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Survey of aerodynamics and aerothermodynamics efforts carried out in the frame of Mars exploration projects

Philippe Reynier [1]

Ingénierie et Systèmes Avancés, Mérignac, France

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ABSTRACT

This contribution is a survey of aerodynamic and aerothermodynamics data related to Mars entry. The survey includes the studies carried out in the frame of projects aiming at preparing exploration missions involving entry probes into Mars atmosphere and the efforts have been concentrated on the aerothermodynamics developments. Russian (including former Soviet Union), European and NASA aerothermodynamics developments for preparing such missions have been accounted for. If a focus has been dedicated to the flight data gathered during Viking and Mars Pathfinder entries, the experimental and numerical activities carried out for the different projects have been also considered. The emphasis has been put on the post-flight analysis of flight experiments. The objective of the activity has been to develop a database of the developments performed for Mars entry that will be of interest for the preparation of future missions and for testing new models related to radiative transfer, and chemical kinetics schemes based on a state-to-state approach.

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E-mail address: Philippe.Reynier@isa-space.eu

[1] Research Engineer, ISA, France.

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1. Introduction

In the frame of planetary exploration, Mars has been the most visited planet in the solar system and a large number of vehicles have been launched carrying landers for surface exploration. The different missions carried out for Mars exploration are summarised in Table 1 where the entry velocity, the existence of flight data with instrumented heat shields, and the cause of the failure of the mission when applicable. The information on the different missions have been found in [1,2].

Two primary uncertainties related to Mars entry are the capability to predict turbulent forebody heating that can be driven by vehicle design or ablative boundary [1,3–5] and surface catalysis in a CO_2 environment [6]. It is well known that transition to turbulence in hypersonic flight generally occurs in the downstream region over the cone surface; for a spherical body (without angle of attack) around the sonic point, located at an angle of 30° from the nose [7]. According to Ahn and Park [8] this can be due to

– the sphere cone junction, that produces an unfavourable pressure gradient due to the disappearance of the centrifugal force there, and
– surface roughness due to ablation,
– possible spallation (but this last does not apply to Mars entry).

The scenario is more complex when using an ablative TPS. After starting of the ablation, if the char layer is not delaminated quickly enough, its porosity enables the transport of pyrolysis gases generated from thermal protection system (TPS) material decomposition [9]. Depending on material properties (presence of fibres, thin liquid film at the wall), the blowing of these gases into the boundary layer can modify the skin friction and convective heating [5,10]. The combined effects of roughness and blowing on turbulent boundary layers have been studied experimentally in several studies. These effects can be accounted for in the TPS design process by one of the following macroscopic approaches:

– the wall boundary condition, and appropriate turbulence model, of the numerical solver can be modified to incorporate these effects;
– the skin friction and convective heating, obtained for a non-ablating smooth wall, can be adjusted using engineering correlations.

For Mars entry, a non-negligible part of the heat-flux is due to the chemical catalytic reactions occurring at the TPS surface. This is particularly the case for Mars entries where the ratio between the predictions of heat-fluxes with and without catalysis can be higher than two [6]. As a consequence, the optimisation of the heat-shields, that represent a non-negligible fraction of the mass budget for entry capsules, requires more accurate predictions of the heat-fluxes over the TPS.

Other issues are related to the modelling of non-equilibrium effects and radiation. To model collisions between atoms and molecules quasi-classical trajectory calculations are usually applied to three-species (atoms and/or molecules) systems. Collisions involving more species are not generally studied with for consequence some model uncertainties. A similar remark applies to the collisions between species and electrons. It has to be noted that vibrational effects are much more complex with polyatomic molecules such as CO_2 than for diatomic molecules and atoms. Concerning the radiation, that can become an important issue for large entry vehicles, the databases generally used have some limitations:

– vacuum ultraviolet (VUV) contributions of the electronic systems of CO, C_2, CO_2 and C_3;
– need to extend infrared (IR) CO_2 spectroscopic data to high temperatures; and
– need to include species produced by the decomposition of TPS material that can possess absorbing or emitting properties.

Table 1
Summary of Mars entry missions.

Mission	Agency	Entry year	Entry velocity (km/s)	Flight data	Failure
Mars 2	MOM	1971	6.0	No	Lander crashed
Mars 3	MOM	1971	5.7	No	Failed after 20 s
Mars 6	MOM	1974	–	No	Lost during landing
Mars 7	MOM	1974	–	No	Targeting error
Viking 1	NASA	1976	4.5	Yes	
Viking 2	NASA	1976	4.5	Yes	
Mars 96 (Mars 8)	VKS (Russia)	1997	–	No	Launch failure
Pathfinder	NASA	1997	7.5	Yes	
Mars Surveyor	NASA	1999	6.9	No	Failed during descent
Beagle 2	UK	2003	5.6	No	Lost after separation
MER A	NASA	2004	5.6	No	
MER B	NASA	2004	5.6	No	
Phoenix	NASA	2008	5.5	No	
MSL	NASA	2012	5.6	Yes	
ExoMars	ESA	In preparation			