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Numerical simulations of radiative heat effects in a plasma wind-tunnel flow under Mars entry conditions

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ABSTRACT

The Mars atmosphere, consisting mainly of CO_2, with a few percent of N_2 and other trace gases, is of interest to future space projects. Entry into its gaseous shell is of current significant research interest. For this application, an arc jet driven plasma wind tunnel is available to simulate relevant entry conditions for the planet. Recent improvements and qualification of the test facility, enables the testing on earth of high enthalpy flows with CO_2 rich compositions. In order to complement the experimental analysis, numerical simulations of the test facility running at relevant ambient pressures of 600–1000 Pa, corresponding to low altitudes, have been completed. The simulations used a density-based Navier Stokes solver and non-equilibrium chemical and thermal effects which are characteristic of these types of high enthalpy flows. Special interest is given to the radiative heat transfer mechanism. Under these high temperature conditions, radiative effects become more relevant and advanced radiation models must be used. The coupling between the Navier Stokes and radiative transfer equations favours the understanding of plasma wind tunnel flows. The radiative heat is estimated using the k-distribution spectral model, which is appropriate for non-homogeneous radiating media. The numerical results and measurements are compared in order to improve the analysis methods for Mars entry flows.

1. Introduction

Future space projects will focus on sample return missions from Mars, asteroids and comets [1]. The increasing interest in interplanetary missions towards the red planet encourages the investigation of the Martian atmosphere and the entry process of space vehicles into the gas layers. Space capsules will need to resist high temperatures due to deceleration before reaching the planet surface. The atmosphere of Mars is described in subsection 1.1. In order to ensure the success of the missions, studies have to be conducted to characterize the environment in which the vehicles will be exposed.

These investigations require ground based testing facilities, which can simulate the thermochemical environment during entry into the Martian atmosphere. An overview of the available test facilities in Europe that support Mars missions was given in 2011 by M. Bugel et al. [2].

As a complement to experiments, numerical simulations represent a potential tool which is used to study and predict these flows. The chemistry of the thermo-chemical non-equilibrium conditions are implemented in the CFD codes and adjusted to the experimental data available.

This work presents numerical simulations of the arc heated plasma wind-tunnel available at the Institute of Thermodynamics at the University of the Federal Armed Forces in Munich. A brief description of the facility is given under subsection 1.2. The numerical results were obtained by the CFD solver NSMB. More information about the code can be found in the literature [3–5]. Similar work can be found in the literature [6]; however in this case special interest is given in the calculation of the radiative energy transfer by applying highly resolved spectral methods. Recent work coupled the solution of the Navier Stokes equations with the radiation problem using advanced spectral models [7]. The approximation used for the spectral properties of the participating media is presented in subsection 1.3.

1.1. Mars atmospheric entry conditions

The Mars atmosphere is mainly composed by CO_2. Its molar composition can be approximated by 97% CO_2 and 3% N_2. Small amounts of other species such as Argon are present but can usually be neglected. Behind the bow shock formed during the entry of space vehicles, the gas mixture heats and dissociates because of the high temperatures. Fig. 1 shows the equilibrium gas composition behind a normal shock wave for

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Nomenclature

I	Radiative Intensity [W/m²·sr]
I_b	Blackbody Radiative Intensity [W/m²·sr]
I_λ	Spectral Radiative Intensity [W/m³·sr]
Gλ	Spectral Incident Radiation [W/m³]
G	Artificial Wavelength [−]
Q	Radiative Heat Flux [W/m³]
S	Direction Variable [m]
T	Temperature [K]
Tv_{ib}	Vibrational Temperature [K]
y^+	Dimensionless wall distance [−]
ε_λ	Spectral Emissivity Coefficient [W/m³·sr/m]
κ	Absorption Coefficient [1/m]
κ_λ	Spectral Absorption Coefficient [1/m]
λ	Wavelength [m]
Ω	Solid Angle [sr]

Acronyms/Abbreviations

CFD	Computational Fluid Dynamics
FSK	Full Spectrum k-distribution
HELM	High Enthalpy Laboratory Munich
RTE	Radiative Transfer Equation

a wide range of Mach numbers.

Trajectory analyses of Mars missions show typical entry velocity ranges between 5.5 and 7 km/s [8]. For that range of velocities, the gas mixture is not bi-molecular any more, but a mixture of mainly CO_2, CO, O_2 and O. Species such as CN and NO, which are also relevant for the radiation problem, appear with lower concentrations [9].

Entry flows are known to be under thermo-chemical non-equilibrium conditions. This regime is usually approximated with two-temperature models, which account for two different excitation modes. The energy state is then described with a second additional temperature. In this formulation, it is assumed that the translational-rotational and vibrational-electronic modes of the gas are only in equilibrium within each other respectively [10].

1.2. Plasma wind-tunnel

As part of the HELM, at the University of the Federal Armed Forces in Munich, an arc heated plasma wind-tunnel, which can provide high enthalpy flows up to around 20 MJ/kg, is used to investigate Mars environment. The advantage of this test facility is the possibility of long-duration experiments, limited only by the test gas reservoir. The principle of the wind-tunnel is the transfer of the energy from an electric arc to the test gas. Fig. 2 shows the Y-shaped design of the plasma torch.

The gas between the cathode and anode is ionized and it becomes electrically conductive. The electrons between the electrodes are accelerated, whereby thermal energy is transferred through collisions with heavier particles. Within the electric arc region a stagnation temperature in the order of 6000 K can be achieved. The test gas runs through a stagnation chamber and is accelerated through a Laval nozzle. Different nozzle modules can be installed in order to cover a broad spectrum of Mach-numbers in the sub- or supersonic regime. The gas expands into the test chamber which allows the conduct of measurements to characterize the flow [11–13] and probe testing [14].

To investigate the thermochemical effects of the Martian atmosphere, the wind-tunnel has to be run with carbon dioxide as test gas. This is an additional challenge for the experiment because the occurrence of carbon monoxide results in a possibly explosive mixture. Recent work done on the facility ensured operability under Mars entry conditions and enabled the analysis of flow properties by applying TALIF techniques [15,16].

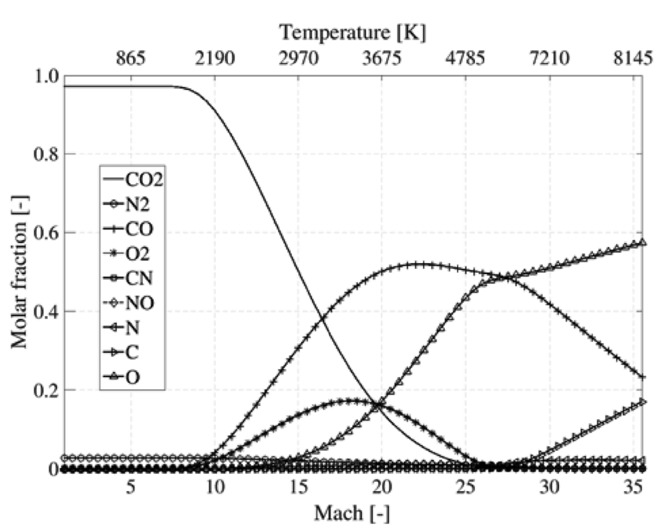

Fig. 1. Equilibrium gas composition after shock wave considering Mars surface mean atmospheric conditions, H = 0 km.

1.3. Radiative heat transfer

The problem of radiative energy transfer is defined by the RTE as shown in Eq. (1), where scattering has been neglected. This equation describes the change of a beam of light intensity passing through a participating medium in a specific direction [17].

$$\frac{\partial I_\lambda}{\partial s} = (\varepsilon_\lambda - k_\lambda I_\lambda). \tag{1}$$

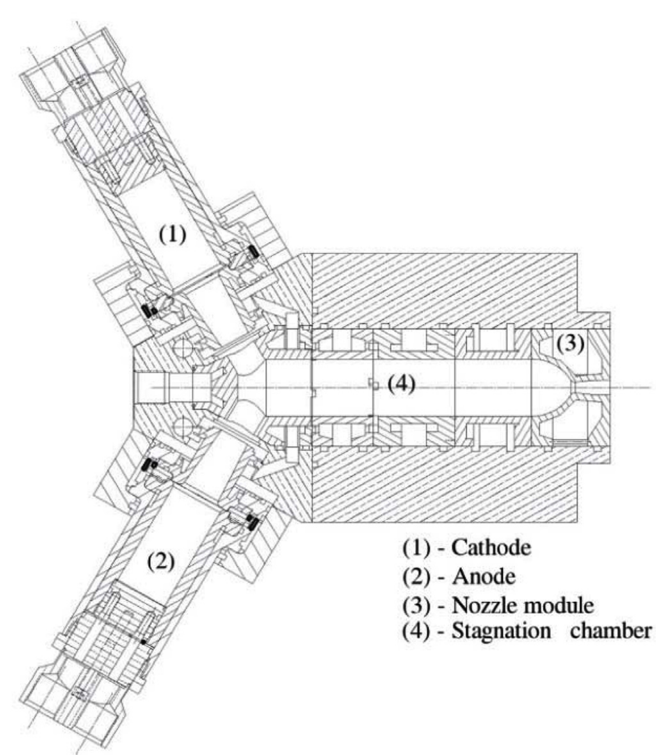

Fig. 2. Plasma wind-tunnel geometry.