HiSST: 3rd International Conference on
High-Speed Vehicle Science & Technology

14–19 April 2024, Busan, Korea

A standard model for the investigation of aerodynamic and aerothermal loads on a re-usable launch vehicle - second stage geometry

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Abstract

This paper presents a generic geometry for the study of aerodynamic and aerothermal behaviour of an upper stage compatible with the RFZ model, a generic, open source geometry of a re-usable launcher. The vehicle design is presented, outlining simplifications made to retain key features of the vehicle while ensuring a manufacturable and meshable geometry. Computational studies will be performed at altitudes between 70 and 90 km, reflecting the phase directly after staging up to the limits of the continuum flow regime. The geometry and results will be made openly available to the research community to promote collaboration in understanding the design challenges associated with re-usable launchers.

Keywords: *open source geometry, reusable launchers, upper stage, RFZ-Model, CFD*

1. Introduction

Aeronautical engineers have a long history of developing standardized models for wind tunnel calibrations and data comparisons between facilities. They are extremely useful in providing baseline datasets for correlation of results, data repeatability over time and verifying model installation or data acquisition systems. Reference models are also particularly relevant from the perspective of numerical analyses, where different codes can be directly compared with each other or assumptions and solver settings can be experimented with to determine solution sensitivity to certain parameters. A standardized reference model typically fulfills two main criteria. Firstly, they are simplistic in shape with a precisely defined geometry and secondly, they are representative of realistic configurations to ensure that the results are relevant. Examples of existing standard models include the AGARD-B [5], ONERA-M [6] and the Standard Dynamics Model (SDM) [1], which have been circulating for decades. Recently, models such as the NASA CRM [8] and the SSAM-Gen5 [3] provide more up to date and relevant aircraft geometries from the past 10 to 20 years.

While aeronautical engineers are well covered with standard aircraft models, the space community is not. Given the sudden and urgent interest in re-usable spacecraft over the past decade, a reference model which serves the research community in facilitating validation of numerical techniques in the generation of aerodynamic and aerothermal data over the entire trajectory is lacking. The purpose of this paper is to introduce a re-usable launch vehicle (RLV) geometry where computational models and results will be made openly available to the research community. It is envisioned that this model will serve as a consistent validation case to promote collaboration and further research into the technical challenges associated with RLVs.

This paper will first introduce the geometry of the second stage of the RFZ vehicle presented in [4] and a reference trajectory based on the flight path of Falcon 9. Next, an overview of the numerical setup used for each of the cases will be presented. This will be followed by some preliminary results for the external aerodynamics and the internal nozzle flow.

2. Methodology

The CFD simulations are done using the well established DLR TAU code [9] with the space craft extensions [7]. The Tau code is a second order finite volume solver for sets of conservation equations,

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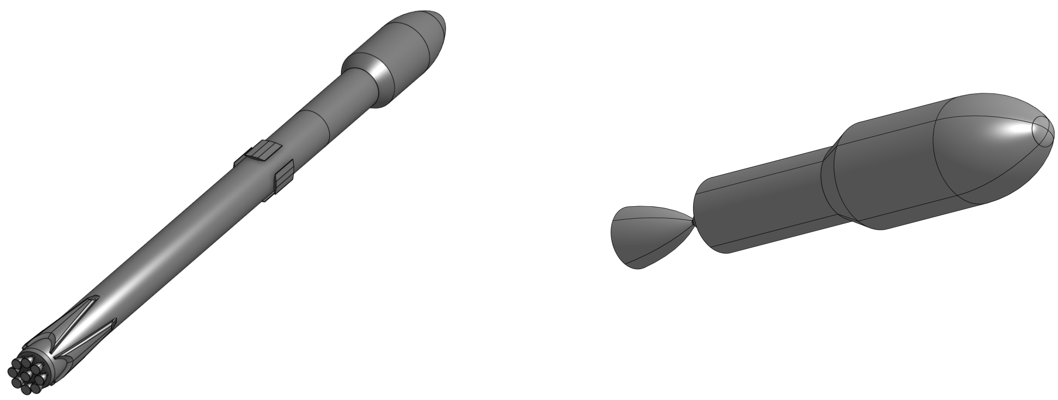
in our case the compressible Euler-equations on hybrid structured-unstructured meshes. We simulate with second order spatial accuracy by using the AUSMDV upwinding scheme with a carbuncle fix [10] combined with least squares gradient reconstruction and second order temporal accuracy with a 3-stage explicit Runge-Kutta scheme. For this work we use stationary simulations. The post combustion in CFD is modeled after the mechanism by Zhukov [11].

3. Numerical Setup and Geometry

3.1. Definition of the Rocket Geometry

The RFZ model is based on the SpaceX Falcon 9 and is presented in Figure 1. This vehicle was chosen because it is the only re-usable launch vehicle which is regularly used for carrying payloads into earth orbit. The geometry was generated using drawings and images of the Falcon 9 freely available on the internet. The vehicle is 70 metres long with a stage 1 diameter of 3.66 metres. Some external features of the outer mold line have been omitted in the interest of keeping the vehicle geometry as simple as possible, while still representing the complexity of a RLV. An example of this is the substitution of the grid fins with planar fins. Grid fins require a significant amount of grid points to represent numerically, resulting in added computational expense. In addition, they would be difficult to manufacture on a small scale, should the model ever be tested in a wind tunnel. Hinge points for the landing legs and externally run lines are also examples of items which have been neglected for simplicity. Various configurations of the first stage exist to be representative of different flight phases.



(a) Launch configuration of the RFZ model

(b) Upper stage of the RFZ model

Fig 1. Isometric views of the open source model geometries

This paper introduces the upper stage geometry as seen in Figure 1b. All RFZ variations (launch, landing, aerodynamic glide and u these geometries, alongside the other configurations are available for download in ref. [2].

The operating conditions of the nozzle are based on using kerosene as a fuel with the combustion chamber pressure set to 108 bar and an oxidiser-to-fuel ratio of 2.35. Initial 1D investigations were made using the NASA CEA tool to determine the species and their respective mass fractions present throughout the nozzle. The mass fractions, pressure and temperature at the combustion chamber exit are used as the boundary conditions for the CFD calculations which are discussed later. The second stage nozzle is based on the vacuum variant of the Merlin 1D+ engine, with an expansion ratio of 165:1 and the same throat radius and length ratio used to define the first stage nozzle geometry. The species at the nozzle exits are summarised in Table 1 where any mass fractions smaller than 1×10^{-4} at the combustion chamber exit have been neglected.

Table 1. Overview of species mass fraction results from NASA CEA analysis for stage 2 engines

Species	Combustion Chamber	Throat	Exit, stage 2
CO	0.44300	0.43407	0.27086
CO_2	0.24605	0.26014	0.51665
H	0.00114	0.00092	0.00000
H_2	0.00960	0.00949	0.01980
H_2O	0.25739	0.264	0.36400
O	0.00366	0.00230	0.00000
OH	0.03058	0.02309	0.00000
O_2	0.00839	0.00554	0.00000

3.2. Settings and Boundary Conditions

The selected trajectory point is used to define the farfield boundary condition with a velocity in x-direction $v_\infty = 2229.72\,\mathrm{m\,s^{-1}}$, a density $\rho_\infty = 9.14 \times 10^{-5}\,\mathrm{kg\,m^{-3}}$ and a temperature $T_\infty = 221.39\,\mathrm{K}$. The gas for the far field is air represented by $N2$, $O2$ and $CO2$. The surfaces of the upper stage are set as viscous walls with an isothermal wall temperature $T_w = 300\,\mathrm{K}$.

A Dirichlet boundary condition is used for the nozzle outflow boundary. An additional steady state 2D axi-symmetric simulation with post-combustion is run with the CEA results shown in table 1 as inflow. The resulting primitive variables and species distribution is the interpolated onto the nozzle outflow surface of the simulation grid.

4. Results

A first look at results is shown in figure 2, showing the Mach number distribution for the upper stage with the full plume.

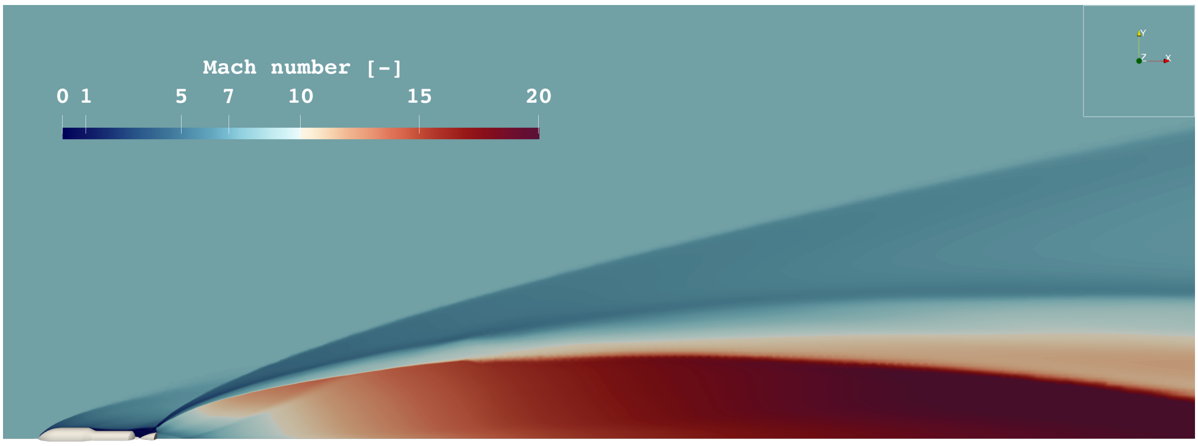


Fig 2. Visualisation of the RFZ-ST2 upper stage showing a 2D slice of Mach number of the vehicle with the exhaust plume

The shocks in front of the fairing and in front of the plume are well visible. The expansion fans at locations where the upper stage tapers to the aft bay and the base can be better seen in a zoomed in, logarithmic plot of density in figure 3. This figure also shows the pressure distribution on the surface of the upper stage.

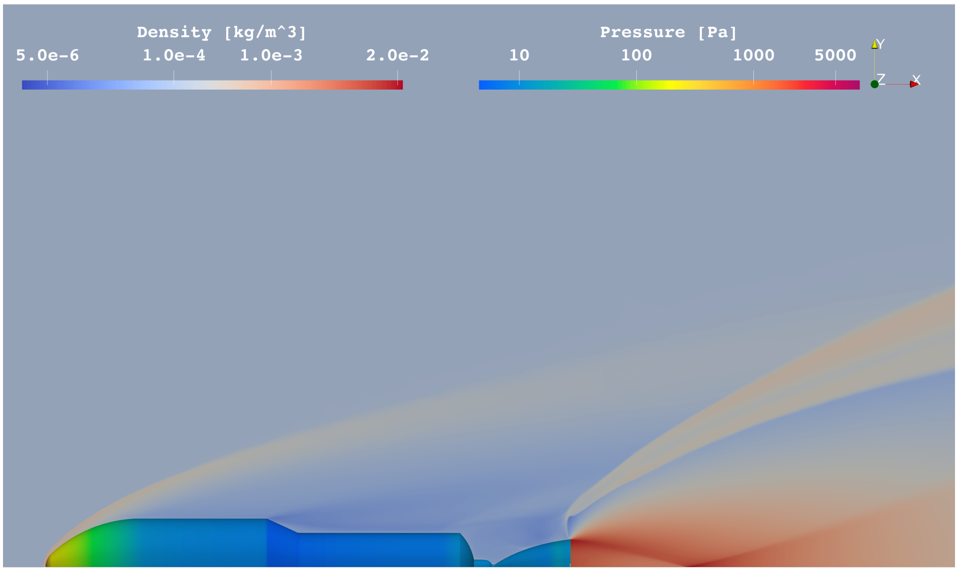


Fig 3. Visualisation of the RFZ-ST2 upper stage showing a 2D slice of density on a logarithmic scale with a surface plot of pressure

5. Conclusion and Outlook

The purpose of this work is the introduction of open source RFZ-ST2 upper stage of the reusable launcher model to the scientific community. We support the publication of the geometric data and the boundary conditions by additionally providing a first set of CFD simulation results done with the DLR Tau code. We will analyse the influence of the grid and the chemistry modelling and and provide result data on flow field, aerodynamic coefficients and surface heat fluxes.

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