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DEVELOPMENT OF A KINETIC SHOCK-TUBE FOR PLANETARY EXPLORATION

The preparation of new Planetary exploration missions needs an adequate planning of the critical Entry, Descent and Landing (EDL) sequences. The planetary entry phase occurs at hypersonic velocities, and the aerodynamic configurations, and the thermal protections of a spacecraft have to be properly tailored. In support of the upcoming European planetary exploration missions, the European Space Agency is funding the development of a new shock-tube facility at the Instituto Superior Tecnico of Lisbonne. The characteristics of this new large facility will be described in this work.

Key words: *atmospheric entry, entry plasmas, shock-tube.*

Introduction

The Entry, Descent and Landing (EDL) phase is generally viewed as the most critical stage of a Planetary exploration mission. The design of a space capsule, tailored for such missions, must accommodate constraints which depend on the aerothermal properties of the shock-induced plasma that is created during the entry phase. Namely, the spacecraft thermal protections must be able to whisthand the severe thermal loads (convective and radiative) that impact their surface during the whole entry phase. The development of predictive CFD codes, capable of supporting the design of such space vehicles, therefore depends on the availability of a reliable aerothermal database. These databases are in turn obtained and validated from experiments in ground-test facilities which reproduce this kind of shocked entry plasmas.

Shock-tube facilities are capable of simulating entry plasmas for a large range of entry velocities (5-10 km/s and above). Different measurement techniques (such as emission and absorption spectroscopy, microwave interferometry, etc.) are deployed for allowing a better qualitative and quantitative understanding of the physical-chemical processes in such a kind of plasmas, and supporting the validation of aerothermal databases. Such facilities are therefore essential for enabling access to space.

At European level, the piston-free shock-tube TCM2 from the University of Provence (Marseilles, France) had been utilized for the support of European space exploration programs. However, the decommissioning of this facility, as well as the necessity of producing novel aerothermal databases for superorbital entry flows (entry speeds above 10km/s), put forward the necessity for a higher-performance facility of such a kind. The European Space Agency decided to fund a competitive bid for the construction of such a facility, which was won by an international consortium led by the Instituto Superior Técnico of Lisbon, Portugal, and grouping other institutions (Fluid Gravity Eng., UK, Université de Provence, France, Ingénieurie et Systèmes Avancés, France, ISQ International, Portugal, Moscow Institute for Physics and Technology, Russia, Shock Waves Laboratory, Germany, University of Manchester, UK, Université Blaise Pascal, France, and Université Paris VI, France). This work describes the rationale that was considered for the design of this new high-performance facility, which has been named ESTHER (European Shock-Tube for High Enthalpy Research).

Section 1 describes the performance design of the facility, which led to its geometrical configuration, and Section 2 describes the mechanical design of the shock-tube. Finally Section 3 briefly outlines the design of the hosting laboratory.

1. Shock-Tube Performance Design

The ESTHER Shock-Tube design is tailored for the obtention of superorbital shock velocities (around 10km/s).

For this kind of velocities to be within reach, one may consider a single-stage design (high-pressure –HP– driver section and low-pressure –LP– driven test section). However, as the shock-speed depends on the HP/LP ratio, and given that the LP value is typically a fixed parameter (around 1-0,1 mbar), reaching such high-speeds requires a very large HP value (in the kbar range), which poses many practical and engineering constraints. The shock-tube equation (Eq. 1) relates the P_2/P_1 ratio (from which the shock speed M_s can be derived) to the HP/LP ratio (P_4/P_1), for a constant area Shock-Tube ($A_4/A_1=1$):

$$\frac{P_4}{P_1}=\frac{P_2}{P_1}\left[1-\frac{(\gamma_4-1)\frac{a_1}{a_4}\left(\frac{P_2}{P_1}-1\right)}{\sqrt{2\gamma_1}\sqrt{2\gamma_1+(\gamma_1+1)\left(\frac{P_2}{P_1}-1\right)}}\right]^{-\frac{2\gamma_4}{\gamma_4-1}}. \quad (1)$$

Alternatively, a two-stage (double-diaphragm) design can be considered. In a two-stage configuration, an additional stage is added between the driver and driven sections, with a gas at an intermediary pressure. This allows reaching higher shock-pressures in the driven section (at a cost of a lower runtime, due to the fast travelling contact surface that follows the shock-wave. One may apply Eq 1. In the two-stage approach in order to derive this conclusion. The shock-tube diagram for a double-stage configuration is presented in Fig. 1.

Another possibility for obtaining higher shock speeds is having a decreasing cross-sectional area from the driver to the test section. In this second case, the relationships for obtaining the shock P_2/P_1 ratio, and hence the shock speed M_s, as proposed by Allen and White [1], are slightly more complicated. We start by determining the Mach number M_{3a} in the fully expanded region of the driver section (post-diaphragm opening). This can be iteratively determined as a function of the area ratio A_4/A_1 between the driver and the test sections (in a single stage configuration):

$$\frac{A_4}{A_1}=\frac{M_e}{M_{3a}}\left[\frac{2+(\gamma_4-1)M_{3a}^2}{2+(\gamma_4-1)M_e^2}\right]^{\frac{\gamma_4+1}{2(\gamma_4-1)}}. \quad (2)$$

We then introduce the equivalence factor g, as proposed by Restler [2]:

$$g=\left\{\sqrt{\frac{2+(\gamma_4-1)M_{3a}^2}{2+(\gamma_4-1)M_e^2}}\left[\frac{2+(\gamma_4-1)M_e}{2+(\gamma_4-1)M_{3a}}\right]\right\}^{\frac{2\gamma_4}{\gamma_4-1}}. \quad (3)$$

And the shock P_2/P_1 ratio can then be obtained according to Eq. 4:

$$\frac{P_4}{P_1}=\frac{P_2}{P_1}g^{-1}\left[1-\frac{u_2}{a_1}\frac{a_1}{a_4}\frac{\gamma_4-1}{2}g^{-\frac{\gamma_4-1}{2\gamma_4}}\right]^{-\frac{2\gamma_4}{\gamma_4-1}} \quad (4)$$

with

$$\frac{a_1}{u_2}=\frac{\gamma_1+1}{2}\frac{M_S}{M_S^2-1}. \quad (5)$$

Where we can define the shock-speed M_s defined as a function of P_2/P_1:

$$M_S=\sqrt{\frac{\gamma_1-1}{2\gamma_1}\left(1+\frac{\gamma_1+1}{\gamma_1+1}\frac{P_2}{P_1}\right)}. \quad (6)$$

The examination of these relationships shows that a variable cross-section may increase sock velocities to a maximum of 15-20%. Indeed, shock speeds drastically increase with a decreasing cross-sectional area from the driver to the test section, but the increases become less marked and eventually stagnate as the A_4/A_1 ratio reaches infinity.

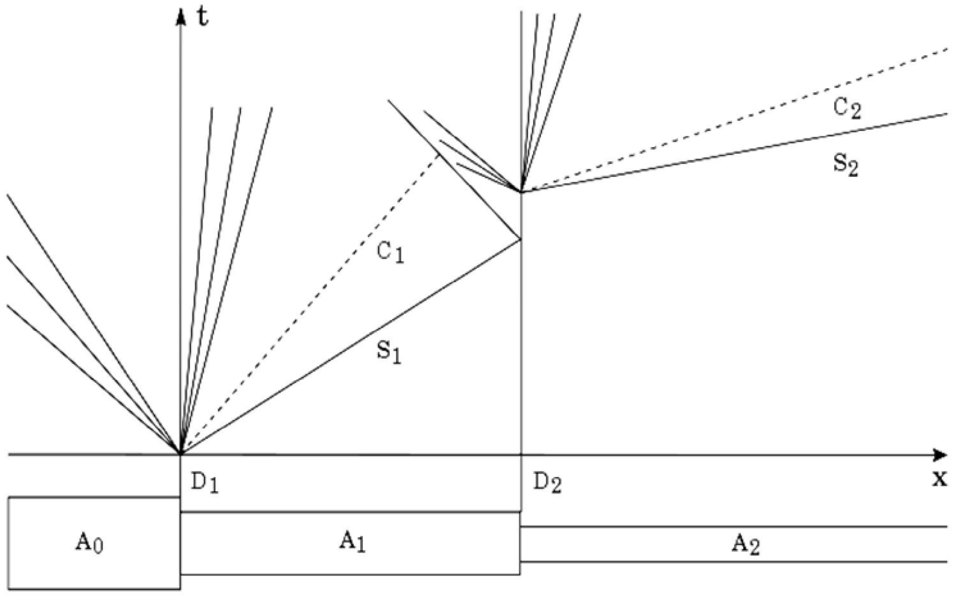

Fig. 1. Shock diagram for a two-stage shock-tube

The optimization study, carried out using the aforementioned relationships, has led to the general guidelines regarding the design for ESTHER, allowing it to reach shock velocities in excess of 10km/s.

- Driver section with final pressures up to 250bar+. The rise in pressure is obtained through the ignition of a stochiometric H_2/O_2 mixture, diluted in He in order to avoid detonations. The final temperature is estimated to be 2800K, according to experience from other experiments in high-pressure combustion (a chemical equilibrium calculation yields a slightly higher value of 3000K).
- Maximum area ratio limited to 6, as higher values have diminishing returns in terms of shock speeds, and lead to impractically large driver sections.

2. Shock-Tube Mechanical Design

The constraints set-up from the performance design lead to the following specifications for the different sections of the ESTHER shock-tube:

High Pressure Driver Section

250bar, internal diameter 200mm, outer diameter 360mm, internal length 1.5m,

Nominal mixture 70%He, 20%H2, 10%O2

Initial pressure 10 to 50 bar.

- High pressure Ignition and safety system.
- Combustion gas preparation system and induction system including mixing, storage, valves, probes and gauges.
- Gasket system with rupture pressures 60 to 250+ bar.

Compression Tube (or second stage)

- Internal diameter 100mm, outer diameter 0,160mm, length 5m
- Initial pressure ~0,1-0,5 bar.
- Gasket system with rupture pressures 5 to 25 bar.

Working Section

Internal diameter 80mm, outer diameter 0,140mm, length 4m from diaphragm to window. the total internal length to the dump tank is 5,4m

Initial pressure ~10 to 1000Pa.

- Pumping system (1 sets 1 primary, 2 molecular pumps to give a minimum pressure of 10^{-8} mbar during cleaning procedures, and to ensure known initial test gas composition.
- Working gas preparation and induction system including probes and gauges.
- Windows (UV/VUV transparent) and window mounting system.
- Shock speed / pressure measurement system.
- Diaphragm to dump tank

Dump Tank

Diameter: 0,8m, Length: 1,2m

- Post window section lead in tube to dump tank.
- Pressure range, vacuum to 2bar pressure post shot.

Due to the severe pressure and mechanical constraints incurred during operational mode, the ESTHER Shock-Tube will be manufactured in duplex and super-duplex low-carbon steel, which provide very good mechanical resistance, including resistance to fatigue. Low-carbon steel also has the advantage of providing protection against corrosion effects from Hydrogen, which will be utilized in this facility.

A 3D view of the final design for the ESTHER Shock-Tube is presented in Fig. 2.

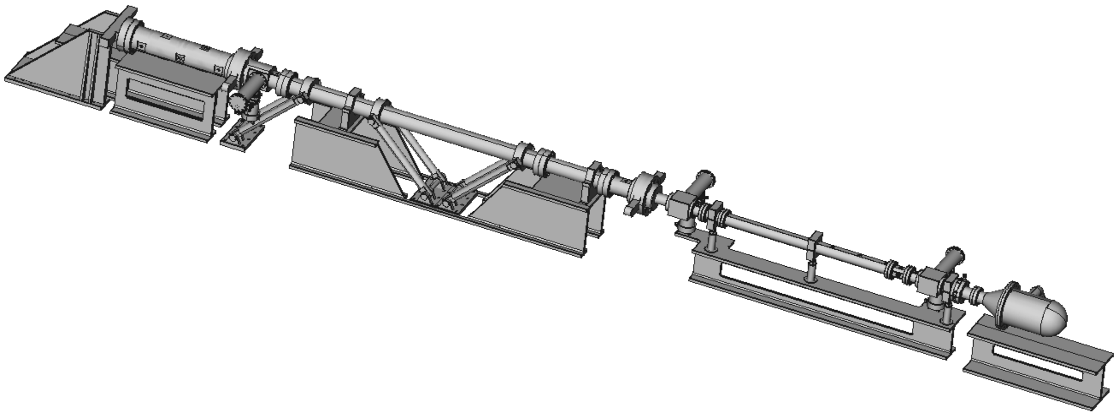

Fig. 2. 3D View of the ESTHER Shock-Tube

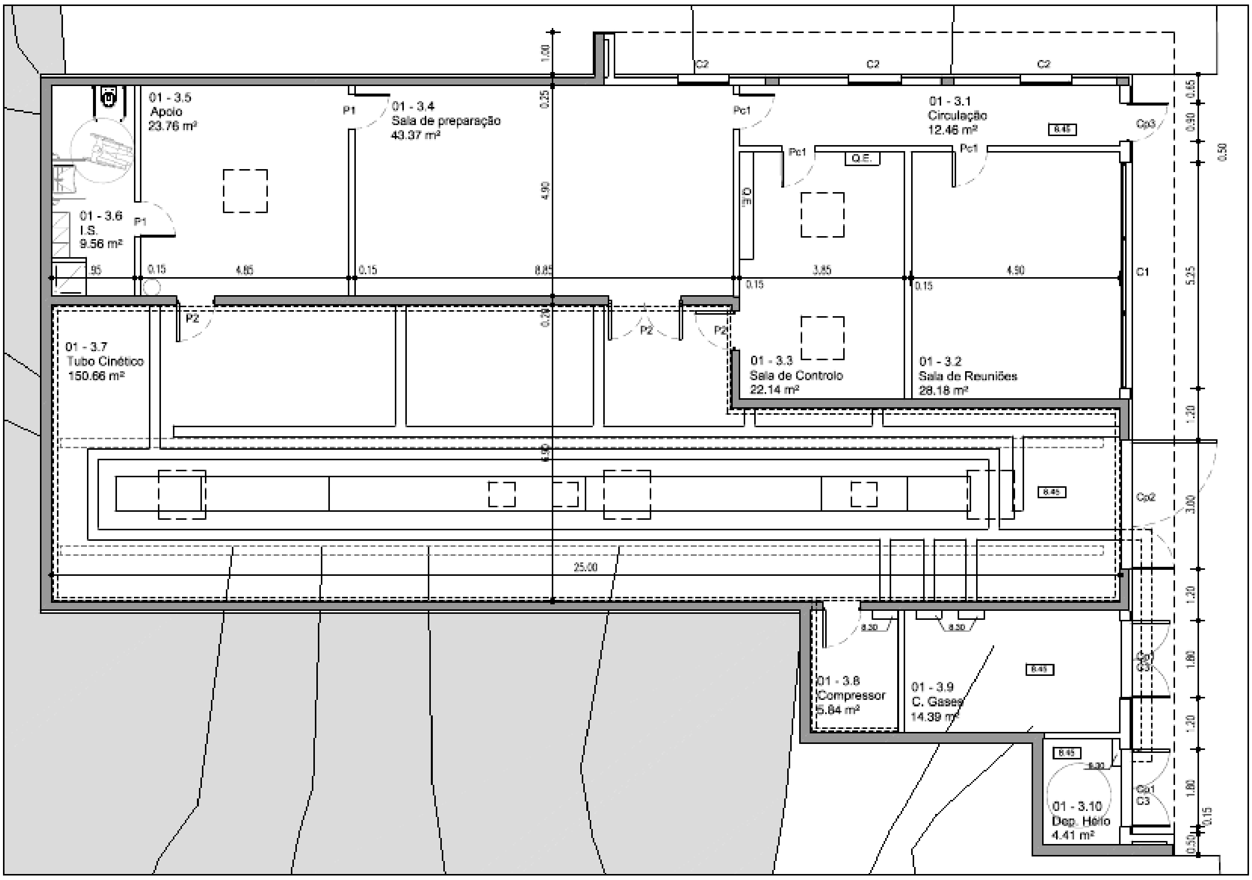

Fig. 3. Architecture plan for the ESTHER hosting building.

3. Hosting Laboratory

The hosting laboratory for the ESTHER facility, located in the IST campus of Sacavém, in the outskirts of Lisbon, is currently under construction.

The hosting laboratory has been designed according to the safety regulations for facilities with the presence of hydrogen. As such, the hosting laboratory is semi-buried, and blast panels are placed on the roof in order to accommodate for any accidental ignitions of hydrogen. Furthermore, the experimental hall is segregated from the control room where the shock-tube is operated remotely. Blast doors isolate the experimental hall (which will be ATEX compliant) from the other rooms whit the presence of humans.

The architecture plan of the hosting building is presented in Fig. 3.

The slab where the shock-tube is to be placed has also been the subject of a careful study, so as to prevent as much as possible any transmission of the shock-tube vibrations (during operation) to the experimental hall itself, where the optical diagnostics are to be placed. The slab itself has been dimensioned with a large inertia (about 40Tonne, and is placed over a series of anti-seismic pads (see Fig. 4) who prevent the transmission of low-frequency vibrations to the rest of the building.

Acknowledgments

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Fig. 4. Current construction status of the shock-tube slab.

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РАЗРАБОТКА КИНЕТИЧЕСКОЙ УДАРНОЙ ТРУБЫ ДЛЯ ИССЛЕДОВАНИЯ ПЛАНЕТ

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Для подготовки новых планетарных разведывательных миссий необходимо проводить адекватное моделирование критических условий запуска, спуска и посадки космических аппаратов на планету. Фаза входа в атмосферу планеты происходит при гиперзвуковых скоростях, поэтому тепловая защита космических аппаратов с точки зрения аэродинамики должна быть очень верно сконструирована. В поддержку предстоящеих европейских планетарных разведывательных миссий Европейское космическое агентство финансирует разработку новой ударной трубы в Instituto Superior Tecnico в г. Лиссабон. Характеристики этого объекта приведены в этой работе.

Ключевые слова: вход в атмосферу, плазма, ударная труба.

РОЗРОБКА КІНЕТИЧНОЇ УДАРНОЇ ТРУБИ ДЛЯ ДОСЛІДЖЕННЯ ПЛАНЕТ

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Для підготовки нових планетарних розвідувальних місій необхідно проводити адекватне моделювання критичних умов запуску, спуску і посадки космічних апаратів на планету. Фаза входу в атмосферу планети відбувається при гіперзвукових швидкостях, тому тепловий захист космічних апаратів з точки зору аеродинаміки повинен бути дуже вірно сконструйований. На підтримку європейських планетарних розвідувальних місій Європейське космічне агентство фінансує розробку нової ударної труби в Instituto Superior Tecnico у м. Лісабон. Характеристики цього об'єкта наведені в цій роботі.

Ключові слова: вхід в атмосферу, плазма, ударна труба.

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