

VALIDATION OF WIND TUNNEL TEST AND CFD TECHNIQUES FOR RETRO-PROPULSION (RETPRO): OVERVIEW ON A PROJECT WITHIN THE FUTURE LAUNCHERS PREPARATORY PROGRAMME (FLPP)

D. Kirchheck, A. Marwege, J. Klevanski, J. Riehmer, A. Gülhan

German Aerospace Center (DLR)
Supersonic and Hypersonic Technologies Department
Cologne, Germany

S. Karl

German Aerospace Center (DLR)
Spacecraft Department
Göttingen, Germany

O. Gloth

enGits GmbH
Todtnau, Germany

ABSTRACT

The RETPRO project is a 2-years activity, led by the German Aerospace Center (DLR) in the frame of ESA's Future Launchers Preparatory Program (FLPP), to close the gap of knowledge on aerodynamics and aero-thermodynamics of retro-propulsion assisted landings for future concepts in Europe. The paper gives an overview on the goals, strategy, and current status of the project, aiming for the validation of innovative WTT and CFD tools for retro-propulsion applications.

Index Terms— RETPRO, retro-propulsion, launcher aero-thermodynamics, wind tunnel testing, CFD validation

1. INTRODUCTION

The *Future Launchers Preparatory Programme* (FLPP) aims at preparing the necessary components for future launch systems to be able to serve Europe's needs for a secured and autonomous capability of access to space in the future. Primary goal is to reduce costs as well as improve flexibility and availability to strengthen European launch operations and industry on the global market. Part of this endeavor, as stated by the European Space Strategy [1], is to supply competence and technology to allow the re-usability of future and existing spacecraft or components.

The paper at hand gives an overview on a 2-years activity, funded by the *European Space Agency* (ESA), under the framework of FLPP, dealing in particular with the making available of necessary tools for a detailed aerodynamic and aerothermal design of future European *vertical take-off*

and landing (VTVL) spacecraft, assisted by retro-propulsion. Up to now, in Europe, knowledge and expertise in that field, though constantly growing, is still limited. Systematic studies were conducted to compare concepts for possible future European launchers [2, 3], and activities on detailed investigations of system components of VTVL *re-usable launch vehicles* (RLV) recently started in the RETALT project [4, 5].

Nevertheless, validated knowledge on the aerodynamic and aerothermal characteristics of such vehicles is still limited to a small amount of experimental and numerical investigations mostly on lower altitude VTVL trajectories, e.g. within the CALLISTO project [6, 7, 8]. Other studies were conducted to analyze the aerothermodynamics of a simplified generic Falcon 9 geometry during its re-entry and landing burns, but up to now without comparable experimental data [9, 10]. Consequently, numerical and experimental tools are not yet validated completely for the full range of a commercially relevant launcher trajectory, including high altitude control and propulsive maneuvers, as well as advanced aerodynamic control surfaces, like grid fins for example.

The project RETPRO, *Validation of Wind Tunnel Test and CFD Techniques for Retro-propulsion*, aims at closing this gap by preparing the necessary tools for a reliable design and simulation of a complete ascent and descent trajectory of an inline proposed launcher configuration, which shall be based on current operational vehicles. For that purpose, the consortium, consisting of the Supersonic and Hypersonic Technologies Department and the Spacecraft Department of the DLR Institute for Aerodynamics and Flow Technology, and enGits, a supporting engineering company, providing efficient computing resources and methods, follows a successive road-map:

1. Definition of a reference configuration, based on an operational launch system, performing VTVL with retro-

The RETPRO project, under which the disclosed research and authorship was conducted, received funding by the European Space Agency (ESA) within the Future Launchers Preparatory Program (FLPP).

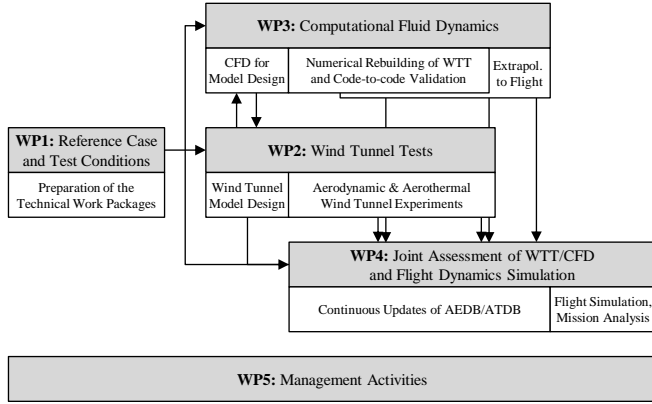


Fig. 1. Work logic scheme

propulsion assisted descent and landing maneuvers.

2. Generation of high-quality aerodynamic and aerothermal test data from wind tunnel experiments throughout the descent trajectory in the hypersonic, supersonic, and subsonic flight regimes with and without propulsive jet.
3. Numerical rebuilding of wind tunnel experiments for validation of the numerical models in order to allow a proper prediction of aerodynamic and aerothermal loads.
4. Numerical extrapolation to full scale flight conditions in order to generate each, a sophisticated *aerodynamic database* and *aerothermal database* (AEDB/ATDB).
5. Simulation of the reference trajectories, enabling mission performance analysis and final validation of the overall modeling approach.

After summarizing the project strategy, the paper elaborates on relevant currently operational launch systems and thereon based derivatives for reference configurations and mission trajectories. The definition of a concept for the experimental tests, numerical computations, and their joint assessment for a reliable extrapolation to full scale flight conditions is presented in line with the necessary experimental and numerical tools for the conduction of wind tunnel tests (WTT), CFD computations, and flight dynamics simulations. The internal work logic scheme, depicting the described road-map is shown in Fig. 1.

2. PROJECT STRATEGY

The main goal of this project focuses on the validation of tools, necessary for future design considerations in the field of supersonic and subsonic retro-propulsion and the generation

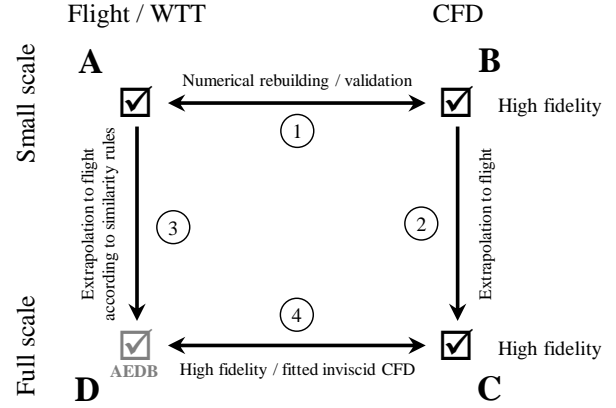


Fig. 2. Strategy for AEDB/ATDB generation

of an AEDB/ATDB for flight dynamics simulations. In industry, those tools are often low-fidelity or simplified computational methods, derived from highly resolved Navier-Stokes computations. Usually, those simplifications are made in order to maintain efficient design processes and short response time. Obviously, the simplification of sophisticated computational methods needs to be validated, but also the use of high-fidelity CFD codes in new fields of application needs to be verified.

Therefore, a strategy of joint assessment of WTT and CFD is developed (Fig. 2). In Step 3 of the before mentioned road map, two high-fidelity CFD codes, the DLR TAU code and the DrNUM code by enGits GmbH (Sec. 6), are used to compare with each other, as well as WTT results, representing all relevant flight phases of a typical retro-propulsion assisted vertical descent and landing trajectory. Prior to that, in Step 2, The different flight phases are experimentally simulated in three complementary WTT facilities at DLR Cologne (Sec. 5). They are suitable for hypersonic, supersonic, and subsonic test conditions with additional cold and hot plume simulation capabilities using pressurized air or *gaseous hydrogen and oxygen* (GH₂/GO₂) combustion in combination with the external ambient flow. Throughout the various flight phases, the DLR TAU code is mainly used for rebuilding of WTT cases with hot plume simulation due to its capabilities in modeling chemically reacting gas mixtures and serves as reference for the calculations with the DrNUM code. The DrNUM code uses simplified hot gas modeling by an ideal gas mixture approach and offers highly parallelized computing capabilities, using *graphics processing units* (GPU)s, which represents a possible setup for an industrialized design process as mentioned above.

Based on a successful validation, both CFD codes are used in Step 4 to extrapolate the WTT results to a realistic flight configuration by performing full scale computations. The results of the full scale computations are gathered in order to sufficiently populate an AEDB/ATDB for a final 3-DoF or 6-DoF flight simulation, which is performed using the DLR

in-house tool FDS (*Flight Dynamics Simulator*) (Sec. 7) in Step 5.

Since the first step of the project's road map is to define reference configurations and missions based on operational launch systems, the derived flight simulations can finally be compared to original flight data of the reference cases in order to close the validation cycle.

3. SELECTION OF THE REFERENCE LAUNCHER AND MISSIONS

3.1. State of the Art

There are a couple of concepts for *reusable launch vehicle* (RLV), existing in the United States, that have already been flown or tested to different degrees. Hence, they involve different *technology readiness levels* (TRL), as well as different ranges of mission envelopes and are therefore more or less sufficient as the project's reference configuration. The *Delta Clipper Experimental* (DC-X) vehicle (later NASA DC-XA), a conceptual single-stage-to-orbit (SSTO) vehicle was tested in the 1990s up to an altitude of 3.1 kilometer (Fig. 3, a). Blue Origin's *New Shepard*, a sub-orbital rocket for technology demonstration and space tourism, which reached an altitude of slightly above 100 kilometer, is sporadically operated since 2015 (Fig. 3, b). But only SpaceX's Falcon rockets, i. e. the *Falcon 9* and *Falcon Heavy*, are currently in regular commercial operation since 2013 and 2019 respectively (Fig. 3, c/d). Recently also SpaceX's *Starhopper*, a technology demonstrator for new engine technologies to be used for future heavy lift rocket concepts is being tested since the middle of 2019. In addition to that, various concepts are being developed that have not been tested until now, but will use similar technologies. Blue Origin develops the *New Glenn* as a future heavy lift rocket, as also SpaceX develops the *Falcon Super Heavy* booster and it's upper stage *Starship*.

In Europe, the implementation of such concepts started recently with the beginning of the HOMER (Airbus Defence and Space, ADS) [11, 12], EAGLE (DLR) [13] and FROG (CNES) [14] projects, representing small scale demonstrators for *Guidance, Navigation and Control* (GNC) systems. This is continued by the medium size launcher demonstrator project CALLISTO, which is a tri-lateral cooperation between CNES, DLR, and JAXA [6, 7, 8]. On European side, those concepts still implicate comparably low TRL for key technologies and a low to medium altitude range. Consequently, for the studies conducted in RETPRO, currently, only the Falcon 9 and Falcon Heavy booster return flights are relevant for a sufficient comparison in a broad MACH number and altitude range.

3.2. Reference Missions

The Falcon 9 rocket is typically used by SpaceX for satellite missions to *low earth orbit* (LEO) or *geostationary transfer*

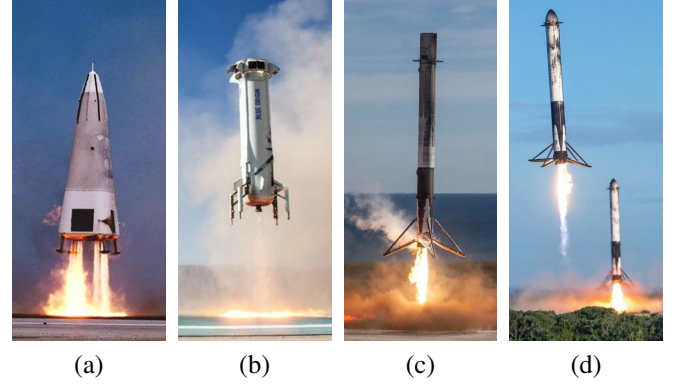


Fig. 3. State of the art in vertical take-off and landing reusable launch vehicle (VTVL RLV) in the United States: (a) DC-X, 1993; (b) New Shepard, 2016; (c) Falcon 9, 2015; (d) Falcon Heavy, 2019

| Mission | Flight | Date | Type | Orbit | Payload |
|---------|--------|------------|------|-------|----------|
| NROL-76 | 33 | 01/05/2017 | RTLS | LEO | 2,800 kg |
| SES-11 | 43 | 11/10/2017 | DRL | GTO | 5,200 kg |

Table 1. Falcon 9 reference missions

orbit (GTO). The LEO missions involve flight profiles with a landing of the first stage booster after a *return to launch site* (RTLS) near the launch pad. The booster landing of the GTO missions is performed as a *downrange landing* (DRL) on an *autonomous spaceport drone ship* (ASDS) at a certain downrange distance.

Obviously, the two approaches incorporate different trajectories and mission events for the descent flight phase and consequently different challenges to face for the flight simulation. The DRL, is typically performed, when more kinetic energy is needed for the orbit insertion, which is the case for GTO missions, or if larger payloads require the use of more fuel. In this case, not only the mission events, but also the flight profile differs considerably between RTLS and DRL missions. To study all parts of the different landing approaches, two reference missions are selected, representing both, an RTLS landing and a DRL.

The current candidates for the reference missions are the NROL-76 mission as the reference for RTLS, and the SES-11 mission for the DRL approach (Tab. 1). Trajectory reference data is taken from the SpaceX launch webcasts, which, in these cases, is provided for the first stage ascent and descent phases as altitude and total velocity over time (Fig. 4). For the SES-11 mission, the webcast is interrupted at approximately 430 seconds, making the final landing approach inaccessible. NROL-76 is therefore taken as the first reference for the validation of the launcher model.

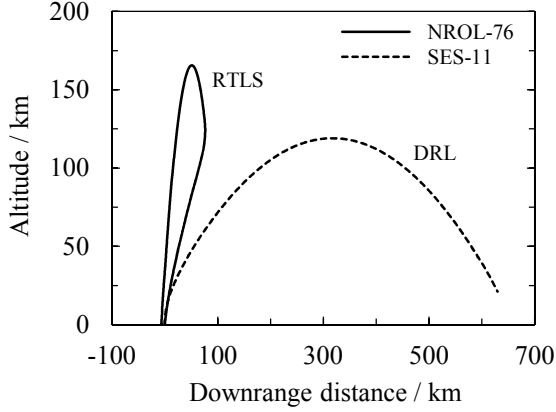


Fig. 4. Flight profiles of the candidate reference missions NROL-76 and SES-11, taken from the SpaceX launch webcast

| Mission | Launcher | Booster | Booster Engine |
|---------|-----------------------|---------|----------------|
| NROL-76 | Falcon 9 v1.2 Block 3 | B1032.1 | Merlin-1D v1.2 |
| SES-11 | Falcon 9 v1.2 Block 3 | B1031.2 | Merlin-1D v1.2 |

Table 2. Reference launcher for NROL-76 and SES-11

3.3. Reference Launcher

For both reference mission candidates, the same Falcon 9 version, v1.2 or *Full Thrust* (FT), was used. Although, between Flights 33 and 39 a transition from the Block 3 to the Block 4 engine was made, the SES-11 mission was performed, using a previously flown booster (B1031.2), which was refurbished after successful landing at the launch site in Flight 30. This was shortly before the NROL-76 launch, using booster B1032.1 (Table 2). This allows to use similar launcher models with simple adaptations regarding the payload and propellant masses for both missions and thus enables comprehensive validation possibilities.

4. DEFINITION OF THE GENERIC REFERENCE CONFIGURATION

From the selected reference missions and launcher, a generic launcher configuration is derived, which is used as the main reference in the project. In order to obtain a consistent design of the reference configuration, it is developed through preliminary 3-DoF simulations of the presented reference mission candidates. The current definition is based on the main properties, which are used as input data for the simulation and which are listed in Tab. 3. The underlying geometry, which will later be used for the wind tunnel model design and CFD calculations is depicted in Fig. 5. It is a generic representation of the reference launcher, including grid fins, landing structures, and a simplified base geometry.

The result of the preliminary flight simulation is shown in Fig. 6 and 7, compared to the webcast telemetry data. It is

| Property | Stage 1 | Stage 2 |
|----------------------------------|----------|-------------|
| Height / m | 47.0 | 23.0 |
| Diameter / m | 3.66 | 3.66 / 5.20 |
| Nozzle exit diameter / m | 0.964 | 3.10 |
| Nozzle expansion area ratio | 16 | 165 |
| Empty mass / t | 26.55 | 4.4 |
| Number of engines | 9 | 1 |
| Oxidizer/propellant | LOX/RP-1 | LOX/RP-1 |
| Specific impulse (sea level) / s | 283.3 | 60.0 |
| Specific impulse (vacuum) / s | 310.6 | 342.0 |
| Thrust (sea level) / kN | 9×758.7 | 160.0 |
| Thrust (vacuum) / kN | 9×831.8 | 915.0 |

Table 3. Properties of the reference launcher configuration for the preliminary 3-DoF simulation

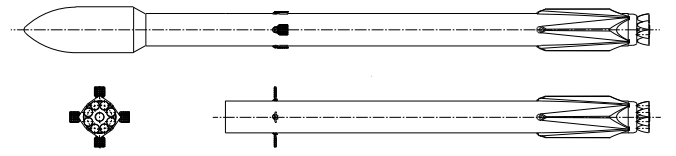


Fig. 5. Shape of the generic reference launcher configuration

sufficient for the definition of the experimental test matrix and test conditions and roughly indicates a proper definition of the reference launcher. The simulation will be updated in the course of the project as detailed aerodynamic data becomes available. This might also have an impact on the definition of the input parameters for the simulation, hence change the launcher definition.

5. WIND TUNNEL TESTING

5.1. Experimental Test Concept

For the design of the wind tunnel test concept, an experimental test trajectory is derived from the reference mission trajectory, taking into account the operating envelopes of the available test facilities. The goal is to represent a complete descent trajectory within the hypersonic, supersonic and subsonic flight regimes. Cold gas and hot gas plume simulation methods are additionally applied for the different retro-burn maneuvers. An exemplary experimental test trajectory is shown in Fig. 8.

The exemplary descent trajectory comprises four major flight phases after entering the atmosphere. These are an aerodynamic descent in the upper atmosphere, followed by a re-entry burn in order to limit the aerothermal loads at hypersonic to supersonic MACH numbers, a second aerodynamic descent phase in the supersonic regime, and the final landing burn, beginning approximately 30 s before touchdown and slowing down the vehicle from low supersonic through transonic and subsonic velocities. The aerodynamic descent in the lower atmosphere and the two retro-burn maneuvers are

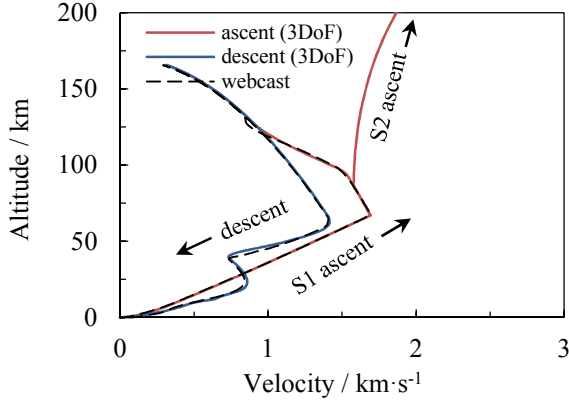


Fig. 6. Preliminary 3-DoF simulation of the LEO reference mission (NROL-76) compared to the SpaceX webcast data

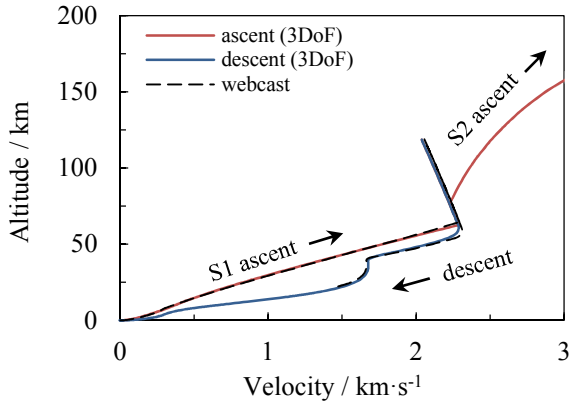


Fig. 7. Preliminary 3-DoF simulation of the GTO reference mission (SES-11) compared to the SpaceX webcast data

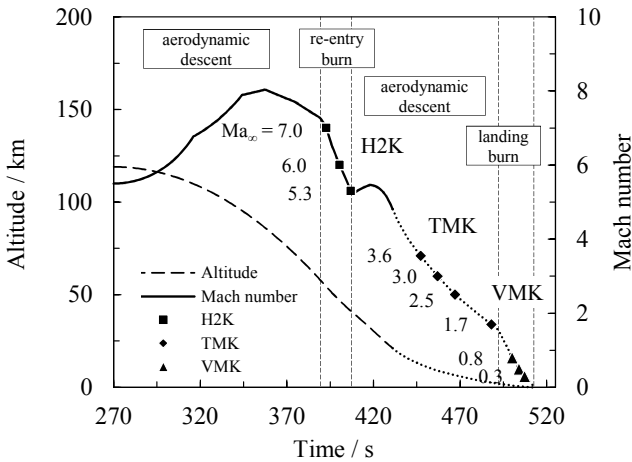


Fig. 8. Experimental test trajectory, based on the candidate GTO reference mission (SES-11) webcast telemetry data; dots: trajectory extrapolated due to interrupted telemetry data

represented by three wind tunnel facilities at DLR Cologne, namely the *Hypersonic Wind Tunnel* (H2K), the *Transonic Wind Tunnel* (TMK) and the *Vertical Test Section* (VMK).

Throughout the whole test trajectory, various parameter variations are applied. Therefore, the different wind tunnel models are designed highly modular to enable variations of the type and deflection angles of control surfaces, thrust vector control angles, engine supply pressure, and nozzle expansion area ratio. Those can be combined with the application of continuous angle of attack polars in the H2K and TMK facilities, as well as discrete angle of attack variation in the VMK facility to create a broad parameter space.

5.2. Hypersonic Re-entry Burn

The H2K is used to duplicate the hypersonic re-entry burn maneuver at discrete MACH numbers between 8.7, 7.0, 6.0, and 5.3. It is a blow-down type wind tunnel with a circular 600 millimeter free jet in an evacuated test section. In the H2K, the plume gas is simulated by high-pressure air supply, which is fed into the nose of the rocket model through a conventional sting support. A strain gauge with a tubular cross-section enables force measurements in four components, also in case of operation with plume simulation. Pressure and temperature are measured at the base of the rocket, along the main body and inside the pressure chamber.

5.3. Supersonic Aerodynamic Descent

The TMK, a closed blow-down type wind tunnel, is used to duplicate the supersonic aerodynamic descent in the lower atmosphere between MACH numbers of 4.5 to transonic speeds by a continuous contour mechanism for the diverging nozzle part. The low supersonic range is limited due to the possibility of wave reflexions from the channel walls of the rectangular 600×600 millimeter test section, impinging on the wind tunnel models surface. In TMK, the same model can be used as for the H2K tests. Since, plume simulation is not necessary, it can be equipped with a common 6-component strain gauge, instead of the 4-component balance used in H2K.

5.4. Subsonic Landing-burn

The VMK facility is used to duplicate the subsonic part of the final landing burn between MACH numbers of 0.9 to 0.3. It is an atmospheric free-jet facility operable in the supersonic and subsonic range using different nozzle assemblies. Its subsonic nozzle has an exit diameter of 340 millimeter and is located in the middle of a large 4×4.5 meter test section.

The test section is prepared to conduct hot gas experiments using e. g. GH₂/GO₂ combustion in a model-integrated combustion chamber. Hence, more realistic rocket exhaust conditions can be reached in combination with the external wind tunnel flow. These experiments are used to validate the hot gas and chemistry models of the different flow solvers.

6. COMPUTATIONAL FLUID DYNAMICS (CFD)

6.1. Flow Solvers

Within the RETPRO project, two flow solvers, TAU and DrNUM, are used to full capacity in a complementary fashion in order to benefit from their specific qualities.

The TAU-code, developed by the DLR Institute of Aerodynamics and Flow Technology, is a well-established and widely used general purpose tool for a broad range of aerodynamic and aero-thermodynamic problems [15]. The TAU code is a second order finite-volume solver for the Euler and Navier-Stokes equations which includes a comprehensive range of RANS-based or scale resolving turbulence models and extensions for chemically reacting high enthalpy flows. It uses unstructured computational grids to facilitate the analysis of complex geometries and is highly optimized for the application on massively parallel high performance computing systems. TAU has been successfully applied to a wide range of subsonic to hypersonic flow problems, both in scientific and industrial applications, including the analysis of re-usable launcher configurations.

The DrNUM code has been firstly introduced to the public in the year 2013 and is jointly being developed by en-Gits GmbH and numrax GmbH. It is high-performance CFD software which makes extensive use of GPUs for massively parallel computing. It allows to process flow simulations in the order of tens of million cells on classical single node desktop computers. In contrast to classical grid methodologies (e.g. structured or unstructured) dual resolution grids are used, which consist of a set of coarsely arranged sub-grids, each with a highly resolved computational grid. This approach leads to achieve an optimal combination of high numerical and algorithmic efficiency within the sub-grids, while keeping geometric flexibility at the same time.

The nature of the two codes makes them well suited for specific tasks within the joint assessment strategy of the RETPRO project.

6.2. Numerical Rebuilding of Wind Tunnel Tests

The rebuilding is done for selected test cases of the scaled wind tunnel experiments. It enables direct comparison of the CFD results with the WTT results. For the numerical rebuilding of WTT, a trade-off between the best possible approximation of the real physical conditions and the computational effort is necessary. Therefore different degrees of complexity in the experiments go hand in hand with appropriate degrees of complexity in the CFD computations.

The DLR flow solver TAU will mainly be used for the rebuilding of hot gas tests in VMK and as additional reference for selected cold gas tests in TMK and H2K to allow code-to-code validation. DrNUM will be used to rebuild the test environment in the H2K and TMK facilities with cold plume simulation and without plume.

6.2.1. TAU Computations

The models which will be applied for the thermodynamics and chemistry of the flow species will depend on the considered computational cases. In cold flow situations (static temperatures less than about 1000 K), air will be modeled as a calorically perfect gas (gas constant and ratio of specific heats are constant and independent of temperature and pressure). This applies to all cases without nozzle exhaust jets and with free stream MACH numbers below 3.5. At larger MACH numbers, an equilibrium air model will be applied. The thermodynamic properties vary correctly with temperature and pressure. Here, air is considered as an infinitely fast reacting mixture of N₂, O₂, N, O and NO. In cases with chemically reacting exhaust jets, air will be modeled as a mixture of thermally perfect gases with 76% mass fraction of N₂ and 24% mass fraction O₂. The properties of the single species vary with temperature and include high temperature effects such as vibrational excitation of the molecules.

The general approach for modeling exhaust gas will be based on a non-reacting (frozen) mixture of thermally perfect gases. The assumption of a non-reacting exhaust allows to define an equivalent single exhaust species whose thermodynamic properties are identical to the considered real mixture and vary only with temperature. This is achieved by the application of suitable mixture rules on the detailed exhaust composition. The exhaust species will include: CO, CO₂, H₂O, H₂, OH, O₂, H, O for JP-1 fueled engines and H₂O, H₂, OH, H₂O₂, HO₂, H, O₂, O for hydrogen fueled engines. The exact exhaust gas composition at the exit of the thrust nozzle will be determined by simplified thermodynamic and chemical analysis of the rocket engine using e.g. the NASA-CEA software.

For sub-scale wind tunnel cases, the model engines are likely to be operated at very low oxidizer to fuel ratios which leaves a significant amount of unburnt hydrogen in the exhaust gas. As a preliminary study on the modeling approach for chemical reactions in the experimental test environment compared to real flight conditions shows, this hydrogen will ignite in the hot stagnation region of the exhaust jets and the resulting exothermic post-combustion will significantly increase the flow temperature and, hence, the thermal surface loads, which can be seen in Fig. 9 and 10. Therefore, chemical reaction between the ambient air and the exhaust jet of the rocket engines will be considered for the rebuilding of WTT.

6.2.2. DrNUM Computations

DrNUM uses Cartesian grids and the boundary conditions are, for most boundaries, imposed via a kind of immersed boundary method. As a result, the grid generation for the DrNUM computations is simple. However, the boundary layers at the model surface are not fully resolved. Due to the hyperbolic nature of the flow investigated, grids can reach the size of approximately 100 million cells. It enables detailed modeling

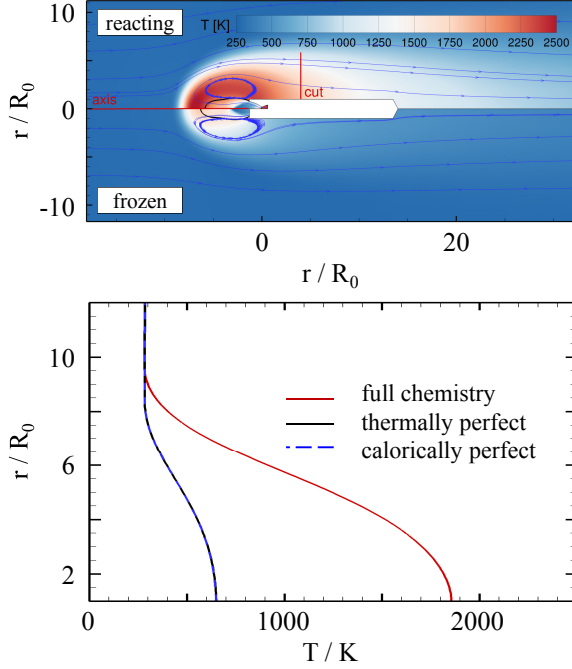


Fig. 9. Comparison of different modeling approaches for chemical reactions under WTT conditions (OFR = 2.5)

of large separated regions, which will, through the resulting complicated wave topology, have a significant impact on the overall aerodynamic coefficients.

Due to the lack of a full boundary layer resolution, simplified friction models have to be used to correctly rebuild the WTT. Several approaches will be tested and compared to the WTT data as well as TAU results for selected cases. With respect to the modeling of the complex grid fin structure, two different approaches will be tested. Grid fins can either be fully resolved or their effect can be modeled via a calibrated source term. Using the latter approach will enable transient simulations of long duration, hence, the variation of additional parameters (e. g. continuous drag polars, variation of the number of active engines, or variation of the thrust vector control angle). A decision on the strategy will be made as the project proceeds and first experiences with the actual geometry and flow parameters are made.

6.2.3. Code-to-code Validation

Code-to-code validation is performed, rebuilding several tests using both flow solvers. These computations comprise the full launcher configuration, including grid fins as control surfaces. Since the computation of the flow through the grid fins is assumed to be sensitive to the modeling of the wall bound flow, grid fins impose uncertainties for the code-to-code validation. Therefore, additional test cases are created, where grid fins are replaced by conventional planar fins.

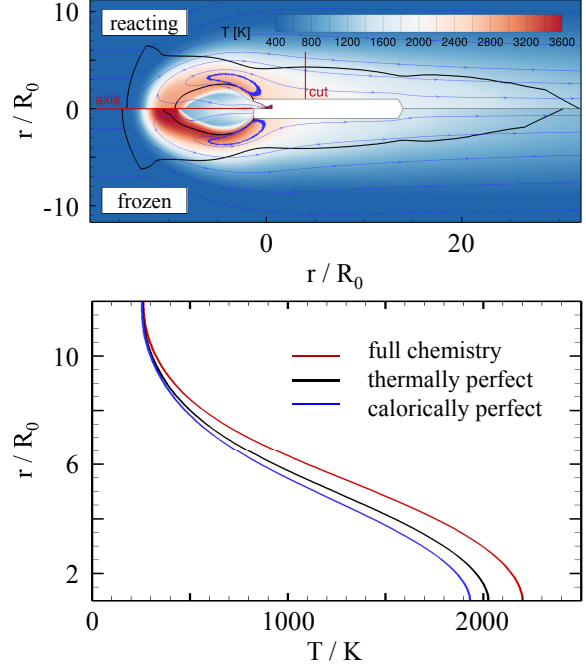


Fig. 10. Comparison of different modeling approaches for chemical reactions under real flight conditions (OFR = 6.7)

6.3. Extrapolation to Flight and AEDB/ATDB

After a successful validation of the the CFD solvers, the first utilization will be made within the project, using them to generate a full aerodynamic and aero-thermodynamic database (AEDB/ATDB) for flight dynamics simulations. For this purpose, full scale CFD computations must be conducted in order to predict aerodynamic coefficients and wall heat flux data without the limitations, imposed by the nature of scaled test environments.

The full scale computations will be performed under the same allocation of TAU and DrNUM capabilities. Thus, high-quality base points are predicted primarily for the databases at the most critical trajectory points and parameter settings. Under the assumption of DrNUM having proofed to be as efficient as supposed to in this scenario, and being sufficiently accurate, though applying the simplified hot gas, chemistry, and wall-bound flow models, it can be used to further populate the AEDB/ATDB for secondary trajectory points or parameter settings.

Further, the databases necessary to conduct flight dynamics simulations must additionally include content for mostly non-relevant flight attitudes or parameter settings, for example in very sparse atmosphere, where the impact of the aerodynamic forces is negligible compared to the propulsive forces. Those entries will be complemented by inviscid low-fidelity CFD computations, which can then be fitted through the high-fidelity base points in order to complete the parameter space for the AEDB.

For the generation of the aerothermal database (ATDB), knowledge of the local wall heat transfer as a function of surface temperature is required. The concept of heat transfer coefficients allows an efficient and accurate estimate of this relation on the basis of the heat transfer distribution for a given fixed wall temperature and the local adiabatic wall temperature. However, this concept fails in zones with large flow separation which occur in the present study during retro-maneuvers and also generally in the base region. Therefore, it is foreseen to repeat CFD analyzes on selected trajectory points for different wall temperature boundary conditions and to use linear interpolation to estimate the local heat flux distributions for given surface temperatures.

7. FLIGHT SIMULATION AND MISSION PERFORMANCE ANALYSIS

Flight dynamics simulations are performed at DLR Cologne with an in-house developed tool, the *Flight Dynamics Simulator* (FDS). It allows simulating launcher ascent and descent trajectories including the use of retro-propulsion for return to launch site (RTL) or downrange landing (DRL) missions. FDS has already been applied to simulate the ROTEX-T flight and the upcoming CALLISTO mission in six degrees of freedom (6-DoF). It has the capability of including high quality experimental or numerical data, which increases the overall quality and accuracy of the results. Further, Monte Carlo type simulations enable to study the influence of different parameters on the mission performance.

FDS will be used at the end of the project to simulate the reference missions with the maximum possible precision after combining all high-fidelity aerodynamic and aerothermal data from the large full scale CFD test matrix. These final 6-DoF simulations in comparison to the reference mission telemetry data will contribute to validate the overall approach of the project and therewith the tools, used for the generation of the databases.

8. CONCLUSION

The knowledge on re-usability of rocket launchers, in particular on performing retro-propulsion assisted landings, is limited in Europe and the necessary tools for upcoming design work still have to be provided. The RETPRO project (Validation of Wind Tunnel Test and CFD Techniques for Retro-propulsion) is one of the current European endeavors to close this gap in order to provide comprehensive wind tunnel test techniques and validated CFD tools for both, a scientific and an industrial approach. Next to the validation of innovative CFD software for efficient computations with a short lead time, also the fundamental knowledge on aerodynamics and aero-thermodynamics for the application of retro-propulsion will be built up in this 2-years activity, led by DLR

in the frame of ESA's Future Launchers Preparatory Program (FLPP).

The work within the RETPRO study bases on the comparability of the results with currently operational VTVL RLV. Therefore, two Falcon 9 missions, the NROL-76 and SES-11 are chosen as reference for the definition of a generic RETPRO launcher configuration. They comprise different approaches of return-flights of the first stage, which are RTL and DRL from LEO and GTO missions respectively.

The preliminary launcher configuration, proposed in the paper at hand, is partly based on publicly available data and used for first preliminary 3-DoF simulations of the reference missions in order to generate a consistent launcher design. The simulations are based on preliminary aerodynamic data from low-fidelity CFD calculations for the ascent and descent configurations. They reach a good agreement with publicly available telemetric data from the SpaceX live mission webcasts, which proofs a reasonable definition of the launcher configuration. However, deviations occur, justifying a strong need for detailed high-fidelity aerodynamic and aero-thermodynamic data.

Based on the reference missions, a comprehensive wind tunnel test campaign is designed, utilizing novel test stand infrastructure to generate outstanding high-quality aerodynamic and aerothermal data for an adequate validation of two kinds of CFD solvers, used in this project.

A preliminary selection of the numerical models, necessary for the rebuilding of the wind tunnel tests, is based on a pilot study, conducted with the DLR TAU code, on the influence of exhaust chemistry modeling on the wall temperature distribution of the wind tunnel model. First computations for the reference configuration proof feasibility of fully resolved CFD as reference for the innovative DrNUM code and further preliminary computations of DrNUM demonstrate the feasibility of efficiently solving a model problem of a retro-burn maneuver at high supersonic speeds.

Therefore, with the selection of the reference missions, definition of a generic launcher configuration, and a proof of concept for the utilization of WTT and CFD, the technical work of the RETPRO study can commence soon.

9. REFERENCES

- [1] "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee of the Regions - Space Strategy for Europe," Ref. COM(2016) 705 final, European Commission, Brussels, 26th March 2016.
- [2] Etienne Dumont, Sven Stappert, Tobias Ecker, Jascha Wilken, Sebastian Karl, Sven Krummen, and Martin Sippel, "Evaluation of Future Ariane Reusable VTOL Booster stages," in *68th International Astronautical*

- Congress (IAC)*, Adelaide, Australia, 25–29 September 2017, pp. 1–18, IAC-17-D2.4.3.
- [3] Sven Stappert, Jascha Wilken, Martin Sippel, and Etienne Dumont, “Assessment of a European Reusable VTVL Booster Stage,” in *Space Propulsion Conference*, Seville, Spain, 14–18 May 2018, pp. 1–12, SP2018.00478.
 - [4] Ali Gülhan, Ansgar Marwege, Josef Klevanski, Sebastian Karl, Davide Bonetti, Jan Vos, Matthew Jevons, Anett Krammer, and João Carvalho, “RETALT - RETro propulsion Assisted Landing Technologies,” in *International Planetary Probe Workshop (IPPW)*, Oxford, UK, 11 July 2019.
 - [5] Ansgar Marwege, Ali Gülhan, Josef Klevanski, Johannes Riehmer, Sebastian Karl, Daniel Kirchheck, Davide Bonetti, Jan Vos, Matthew Jevons, Anett Krammer, and João Carvalho, “Retro Propulsion Assisted Landing Technologies (RETALT): Current Status and Outlook of the EU Funded Project on Reusable Launch Vehicles,” To be published at 70th International Astronautical Congress (IAC), 21–25 October 2019, Washington, D.C.
 - [6] Pascal Tatiossian, Jean Desmariaux, and Matthieu Garcia, “CALLISTO Project - Reusable First Stage Rocket Demonstrator,” in *7th European Conference for Aeronautics and Space Sciences (EUCASS)*, Milan, Italy, 3–6 July 2017.
 - [7] Etienne Dumont, Tobias Ecker, Christophe Chavagnac, Lars Witte, Jens Windelberg, Josef Klevanski, and Sofia Giagkozoglou, “CALLISTO - Reusable VTVL Launcher First Stage Demonstrator,” in *Space Propulsion Conference*, Seville, Spain, 14–18 May 2018, pp. 1–10, SP2018.00406.
 - [8] Josef Klevanski, Tobias Ecker, Johannes Riehmer, Bodo Reimann, Etienne Dumont, and Christophe Chavagnac, “Aerodynamic Studies in Preparation for CALLISTO - Reusable VTVL Launcher First Stage Demonstrator,” in *69th International Astronautical Congress (IAC)*, Bremen, Germany, 1–5 October 2018, pp. 1–10, IAC-18-D2.6.3.
 - [9] Tobias Ecker, Sebastian Karl, Etienne Dumont, Sven Stappert, and Daniel Krause, “A Numerical Study on the Thermal Loads During a Supersonic Rocket Retro-Propulsion Maneuver,” in *53rd AIAA/SAE/ASEE Joint Propulsion Conference (JPC)*, Atlanta, Georgia, 10–12 July 2017, pp. 1–20, AIAA 2017-4878.
 - [10] Tobias Ecker, Franziska Zilker, Etienne Dumont, Sebastian Karl, and Klaus Hannemann, “Aerothermal Analysis of Reusable Launcher Systems During Retro-propulsion Reentry and Landing,” in *Space Propulsion Conference*, Seville, Spain, 14–18 May 2018, pp. 1–12, SP2018.00040.
 - [11] Clément Gu, P. Vernis, J. F. Jourdas, N. Hachelef, Stéphane Heynen, Thierry Poirrier, A. Schwientek, and O. Boudillet, “HOMER PROJECT: Development, Validation, Qualification and Flight Test Results of the Autonomous Flight Control of the Test Vehicle,” in *9th International ESA Conference on Guidance, Navigation & Control Systems*, Oporto, Portugal, 2–6 June 2014.
 - [12] Clément Gu, Stéphane Heynen, and Thierry Poirrier, “HOMER Take-off: A Review,” *dSPACE Magazine* 2015, vol. 2, pp. 32–35, June 2015.
 - [13] Michael Dumke, Marco Sagliano, Piyapat Saranritichai, Guilherme Fragoso Trigo, and Stephan Theil, “EAGLE - Environment for Autonomous GNC Landing Experiments,” in *10th International ESA Conference on Guidance, Navigation & Control Systems*, Salzburg, Austria, 29 May – 2 June 2017, pp. 1–25.
 - [14] David Monchaux, Badr Rmili, Jérémie Hassin, Sylvain Besson, Hinda Amrouchi, Julien Franc, Gilles Poirrey, Stéphane Querry, and Imran Hamada, “FROG, a Rocket for GNC Demonstrations,” in *69th International Astronautical Congress (IAC)*, Bremen, Germany, 1–5 October 2018.
 - [15] Dieter Schwamborn, Thomas Gerhold, and Ralf Heinrich, “The DLR TAU-code: recent applications in research and industry,” in *European Conference on Computational Fluid Dynamics (ECCOMAS CFD)*, Pieter Wesseling, Eugenio Oñate, and Jacques Périaux, Eds., Egmond aan Zee, The Netherlands, 5–8 Sep 2006, pp. 1–25.