HiSST: 3rd International Conference on High-Speed Vehicle Science Technology

14 -19 April 2024, Busan, Korea

Initial Investigation of a Combustion-Driven Shock Tunnel Operating as a Shock Tube – Preliminary Results

Marco A. S. Minucci [1], Israel S. Rêgo [2], Marcos M. Borges [3], Giannino P. Camillo [4], Lucas A. G. Ribeiro[5], Rafael O. Santos [6], Thiago L. Assunção [7], Ivo P. M. Alves [8], Thiago V. C. Marcos [9], Bruno B. Nascimento [10], Pedro S. Matos [11], Lucas Galembeck [12], and Demerval Carinhana Jr. [13]

Abstract

A new high-enthalpy hypersonic pulsed facility is being commissioned at the Aerothermodynamics and Hypersonic Division – EAH of the Institute for Advanced Studies – IEAv, in Brazil. The single-diaphragm combustion-driven shock tube operating mode was initially investigated. Both driver and driven sections were instrumented with pressure transducers. The combustion driver was filled with a pressurized stoichiometric mixture of Hydrogen and Oxygen diluted in Helium, which was ignited through specially built spark plugs evenly distributed along the driver tube wall. Mixture dilutions of 65% and 75% were investigated with filling pressure up to 3.0 MPa. The shock tube performance was also evaluated in terms of incident shock wave velocity. Diaphragm rupture behaviour was assessed for several operational conditions, in order to minimize diaphragm debris formation and to guarantee repeatable flow conditions. In addition, the combustion-driven shock tunnel safety procedures were practiced starting from milder configurations before ramping up the operating conditions.

Keywords: *hypersonic shock tunnel, high-enthalpy pulsed facility, shock tube, combustion*

Nomenclature

Latin
P – Pressure
T – Temperature
H – Enthalpy
M – Mach Number
Subscripts
1 – Initial Driven Tube Conditions
4 – Driver Tube Conditions (after combustion)
5 – Reflected Conditions
b – Test Section Initial Pressure
s – Incident Shock Wave
mix – Driver Tube Gas Mixture
∞ – Free Stream Conditions

[1] *Principal Investigator, Institute for Advanced Studies, São José dos Campos, Brazil, salamasm@fab.mil.br*
[2] *Investigator, Institute for Advanced Studies, São José dos Campos, Brazil, israelisr@fab.mil.br*
[3] *Investigator, Institute for Advanced Studies, São José dos Campos, Brazil, marcosborgesmmb@fab.mil.br*
[4] *Investigator, Institute for Advanced Studies, São José dos Campos, Brazil, gianninogpc@fab.mil.br*
[5] *Research Engineer, Institute for Advanced Studies, São José dos Campos, Brazil, lucaslagr@fab.mil.br*
[6] *Research Engineer, Institute for Advanced Studies, São José dos Campos, Brazil, rafaelros2@fab.mil.br*
[7] *Investigator, Institute for Advanced Studies, São José dos Campos, Brazil, assuncaotla@fab.mil.br*
[8] *Research Engineer, Institute for Advanced Studies, São José dos Campos, Brazil, ivoipma@fab.mil.br*
[9] *Technician, Institute for Advanced Studies, São José dos Campos, Brazil, thiagovcm@gmail.com*
[10] *Technician, Institute for Advanced Studies, São José dos Campos, Brazil, bbarreto51@gmail.com*
[11] *Investigator, Institute for Advanced Studies, São José dos Campos, Brazil, pedrosmatos@gmail.com*
[12] *Project Manager, Institute for Advanced Studies, São José dos Campos, Brazil, galembecklg@fab.mil.br*
[13] *Division Head, Institute for Advanced Studies, São José dos Campos, Brazil, dermevaldcj@fab.mil.br*

1. Introduction

Ground-based experiments play a crucial role in the development of new technologies in hypersonic flight and high-speed airbreathing engines. In this context, hypersonic impulse facilities stand out due to their capacity to generate high enthalpies and pressures, allowing for the reproduction of flight properties requirements on the ground. One of the most widely used impulse facilities is the hypersonic shock tunnel, which not only duplicates flight conditions with good quality and repeatability but also operates safely and has affordable operational costs. Despite its inherently short test times, the shock tunnel enables a variety of experiments and provides reliable, high-quality data when used with appropriate instrumentation and diagnostic techniques.

With the aim of simulating Mach 10 flight conditions encountered at an altitude of 30 km, the Aerothermodynamics and Hypersonics Division – EAH of the Institute for Advanced Studies – IEAv, in Brazil, is commissioning a new high-enthalpy combustion-driven reflected hypersonic shock tunnel [1]. Higher enthalpies can be achieved by operating the new facility in the equilibrium-interface mode [2]. It spans 50 m in total length and features a test section designed to accommodate large test articles, up to 4.2 m long and 1.2 m span. A Mach 10 1.1-m exit diameter contoured nozzle was designed and is currently being constructed. The nozzle design methodology employed was validated in another IEAv's shock tunnel and is better described in other two recent works [3,4]. Fig. 1 illustrates the completed shock tunnel and its expected operating conditions.

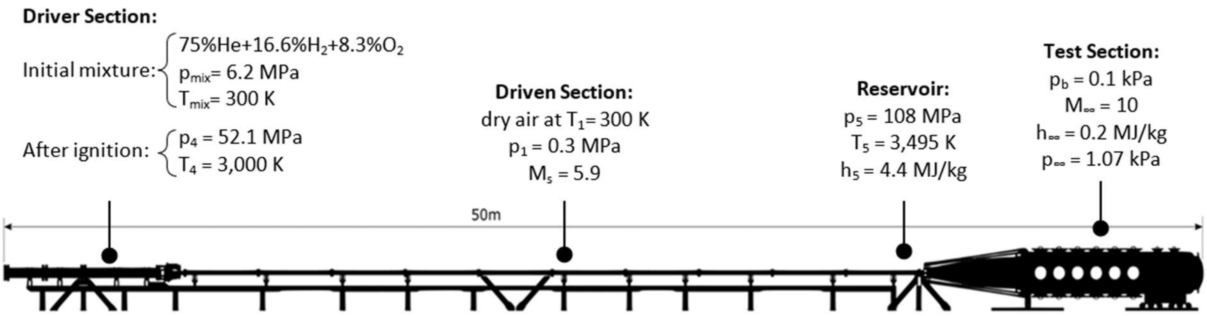

Fig. 1 Hypersonic shock tunnel operating conditions. Adapted from [1].

The operational principles of shock tubes and shock tunnels have been outlined in detail elsewhere [5,6] and are beyond the scope of the present work. However, it is worth noting that to produce high stagnation enthalpy, it is necessary to increase the incident shock wave speed. To enhance the strength of the incident shock wave, it is not enough to solely increase the driver-to-driven pressure ratio; it is also necessary to increase the speed of sound of the driver gas [7]. Hence, light gases such as Helium and Hydrogen are frequently employed as driver gas. To further increase the speed of sound, heating the driver gas by various means is necessary. The available literature outlines numerous methods to achieve this [7,8].

The deflagrative combustion driven is the method adopted in the present work. Initially, the driver is filled with a stoichiometric mixture of Hydrogen and Oxygen, diluted in Helium, and ignited using a set of equally spaced spark plugs. This methodology has been successfully used and is documented in the available literature [8-10]. The dilution of reactive gases with helium, coupled with a precise filling strategy utilizing evenly spaced angle-drilled gas injectors to induce swirl motion in the mixture, aims to prevent inadvertent detonation during the loading process and to ensure deflagrative reaction during operation. Avoiding detonation is of utmost importance, as these events can result in pressure spikes exceeding those expected by the deflagration process. Studies on ignition process under different loading conditions using a separate, small-scale test cell are detailed in another recent work [11].

2. Materials and Methods

2.1. Shock Tube Description

The shock tube has a total length of approximately 40 m and is basically composed of two well-defined sections, the Driver and the Driven. The Driver Section is 6.1 m long and 152.4 mm internal diameter, made of a forged chromium-molybdenum steel with approximately 100 mm wall thickness, and 140 MPa maximum operating pressure after combustion. The inner walls have been coated with hard chromium plating 0.127 mm thick to prevent corrosion. The length of the Driver was designed to prevent the early arrival of reflected expansion waves at the end of the Driven, in order to avoid interfering with the useful test time of the facility when operated in Shock Tunnel mode. The Driver is anchored to a seismic mass on the laboratory floor using two struts and a special polymer, enabling it to recoil due to the strong shock waves operation. This anchoring mechanism allows for unrestricted movement of the Driver Section in both longitudinal directions. To achieve uniform deflagrative combustion and mitigate the risk of detonation, eighteen spark plug installation positions are evenly distributed along the driver's length in a spiral pattern. Additionally, filling gases are injected into the driver from six different positions using 4-hole injectors drilled at an angle to induce swirling gas motion.

The Driven Section consists of a stainless-steel tube with a total length of 32 m, 101.6 mm inner diameter, and walls measuring 25.4 mm in thickness. It has a maximum operating pressure of 69 MPa. To minimize viscous wall effects, the internal surface of the tube has undergone meticulous boring and honing, resulting in an exceptionally smooth finish. For the nominal operating conditions of Mach 10 at an altitude of 30 km, the Driven tube will be initially filled with 300 kPa of dry air, achieving the desired pressure ratio (p_4/p_1) and aiding in reducing wall viscous effects. Despite the mechanical loads during shock tunnel operation, the tube will remain securely in place, supported by a welded rail and I-beam structure anchored to the laboratory floor. A heavy section will be attached to the end of the Driven in the stagnation region to withstand pressures up to 500 MPa, around five times the expected stagnation pressure levels. Photographs of the Driver and Driven Tubes are shown in Fig. 2.

Fig. 2 Driver (left) and Driven (end view) Tubes.

A Diaphragm Section separates the Driver and the Driven Sections, connecting them through a 1.2 m long conical transition piece with a contraction area ratio of 2.25:1. This change in area leads to stronger incident shock waves [12]. The gases from driver and driven are separated by a circular diaphragm with a cross-shaped groove, whose material and depths to be milled are designed to provide a proper opening. Given the sudden and strong jump in pressure in the Driver tube to be observed once the combustible mixture is ignited, the requirements for mechanical resistance of the diaphragm are less stringent than in other kinds of shock tunnels. The diaphragm opening dynamics are therefore not expected to require any special attention. The clamp for the Diaphragm Section is operated by three hydraulic pistons at 21 MPa pressure. Check valves and mechanical locks are used to prevent opening during combustion.

2.2. Experimental Setup

The operation of the new shock tunnel is started in shock tube mode, that is, with the Driven tube ended in a blind flange. While the final configuration of the facility includes a heavy section at the end of the Driven tube to withstand elevated stagnation pressure (up to 500MPa), this section has not yet been commissioned. Therefore, for safety reasons, in the present exploratory experiments the Driven tube was kept under 3 kPa, preventing the generation of stagnation pressures exceeding the Driven tube's operating pressure. Higher filling driven pressure will only be done when the heavy section is fully commissioned.

To study the shock tube response to different operating conditions, driver pressure variation was achieved by varying the total pressure of the combustion mixture, while maintaining the partial pressures of the fuel, H_2, oxidizer, O_2, and inert gas, Helium. The dilution of the reactive gases in Helium is performed to prevent any inadvertent detonation during the loading process, and to ensure a deflagrative reaction during operation. In all tests, the gases will be filled into the Driver tube following the same strategy, conceived to maximize safety during operation [11]. The same filling procedures adopted when operating in shock tube mode will also be employed later on, when the complete shock tunnel is commissioned. This process consists of first evacuating the Driven tube and injecting 50% of the final Helium pressure. Helium is chosen as the first gas as a means to purge the loading system before the reacting gases are introduced. This is followed by 50% of the O_2 pressure. The remaining filling amount of He and O_2 are injected next, in this order. Finally, the fuel gas H_2 is injected. A small amount of He is injected last and at a high pressure. This serves two purposes: to clear the charging lines of any H_2 for safety reasons; and to induce a spiral motion of the mixture in the Driver. The latter, together with a few minutes given to allow diffusion between the gases, aims at enhancing homogeneity of the mixture. The tube is then ready for operation.

As previously mentioned, once the facility is fully commissioned, the driver mixture will be filled at 6.2 MPa and ignited by eighteen spark plugs to ensure deflagrative combustion. However, in the current experiments, the driver was partially pressurized from 0.2 to 3.0 MPa, requiring the use of a smaller number of spark plugs. The combustible mixture dilution was also investigated, with 65% and 75% of Helium. Throughout the experiments, H_2 and O_2 detectors near the Driver tube remained active and connected to an alarm system. If a gas leak of either species is detected, light and sound emitters alert the operating personnel, and an active exhaust system located directly above the Driver tube is activated.

The instrumentation primarily consists of dynamic pressure transducers, including one Kistler model 701 K in the Driver tube to monitor combustion pressure and two Kistler model 7005 transducers along the Driven tube to measure incident shock wave velocity. The signals from the transducers pass through the Kistler conditioner model type 5064-C and are then recorded in an oscilloscope Yokogawa model DL850E. Figure 3 illustrates a schematic of the experimental setup.

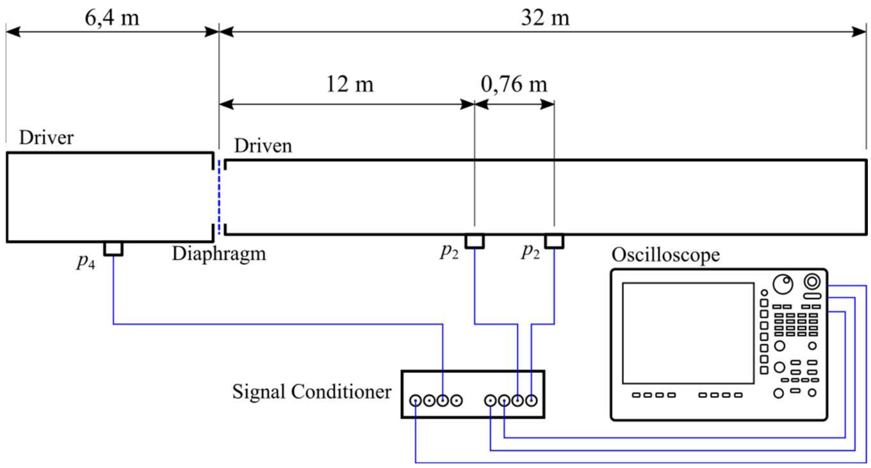

Fig. 3 Schematic of the experimental setup.

Given that the initial pressure in the Driven tube was kept under 3.0 kPa, no attempts were made to measure stagnation pressure at the shock tube end wall.

3. Results

The first exploratory experiments were performed with a gas mixture consisting in 65% of Helium and fill pressure from 0.2 to 2.5 MPa, with three spark plugs only. Up to 2.0 MPa, no detonation was observed but, for a fill pressure of 2.5 MPa and a thicker stainless-steel diaphragm, all four petals were lost, as shown in Fig. 4 (top row).

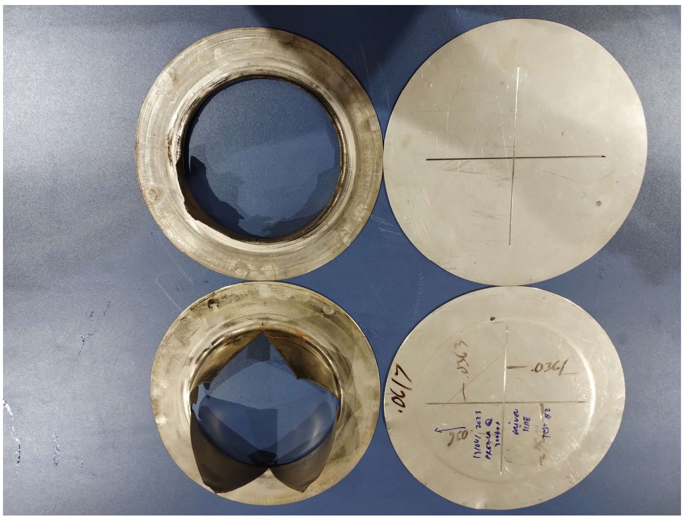

Fig. 4 Diaphragms after and before opening.

Figure 4 also illustrates the thinner diaphragm opening for the same 2.5 MPa fill pressure (bottom row). Under this condition, the onset of detonation was detected, reaching a peak pressure of approximately 40 MPa, which is sixteen times the initial pressure. Oscillations shown in the Fig. 5 also serve as indicator of detonation occurrence [13]. By theoretical predictions, after combustion the driver gas temperature increased from 300 K to at least 3,200 K.

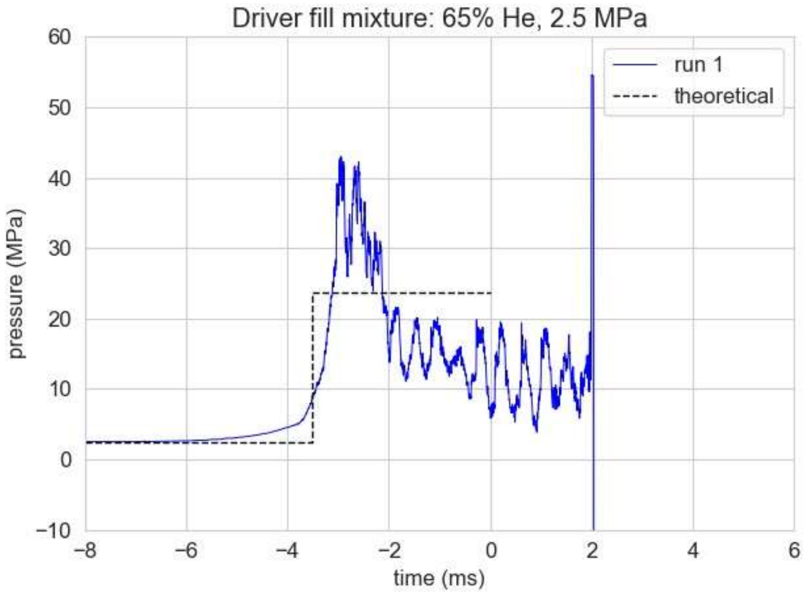

Fig. 5 P4 pressure trace obtained for a driver fill pressure of 2.5 MPa and 65% Helium dilution.

For the experiments with a Driver filling mixture diluted in 75% Helium were observed peak pressures of 30 and 45 MPa, approximately 10 to 15 times the initial filling pressure of 3.0 MPa. Figure 6 depicts these recorded pressure traces along with the estimated theoretical pressure. According to the combustion model used, the final Driver pressure (p_4) and temperature (T_4) for this condition are 25.5 MPa and 2,750 K, respectively. The lower pressure ratio and the oscillations with smaller amplitudes indicate a detonative to deflagrative combustion process. In this condition the number of spark plugs used increased to 6. It is worth to mention that the complete spark plug set is not fully commissioned, so it is expected a smother deflagrative combustion when the eighteen spark plugs are operational.

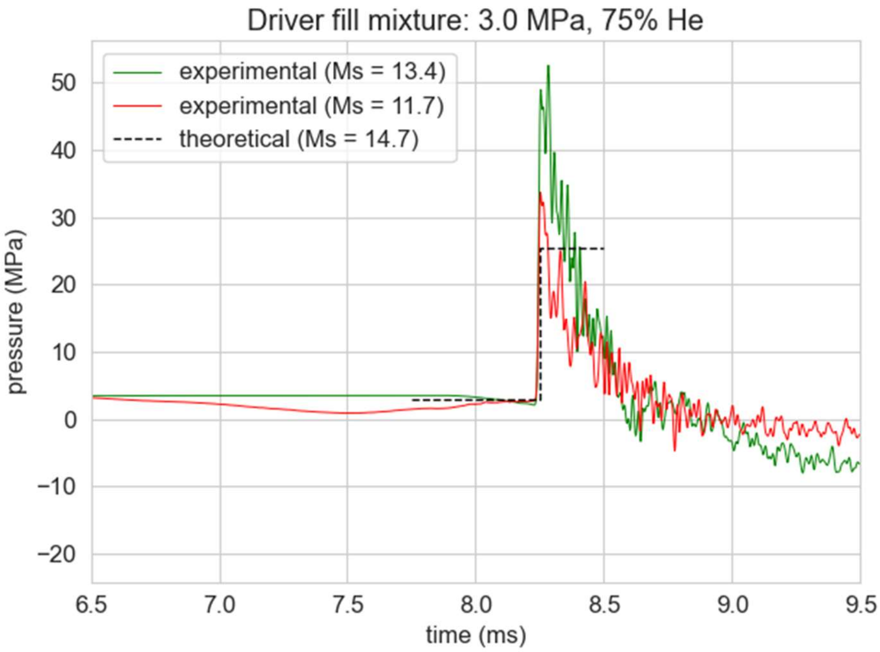

Fig. 6 P_4 pressure trace obtained for a driver fill pressure of 3.0 MPa and 75% Helium dilution.

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Diaphragm debris ended up at the end of the Driven Tube and it is shown in Fig. 7. This is a very undesirable situation since the debris, during the operation of the facility as a Shock Tunnel, could go through the nozzle throat damaging it as well as the hypersonic nozzle and test articles in the Test Section.

Fig. 7 Diaphragm debris found at the end of the Driven Tube.

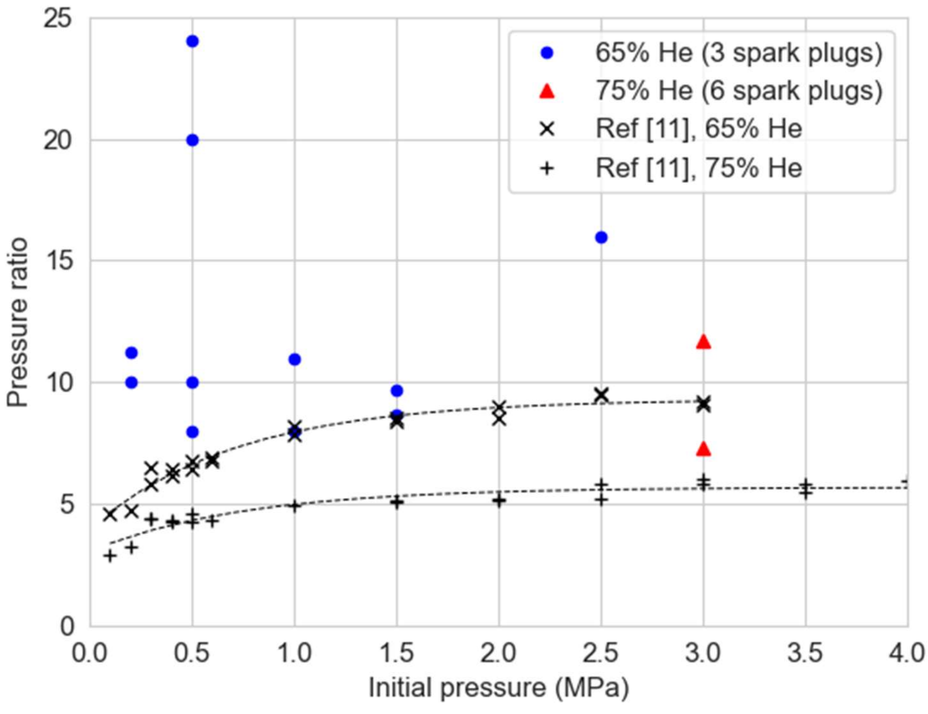

Fig. 8 Ratio of peak pressure to initial driver fill pressure against the initial total pressure of the mixtures.

Figure 8 shows the effect of changing the initial total pressure (p_{mix}) of the mixture (or initial driver fill pressure) on the peak pressure developed (p_4). It can be seen that an increase in total pressure led to an increasing pressure ratio for both He concentrations in the mixtures. As mentioned, it was observed transitions to detonation in 65% He concentration at low driver fill pressures tested.

4. Conclusion

The new high-enthalpy hypersonic pulsed facility being commissioned at the Aerothermodynamics and Hypersonics Division – EAH of the Institute for Advanced Studies – IEAv was preliminarily investigated in the shock tube operating mode. The Driver initial combustible mixture of Hydrogen and Oxygen was tested with filling pressure from 0.2 to 3.0 MPa and Helium dilution of 65% and 75%. Stronger detonation events were observed for 65% He and 2.5 MPa of initial pressure, reaching a post combustion peak pressure of 41 MPa, about 16 times the initial pressure. For 75% He and 3.0 MPa the peak pressure achieved 10 to 15 times the initial pressure, respectively 16 and 21 MPa. This lower pressure ratio and the signal oscillations with smaller amplitude indicate a detonation to deflagrative combustion transition, what is plausible due to the more diluted mixture. As the experiments were all carried out with the Driven initial pressure kept under 3.0 kPa, no reflected pressure measurements were attempted. In addition, these first exploratory experiments were also useful to forecast and solve some undesirable behaviours like the diaphragm debris, and also to practice the combustion-driven shock tunnel safety procedures.

Acknowledments

This work was performed within the 'Technologies for Hypersonic Flights' project, coordinated by the Institute for Advanced Studies, is supported by the Brazilian Funding Agency for Studies and Projects (FINEP) under the Contract no.: 01.22.0255.00 and by the Brazilian Air Force (COMAER).

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