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ORIGINAL ARTICLE

Perspectives and Recent Progresses on the Simulation of the Entry into the Atmospheres of the Outer Ice Giants

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Abstract
The relatively recent decision of NASA and ESA to plan new missions to the so-called Ice Giants, namely Uranus and Neptune, has prompted a resurgence of interest in the experimental analysis of the aero-heating environment that probes entering such atmospheres would experience. In the present study, arc-jet facilities, previously used to simulate space flight in the atmospheres of Earth, Mars, and Titan, are considered as a relevant basis for the implementation of a more complex framework adequately accounting for the atmospheric features of the Ice Giants. It is shown that the key to the successful realization of such an endeavor is a new operating mode for the plasma torch (relying on a nitrogen–hydrogen mixture) together with the inclusion of a new gas control unit, a new mixing chamber to generate relevant gas mixtures (mimicking to a sufficient extent the Ice Giants atmosphere) and a new thermo-chemical model of the overall flow process. The outcomes of some initial tests are presented to demonstrate the adequacy and performances of the implemented approach with respect to typical entry conditions related to these two planets.

Keywords Planetary entry · Arc-jet facility · Ice Giants

1 Introduction

Present knowledge about Uranus and Neptune, the two giant gas planets on the edge of our solar system, is relatively limited due to a lack of information coming from "direct measurements". Most of available data result from observations of their atmospheres, as provided, e.g., by the Voyager 2 mission, which flew over the two planets in 1986 and 1989 (for Uranus and Neptune), respectively. Although studies exist [1, 2] where possible ways to explore these planets have been outlined, the intention of NASA and the other major space agencies to return to these planets to get more precise (quantitatively accurate) data are much more recent [3, 4].

Using dedicated probes, the atmospheres, rings, and satellites of these planets will be studied. The proposed missions display some interesting aspects: while the first involves sending a probe into the orbit of Uranus with 50 kg of instruments on board; another, still towards Uranus, will rely on a much better equipped vehicle (carrying up to 150 kg of scientific instruments); a third mission will head towards Neptune, with a probe carrying 50 kg of instruments. Special attention will be paid to Triton, Neptune's largest moon, given the widespread consensus that this moon might be an object from the Kuiper Belt (a belt of asteroids and comets that lies beyond Neptune), probably captured during a pass close to the planet. Geysers have been discovered on Triton and it appears to have a tenuous atmosphere.

Better exploration of these planets will certainly contribute to improve our knowledge of our Solar System and its formation dynamics. This renewed interest, however, also stems from recent discoveries about extrasolar planets. Giant gas planets seem to be a rule rather than an exception [5]. Clarifying why the outer gas planets of our system are so different from Jupiter and Saturn will help scientists to disentangle the conundrum about the different possible compositions of gas planets and the mechanisms driving such a diversity.

Uranus and Neptune are often referred to as the "frozen giants", because their atmosphere, although rich in

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hydrogen and helium (like Jupiter and Saturn), contains a high proportion of water, ammonia and methane ices, as well as traces of hydrocarbons. Uranus also has the coldest atmosphere in the Solar System, with temperatures of − 224 °C. What drives a wedge between these two planets and the other two gas giants of our Solar System is also the unique fluid-dynamic behavior of their atmospheres, for which a convincing explanation has not been elaborated yet.

Moreover, Uranus has recently returned to the spotlight for a study related to the characteristics of its moons Ariel and Miranda [6]. The research is based both on computer models and on the archival data of Voyager 2 which, more than 37 years after the flyby of Uranus, have revealed new details about its entourage of natural satellites. Scientists have thoroughly analyzed the magnetic data and those relating to solar radiation collected by the historic NASA probe in this ice planet system and have found some anomalies; from their examination, the team hypothesized that Ariel and Miranda, belonging to the group of 27 "major moons" accompanying Uranus, could host oceans beneath their surface. This discovery, according to scholars, reinforces the belief in the need for an exploratory mission dedicated to Uranus.

All these factors have contributed to create new stimuli for the in-depth exploration of these worlds, and the recent plans of NASA and ESA [7, 8], as also detailed in the 2023–2032 Decadal Survey [9], should be regarded as the natural consequence of such a widespread interest. New probes are being designed and the major challenges obviously relate to the extreme heating environment that they will experience, comparable perhaps only to the Galileo probe entry to Jupiter in 1995 [10].

Given these premises, the present work is devoted to a critical analysis of a facility, which has already enjoyed a widespread use in past years for the experimental simulation of entry into the atmospheres of rocky planets such as Earth, Mars, and Titan [11–13]. The obvious objective is a proper extension of the capabilities of this facility to represent a wider category of possible atmospheres and entry conditions. After a description of its "basic" (original) architecture, we discuss the modifications implemented in the attempt to address such a challenge. These include: a new operating mode for the plasma torch (relying on a nitrogen hydrogen mixture), a new gas control unit to manage the considered gases, a mixing chamber to generate relevant gas mixtures, and the elaboration of a new model of the overall flow process able to account for the considered specific chemical compositions. The outcomes of some preliminary testing activities are presented together with indications for possible future developments and improvements.

2 Entry Parameters for Ice Giants Atmospheres

For the convenience of the reader, it is worth starting from the simple remark that the first step towards the experimental simulation of planetary entries relates to the need to represent or mimic adequately the involved specific enthalpies. For entries from a circular orbit, the initial entry speed is in the order of the first cosmic velocity:

$$V_1 = \sqrt{G\frac{m_{\text{body}}}{r_{\text{body}}}}, \quad (1)$$

where G is the gravitational constant (6.67 10^{-11} m^3 kg^{-1} s^{-2}), m_{body} is the mass of the considered planet and r_{body} is its radius). As the general definition of the mass specific total enthalpy simply reads:

$$H_{\text{tot}} = h + \frac{V^2}{2}, \quad (2)$$

where h is the mass specific enthalpy and V is the vehicle speed, the initial total enthalpy can be estimated accordingly as ½$(V_1)^2$.

Figure 1 shows the typical outcomes of this way of thinking. As the reader will immediately realize by inspecting this figure, a low Earth orbit reentry, typically associated with an initial specific enthalpy of 32 MJ/kg, differs by orders of magnitude with respect to a Jovian entry, for which the specific enthalpy can even exceed 1 GJ/kg [14]. This figure is, therefore, instrumental in revealing the wide range that has to be covered in terms of specific enthalpy and the hard requirements that relevant facilities must meet to simulate adequately such entry missions. In particular for Ice Giants, the initial specific enthalpies are 250 MJ/kg for Uranus and

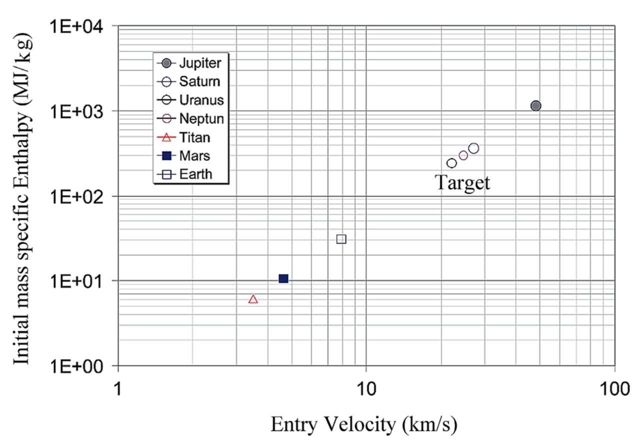


Fig. 1 Initial entry velocity and specific enthalpies for planetary entries (after [14] under the terms of the creative commons attribution non-commercial license)

306 MJ/kg for Neptune, corresponding to entry velocities of 22.34 and 24.73 km/s, respectively.

The problems to be addressed, however, are not limited to the value of the specific enthalpy per se. Adequate care must also be put in ensuring that the composition of the gas is representative of the considered conditions. As even a cursory perusal or the literature would immediately reveal, in many studies, the influence of trace components such as CH_4 on the aero-heating environment has been ignored [15]. An interesting review of the presence of various tropospheric and stratospheric constituents in the Ice Giants can be found in Moses et al. [16].

It is also worth recalling that, as made evident by past Titan entry experiments, CH_4 can significantly contribute to the radiative heat flux. In this regard, the recent efforts by Coelho [17] are instructive. It has been shown there that even concentrations as low as 1.5% CH_4 can significantly enhance the radiative heat flux for Ice Giant entry trajectories. More precisely, while Cruden et al. [18] found that radiative heating can be disregarded for speeds lower than 25 km/s, according to Coelho, the presence of CH_4 may make radiative heating comparable to convective heating even for relatively speeds as small as 18 km/s.

We wish also to remark that, however, this problem is less significant in the case of Ice giants. The major deceleration and therefore aero-heating for Ice Giant trajectories is expected to occur in the stratosphere [8]. Accordingly, the CH_4 percentage in the case of Neptune is expected to be an order of magnitude lower than the value modeled by Coelho; the corresponding percentage for Uranus should even be three orders of magnitude smaller.

Nevertheless, in the present study, some attention is still paid to radiative heating as assessing this capability should be regarded as a relevant part of any attempt devoted to establishing relevant atmosphere models [19].

In particular, we refer to the analysis by Prabhu [20], who conducted a detailed study of Uranus and Neptune atmospheric entries on a 45° sphere–cone probe forebody geometry with nose radii $R_N = 0.2/0.3/0.4$ m. For the case with $R_N = 0.4$ m, this author found a stagnation point heat flux spanning the interval from 10.5 to 42 MW/m^2 and a stagnation point pressure ranging between 0.18 and 1.8 MPa. Additional details about the (relatively similar) ranges considered here are reported in Sect. 3. As a concluding remark for this introduction, we wish to highlight that, while both the above total enthalpy and stagnation point heat flux are within the reach of the present study, this concept does not apply to the stagnation point pressure (given the intrinsic limitations of the facility described in Sect. 3, in particular, in terms of maximum mass flow rate). A smaller stagnation pressure with respect to that obtained by Prabhu [20], obviously, sets limits to the utilization of the present facility for vehicle structural tests. Its recommended use and the outcomes of the present study are, therefore, limited to the simulation of purely thermo-fluid-dynamic aspects.

3 Experimental Apparatus (SPES)

3.1 Facility Description

Experiments have been carried out using the arc-jet facility named SPES (small planetary entry simulator) [21], see Fig. 2a. In its basic configuration, this facility should be regarded as a continuous, open circuit arc-driven system; its main components are summarized in Fig. 2b and consist of:

1. An electric arc-heater (industrial plasma torch, Sulzer-Metco 9-MB, with arc swirl stabilization), able to deal with pure inert gases such as argon, nitrogen, helium and related mixtures. The maximum achievable power is 80 kW, the maximum mass flow rate is 3 (g/s).
2. A mixing chamber, specifically used to mix nitrogen plasma with other cold gases (oxygen, carbon dioxide and others) as desired (depending on the specific planetary atmosphere to be simulated).
3. Conical nozzles with different area ratio (4, 20, 56), by which supersonic and hypersonic velocities can be achieved.
4. A cylindrical vacuum test chamber (minimum pressure of 50 Pa about).

3.1.1 Instrumentation

The gas mass flow rates to the plasma torch are measured by thermal mass flowmeters, while variable-area flowmeters are used for the corresponding coolant flow rates and other gas flows. Other relevant parameters such as the voltage and current provided to the arc-heater are determined by means of digital instruments. Moreover, other measures related to the temperatures from thermocouples located on the arc-heater, the nozzle and other components, rely directly on a dedicated electronic data acquisition system. Pressure measurements are managed by means of absolute transducers, previously calibrated by a capacitive vacuum gauge.

3.1.2 Data Reduction

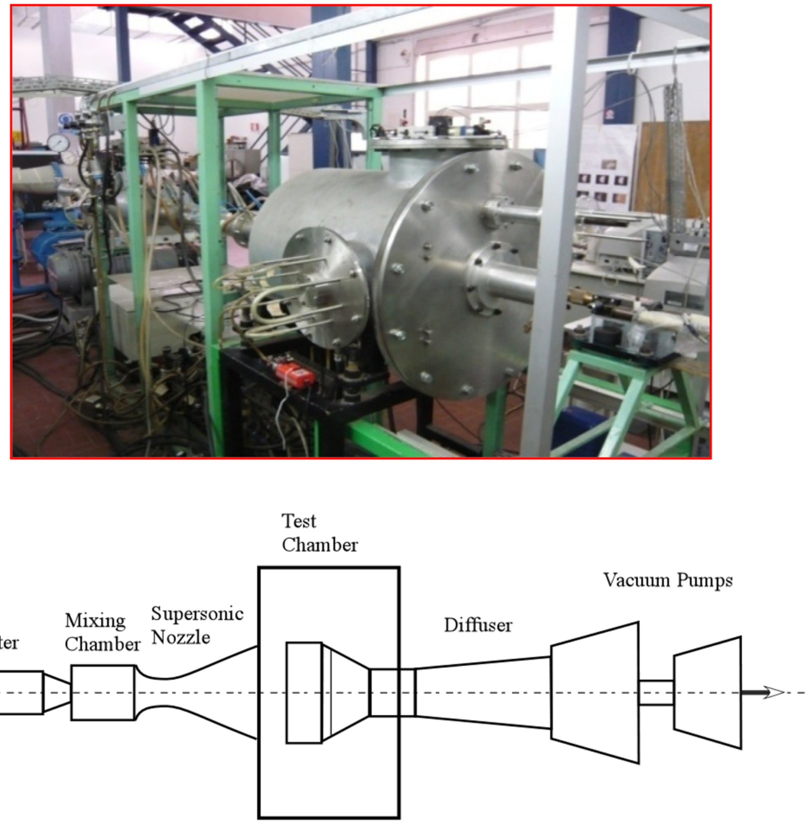
The bulk enthalpy of gas is typically calculated at three different positions along the arc-jet, in the framework of the energy balance method [22]. The measured enthalpies result from averaged values of all the forms of energy at each position in the arc-jet. More specifically:

(i) The enthalpy of the gas leaving the arc heater and entering the mixer is estimated as the difference

Fig. 2 SPES **a** overall picture **b** layout

(a)

(b)



between the input electric power and the losses due to the cooling water:

$$H_{ah} = \frac{P - (m_{H2O} C \Delta T)_{ah}}{m_{g,ah}}, \tag{3}$$

where C= 4186 J/kg, P is the electrical arc power, m_{H2O} is the water mass flow, ΔT is the water temperature rise, $m_{g,ah}$ is the gas mass flow.

(ii) The enthalpy of the gas leaving the mixer and entering the nozzle reads:

$$H_{mc} = \frac{H_{ah} m_{ah} - (m_{H2O} C \Delta T)_{mc}}{m_{g,t}}, \tag{4}$$

where $m_{g,t}$ is the total mass flow rate.

(iii) Accordingly, a reliable estimation of the enthalpy of the flow at the nozzle exit can be obtained as:

$$H_n = H_{mc} - \frac{(m_{H2O} C \Delta T)_n}{m_{g,t}}. \tag{5}$$

During each test, the following pressures are also needed, the pressure at downstream end of the mixing chamber (p_t), at nozzle outlet (p_{ne}), and in the test section (p_{ts}). These are measured by means of electronic vacuum transducers.

The relative uncertainty on the total enthalpies ranges from 10 to 20%, depending on the considered arc power level; the uncertainty on the measured pressures can be estimated to span the interval from 2 to 5% of the measured values.

3.2 Using SPES to Simulate Entry in the Titan Atmosphere: The Implications of Methane-Containing Atmospheres

As already discussed to a certain extent in the introduction, the SPES facility described in the preceding subsection has already been successfully used to mimic entry in the Titan's atmosphere [23, 24, 25]. The related operating configuration is shown in Fig. 3:

For the convenience of the reader (and to put in perspective the information reported in Sect. 3.3), some critical insights into such earlier results are reported below:

(1) The SPES facility in its original configuration allows faithful control of all the aero-thermodynamic parameters of interest, i.e., total enthalpy, stagnation point heat flux and stagnation point pressure;
(2) The mixing between nitrogen thermal plasma and cold methane (in the stagnation chamber upstream of the supersonic nozzle, see Fig. 3) leads to the formation of

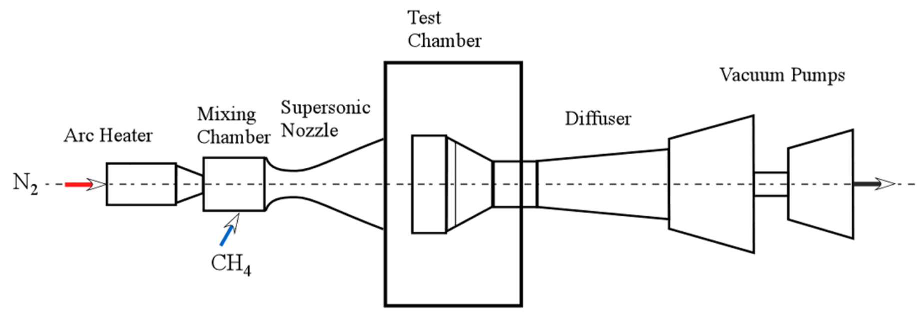


Fig. 3 SPES operating configuration for Titan entry simulation (N_2–CH_4 case [23, 24, 25])

carbonaceous substances of a rather complex nature, which are deposited both on the surfaces of the supersonic nozzle and on the diagnostics probes (see Fig. 4); in particular, these substances have a brown color and a powdery consistency when the flow is of a stagnation type (Fig. b and c), while the color is black and the consistency becomes carbonaceous if the flow is of a shear type (Fig. a).

Since the atmospheres of the Ice Giants also contain a certain percentage of methane (see Sect. 1), in principle, the formation of such substances should also be expected (although to a much smaller extent with respect to the case of Titan). In this regard, we wish to highlight that different options exist with regard to the simulation of these environments and should be considered depending on the desired level of fidelity and (especially) according to a proper assessment of the "benefits/drawbacks" ratio, as further critically discussed in the following:

(1) The simulation of high enthalpies, such as those illustrated in Sect. 2, requires the plasma torch of SPES to be operated with a nitrogen–hydrogen mixture (Fig. 5a); in this case, given our earlier experience, the formation of substances of the type described above should effectively occur if methane and helium are present in the mixing chamber; for this case, the use of methane should, therefore, be avoided. Although, neglecting this gas will obviously lead to a less accurate simulation of the Ice Giants atmosphere, however, this should be regarded as a good compromise between fidelity (methane being a minor percentage for these planets) and "cost-effectiveness" (no need to remove these undesired substances and clean the entire system after the execution of each test).

(2) A possible alternative to retain the atmospheric chemical composition is to operate the plasma torch with an argon–hydrogen mixture, by adding methane and helium downstream as indicated in Fig. 5b; in this case, however, the mixing chamber should be suppressed to prevent the total enthalpy from decreasing too much (such a decrease being obviously produced by the very intense heat transfer through the walls of the mixing chamber, that is water cooled).

In the following, however, the above-mentioned methane-related (purely practical) issue is ignored and for completeness all the discussions and related insights are elaborated taking this gas into account.

3.3 Modifying SPES to Simulate Entry in Uranus and Neptune Atmospheres

In the light of the considerations made in the foregoing, the present section provides an overview of the technological modifications that have been implemented in the SPES

(a) **(b)** **(c)**

Fig. 4 Experimental evidence of carbon deposition on **a** nozzle walls (left picture, and after being detached from the wall, right picture), **b** heat flux probes (black soot) and **c** total enthalpy probe (brown powder and black soot)

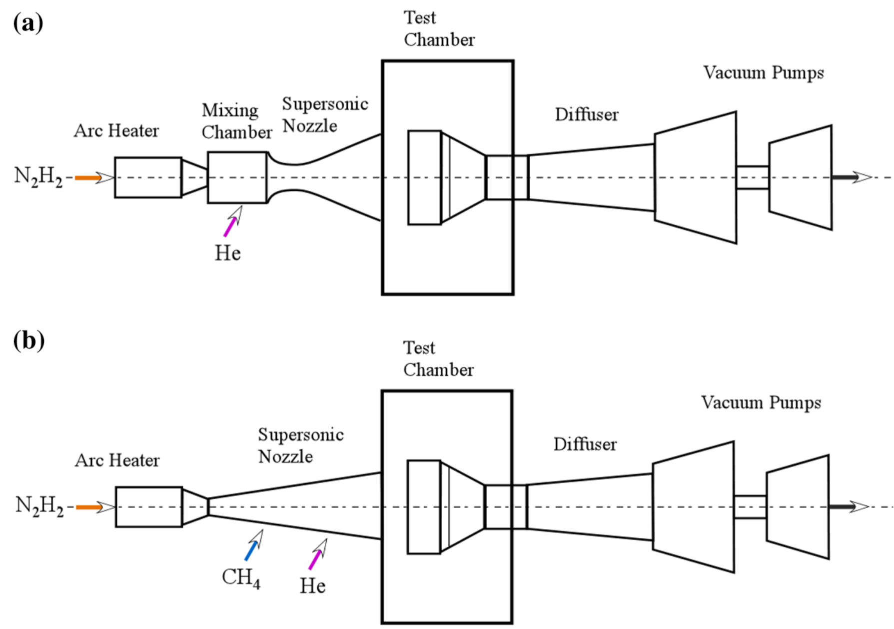


Fig. 5 SPES operating configuration for Ice Giants entry simulation: **a** for enthalpy simulation **b** for chemical composition simulation

Table 1 List of conditions to be met for the simulation of the Ice Giant atmospheric entry

Atmosphere composition	Hydrogen 83–85%—helium 15–13%—methane 2%
Specific total enthalpies	250 MJ/kg for Uranus—306 MJ/kg for Neptune
Stagnation point heat flux	10.5–42 MW/m^2 with $R_N = 0.4$ m
Stagnation point pressure	0.18–1.8 MPa

facility in an attempt to overcome the aforementioned challenge represented by the very high values of the aero-thermodynamic parameters to be simulated. Some proper rationale supporting such modifications and the related procedures are also provided. Along these lines, the Table 1 illustrates the typical conditions to be met:

To fix the ideas in the following we consider for simplicity hydrogen 85%—helium 13%—methane 2%. Since the volumetric composition is fixed, then 1 L of mixture will contain 0.075 g of hydrogen, 0.027 g of helium, and 0.014 g of methane, i.e., in total 0.116 g of matter.

As already discussed to a certain extent in Sect. 3.2, the best operating mode to keep the enthalpy as high as possible is the configuration shown in Fig. 5a. In particular, based on preliminary plasma torch tests, the flow rates should be reduced to (0.05/0.075) = 67% of their masses per liter, that is, 0.05 g for hydrogen and 0.018 g for helium; accordingly, as shown in Table 2, one would get:

Table 2 List of gas mass flow rates to be set for the simulation of the Ice Giant Atmospheric entry

Gas	Mass flow rate (g/s)	Note
Nitrogen	0.45	From plasma torch
Hydrogen	0.05	From plasma torch
Helium	0.018	From mixing chamber

The modified SPES configuration is shown in Fig. 6; the plasma torch is configured for nitrogen–hydrogen use (nozzle "730" or nozzle "G", depending on power levels, see Fig. 7). The stagnation chamber has two holes for the injection of helium, the nozzle is identified by the "C" letter and it is divided in two parts as shown in detail in Fig. 6b. The nominal Mach number is 4.85 at the intermediate section (Φ 22) and 6.94 at the final section (Φ 46); the total pressure is 40 kPa for a mass flow rate of 0.518 g/s.

3.4 Preliminary Tests (After SPES Modifications)

An estimate of the total (mass specific) enthalpy that can be reached using the modified configuration is reported in Fig. 8.

By extrapolating these data to the maximum power levels that could be reached with the torch (up to about 80 kW, provided these levels are sustainable when a threshold of 55 kW is exceeded, to be verified later), the conditions summarized in Fig. 9a should become accessible from a purely theoretical point of view (note: only the values exceeding 55 kW have been extrapolated, all the other values correspond to effective measurements).

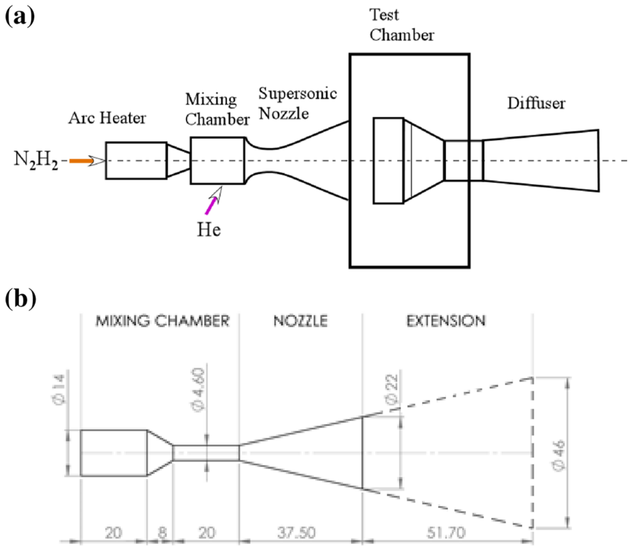


Fig. 6 SPES modifications **a** layout, **b** nozzle "C" geometry

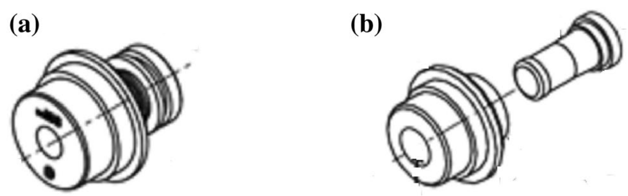


Fig. 7 Torch nozzle "G" (**a**) and "730" (**b**)—the geometry is the same, only the cooling is different to sustain different high-power levels (up to 40–60 KW for the "G" nozzle and up to 60–80 KW for the "730" nozzle, respectively)

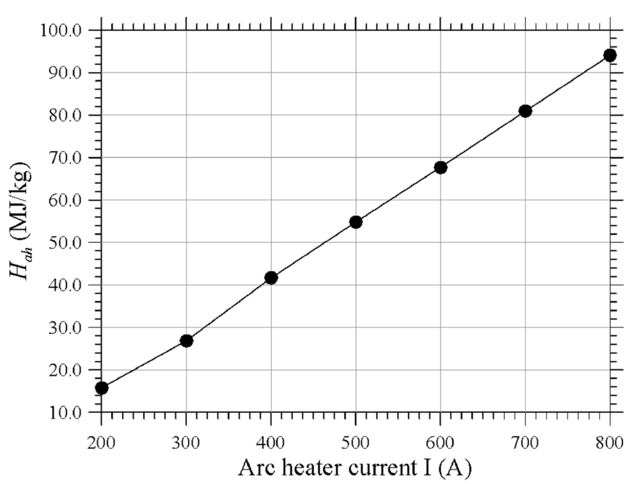


Fig. 8 Results of preliminary test for the nitrogen–hydrogen case—Arc heater total enthalpy H_{ah} as a function of the arc-heater current I (torch with 730 anode-nozzle, the solid line is used to guide the eye)

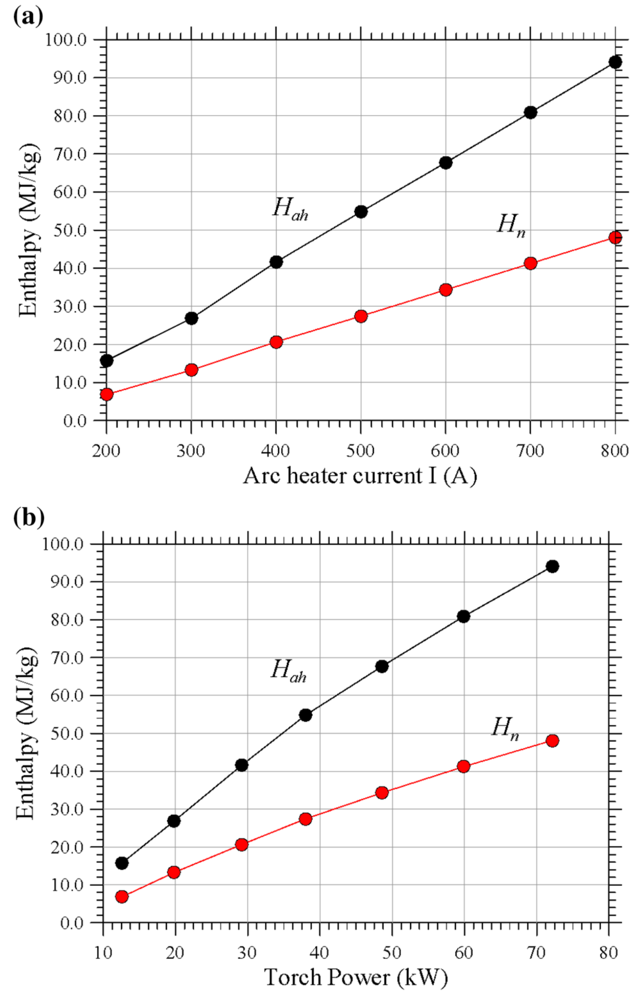


Fig. 9 Total arc-heater enthalpy H_{ah} and enthalpy at the nozzle exit H_n versus **a** arc-heater current, **b** torch power (extrapolation of nitrogen–hydrogen preliminary test results, solid lines are used to guide the eye)

Figure 9a is complemented by Fig. 9b, where the enthalpy is reported as a function of the torch power. In this specific regard, we wish to highlight that the validity of the above-mentioned extrapolation (linear in the enthalpy-vs-current case) has been verified through comparison with additional data obtained by using the (different) torch nozzle of the "G" type shown in Fig. 7b for power levels up to 55 kW and currents up to 800 A. The relationship has been found to be linear in both cases (730 and G torch nozzles). Remarkably, the same extrapolated values for enthalpy (for $I = 700$ and 800 A) have been found using a different procedure by which enthalpy has been extrapolated linearly in terms of torch power (for a power larger than 40 kW) rather than in terms of arc current, which indicates that the method to obtain them is relatively robust.

At this stage, we wish also to highlight that, although the enthalpy levels are relatively high, however, they would drop significantly at the nozzle outlet (about 40%). On the other hand, since it is almost impossible to operate with a vacuum torch alone, the addition of a "short" nozzle that dissipates as little as possible should also be envisaged (efficiency 0.75–0.8 to be verified; the efficiency being defined as H_n/H_{mc} if the considered configuration includes the mixing chamber or as H_n/H_{ah} if this component is not included). In practice, if constituted only by a water-cooled divergent, the nozzle "C" should be regarded as a viable solution in this regard.

For what concerns the thermal flow in the stagnation point (for a sphere with a radius of 0.01 m) and the pressure in the stagnation point, numerical estimates are reported in Fig. 10, based on the Zoby formula [26] (again for the nitrogen–hydrogen case). This figure is instrumental in revealing the "limitations" (in terms of stagnation pressure) of the present configuration highlighted at the end of Sect. 1 (such a limitation essentially stemming from the relatively small allowed mass flow rates, which are of O(1) g/s). As already pointed out there, however, these constraints have almost negligible implications when the main objective of the testing campaign is the simulation of purely thermo-fluid-dynamic aspects rather than the assessment of the probe/vehicle response from a structural standpoint.

3.5 Aero-thermochemical Model of the Overall Flow Process

As already emphasized in the introduction and Sect. 3.3, the most important parameter to be reproduced is the flow total enthalpy, which typically attains its maximum value at the nozzle centerline and then decreases toward the nozzle walls. We also wish to recall that the mass average of the enthalpy in the stream, including the portion in the outer cold region, is called the "mass-averaged" enthalpy. Although this quantity can be easily measured in arc-jet facilities, however, the centerline total enthalpy plays a much more important role in arc-jet simulation, because it is at the flow centerline that test articles are typically located during effective tests. In this regard, the so-called Frozen Sonic Flow (FSF) method, developed by Jorgensen [27] and adapted by Pope [28] for low density arc-heated flows, is particularly efficient because it can accurately evaluate the centerline total enthalpy relying on a few flow measurements and a simple physical model of the overall fluid-dynamic process; the reader is referred to [29] for a detailed description of the method and the related underlying assumptions. For a chemically frozen mixture of atomic and diatomic species with frozen vibrational energy, such as a nitrogen–hydrogen mixture, application of the FSF method is a relatively straightforward practice (see, e.g., Figure 11 for the value of centerline total enthalpy H_{ah} as a function of the nozzle-exit total enthalpy H_n; it can be seen that the related ratio is about 1.6, quite constant with respect to the total mass flow rate and the percentage of hydrogen).

Obviously more complex situations can be encountered. A typical example is a mixture of (nitrogen–hydrogen)–methane–helium, for which tri-atomic molecules are involved in addition to mono-and bi-atomic ones, e.g., HCN. Although the FSF method in its basic formulation is not immediately applicable to situations like these, however, recently some relevant extensions have been proposed where these constraints have been overcome. More precisely, Esposito and Lappa [30] have shown that extension of this method to the case of polyatomic species can be made "well posed" if it is properly elaborated starting from the original assumptions of Vincenti and Kruger [31]. The application

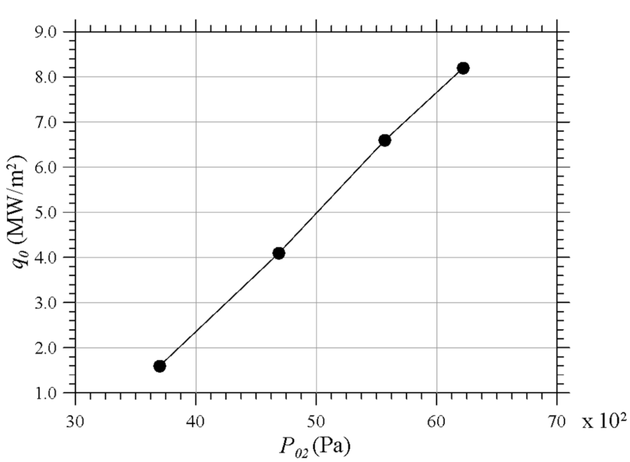


Fig. 10 Theoretical evaluation of stagnation point heat flux as a function of the pressure based on the Zoby formula [26] (nitrogen–hydrogen case, the solid line is used to guide the eye)

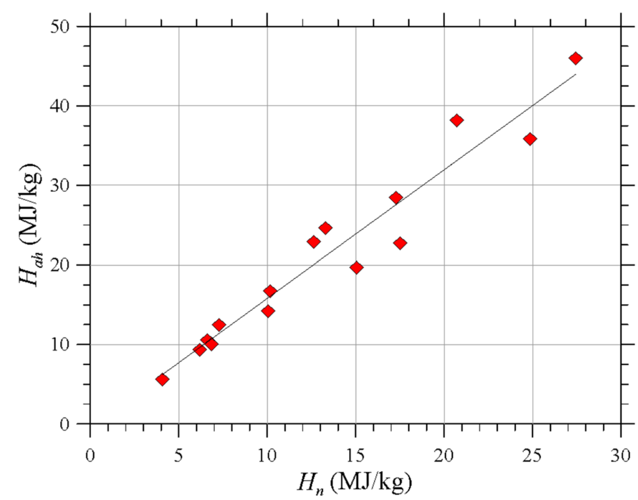


Fig. 11 Centerline total enthalpy as a function of the nozzle-exit total enthalpy (application of the FSF method to a nitrogen–hydrogen mixture, the solid line is a linear fit: $H_{cl} \cong 1.616\ H_n$)

of the FSF method in this extended form will be the subject of experimental verification in the near future.

3.6 Data Analysis

Based on the preliminary results obtained, the following critical considerations or arguments can be provided:

(1) The achieved flow total enthalpies can be considered representative of a close flyby in the atmosphere of the Ice Giants, or of a first phase of entry into their atmospheres; a margin of improvement of about 10% may also be considered as a feasible target;
(2) The stagnation point heat fluxes are also representative of situations similar to those described in point (1);
(3) However, the stagnation point pressures are not comparable to the real ones;
(4) Moreover, the composition of the atmosphere shall be upgraded to account for the presence of methane and special countermeasures shall be taken accordingly. This gas has already been proven able to support the formation of carbonaceous substances in the solid state, which could compromise parts or instruments of the vehicle or probe during the entry into the atmosphere of these planets.

4 Conclusions and Possible Future Developments

The arc-jet facility SPES, previously used to simulate space flight in the atmospheres of Earth, Mars, and Titan, has been considered as a relevant basis for the implementation of a more complex framework adequately accounting for the atmospheric features of the Ice Giants, Uranus, and Neptune.

In a first stage of such a complex process, efforts have been limited to elaborating a simplified aero-thermochemical flow model (nitrogen–hydrogen mixture, Frozen Sonic Flow method for bi-atomic molecules) and implementing some initial, but necessary, plant modifications. The outcomes of some initial tests have been presented and critically discussed in relation to the ability of the new theoretical–experimental framework to mimic adequately conditions of effective interest.

In future stages of this endeavor, we plan (a) to complete the required modifications of the facility and to verify its new performances and (b) to apply a more sophisticated aero-thermochemical model, able to account for the presence of polyatomic molecules in the atmosphere of Ice Giants.

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Data availability statement All the required data are included in the manuscript.

Declarations

Conflict of Interest Authors declare that there are no financial or non-financial interests that are directly or indirectly related to the work submitted for publication.

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