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Numerical analysis of hypersonic flows around blunt-nosed models and a space vehicle

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ABSTRACT

This work addresses the problem of the aerothermodynamics of hypersonic nonequilibrium flows over blunt nosed models and space vehicles with rarefaction effects. First, the in-house Navier–Stokes solver, UNIC-UNS code, with the slip boundary condition and finite-rate chemistry is used to simulate the hypersonic flows over a blunt nosed model and the simplified European eXPErimental Re-entry Test-bed (EXPERT) model V4.4. Next, hypersonic flows over the whole EXPERT 3D model, which correspond to the expected descent trajectory with allowance for rarefaction and thermochemical nonequilibrium are simulated. By comparing with the Direct Simulation Monte Carlo (DSMC) method, it is observed that the UNIC-UNS code is reliable in simulating hypersonic flows with rarefaction and thermochemical non-equilibrium effects. A detailed analysis of the aerothermodynamics for EXPERT for a wide range of flow regimes is also provided by utilizing the numerical flow visualization. The present numerical simulations provide some important data for EXPERT, which cannot be easily derived by experiments. This study aims to work as a precursor for future studies and to provide to the scientific community with quality data that can be used to improve tools for the design of hypersonic vehicles.

1. Introduction

Following renewed interest in manned missions to Mars and the moon as well as increasing success in the development of new thermal protection materials offering higher possibilities of developing space vehicles capable of withstanding the higher temperatures caused by higher speed reentries, the problem of studying specific features of high-velocity flows has brought renewed attention to the field of hypersonic aerothermodynamics. Several space agencies, e.g., NASA and ESA (Crew Exploration Vehicle [1], LAPCAT I and LAPCAT II [2]) as well as private companies (ZEHST by EADS [3] and Dragon by Space Exploration Technologies Corporation [4]) are currently designing several hypersonic vehicles that, hopefully, will become the next generation of high-speed vehicles.

The development of future generation of space vehicles requires a complete and detailed knowledge of their aerothermodynamics along with the complete descent trajectory. For this reason, it is necessary to study phenomena associated with rarefaction and thermochemical non-equilibrium of the gas in a hypersonic flow. Such a study could be of help in accurately predicting the in-flight heat flux, pressure and shear stresses from which the thermal load, aerodynamic forces and moments can be calculated. The geometry of the vehicle, and in particular, of the nose and the leading edges of wings and other aerodynamic surfaces, is of a critical consideration in vehicle design.

However, for nearly every ground-based facility, typical parameters (Mach number, *Ma*; and Knudsen number, *Kn*) associated with flow around the space vehicle at high altitudes are limited to certain ranges. Therefore, computational fluid mechanics (CFD) has become a necessary supplementary tool in studying these phenomena [5]. Further, the flight-testing and reproduction of these varied flow conditions in ground-based laboratories are

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Nomenclature

a	speed of sound	ν	stoichiometric coefficients
C	heat capacity	ω_n	species production source term
Cf	pressure coefficient	X	axial location
Ch	force coefficient in the x direction	α_n	nth species mass fraction
Cp	pressure coefficient	γ	ratio of specific heat
D	nose diameter	$\tilde{\Delta}$	dimensionless stand-off distance
H	enthalpy or energy	ϑ_r	turbulence kinetic energy production rate
K	thermal conductivity	μ_l	laminar viscosity
k, ε	turbulence parameters	μ_t	turbulence eddy viscosity
m_w	mixture molecular weight	μ_e	effective viscosity
p	surface pressure	ρ_b	body density
p_∞	freestream pressure	ρ_{b}	equilibrium density
q	convection heat flux	ρ_s	density right after the normal shockwave
Q	volumetric heat source	σ	Prandtl number/Schmidt number
Q_t	heat source	τ_w	wall shear stress
$\Re$	universal gas constant	Φ	energy dissipation function
T_s	Solid Temperature	$\tilde{\Omega}$	dimensionless chemical reaction parameter

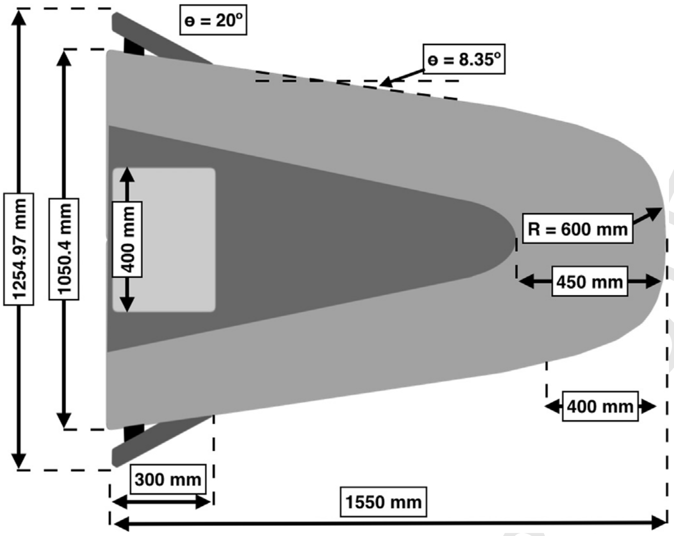

Fig. 1. Geometry of the EXPERT (V4.4) capsule.

both expensive and technically challenging. Hence, computational models play extremely important roles in the development of hypersonic vehicles.

Nevertheless, the lessons learned from past flight-test programs, such as the ESA Atmospheric Re-entry Demonstrator (ARD) have underlined the need for more accurate and extensive hypersonic flight data. This is particularly true with the characterization of hypersonic phenomena such as high temperature and chemistry effects, gas-surface interaction, catalysis and oxidation. The European Experimental Reentry Test bed (EXPERT) is a flight vehicle aiming to collect the aerothermodynamic (ATD) flight data needed in validating design tools, ground test facilities and verification techniques [5]. Therefore, EXPERT has been developed to benefit future atmospheric re-entry activities ranging from cargo to human orbital transportation systems as well as reusable launchers and scientific probes. The EXPERT configuration (see Fig. 1) is composed of a conical body with a cone angle of 12.5°, truncated by planes at an angle of 8.35° to the axis of symmetry featuring four control flaps deflected by 20°; and a nose with a local radius of 0.6 m; the nose–cone junction is described by a clothoid.

Due to the expected high temperatures around the capsule surface, EXPERT was designed to have two main structures; a hot outer structure and a cold structure, which are decoupled from each other. The three main parts of the hot body structure are: the nose cap and flaps made of ceramic composite materials, and the general body made of oxide dispersion strengthened super alloy.

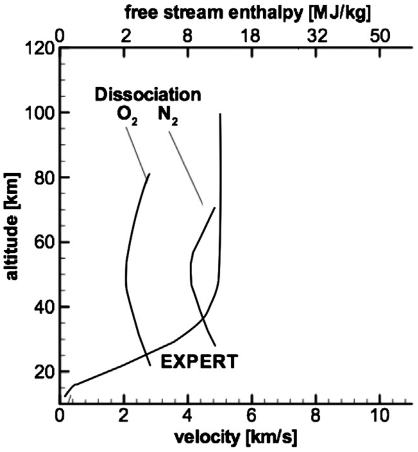

Fig. 2. Evolution of the velocity and enthalpy of the EXPERT capsule along its descent trajectory [5].

It was planned that EXPERT will be launched with a Russian converted ICBM Volna missile from a submarine, flying a suborbital ballistic trajectory from the Pacific Ocean to a landing site located on the peninsula of Kamchatka. It will be injected with an initial flight path angle of −5.5° and a velocity of 5 km/s at an altitude of 100 km. The EXPERT test window will last around 140 s until the drogue parachute is deployed, allowing a landing speed lower than 10 m/s [5]. The evolution of the velocity and enthalpy are shown in Fig. 2. The mission was designed such that the flight speeds are compatible with conditions that can be achieved from ground facilities, thus allowing extensive comparisons between flight and ground data, which is of primary importance to validate theoretical models. Notably, as of 2012, Russia has withdrawn from the EXPERT project and the launch by its Volna rocket was canceled. The launch is now expected to be carried out by the ESAs Vega small-satellite launcher [6].

Several studies have been performed on the EXPERT capsule. For example: Vashchenkov et al. [7] ran a series of numerical simulations for different angles of attack and rolling of the capsule using nitrogen at altitude of 107 km down to 85 km; Schettino, et al. [8] performed an analysis for aerodynamic characteristics at an

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