SACOMAR

Technologies for Safe and Controlled Martian Entry

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### Title
Validation Strategy

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### Approved by
Ali Gülhan

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Nomenclature

\begin{align*}
\text{h} & \quad [\text{MJ/kg}] \quad \text{Enthalpy} \\
\text{p} & \quad [\text{Pa}] \quad \text{Pressure} \\
\text{T} & \quad [\text{K}] \quad \text{Temperature}
\end{align*}

Acronyms

\begin{itemize}
\item ATD \quad \text{Aerothermodynamics}
\item CFD \quad \text{Computational Fluid Dynamics}
\item DLR \quad \text{German Aerospace Center}
\item HEG \quad \text{DLR Shock Tunnel in Göttingen}
\item IPM \quad \text{Institute for Problems in Mechanics}
\item IT-2 \quad \text{Hot Shot Wind Tunnel of TsAGI}
\item ITAM \quad \text{Institute of Theoretical and Applied Mechanics}
\item L2K \quad 1.4 MW Arc Heated Facility of DLR in Cologne
\item LIF \quad \text{Laser Induced Fluorescence}
\item TsAGI \quad \text{Central Aerohydrodynamic Institute}
\item TsNIImash \quad \text{Central Research Institute of Machine Building}
\item TN \quad \text{Technical Note}
\item WP \quad \text{Work Package}
\end{itemize}
1 Introduction

The main shortcoming of the CFD tools for the simulation of the Martian entry is strongly linked to the missing correct modeling of the physical phenomena related to the high velocity, i.e. high enthalpy effects. In the high enthalpy flow field behind the bow shock of a Martian entry vehicle the gas species undergo chemical reactions including dissociation, ionization and recombination reactions. The heat flux rate to the vehicle surface depends strongly on parameters like thermodynamic properties of the gas, gas transport parameters, reaction kinetics in the gas phase and surface reactions depending on catalysis.

Compared to Earth atmosphere the thermo-chemical modelling of Martian atmosphere is more complex and covers a wider range of thermo-dynamical states due to several aspects:

- The main species in Martian atmosphere is CO$_2$, which is a polyatomic species. There are models that describe the thermo-dynamical behaviour of polyatomic models, but the experience and the degree of validation of these models are less compared to atomic or diatomic species.

- The surface pressure level of the Martian atmosphere is below 1000 Pa. Therefore, chemical reactions as dissociation and ionisation are initiated at lower temperatures.

- Due to the lower density of the Martian atmosphere compared to Earth thermal and chemical freezing is to be expected, which has a significant influence on surface chemistry and heat flux rates.

2 Validation Concept

The overall objective of SACOMAR is the investigation of the thermochemistry of high enthalpy CO$_2$ flows in order to improve the existing analytical and numerical engineering capabilities for future explorations missions to Mars involving hypersonic entry into Martian atmosphere [1]. Experimental work in high enthalpy ground facilities helps to identify physically relevant phenomena and by that will improve the efficiency of the work on thermo-chemical modelling. Numerical simulation is required, since it provides the natural framework for all thermo-chemical models. In combination with the experiments numerical simulation is able to achieve validation for the considered models.

The technical work of SACOMAR is broken down in four main technical activities (WP4 to WP7). WP4 defines the requirements based on the flight trajectory of the actual EXOMARS project [2]. As shown in Figure 1 the most critical trajectory points with respect to aerothermal loads are selected for the simulation.
In the frame of WP5 validation experiments with respect to aerothermal modelling are carried out in high enthalpy facilities. Tests in the short duration facilities allow to simulate thermal and chemical relaxation phenomena comparable with a typical Martian entry flight. In order to have relatively large shock stand-off distance a cylindrical model with a flat front surface is used. A heat flux sensor on the flow axis measures the stagnation point heat flux rate. An identical model philosophy is used in the long duration facilities (Plasmatron and arc heated), which have some limitations in the Reynolds number but are more suitable to measure the gas parameters using spectroscopic measurement techniques.

The work package group WP6 relating the physico-chemical modelling intends to achieve modelling improvements in the general areas of high temperature Mars mixture thermodynamic and transport properties, non-equilibrium modelling of dissociation and ionisation and radiation simulation. The focus is on gas transport properties and gas chemistry. Because the heat flux rate in such high enthalpy environment strongly depends on the surface catalysis, surface chemistry modelling is a further important task. The study of the gas-surface-interaction on ablator materials is very complex and requires significant resources. Therefore SACOMAR will investigate only fully catalytic and non-catalytic generic material probes.

The work package group WP7 performs first code-to-code validation of numerical tools. The simulation of an identical test case should show the sensitivity of the data to the deviations in the numerical schemes and modelling. High altitude effects including rarefied gas phenomena are studied using the code of ITAM. ASTRIUM is responsible for the simulation of the HEG and IT-2 tests using the TAU code. The rebuilding of the tests in the arc heated facility L2K is carried out by CIRA. The experiments in the Plasmatron facilities are simulated by TsNIImash and IPM.

2.1 Experiments

Gas-phase chemistry in Martian atmosphere and its influence on heat fluxes is a topic that itself is dominated by complex physico-chemical phenomena. Therefore, the geometry of the model that is used for heat flux evaluation should not introduce major additional complexity. It should be kept as simple as possible to enable best possible link between heat flux measurements on one side and
the measured free stream properties as well as modelling parameters and correlated numerical results on the other side.

Vehicles that are supposed to enter Martian atmosphere are designed as blunt bodies which in an hypersonic flow field cause the formation of a strong bow shock on the front side generating substantial heating of the gas and subsequently of the vehicle. Of course, the test configuration should reflect this scenario. A well-suited simplification of a capsule-like geometry is a flat-faced cylinder. Its principal geometry is sketched in Fig. 2. Compared to other blunt geometries, a flat-faced cylinder provides the largest possible shock stand-off distance for the hypersonic test facilities (HEG, IT-2 and L2K). By that, it maximizes the experimental possibilities of probing the gas properties in the shock layer. The flat-faced cylinder geometry will be used for all facility tests. To avoid grid related problems related to sharp edges during numerical simulation the edge of the cylinder should be rounded.

Due to individual constraints, which either arise from facility size or from measurement techniques, a fully identical test geometry cannot be used in all facilities. For the plasmatron facilities the cylinder’s diameter will be $D = 50\text{ mm}$ and the edge radius $r_e = 11.5\text{ mm}$. At almost all long duration high enthalpy facilities corresponding models and model holders are available which keeps the manufacturing necessities for the SACOMAR test programme small and provides good chances for an easy comparison to already existing data from different atmospheres.

For the short duration facilities HEG and IT-2 a $50\text{ mm}$ cylinder is supposed to be too small to embed all necessary instrumentation. Therefore, a flat-faced cylinder with a diameter $D = 100\text{ mm}$ is foreseen for measurements in HEG and IT-2. The edge radius should be identical to the smaller cylinder, i.e. $r_e = 11.5\text{ mm}$.

In the L2K facility tests will be performed on both cylinder geometries. These tests are supposed to identify size effects and provide a bridge between the measurement in short duration hypersonic and the long duration subsonic ground test facilities.

The definition of test conditions is based on characteristic points of the EXOMARS entry trajectory. These trajectory points are listed in Table 1. They cover almost the complete entry phase from high enthalpy conditions at nearly interplanetary cruise speed to low enthalpy conditions at low altitude.
Table 1: EXOMARS trajectory points

<table>
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<tr>
<th>trajectory point</th>
<th>entry time [s]</th>
<th>velocity [m/s]</th>
<th>enthalpy [MJ/kg]</th>
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2.2 Modelling

During entry the dissociated atoms in the shock layer reach the surface of the body and tend to recombine at the surface releasing the dissociation energy which contributes to the overall heat flux into the Thermal Protection System. The mechanisms governing catalytic recombination are still poorly understood, in part due to difficulties in performing surface diagnostics at realistic pressure and temperature conditions [4].

One commonly used model assumes the limiting case of a non-catalytic surface. This assumption leads to the lowest possible heating rates, and therefore is not often employed for design purposes due to its non-conservative nature. Another limiting case is the fully-catalytic modelling of the gas mixture at the wall to local thermochemical equilibrium. Sometimes partially-catalytic modelling with the possibility to consider different recombination efficiencies for the chemical surface reactions is employed. This requires the proper selection of values for different recombination probabilities. As demonstrated by Marshall [5], [6] under test conditions at room temperature, for recombination on quartz, platinum, constantan, stainless steel and chrome surfaces, atomic oxygen recombination O+O to molecular oxygen is the dominant mechanism, while other models consider only CO+O recombination or both recombination processes occurring at the same time but with different efficiencies.

While the limiting cases of fully catalytic vs. non-catalytic surface modelling offer ways to obtain the upper and lower physically possible limits of the aerothermal heat fluxes, much more uncertainty exists in the quantitatively correct heat flux calculation of partially catalytic surface materials. Comparative analysis of the heat transfer data and catalycity determination for different surfaces (metals and quartz) in the frame of this study will help to improve the modeling quality and associated uncertainties for partially catalytic surfaces. Experiments using Quartz (SiO$_2$), Ag, Cu and Steel surfaces are tentatively foreseen.

Surface chemistry and catalysis models will be studied in detail and proposed for use within the consortium in the frame of the experimental/CFD comparison work of IPM. An electronic library containing recombination coefficients and energy accommodation coefficients relevant for the surface reactions relevant to hypersonic re-entry flow fields in a CO$_2$/N$_2$ atmosphere will be worked out and provided to the consortium.

2.3 Validation of the CFD tools

First step of this activity will be code-to-code validation. In order to see a direct comparison between the real flight conditions and conditions in ground testing facilities, computations for the code-to-code validation will be carried out for the same model shape as ground tests. Therefore all codes of the SACOMAR consortium will compute the test model of experiments at selected...
Exomars trajectory flow conditions. This work will be carried out in two steps. First comparisons will be carried out without implementing new physical models in the codes. Here the differences between codes will be discussed and possible improvements related to numerical aspects will be carried out.

As a second step the new physical models developed within this project will be implemented in the codes and numerical rebuilding of the tests will be carried out using existing and new physical models.

As mentioned before ASTRIUM is responsible for the simulation of the HEG and IT-2 tests using the TAU code. The rebuilding of the tests in the arc heated facility L2K is carried out by CIRA. The experiments in the Plasmatron facilities are simulated by TsNIIimash and IPM. High altitude effects including rarefied gas phenomena are studied using the code of ITAM.

Fig. 3: Validation logic of SACOMAR
3 References


