERA F4 wind tunnel was commissioned during the course of the ESA HERMES program in the early 1990s, and has since then been extensively used to test various re-entry vehicles, for both terrestrial and Martian atmosphere. These tests are always performed in association with ONERA's scientific departments, who share their knowledge and provide support on aero-thermodynamic flow analysis and measurement techniques.

The F4 wind tunnel, shown on Fig. 4, is a hot shot type, meaning that the operating conditions are obtained by heating the test gas with an intense electric arc in a chamber of 10 to 15l volume initially pressurized at ambient temperature. The energy is delivered by an impulse generator, at a power of up to 150 MW for several tens of milliseconds. The reservoir pressure Pi can be as high as 1000 bar, and the total enthalpy can be as high as 18 MJ/kg for air, at the end of heating process.

After the arc-chamber conditions reach the desired levels, the arc is stopped and the nozzle throat is opened by igniting a pyrotechnic plug to initiate the nozzle flow. The blown down is interrupted by firing a pyrotechnic valve in the arc chamber, quickly evacuating the remaining gas into a dump tank. Run duration of up to 400ms can be achieved, for IXV campaign, according to requested test conditions, duration of 200 ms has been considered.

The flow being the result of the arc chamber expansion in the nozzle, the reservoir conditions decrease with time. However, reservoir pressure and enthalpy decays are slow enough (~1% maximum per millisecond) to allow force measurements to be performed.

The useful run period is established after a perturbed period of at a maximum 15-20 ms due to the plug expelling phase and flow stabilization time. Synthetic air, nitrogen and since 1999 CO2 are used as test gases. F4 can be equipped with different contoured nozzles with varying area ratio. The nozzle 2 (T#2) with an area ratio of about 4500, a length of 3.4m, and an exit diameter of 0.67m, is the most common one and has been used for IXV tests.

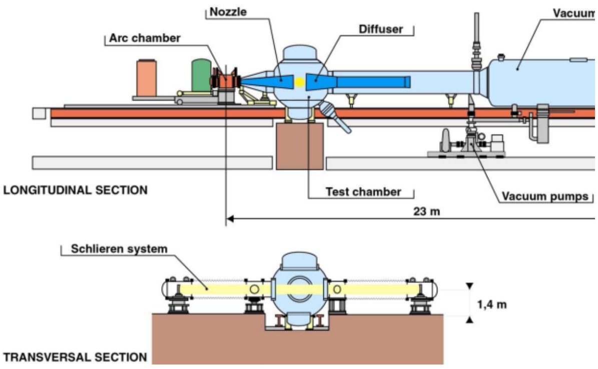

Fig 4: Sketch of the ONERA F4 facility

Fig 5: F4 Wind Tunnel, general overview

Different types of intrusive and non-intrusive instrumentation techniques have been adapted to or developed for F4. They allow the characterization of the test conditions and flow parameters.
The reservoir pressure is directly measured in the arc chamber, whereas the reservoir enthalpy is deduced from test section reference probes measurements of stagnation heat flux and stagnation pressure using semi empirical formula [1].
Use of two pairs of reference probes gives an indication of core flow symmetry and allows measurement redundancy.

The nozzle is instrumented with 19 pressure sensors and 16 thermocouples spread along the wall. Together with reference probes, this nozzle wall instrumentation is used for crosschecking with flow rebuilding from PNS (Parabolized Navier-Stokes) ONERA code PANASCE assuming thermo-chemical equilibrium with air as test gas.

Fig 6: ONERA F4, IXV model in test section

III CFD

The CFD methodology is based on reconstruction of wind tunnel tests for both ONERA S4ma and ONERA F4 and the flight conditions enabling to analyze the flow physics aiming to derive aerodynamic uncertainties in the ground to flight extrapolation process.

RTECH, CFSe and Dassault Aviation are involved in CFD activities.

III I RTECH

The MISTRAL [3] flow solver developed by RTECH has been used to perform the numerical rebuilding of the experiments.
MISTRAL is able to perform the necessary computations assuming either perfect gas, thermo-chemical equilibrium gas, or thermo-chemical non-equilibrium gas chemistry. While being originally developed for high speed flows, it can currently handle flows from subsonic to hypersonic flows. Flows can be laminar or turbulent, for which a large number of turbulence models is available. For the current turbulent cases the SST (Shear Stress Transport) model of Menter is used
An upwind finite volume method is used with an AUSM (Advection Upstream Splitting Method) derived inviscid flux scheme.
The massively multi-blocked structured mesh approach allows a great flexibility in the geometrical modeling combined with efficient and accurate resolution of the physical phenomena. The large number of blocks makes also possible effective domain decomposition for parallelization on large scale computational facilities. The direct integration of the grid generator GridPro allows the efficient creation of these massively multi-blocked grids. MISTRAL and GridPro have been used extensively in various European and National projects.

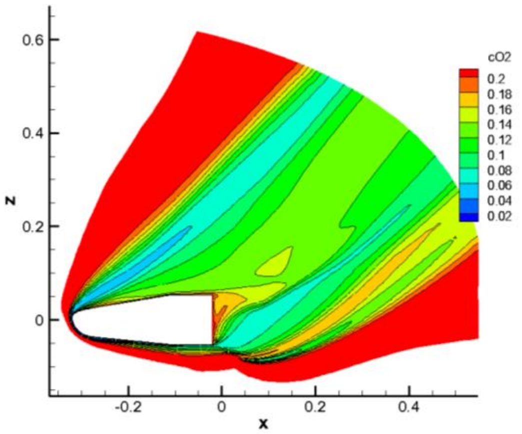

Figure 7: RTECH, NS computation, F4 conditions, Oxygen mass fraction distribution

III II CFSe

CFS Engineering used the NSMB (Navier Stokes Multi Block) CFD code for the simulations [4]. The Navier-Stokes equations are discretized using the finite volume method on multi block structured grids. Each block is composed of 6 faces (which may be collapsed) and each face may have an arbitrary number of windows each having its own boundary condition. NSMB uses so called patch block interface boundary conditions to facilitate the mesh generation for complex geometries. NSMB has been used for hypersonic flow simulations since the days of the Hermes project, and includes all required chemistry modeling for this kind of flows (chemical equilibrium, chemical non-equilibrium, thermo-chemical non-equilibrium). Different turbulence models of various levels of complexity are available, as for example Bladwin-Lomax, Spalart-Allmaras, Chien k-ε and Wilcox k-ω two-equation turbulence model, etc.
For hypersonic flow simulations a shock adaptation approach is used ensuring the bow shock surface alignment with a grid surface. This procedure improves the prediction of the heat flux and pressure at the stagnation point.
All NSMB calculations discussed in this paper used a central space discretization scheme with TVD type artificial dissipation and the semi implicit LU-SGS time integration scheme. Turbulence was modeled using the Wilcox k-ω turbulence model.

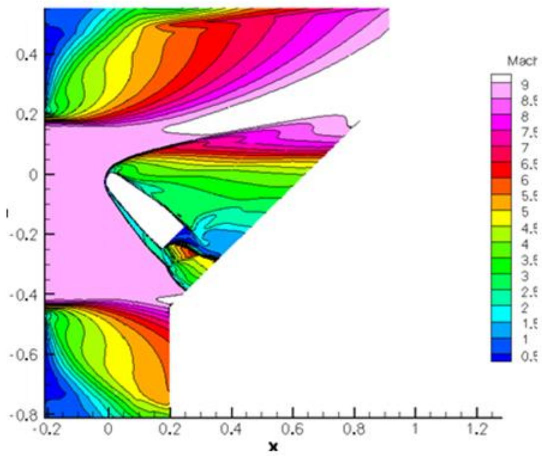

Figure 8; CFSe, 3D NS computation from the exit nozzle, F4 conditions, Mach number distribution

III III Dassault Aviation

Dassault Aviation in house Euler code so called EUGENIE [5] is based on an upwind finite-volume type approximation scheme implemented using a Galerkin integration. In order to compute stationary solutions efficiently, an implicit temporal integration is considered. The MUSCL approach gives the second-order accuracy in space. Non reactive, equilibrium and chemical and thermal non-equilibrium gas can be considered. The solver is able to take into account non-homogeneous limit condition for the free stream. The usage of unstructured grids (Fig. 9a-9b) has been long time motivated by the necessity to employ meshes made on non trivial geometry and to permit local mesh adaptation.

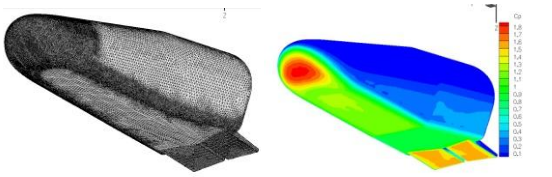

Fig 9a: IXV, Example of skin mesh and pressure coefficient distribution at wall for ONERA F4 wind tunnel conditions

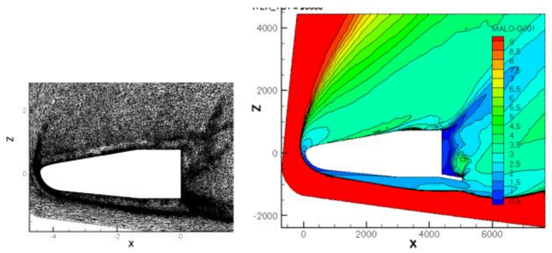

Fig 9b: IXV plane of symmetry, mesh adaptation and Mach number distribution (ONERA F4 conditions)

IV CFD – WTT data analysis [6]

Figure 10 displays the evolution of the pitching moment versus angle of attack for two different flap settings: 0° and 10° for the reference conditions measured in the ONERA S4ma facility. The Reynolds number reproduced in the tunnel is identical to the flight one.

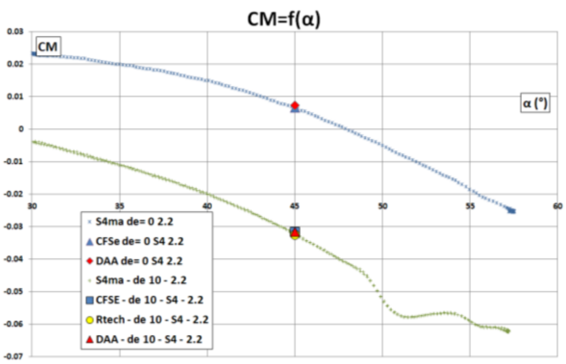

Fig 10: Pitching moment evolution versus AoA, ONERA S4-CFD comparisons for flap setting 0 and 10.

As expected for such conditions, the WT – CFD comparison is quite perfect for both configurations.

The general uncertainty on the measurements is about .0026 in pitching moment coefficient to be compared to the .0012 given for CFD data.

For the ONERA F4 reconstruction, the flow field is considered at chemical non equilibrium and laminar.

For the ONERA F4 reconstruction, two types of inflow conditions are available:

- before test: generic conditions
- After test: reconstruction of the facilities nozzle by means of PNS computation performed by ONERA. The computed nozzle exit plane is then used as inflow conditions for the computations of the flow around the model
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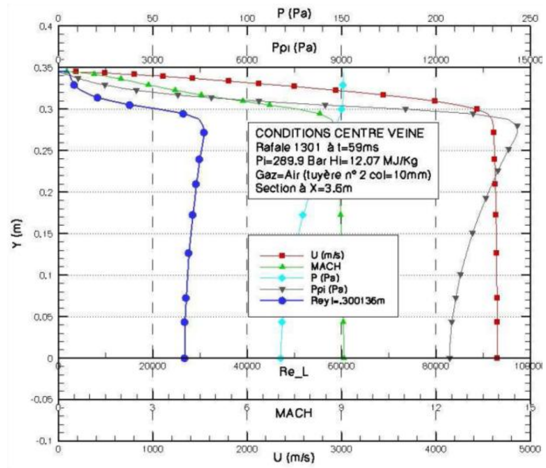

Fig 11: Nozzle #2, PNS computation, nozzle exit radial distribution, Mach, Pressure, Pitot pressure

The Figure 12 below shows a comparison between the static pressure distribution along the nozzle, measured and reconstructed. A satisfactory agreement is observed for the pitot pressure, providing a good level of confidence for the non measured flow parameters such as Mach and Reynolds numbers.

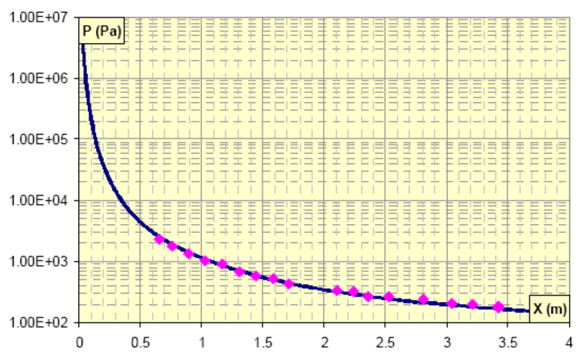

Fig 12: ONERA F4, Static pressure distribution along the nozzle, comparison between measured and reconstructed data.

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The experimental conditions allow to consider a laminar flow in the nozzle. Past experiments in the F4 facility, with nozzle static pressure transducers and DLAS measurement (NO) indicated thermochemical equilibrium for nozzle flow exit for the enthalpy level tested with air as media

The IXV reference configuration selected to underline the real gas effect is the flap setting 10°. Figure 13 shows the evolution of the pitching moment for the generic conditions, CFD-CFD and CFD-WT comparisons. A quite smooth deviation between Euler and Navier-Stokes is observed showing a low viscous effect for this configuration. It was demonstrated also that the scatter noticed between the two Navier-Stokes results is coming from the different chemical modelling used (Park-Blottner for CFSe and Dunn-Kang for RTECH)

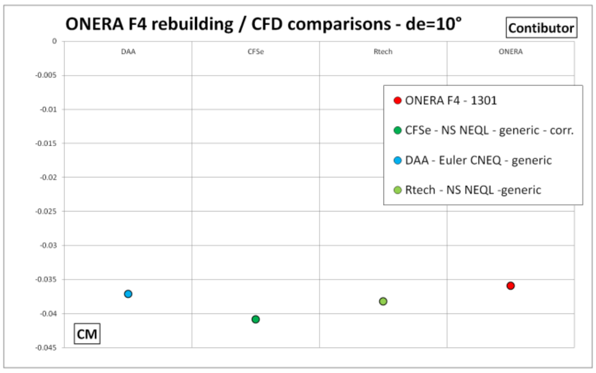

Figure 13: F4 generic conditions: Euler, Navier-Stokes and WTT comparisons

Thanks to the PNS computations provided by ONERA, a second set of computations was performed to rebuild more accurately the run selected in that case.

The comparisons between the different results show that the viscous effect (NS – Euler) is equivalent to the inflow condition effect (i.e. PNS – generic) which remains negligible as regards with the order of magnitude of the pitching moment itself (Fig. 14).

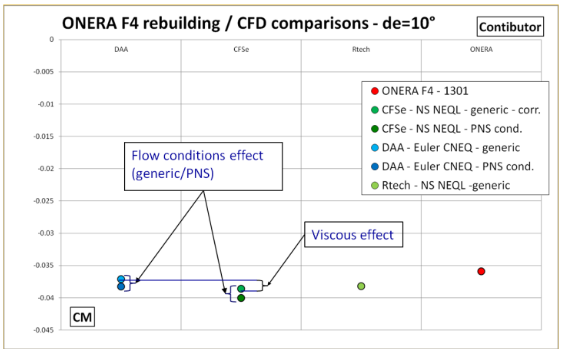

Figure 14: F4 generic and PNS conditions – CFD-CFD and CFD-WT comparisons

The real gas effect is addressed by comparing high enthalpy results and data coming from a reference condition usually a condition which can be obtained in a conventional "cold hypersonic wind tunnel" (i.e. ONERA S4ma).

Figure 15 presents the evolution of the pitching moment versus angle of attack for the IXV configuration with flap setting 10° for both ONERA S4 and F4 wind tunnels. CFD data for each wind tunnel conditions are put on top. For IXV, the real gas effect induces a pitch down (equivalent to 1.2° flap deflection)

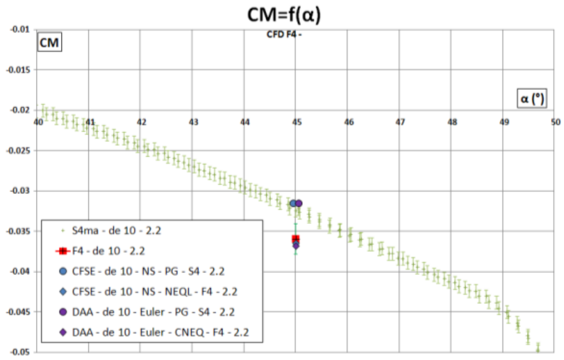

Figure 15: Pitching moment evolution, flap setting 10°, S4, F4 and CFD comparisons for angle of attack 45°.

Basically real gas effect is very local on the wall pressure, and occurs mainly where pressure gradients are located such as expansion or compression areas. In fact only the pitching moment is affected by the real gas effect (lift and drag no significantly impacted)

For lateral aerodynamic coefficients, no significant real gas effects are observed as shown in the Fig. 16 to Fig. 18, respectively lateral force, rolling moment and yawing moment.

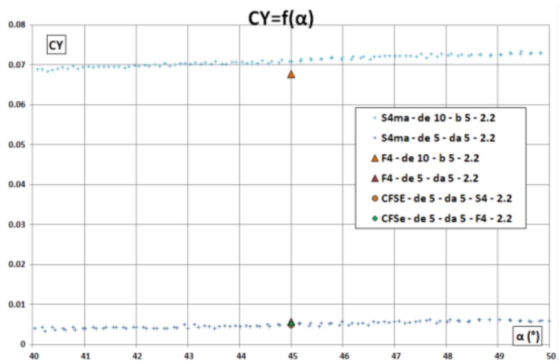

Figure 16: Lateral force evolution: S4, F4 WT data and CFD reconstruction comparison

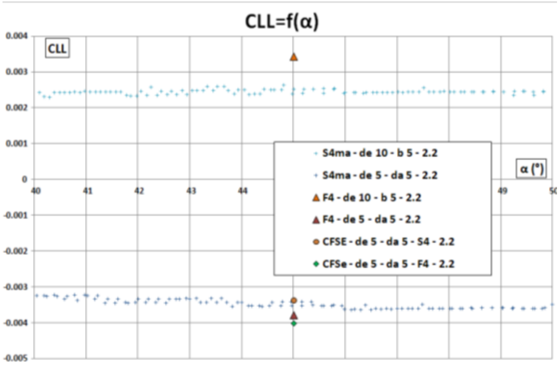

Figure 17: Rolling moment evolution: S4, F4 WT data and CFD reconstruction comparison

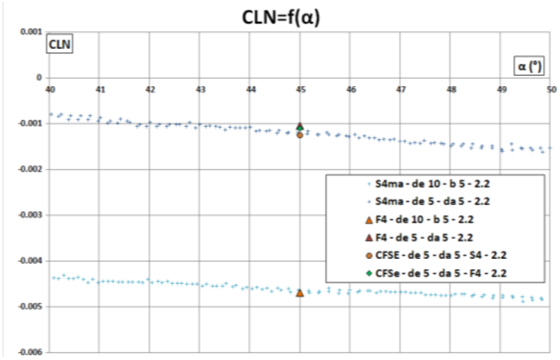

Figure18: Yawing moment evolution: S4, F4 WT data and CFD reconstruction comparison

V EXTRAPOLATION GROUND TO FLIGHT

The good quality of the cold reference point rebuilding (ONERA S4), involving various contributors is the base the current methodology applied in the extrapolation process.

Considering a reference condition (S4) for which the uncertainties are demonstrated and minimized, the extrapolation process uses the same numerical tools for references and flight conditions.

Pitching moment and the flap effectiveness are assumed to be mainly affected by the real gas effect.

Figure 19 presents the pitching moment evolution versus reduced enthalpy for S4, F4 and flight conditions, obtained from computations for three different modeling (perfect gas, equilibrium chemistry and finite rate chemistry) and from experiment. The results presented are collapsed to the results obtained in ONERA S4 facility which is the reference point.

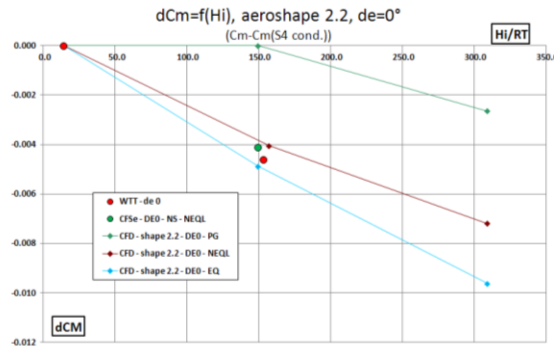

Fig 19: Pitching moment evolution versus reduced enthalpy

For the flight conditions, the major part of the real gas effect is observed when using the equilibrium chemistry assumption meanwhile finite chemical rate is smaller. For ONERA F4 conditions, due to the smaller value of the binary factor, the real gas effect is reduced.

From the Fig 19, without flap setting (ie: de= 0), the following table can be edited for the flight conditions:

Effect of Mach number	-0.002654
Effet of Equilibrium chemistry	-0.006958
Effect of finite rate chemistry	0.002428
Total real gas effect	-0.004530

Table 1 : Decomposition of real gas effect, Mach 25.0, de =0°

For the flight point selected, the real gas effect includes the different contributors as follows:

- Mach number effect (ie: PG @M25 – PG (S4 cond.))
- Equilibrium chemistry effect (ie: EQ @M25 – PG @M25)
- Finite rate chemistry effect (ie: NEQL @M25 – EQ @M25)

The effect of equilibrium chemistry on the pitching moment is of the same order of magnitude between F4 and the flight conditions. A better agreement is observed between CFD and F4 when considering equilibrium chemistry modeling. In the current methodology, such result would validate the effect of equilibrium chemistry. For the finite chemistry modeling, not yet validated at this stage, a 50% of uncertainty is applied arbitrarily.

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Nature	Contribution to real gas effect, %	Intrinsic uncertainty, %	Contribution to global uncertainty
Equilibrium chemistry	153.6	5.7	8.8
Finite rate	-53.6	50	26.8
Total	100		35.6

Table 2: Real gas effect, Contribution to the global uncertainty assessment

The contribution of real gas effect to global uncertainty is of 36% for CM coefficient.

In the current aerodynamic database of IXV, the uncertainty applied on the CM at Mach 25.0 is 0.00623 and at Mach 10.0 in S4 conditions, 0.00471; in such a case the real gas effect contribution is about 0.00152 in nominal.

The value of the CM at Mach 25.0 for de=0° configuration at AoA=45° is 0.002056, so the uncertainty, related to real gas effect, implemented in the database is about 73% of the nominal value to be compared with 36% from the current methodology. The delta observed is due to the wind tunnel data not considered when defining the first set of uncertainties in the aerodynamic data base.

Figure 20 shows the result for the flap efficiency using the same method as for smooth configuration.

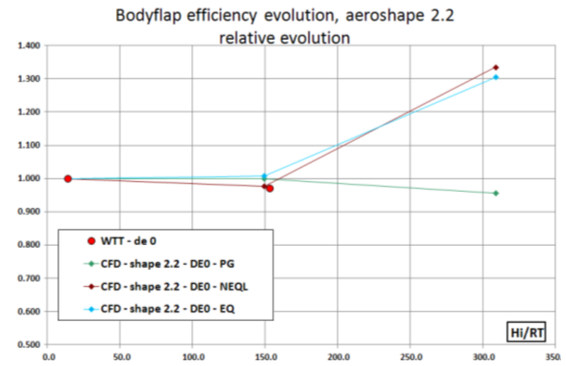

Fig 20: Flap efficiency evolution versus reduced enthalpy

The real gas effect can be decomposed in the same way.

Effect of Mach number	-4.4
Effect of equilibrium chemistry	34.9
Effect of finite rate chemistry	3.0
Total	38.0

Table 3: Real gas effect on flap efficiency

It is noticed that for flap efficiency, the Mach number effect between F4 and flight conditions doesn't play a significant role.

Nature	Contribution to real gas effect, %	Intrinsic uncertainty, %	Contribution to global uncertainty
Equilibrium chemistry	92.0	3.8	3.5
Finite rate	8.0	50	4.0
Total	100		7.5

Table 4: Real gas effect on flap efficiency - Contribution to the global uncertainty assessment

In the current aerodynamic database, the uncertainty applied on flap efficiency at Mach 25.0 is 26 % and the uncertainty applied at Mach 10.0 corresponding to S4 conditions is 17. %; so the component of uncertainty affected to real gas effect in the database is about 9%, to be compared with 7.5% in the current methodology.

VI CONCLUSIONS

The extrapolation ground to flight aerodynamics strategy based on CFD and WTT approach provided promising results in the case of IXV vehicle.

This methodology was originally tested to reconstruct the US Shuttle case experiencing the so called "pitch-up anomaly".

As support of the F4 high enthalpy wind tunnel tests, CFD activities were carried out to address real gas effects for the IXV vehicle. The results of Euler and Navier-Stokes computations showed that the viscous effect seems rather low for the reference configuration tested.

The real gas effect analysis issued from the comparison between ONERA S4 and F4 as well as CFD demonstrated a small pitch down induced. It was also showed no significant real gas effect on lateral components.

The current methodology involving WTT and CFD consolidates the aerodynamic behavior of the IXV configuration implemented in the Aerodynamic Data Base.

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