SIMULATION OF TITAN ATMOSPHERE BY AN ARC-HEATED FACILITY

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ABSTRACT

Small Planetary Entry Simulator (SPES) is an arc-jet hypersonic wind tunnel in operation from long time at the University of Naples “Federico II”. Up to now SPES has been used to simulate entry conditions for Earth and Mars atmospheres. Recently, the opportunity to use methane as cold gas to be mixed with the nitrogen plasma, in order to upgrade SPES for entry applications in the Titan’s atmosphere, has been investigated. This paper summarizes preliminary theoretical, numerical and experimental results. The analysis of a typical entry trajectory in the Titan’s atmosphere allowed to estimate flow conditions to be simulated in SPES. After the validation of an aerothermodynamic and thermo-chemical model including non-equilibrium chemical reactions in methane-nitrogen gas mixtures, numerical simulations of the experiment performed in the wind tunnel have been carried out. Preliminary comparisons between experimental and numerical results are presented and discussed in the paper.

1. INTRODUCTION

The largest Saturn’s moon, Titan, has been widely studied in the last years because it shares features with other large icy satellites and, above all, with Earth.

Despite the high number of scientific discoveries performed thanks to Cassini-Huygens mission [1,2], several issues, regarding e.g. Titan’s geology and morphology, the seasonal variations of its atmosphere, are still unsolved. It is the reason why for the next future other space exploration missions toward the Saturn’s largest moon are scheduled. Possible future studies of Titan, from orbit and in situ, with conceptually new and technologically enhanced instruments, would provide, as estimated, the potential for an increase in Titan science return from 2 to 3 orders-of-magnitude over that of the Cassini-Huygens mission [2].

In the present work the possibility to reproduce Titan’s atmosphere upgrading the arc-jet wind tunnel available at the Department of Aerospace Engineering (DIAS) of the University of Naples “Federico II”, has been investigated. The above mentioned facility would allow to test, in hypersonic and high enthalpy conditions, candidate materials to be used for the Thermal Protection System (TPS) of a potential Titan entry capsule.

Preliminary experimental heat flux measurements will be in the following compared to results of a Computational Fluid Dynamics (CFD) analysis, carried out implementing a proper kinetic model for chemical reactions between methane and nitrogen.

The article is organized as follows. In Section 2 the main features and performances of the arc-jet wind tunnel available at DIAS are presented. In Section 3 numerical models implemented to compare experimental results with CFD analyses are reported. The comparison between preliminary experimental results and CFD analyses is presented in Section 4. Finally, in Section 5 the main conclusions of the study are summed up and possible future developments are underlined.

2. SPES ARC-JET WIND TUNNEL

SPES (Small Planetary Entry Simulator) is available at the Department of Aerospace Engineering (DIAS) of the University of Naples “Federico II”. This facility belongs to the continuous, open circuit, electric arc-based wind tunnels. Its main components are:

- an electric arc-heater (industrial plasma torch, Sulzer-Metco type 9-M), operating with pure inert gases (argon or nitrogen);
- a mixing chamber where the nitrogen plasma can be mixed with cold gases (oxygen, carbon dioxide or, in this case, methane) to simulate planetary atmospheres;
- four different conical nozzles (area ratios 4, 20, 56, 100) for operations in supersonic and hypersonic flow regime;

- a cylindrical vacuum test chamber (ultimate pressure is in the order of 50 Pa).

Fig. 1 shows the main component of the test facility available at DIAS.

Fig. 1: Main components of SPES facility

Typical SPES operative conditions for entry simulation applications are (order of magnitude): a total mass flow rate of 1 g/s, an average total enthalpy of 15 MJ/kg and a total pressure of 0.5 bar.

In the last years the experimental activities carried out in SPES have been mainly focused on the aerothermal testing and characterization, in high enthalpy and heat flux conditions, of advanced Ceramic Matrix Composite (CMC) materials, to be employed as Thermal Protection System (TPS) of hypersonic Earth re-entry vehicles. In particular the material oxidation, its surface emissivity and catalycity have been investigated in order to completely assess the aerothermal behavior of the analyzed sub-scaled samples [3,4,5]. Fig. 2 shows one of the typical experiments carried out in SPES: the aerothermal heating of a sharp wedge, realized in Ultra High Temperature Ceramic (UHTC), exposed to high enthalpy hypersonic conditions.

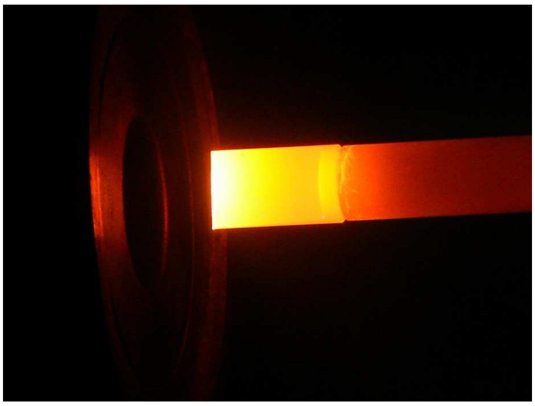


Fig. 2: Sharp wedge in UHTC tested in SPES facility

In the past, using as cold gas the carbon dioxide, SPES made also possible to experimentally reproduce the Martian atmosphere and even to test materials for the Mars Pathfinder thermal protection system [6].

The relatively recent discoveries provided by Cassini-Huygens mission and the great interest of the scientific community in the possibility to perform, in the next future, novel space exploration missions toward Titan, led to study the possibility to upgrade SPES in such a way to simulate Titan atmosphere using the methane as cold gas, instead of oxygen.

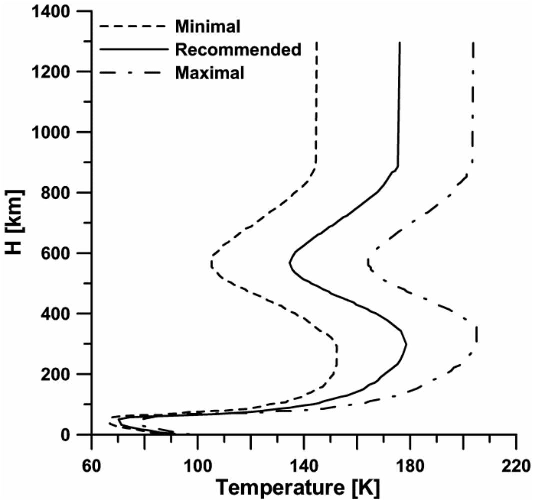
3. NUMERICAL MODELS

The numerical and experimental simulations of the entry phase into Titan's atmosphere required the implementation of different models, in order to take into account the differences between the Titan's atmosphere and the Earth's one. In the following paragraphs they will be presented and discussed.

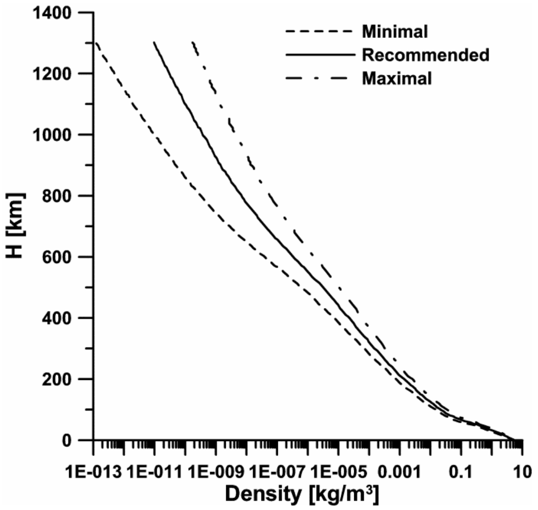
3.1 Engineering models for Titan's atmosphere

In the present paragraph the engineering models for Titan's atmosphere provided by Yelle et al. [7] will be reported. These models are mainly based on observations made by the Voyager 1 Radio Science Subsystem (RSS) and by its infrared and ultraviolet spectrometers. In particular, three different profiles have been considered for temperature and density (maximal, minimal and recommended), in order to take into account several kind of uncertainties which could affect the model, namely: 1) the uncertainties in the analysis of Voyager data; 2) possible latitudinal variations in the atmospheric structure; 3) possible temporal variations of the atmosphere properties.

The recommended model provides an adequate fit to all data sets available [7]. It has therefore considered in the entry trajectories calculation. Fig. 3 shows the above mentioned profiles.



a)



b)

Fig. 3: Temperature (a) and density (b) profiles as functions of altitude

3.2 Chemical kinetic model for Titan entries

One of the most critical aspects of a space mission which foresees the atmospheric entry phase of a spacecraft component is the dimensioning of its heat shield. The accurate estimation of the heat fluxes experimented by the entry module is therefore necessary to guarantee its integrity.

In the present work, the heat fluxes measured in the arc-jet facility will be compared to the ones estimated by means of CFD analyses. In hypersonic aerodynamics, a key factor for an accurate heat flux numerical evaluation is the correct definition of the chemical kinetic model for the reacting species of the working gas.

A reduced chemical kinetic model involving the most significant species produced during a typical entry into Titan’s atmosphere, has been included in this work. This model, proposed and numerically validated by Savajano et al. [8], comprises 18 species (N2, CH4, CH3, CH2, CH, C2, H2, CN, NH, HCN, N, C, H, N2+, CN+, N+, C+ and e-) and 28 reactions.

The kinetic chemical model has been implemented in the software FLUENT and DS2V, solving the flow equations in continuum and rarefied aerodynamic regimes (Navier-Stokes equations and molecular approach, respectively). As test case, two-dimensional and axisymmetric numerical simulations, in chemical non-equilibrium conditions, have been performed around the Huygens entry capsule, for the entry conditions reported in Tab. 1.

Fig. 4 shows the pressure distributions on the capsule surface computed by means of CFD and DSMC analyses.

Tab. 1: Asymptotic conditions for the validation of the reduced chemical kinetic model

Velocity [m/s]	Temperature [K]	Pressure [Pa]	Mass fraction	
			N_2	CH_4
5126	176.6	16.1	0.95	0.05

The results are in sufficient agreement, considering that they are obtained with completely different approaches.

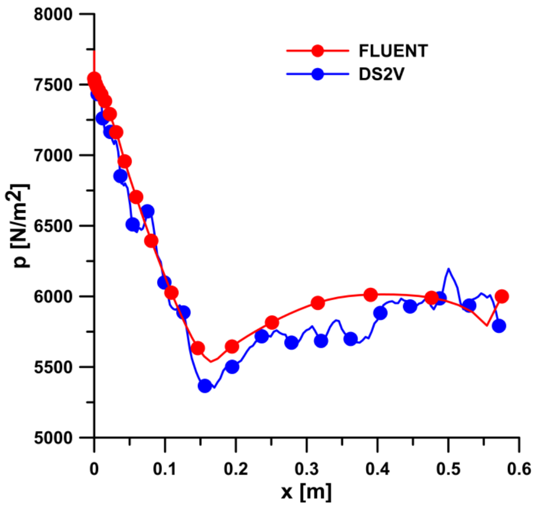


Fig. 4: Comparison between the static pressure distributions on the Huygens capsule surface, calculated by means of CFD and DSMC analyses

Analyzing the chemical species concentrations distributions, the results show a satisfactory agreement among CFD and DSMC results and the values reported in literature [8,9]. In particular, both CFD and DSMC analyses show that the maximum mole fraction of CN (the most important chemical radiator) along the stagnation line is close to 0.02 (see Tab. 2). Tab. 3 reports the comparison between the stagnation point convective heat fluxes calculated by means of the above mentioned analyses and the analogous CFD results available in literature [9]. The present results correspond to a peak heat flux of 480 kW/m^2, which is slightly greater than the literature value. This can be explained by the different boundary conditions considered (cold wall at T=300 K in the present work, equilibrium radiative temperature in [9]).

Tab. 2: Comparison between the peak CN mole fractions on the Huygens capsule stagnation line

	Present work	Literature [9]
Peak CN mole fraction	0.018	0.020

Tab. 3: Comparison between the stagnation point heat fluxes on the Huygens capsule surface

	Present work	Literature [9]
$\dot{q}$ [kW/m^2]	480	450

3.3 Modelling of convective and radiative heat fluxes along re-entry trajectories

Simple engineering correlation are usually employed to preliminarily estimate the convective and the radiative heat flux distributions along re-entry trajectories into Earth's atmosphere. These models are, in principle, not valid for the entry phase into Titan's atmosphere, because its chemical composition leads to the formation of different species and, in addition, to different kinetic mechanisms.

Huge differences can be noticed, in particular, between the models employed to estimate the radiative heat flux for Earth re-entry (like the one provided by Tauber-Sutton [10]) and the ones recommended for entry into Titan's atmosphere. This is mainly due to the presence, in the shock layer of a capsule entering Titan's atmosphere of strong radiators, like CN and HCN, totally absent for Earth re-entry [8]. The empirical correlation implemented in the present work for the radiative heat flux distribution along entry trajectories is reported in Eq. 1 [2,11], being r_C the radius of curvature of the capsule, ρ the atmospheric density and V the asymptotic velocity.

$$q_{rad} = 3.52 \cdot 10^{-10} \cdot r_C \cdot \rho^{1.65} \cdot V^{5.6}, W/m^2 \qquad (1)$$

Detra-Hidalgo model [12] has been implemented, on the other hand, for convective heat fluxes (see Eq. 2).

$$q_{conv} = 5.16 \cdot 10^{-5} \cdot \sqrt{\frac{\rho}{r_C}} \cdot V^{3.15}, W/m^2 \qquad (2)$$

This method generally registers, for Earth re-entry, an accuracy of 10% for velocities between 1.8 km/s and 8 km/s and for altitudes up to 70 km. Nonetheless, the convective heat flux variation along the Huygens entry path into Titan's atmosphere, obtained implementing Eq. 2 resulted to be, among the different ones analyzed, in good agreement with results provided by Mazoué et al. [13]. Fig. 5 shows the convective and the radiative heat fluxes along the computed Huygens entry trajectory.

It has to be specified that the entry trajectory considered has been numerically computed integrating the dynamic equations of motion for the Huygens capsule (having a ballistic parameter of about 37 kg/m^2 [13]) assuming as initial conditions the ones reported in Tab. 4.

Tab. 4: Initial conditions for entry trajectories computation

Altitude [km]	Velocity [m/s]	Flight path Angle [°]
1270	6040	-68

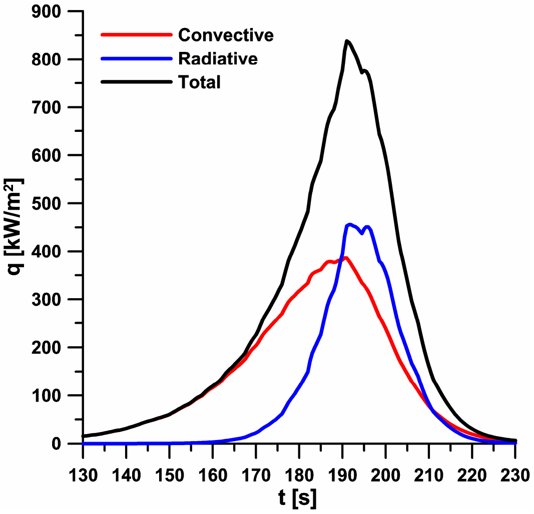
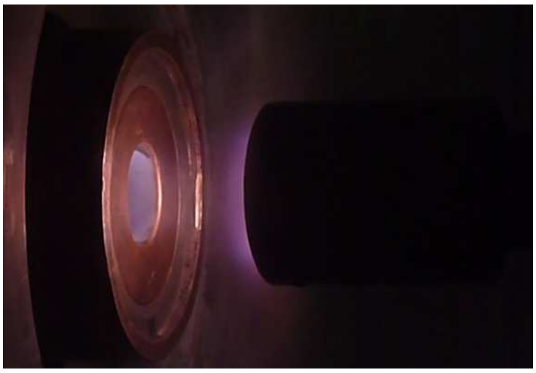


Fig. 5: Convective and radiative heat fluxes variation along Huygens entry trajectory

4. EXPERIMENTAL TESTS IN SPES AND NUMERICAL REBUILDING

The experimental tests in SPES facility have been carried out using a conical nozzle characterized by an area ratio of 20 (and to a corresponding outlet Mach number of about 3), and setting the power at the electric arc between 9 and 10 kW. The heat flux measurements have been performed by means of a slug calorimeter located at 2.5 cm distance from the nozzle exit.

During each test, the first heat flux measurement has been carried out with the probe inserted into a pure nitrogen supersonic jet, characterized by a mass flow rate of 0.4 g/s. Then, a secondary methane jet with flow rate of 0.1 g/s has been mixed to the primary jet and the probe inserted for a second measurement. Fig. 6 shows the impressive difference of brightness between the two configurations. This is mainly due to the high amount of radiation due to some products of the exchange chemical reactions between nitrogen and methane, such as CN and HCN.



a)

b)

Fig. 1: Heat flux probe inserted into the pure nitrogen jet (a) and into the mixed nitrogen-methane jet (b)

Tab. 5 summarizes the measured total stagnation point heat fluxes, compared to the results obtained by means of a numerical rebuilding of the experimental test, under the assumptions of Non-Catalytic (NC) and Fully-Catalytic (FC) wall.

Tab. 5: Comparison between experimental and numerical stagnation point heat fluxes

	$\dot{q}$ [kW/m^2]
Experimental (N_2)	875 ± 35
Experimental (N_2+CH_4)	1240 ± 40
Numerical (NC wall)	475
Numerical (FC wall)	1300

Tab. 5 shows that the addition of methane to the primary jet (for the same electric power), produces an enhancement of the heat flux measured by the probe, in the order of 400 kW/m^2 (i.e. about 45%).

This results can be explained not by the different radiative contributions (as explained below), but by the different gas compositions and by the different catalytic recombination behaviour of the chemical species on the calorimeter surface. In particular, the results suggest that the calorimeter surface exhibits a higher catalyticity with the nitrogen-methane mixture than for the pure nitrogen jet.

In order to better investigate the effect of radiation on the heat flux, further experiments have been carried out at the same experimental conditions, but using a black-painted calorimeter. Tab. 6 shows the comparison between the measured heat fluxes for the "Untreated" calorimeter and the "Black-painted" one.

Tab. 6: Comparison between stagnation point heat fluxes measured on the untreated and on the black-painted calorimeter

$\dot{q}$ [kW/m^2]	N_2	N_2+CH_4
Untreated	875 ± 35	1240 ± 40
Black-painted	613 ± 28	868 ± 20

The heat fluxes are 30% lower for the black-painted calorimeters, for both nitrogen and nitrogen-methane supersonic jets. This result pointed out that there is a negligible influence of the non-luminous radiation on the heat transfer, as also found in similar experimental studies available in literature [14,15].

The smaller measured heat fluxes for the painted surfaces can be explained by the reduction of the catalytic efficiency, related the smoother surface profile established when the calorimeter wall is coated by the black paint.

5. CONCLUSIONS AND FUTURE INVESTIGATIONS

A kinetic model for reactions between nitrogen and methane has been implemented and validated.

Preliminary experimental tests in SPES facility have been carried out in order to investigate the possibility to simulate, in the future, material resistance to entry conditions into Titan's atmosphere.

The experiments show that, despite the high luminescence of the nitrogen-methane jet, the radiative heat flux has a negligible role. This is probably explained by the relatively small scale of the hypersonic jet. A radiation model has to be implemented into CFD codes only in order to simulate hypersonic flows on large blunt bodies.

The huge differences between the convective heat fluxes evaluated, by means of CFD analyses, for non-catalytic and fully-catalytic conditions, suggest that a correct evaluation of the surface catalyticity will be fundamental to have a reasonable estimation of the convective heat flux.

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