



T5 Combustion-Driven Shock Tunnel: Finalized Shock-Tube Flow Studies

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Abstract

Hypersonic impulse facilities are crucial for reproducing high-enthalpy flight conditions during ground testing, allowing for the evaluation of hypersonic systems with relatively good fidelity and repeatability, and significantly lower costs and risks compared to flight testing. Among these, combustion-driven shock tunnels are notable for generating high-enthalpy flows through the deflagration of combustible mixtures, producing strong shock waves and transient hypersonic flows for testing. This paper presents the ongoing development of the T5 hypersonic shock tunnel at the Institute for Advanced Studies (IEAv) in Brazil, a combustion-driven facility designed to simulate Mach 10 flight conditions in the sensible atmosphere while accommodating large-scale test models. The results discussed herein emphasize the T5 facility's readiness to support research and development of hypersonic technologies in Brazil, including preliminary shock-tube flow studies with measurements of combustion pressure, incident shock velocity, and stagnation pressure obtained in the deflagrative combustion mode of operation.

Keywords: Hypersonics, Shock tunnel, Oxyhydrogen combustion, Acceptance and qualification tests

Nomenclature

IEAv – Institute for Advanced Studies
DCTA – Department of Aerospace Science and Technology
T5 – Shock tunnel
DDT – Deflagration-to-Detonation Transition
MOC - Method of Characteristics
a – Sound speed
u – Shock velocity

p – Pressure
T - Temperature
Subscripts
1 – Initial driver gas conditions
2 – Wake conditions
5 – Stagnation conditions
s – Moving wave

1. Introduction

Hypersonic testing and evaluation are key throughout the life cycle of hypersonic systems. In this sense, hypersonic impulse facilities play a role in production of high enthalpy flows in laboratory, allowing the replication of the hypersonic flight conditions for concept definition, trade-off studies, and even preliminary designs and improvements of the hypersonic systems. Hypersonic shock tunnels are widely utilized as impulse facilities for good replication of most of the salient physics at a representative scale to evaluate the true performance of hypersonic systems with relatively good fidelity and confidence at low cost and risks when compared to flight test campaigns.

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It is well known that hypersonic flows imply high enthalpy and temperature flows, both of which can be attained in combustion-driven shock tunnels. In practice, the combustion-driven shock tunnel achieves high enthalpy in the reservoir not only by increasing the driver-to-driven pressure ratio but also by heating a light driver gas, such as helium or hydrogen, via combustion reactions that result in a further increase in the speed of sound of the driver gas that, in turns, promotes strong incident shock waves. Subsequently, the stagnant test gas accelerates through a convergent-divergent nozzle, resulting in a transient hypersonic flow at chemical equilibrium within the test section. Further details about combustion-driven shock tunnels for hypersonic testing can be found in the references [1-5].

A new impulse hypersonic facility is being developed at the Institute for Advanced Studies (IEAv) of the Department of Aerospace Science and Technology (DCTA) in São José dos Campos, Brazil [6-10]. The facility, named T5, is a combustion-driven hypersonic shock tunnel designed to produce freestreams with sufficient enthalpy necessary to replicate Mach 10 flight conditions in the stratospheric layer and is capable of accommodating large test models (see Fig. 1). The next section includes: (a) the first acceptance tests of the T5 combustion driver section operating in the deflagrative combustion mode with eighteen spark plugs and filling pressures of the combustible mixture at 6 MPa (nominal condition); (b) the preliminary T5 shock-tube flow studies at 3 MPa of filling pressure; where measurements of combustion pressure, incident shock wave velocity, and stagnation pressure achievable were done; and (c) the design, fabrication, and integration of a heavy section (reservoir) mounted at the end of the T5 driven section to withstand pressures as high as 500 MPa, a contoured axisymmetric nozzle fully instrumented for producing a Mach 10 freestream, as well as a large test section designed to accommodate full size models.

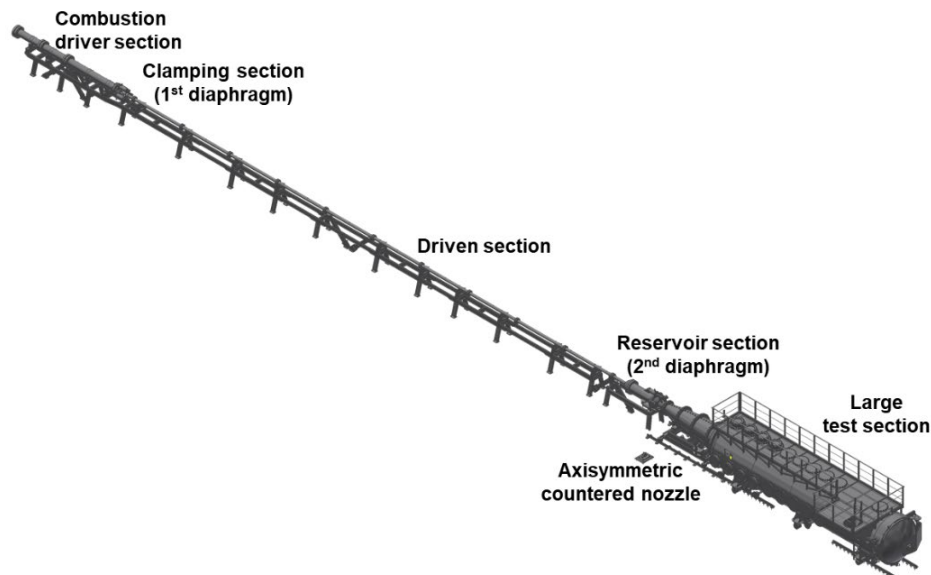


Fig. 1. Schematic view of the T5 impulse hypersonic facility.

2. Definition of T5 freestream conditions

The T5 freestream at the nozzle exit should be: a) as uniform as possible, that is, flow divergence should not exceed 1 degree, which can be achieved by a contoured nozzle design; b) quiet enough, with turbulence intensity up to 2% due to the long axisymmetric nozzle being fabricated with strict specifications on contour accuracy, waviness, and surface finish; c) the best Mach number uniformity at the entrance of the test section (around 10 at different radial and spatial locations with a maximum of 1° deviation from the freestream axis) under a total pressure of up to 108 MPa, which may induce early transition along the nozzle walls; d) not blocked, meaning the cross-sectional area of the test section is much larger (4.25:1) relative to the exit area of the countered nozzle to mitigate the interference of reflected waves from the walls of a larger test article installed therein; e) transient, with a duration of up to 3 ms, which can be achieved due to the length of the driver section combined with the filling pressure of the test gas; and f) of high enthalpy, in the order of 4,4 MJ/kg, which can be achieved through proper reservoir conditions during reflected mode operation. In order to achieve such requirements, Tab. 1 lists the expected T5 operational parameters and freestream conditions in the T5 test section.

Table 1. T5 nominal operational parameters and freestream conditions.

System	Parameters	Values
Driver section	Mixture composition	75% He + 16,6% H ₂ + 8,3% O ₂ @ 300 K
	Mix pressure (p_{mix})	6 Mpa (60 bar)
	Deflagration pressure (p_4)	52,1 Mpa (521 bar) of Helium
	Deflagration temperature (T_4)	Helium @ 3000 K
Driven section	Gas test composition	Dry air @ 300 K
	Driven pressure (p_1)	300 kPa absolute (3,0 bar)
	Incident Mach number (M_s)	5,9
Reservoir section	Reservoir pressure (p_5)	108 Mpa (1080 bar)
	Reservoir temperature (T_5)	4500 K
	Reservoir enthalpy (h_5)	4.4 MJ/kg
Vessel test section	Vacuum pressure (p_b)	10^{-2} mbar
	Freestream Mach number (M_∞)	10
	Freestream enthalpy (h_∞)	0,2 MJ/kg
	Freestream pressure (p_∞)	1070 Pa
	Test time (Δt)	3 ms

3. Definition of shock tunnel system requirements

To meet the T5 freestream conditions mentioned above, a combustion-driven shock tunnel has been developed, equipped with a combustion driver section for high-enthalpy flow conditions, an axisymmetric contoured nozzle for high-quality flow uniformity, and a large test section for testing full-scale model. Some system requirements include: (a) the T5 combustion driver section should have 18 igniters (helically distributed) that produce a 44 kV spark each within 330 μ s to ensure instantaneous and uniform ignition, where each igniter must deliver enough energy for H₂-O₂ deflagration (significantly above the minimum ignition energy of pure H₂ for accounting He dilution in a stoichiometric H₂-O₂ mixture and spark efficiency) and be resistant to plasma erosion; (b) the T5 combustion driver should be capable of operating at pressures exceeding 900 bar and temperatures above 3000°C, and be manufactured with a cylindrical shape to optimize stress distribution during deflagration or detonation modes, with a wall thickness based on a 3447-bar safety margin (four times the expected detonation pressure). It should be made of thermally treated stainless steel with an inner wall coated by chrome to resist erosion; (c) the T5 reservoir section or heavy section must address extreme structural and thermal demands, that is, it should be constructed from stainless steel in a cylindrical shape with wall thickness capable of withstanding stagnation pressures of around 1080 bar with a 1.8-safety margin, and with a refractory inner liner to address stagnation temperatures of around 3495 K; (d) the T5 nozzle should be aerodynamically contoured using the method of characteristics (MOC) and applying the correction for the boundary layer displacement thickness to prevent parasitic shock waves and ensure flow uniformity at the nozzle exit, with an expansion ratio precisely tuned to accelerate the flow up to Mach 10 while keeping Mach number and total pressure fluctuations less than 5% of nominal values in the test section. Its throat should be made of refractory material (e.g., molybdenum) for surviving the severe stagnation conditions exceeding 4000 K therein, while its main body should utilize stainless steel to withstand mechanical fatigue during repeated runs, being the manufacturing precision paramount in terms of aerodynamic contour and surface roughness to minimize early transition inside a longer nozzle (around 4.7 m); (f) the T5 test section must be large enough to maintain the flow quality while accommodating full-scale test models minimizing both the blockage model effects (up to 10% of the test section cross section), and all sources of interference (e.g., shock reflection and boundary layer growth along inner walls) throughout the test time of 3 ms. Also, multiple large quartz viewports should ensure transmission across visible to infrared wavelengths for flow visualization and

laser diagnostics; (g) A model carriage on a roller coaster-inspired rail system (both with high-load capacity) should allow complete external model installation, instrumentation checks, and pre-test calibrations in the laboratory environment and subsequent insertion into the test section, being the rail system capable of ensuring perfect realignment when the model carriage transitions back into the test section.

4. Design, fabrication and verification tests

Next, the analysis and design of the mechanical parts for the T5 facility are presented, followed by their fabrication and pre-integration. Additionally, system verification tests of the T5 shock tunnel are discussed, including diaphragm selection tests. Although significant progress has been made toward completing the T5 shock tunnel, much work remains before its commissioning in the Fall 2025.

4.1 Combustion driver section

The T5 combustion driver was designed to maintain controlled deflagration while withstanding extreme mechanical and thermal conditions. It was constructed from forged steel that provides exceptional yield strength and fracture toughness, both critical for preventing catastrophic failure under cyclic mechanical and thermal loadings. Its inner wall features hard chromium lining that provides thermal shock resistance and protects against corrosive combustion by-products (e.g., water vapor). Its structural cradle is fixed onto a massive block made of reinforced concrete that absorbs the recoil impulse from the rapid combustion process, preventing mechanical misalign. To avoid unwanted deflagration-to-detonation transitions (DDT), the T5 combustion driver incorporates the following systems: (a) helical distributed ignition, where 18 spark plugs were arranged in a helical pattern (see Fig. 2), ensuring homogeneous flame propagation that suppresses DDT onset [11]. However, due to technical issues, only eight spark plugs were operational during the tests reported in this paper; (b) the spark plug spacing (L) relative to driver tube diameter (D) is lower than 10 to suppress flame turbulence acceleration that could lead to DDT; (c) helium dilution, where the stoichiometric H_2-O_2 mixture were diluted with 75% helium, achieving subsonic combustion regimes (deflagration) while still enabling enough peak combustion pressure for operation below the driver's structural limit; and (d) operation at loading pressures up to 60 bar in the driver avoids DDT thresholds for pure H_2-O_2 mixtures, while autoignition remains negligible below 150 bar [12].

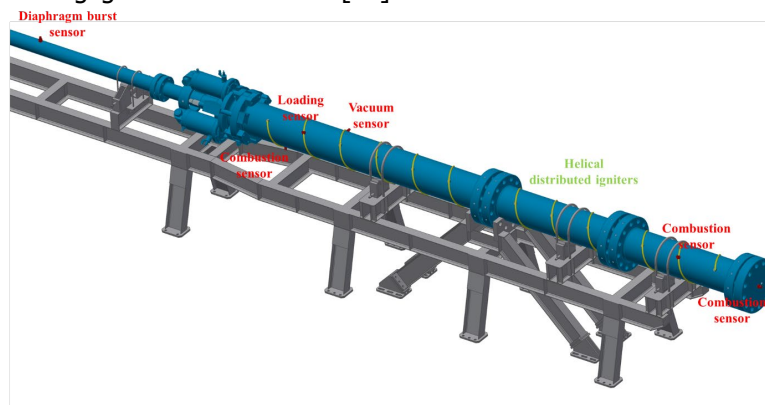


Fig. 2. CAD model of the as-designed configuration showing instrumentation location (Driver).

The driver's pressure instrumentation includes three Kistler 6215 dynamic transducers (up to 6000 bar) for combustion, an Omega PX429 static sensor (up to 5000 psi) for loading, a Kistler 7005 (up to 600 bar) for diaphragm rupture detection, and a vacuum gauge (see Fig. 2). They provide monitoring from pump-down to diaphragm rupture detection. Table 1 details other driver's subsystems, their main function, key parameters, and the critical conditions involved. Particularly, the features of the driver diaphragm to ensure bursting at predetermined pressures before peak combustion will be discussed in section 5.2.

Table 2. Auxiliary systems of the T5 combustion driver

Driver systems	Primary function	Key parameters	Critical conditions
Hydraulic clamping system	Ensures proper sealing of the combustion chamber via a diaphragm	Compression pressure of 300 bar (safety factor of 5) and quick diaphragm replacement	Diaphragm failure leads to propellant leakage
Supplying line system	Delivers a controlled stoichiometric H ₂ -O ₂ mixture with 75% He dilution	75% He+ 16,6% H ₂ + 8,3% O ₂ @ 300 K	Deviations lead to risk of DDT
Instrumentation	Monitors pressure during vacuum, loading, and combustion	Full operational range (vacuum to 6000 bar) with μ s response	Abnormal reading leads to test abort
Leak detection alarm	Detects O ₂ and H ₂ leaks	Sensitivity of 1 ppm (H ₂) and 1% variation (O ₂)	Unacceptable leak rates lead to shutdown and test abort
Line isolation system	Prevents backflow pulses and provides pressure relief during ignition (if needed)	Operating pressures of 60 bar (nominal) and 600 bar (burst)	Partial sealing leads to explosive atmosphere buildup
Ignition system	Triggers spark plugs simultaneously	Energy/spark greater than 17 μ J (MIE of H ₂) and pulse of 0,3 ms	Misfire leads to retry up to 5 times before aborting
Drying system	Eliminates chamber moisture after test	Acceptable humidity up to 60% via heating	Residual moisture leads to surface corrosion and or electrical damage
Vacuum cleaning	Removes residual post-combustion gases and moisture	Final pressure of 100 mbar via mechanical rotary pumps	Failure leads to contamination for next test
Exhaust system	Vents explosive gases safely outside the lab	High exhausting flow rates and spark-proof materials	Inadequate exhaust leads to detonation hazard inside the lab

4.2 Driven section

The T5-driven section includes 10 interconnected stainless-steel tubes totaling 34,4 meters in length, optimized for reflected-mode operation by considering both shock velocity and post-reflection sound speed to ensure a 5 ms freestream duration. Each tube consists of 25,4-mm thick stainless steel with honed 101,6-mm inner diameter surfaces to reduce boundary layer effects. The tubes feature circumferential reinforcement rib flanges at their ends and are connected by conical joints with lateral o-ring seals. The driven's instrumentation system incorporates pressure and vacuum sensors for shock tube testing under extreme conditions. The final stainless steel tube features two dynamic pressure transducers (Kistler 601CAA up to 600 bar and Kistler 701A up to 250 bar, both with μ s response times) positioned upstream of the reservoir region. These transducers are spaced 0.73 meters apart and serve as time-of-flight markers for monitoring shock velocity (u_s) while simultaneously measuring wake pressure (p_2). Moreover, two Kistler 7005 dynamic pressure transducers (up to 600 bar with μ s response time) have been temporarily installed 20 cm from a 15-mm thick disk at the upstream end of the driven tube, diametrically opposite to each other, to measure stagnation pressure (p_5). This provisional setup provides stagnation pressure data until the final shock tube configuration is completed. A vacuum gauge is installed in the mid-section of the driven tube to monitor the initial test gas pressure (p_1) before

diaphragm rupture. All signals are recorded using a high-speed data acquisition (DAQ) system, comprising SCP Slim Type 2852A amplifiers and Yokogawa DL8505 oscilloscopes.

The driver-driven interface utilizes a 2.5-mm-thick stainless-steel diaphragm, designed to burst at 135 bar. The driven section includes two mechanical vacuum pumps (rotary) with Pirani gauges, protected by safety valves along the tubes to monitor vacuum levels during setup. This vacuum system manages the initial test gas pressure (p_1) and can reach a baseline pressure of 2 mbar (air). The entire assembly is built to withstand peak pressures of 600 bar during reflected-wave operation (see Fig. 3).

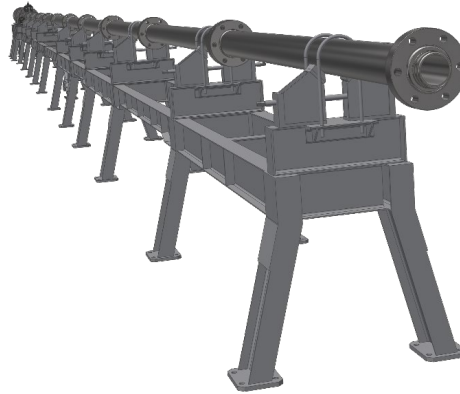


Fig. 3. CAD model of the as-designed configuration (fully assembled driven).

4.3 Heavy section (reservoir)

The end of the T5 driven section, known as heavy section (see Fig.4), is reinforced to ensure reliable operation under reflected shock conditions, where conventional tubes might fail due to the combination of high pressure and thermal loads. The design includes a pressure vessel with a 400-mm outer diameter made of stainless steel, featuring an inner refractory lining. The lining is 1 meter in length and has a wall thickness of 10 mm, coated with a 0.3-mm thick layer of copper, able to maintain structural integrity even at sustained stagnation temperatures of 4,000 K and 1080 bar of stagnation pressures (with a 2x safety factor). The heavy section incorporates machined instrument ports for dynamic pressure transducers (with 2 μ s of rise time and pressure range up to 10,000 bar), strategically positioned to measure stagnation pressure (p_5) without compromising structural integrity. A dedicated hydraulic clamping system enables rapid opening/closing cycles for diaphragm replacement, utilizing three actuators with 55-ton sealing force to securely clamp a metallic diaphragm in place and absorb recoil forces during shock tunnel operation. Moreover, it ensures leak-free containment during firing conditions and dissipates energy, preventing load transmission to the facility and instrumentation. In addition, its structural cradles are bolted to a large, reinforced concrete block, designed to absorb the recoil forces from firing and maintain mechanical alignment. The heavy section is still under construction and should be commissioned soon.

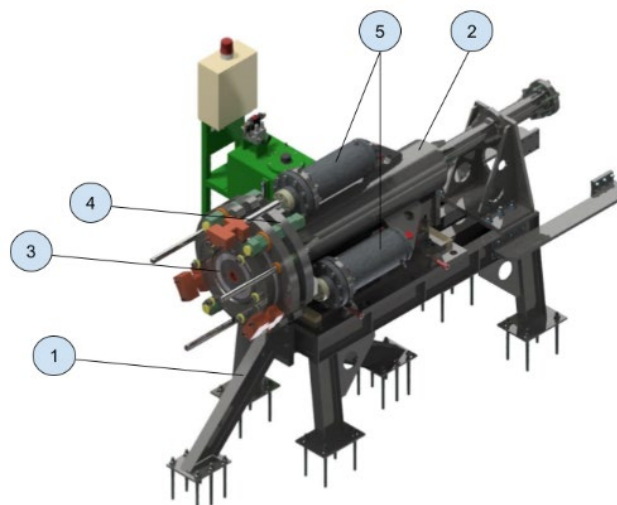


Fig. 4. T5 heavy section, as-designed CAD model.

4.4 Axisymmetric contoured nozzle

The T5 nozzle features an aerodynamically optimized contour, designed using the Method of Characteristics (MOC) and corrected for the boundary layer displacement thickness to ensure uniform Mach 10 flow at the nozzle exit with a maximum of 1 degree of deviation from the freestream axis. A throat diameter of 25,57 mm and an exit diameter of 1100 mm result in an area ratio of 1,850:1 for extreme gas expansion. The 4.73-meter-long internal flow path maintains a smooth surface to delay boundary layer transition and reduce flow disturbances during internal expansion. To address erosion, the throat section includes a replaceable molybdenum insert in the subsonic region, capable of enduring expected stagnation temperatures above 3495 K, while allowing quick maintenance between test cycles. The entire nozzle assembly is supported by an adjustable structural cradle mounted on a rail-guided system and actuated by a hydraulic system that enables smooth translation for reservoir diaphragm replacement, compression, and mechanical realignment (see Fig. 5). The main nozzle body is constructed from stainless steel to resist fatigue during repeated dynamic loads (mechanical and thermal). Instrumentation ports, spaced every 153 mm along the nozzle centerline, provide flow diagnostics (wall pressure and temperature). The external surface of the aft nozzle section is polished sufficiently to ensure smooth sliding through a brass bushing (see Fig. 5) at the test section interface, preventing superficial damage during integration, alignment, and firing cycles, while maintaining seal integrity. All these features combined should ensure long-term durability and consistent performance in reflected-shock tunnel testing under dynamic loads and cyclic fatigue. As the heavy section, the nozzle throat insert is still under construction and will be commissioned soon.

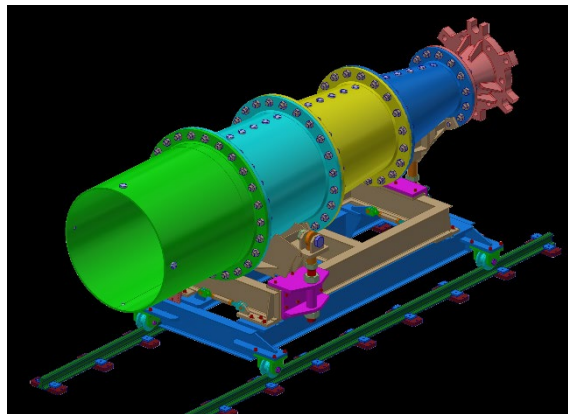


Fig. 5. CAD model of the as-designed configuration, the axisymmetric contoured nozzle.

4.5 Large test section vessel

The T5 test section features an 11.8-meter long cylindrical vessel with a 2.26-meter inner diameter, specifically designed to host large-scale aerodynamic test models (see Fig. 6). The vessel maintains excellent flow quality thanks to its dimensions, which provide a 4.25:1 area ratio compared to the nozzle exit, helping to reduce reflected wave interference on the freestream. Its structure has thick A285-C steel walls (12.7-mm thickness) to withstand vacuum loads, as well as mechanical and thermal stresses during operation. Instrumentation and visualization ports are available through eight flanges on each side and eight on top, offering versatility for various experimental needs. These ports include large diameter quartz observation windows for optical diagnostics and schlieren visualization, feedthroughs for electrical and fuel connections, and interfaces for vacuum pumps. The vessel can achieve a vacuum environment down to 10-1 mbar using a roots pumping system. Inside, a rail system runs the entire length of the vessel, allowing precise positioning of the test model (relative to the nozzle exit) via a sliding support mechanism designed for heavy test models. An autoclave-style door allows for quick installation and removal of large test models, enabling rapid cycling while maintaining leak-tight integrity during operation. The test model is mounted on an external cart that connects with the vessel's internal rail system via a male-female coupling. This setup allows all model assembly, instrumentation, and calibration procedures to be performed externally, removing the need for confined space work inside the vessel. The external cart engages with internal rails, facilitating safe insertion and removal of the large test model from inside the vessel. Additionally, the entire vessel can be moved along an external rail system, making it easier to install and replace the contoured nozzle for different design

Mach numbers. These features offer an optimal balance between experimental capability and practical operation, supporting hypersonic test and evaluation with large test models.

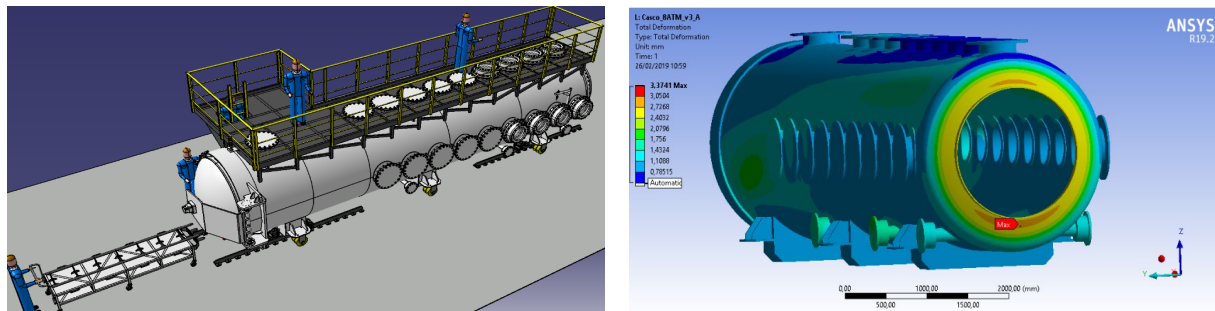


Fig. 6. Large test section vessel: CAD model of the as-designed configuration.

5. Results and discussion

Our experimental campaign was divided into two sequential phases: first, confined combustion tests were conducted across loading pressures ranging from 5 to 60 bar of a fixed stoichiometric $\text{H}_2\text{-O}_2$ mixture diluted in 75% He to characterize the deflagration process within a closure driver section. These tests employed a 15-mm thick stainless-steel disc instead of a thin diaphragm, allowing detailed analysis of timing jitter, ignition characteristics, combustion stability, and pressure rise rates across the operational driver envelope. Following combustion characterization, the second phase proceeded with shock tube tests using the nominal diaphragm configuration. As a safety precaution, given that the heavy test section remains under fabrication, these experiments were done at reduced loading pressures ranging from 30 to 45 bar and 2 mbar of air in the driven section (vacuum), planned to evaluate: a) Diaphragm burst repeatability; b) Shock-tube flow development in the driven tube; and c) Achieved stagnation conditions. Critical insights into both component-level performance and integrated system behavior, as well as safety protocols, were gained during this pre-nominal testing phase, as discussed next.

5.1 Confined combustion tests

The combustion-driven shock tunnel relies on controlled combustion of a fixed stoichiometric mixture of $\text{H}_2\text{-O}_2$ diluted with 75% helium to generate high-pressure, high-temperature He gas. Firstly, tests were conducted with a mixture loading pressures ranging from 5 to 60 bar confined in the driver section, and a 15-mm thick stainless-steel disc was used in place of the diaphragm. A loading sequence procedure was designed to respect the 65% helium detonation threshold limit [1] throughout the entire procedure, summarized as follows: the test procedure began with thorough vacuum cleaning of the driver section, evacuating it to 100 mbar to eliminate any residual contaminants. Following evacuation, a controlled gas loading sequence (see Fig. 7) is executed to ensure safety. The process begins with a helium purge to create an inert environment in the driver, followed by the introduction of oxygen. A secondary helium purge then isolates the oxygen before hydrogen is introduced, preventing direct mixing of both reactive gases. A final helium purge eliminates residual hydrogen, further mitigating detonation risks. After loading, the mixture is allowed to homogenize for approximately 5 minutes before ignition. Again, the Omega static pressure transducer (from 0 to 5000 psi range), positioned at the mid-driver location, was used to monitor the total loading pressure and track the development of partial pressures during the gas loading sequence, providing information on the initial driver conditions before ignition. The ignition process follows a strict safe-arm-fire protocol designed to prevent inadvertent activation while ensuring the ignition energy and timing necessary for the operation of the combustion driver section. In safe mode, the ignition system remains inactive, that is, in stand-by

mode: the ignition controller is turned off, and all capacitive ignition modules are de-energized or disabled. When in arm mode, the ignition controller is activated, and the capacitive ignition modules are energized, that is, enabled. Before switching to this mode, it is essential to isolate the driver section and clear the surrounding area. The fire command is executed only after thorough checks of the driver section conditions have been completed. This command activates the capacitive ignition modules, generating a 475 V signal to the primary of all induction coils, which simultaneously discharges 44 kV to the eighteen spark plugs for multi-point ignition. Figure 8 shows a typical time-resolved combustion pressure for a stoichiometric hydrogen-oxygen mixture diluted with 75% helium at an initial loading pressure of 41 bar in the combustion driver section. Note that there is a jitter window of about 10,8 ms, possibly caused by inconsistencies in spark discharge timing or local mixture conditions near the igniter.

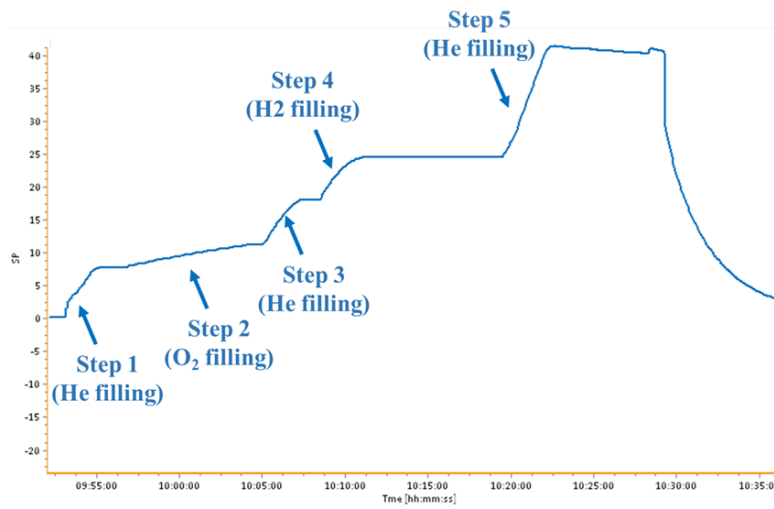


Fig. 7. Sequential gas loading procedure to achieve partial pressures, prevent premature detonation in a stoichiometric mixture of H_2 - O_2 diluted with 75% helium, and ensure homogeneous mixing. An Omega static pressure transducer (range up to 5000 psi) was used for pressure monitoring.

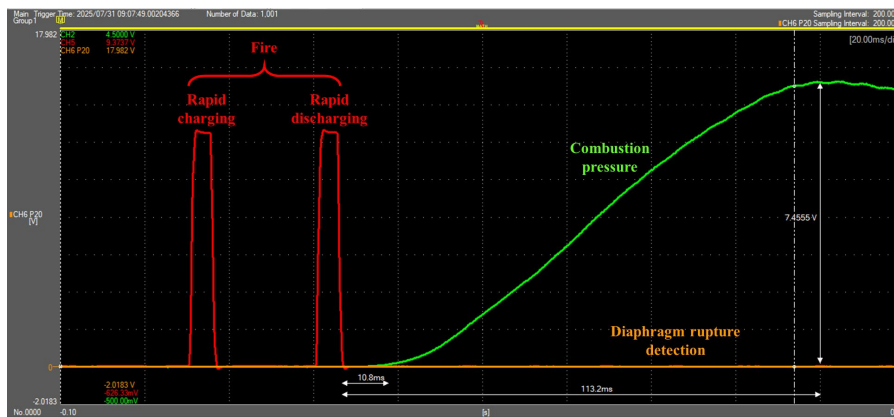


Fig. 8. Time-resolved combustion dynamics of a stoichiometric hydrogen-oxygen mixture diluted with 75% helium at an initial loading pressure of 41 bar in the combustion driver section, including fire signal, confined combustion phases, and diaphragm rupture detection.

Moreover, smooth deflagration occurred (without sharp pressure sparks), with a pressure rise rate of up to 3 bar/ms and a peak pressure ratio up to 7 times the initial load pressure, closely matching predictions for the pressure amplification factor expected in the deflagration regime. The adiabatic flame temperature was estimated using Cantera [13], resulting in an equilibrium temperature of 2760 K (considering water vapor and hot helium in the products). Additionally, a more realistic temperature, accounting for water condensation and heat losses through the driver section walls, was calculated at 2301 K using an in-house code developed at our laboratory [14], which extends Cantera's capabilities.

Finally, the absence of pressure registration from a diaphragm rupture detection sensor (dynamic pressure transducer) located in the driven section (near the diaphragm) indicates that no rupture occurred, as intended and desired for confined combustion tests. Fig. 9 shows the experimental data points clustering closely around the theoretical pressure amplification for deflagration, indicating that the driver section exhibited subsonic combustion behavior across the tested loading pressure range. This confirms that, in fact, high helium dilution effectively suppressed any potential transition to detonation (DDT), thus maintaining controlled confined combustion under the tested loading pressures.

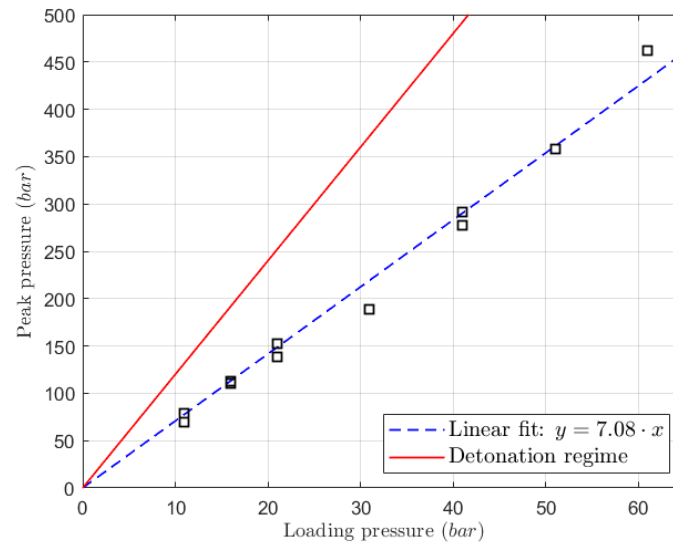


Fig. 9. Peak pressure versus initial loading pressure relationship for a stoichiometric hydrogen-oxygen mixture diluted with 75% helium in the combustion driver section. Note that the experimental points cluster near a pressure amplification factor of 7 as expected for the deflagration regime (blue line).

5.2 Diaphragm selection

The diaphragm in the combustion driver section was carefully designed to rupture predictably at 135 bar, which is above the initial fuel loading pressure of 60 bar and at around 21% of the peak pressure, thereby balancing the production of stronger incident shock waves in the driven section with sufficient heat retention. This ensures controlled driver section operation and performance [1,2,15]. The diaphragm material selected was stainless steel 304, chosen for its predictable fracture behaviour, good compatibility with the fuel mixture, and corrosion resistance. The thickness was set at 2.5 mm, a value determined through several burst tests that balanced the target rupture pressure with the need to minimize fragmentation. A cross-shaped V-notch stress concentrator (90° grooves pattern) was machined using milling process to initiate rupture at the target pressure (see Fig. 10). This manufacturing method ensured reliable performance without premature failure or significant degradation. The diaphragm rupture tests were conducted using a high-pressure air compressor system to incrementally increase the pressure across the diaphragm until failure occurred, allowing measurement of the rupture threshold. This testing method ensured the selection of diaphragm material, thickness, and cross-shaped V-notch stress concentrators, as well as the establishment of the diaphragm rupture behaviour (petal-free rupture). In summary, the selection of the T5 driver's diaphragm was a compromise between three requirements: maintaining structural integrity during propellant loading, ensuring a predictable and clean rupture upon combustion, and maximizing the strength of the incident shock wave generated. The cross-notch design was ultimately chosen as it facilitates rapid and complete opening, which in turn, enhances shock generation.

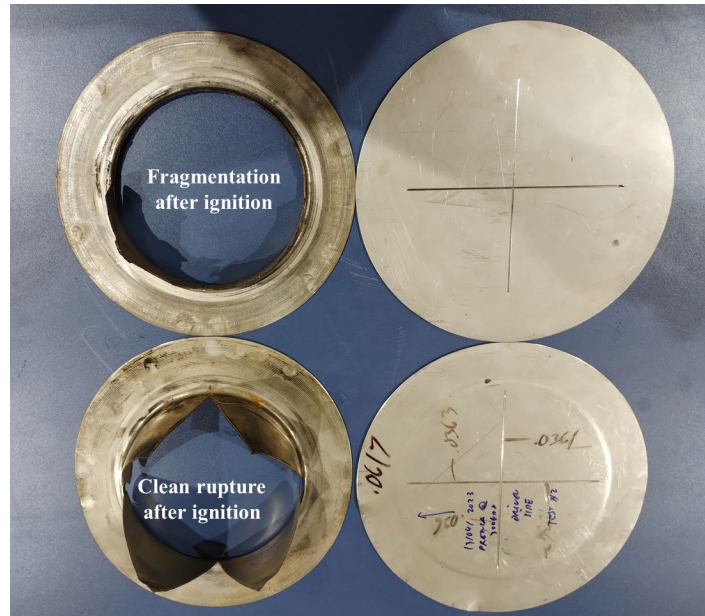


Fig. 10. Diaphragm rupture patterns, comparing distinct ruptures characterized by clean burst and fragmentation after ignition.

5.3 Shock-tube flow tests

Our current investigations with the T5 combustion-driven shock tube have successfully demonstrated the facility's capability to generate extreme stagnation conditions through reflected shock wave operation. For the following tests the 15-mm thick stainless-steel disc was replaced by a scored diaphragm 2,5 mm thick. The main results include the reproducible production of driver gas at pressures (p_4) ranging from 169.93 to 496.53 bar (mean amplification factor of 6.88), with expected He temperatures (T_4) between 2298 and 2302 K, accomplished through controlled deflagration of stoichiometric H_2 - O_2 mixtures with 75% helium dilution. The instrumentation used to acquire the loading pressure, driver pressure, and the diaphragm burst pressure was the same as previously detailed in section IV.A. Figure 11 shows a typical time-resolved driver pressure (p_4) for a stoichiometric hydrogen-oxygen mixture diluted with 75% helium at an initial loading pressure of 41 bar in the combustion driver section. A jitter window of approximately 13 ms was observed, accompanied by a rapid pressure rise of 8.9 bar/ms. The diaphragm burst occurred at a measured pressure of 103 bar, marking the transition to shock formation in the driven section. At the same time, the combustion pressure in the driver section continues to rise, reaching a peak of 218,18 bar, which is typical of deflagration. Subsequently, the driver section begins to depressurize.

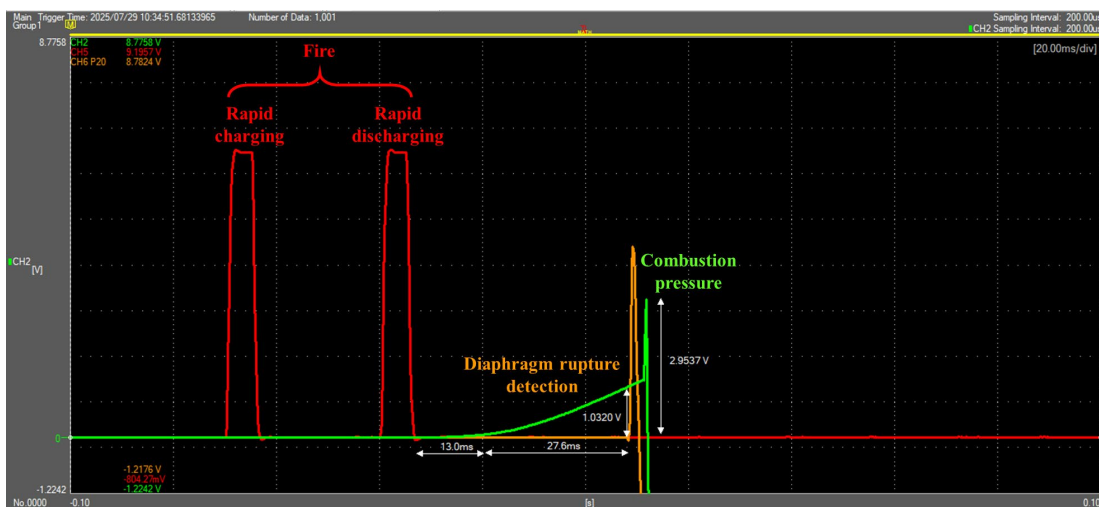


Fig. 11. Time-resolved combustion dynamics of a stoichiometric hydrogen-oxygen mixture diluted with 75% helium at an initial loading pressure of 41 bar in the combustion driver section, including fire signal, combustion phases, and diaphragm rupture detection.

The characterization of the T5 shock tube performance was conducted through 16 runs. Figure 12 shows the initial pressure of the unburned fuel-oxidizer mixture (loading pressure) against the peak pressure achieved after deflagration (p_4), which drives the generation of shock waves. The curve shows that increasing the driver's loading pressure raises the driver pressure. This relationship is characterized by an average pressure amplification factor of 6.88 and a linear regression slope of 7.12, both of which are key parameters for evaluating driver performance. Pressure transducers along the driven section (see comments in section 4.2) recorded wake pressures (p_2) ranging from 0,6 to 35 bar, with rapid rise times, confirming clean shock formation across the tested envelope. The shock Mach number range of 1.3 to 6.3 was determined via time-of-flight measurements between pressure transducers spaced 0.76 m apart. The local speed of sound in the pre-evacuated driven section (344 m/s), was used in the calculation. Initial driven section pressures (p_1) were maintained within a low range of 2.2 to 22 mbar. These low initial pressures were essential to ensure that the reflected shock pressure (p_5) remained within the structural limits of the driven tube end, a necessary precaution while its heavy section was still under construction. Transducers positioned 20 cm from the driver end measured stagnation pressures (p_5) reaching up to 445 bar, validating the reflected shock operation method. Stagnation temperatures up to 3200 Kelvin were estimated using our customized Cantera code across the tested envelope, which will be verified soon via spectroscopic techniques.

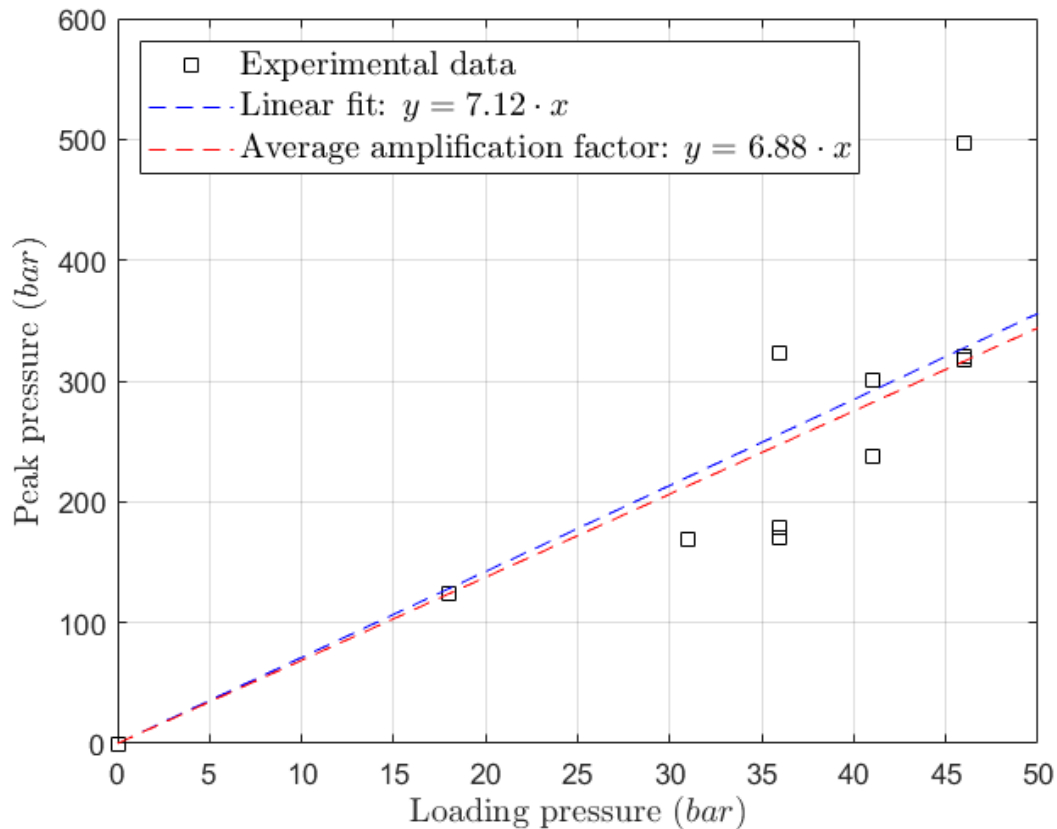


Fig. 12. Performance curve of the T5 driver section, showing the relationship between initial loading pressure and peak combustion pressure for a stoichiometric hydrogen-oxygen mixture diluted with 75% helium.

Figure 13 shows how the strength of the generated shock wave (M_s) depends on the initial pressure ratio across the diaphragm (p_4/p_1). The driver gas is composed of 75% hot helium and 25% water vapor at a temperature of 2301 K, which is the result of the combustion process. While the presence of water vapor decreases the speed of sound compared to pure helium (1838 m/s for the mixture versus 2150 m/s for pure helium) the calculated driver-to-driven sound speed ratio (a_4/a_1) of 5.3 remains high.

This ratio is crucial for determining the strength of the generated shock wave. When this mixture is discharged into the rarefied environment of the driven section, it can produce incident Mach numbers of up to 7. Nevertheless, the fundamental trend remains clear, that is, the shock strength increases with the pressure ratio.

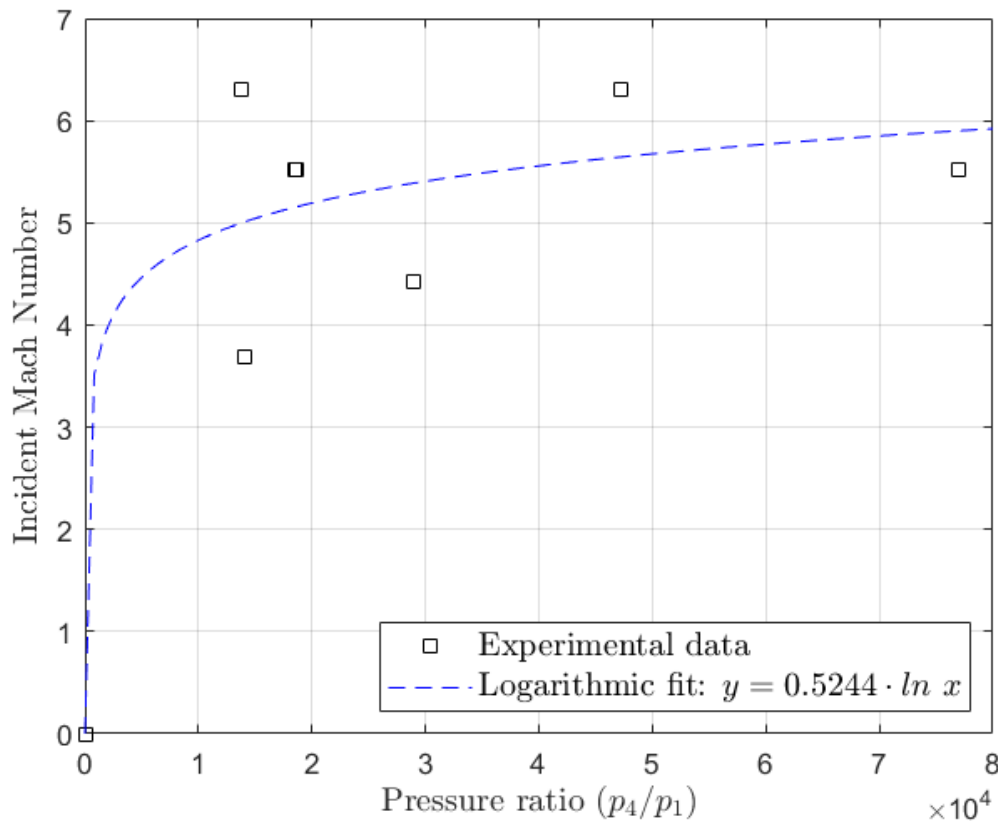


Fig. 13. Performance curve of the T5 shock tube, showing the relationship between the incident shock Mach number and the diaphragm pressure ratio for a high-temperature driver gas mixture of 75% helium and 25% water vapor.

Figure 14 shows the correlation between the incident shock Mach number (M_s) and the measured stagnation pressure (p_5) behind the reflected shock wave at the end wall of the T5 shock tube. As expected, as the strength of the incident shock wave increases, the stagnation conditions of the test gas after the shock also increase. The stagnation pressure represents the highest dynamic mechanical load expected by the T5 shock tube, particularly at its end wall. To manage this pressure, we intentionally operated with a rarefied driven section to keep p_5 within the current structural limits of the tube (600 bar). This approach allows for safe testing until the installation of the heavy-duty driver section, which will enable future operations at the nominal driven pressure of 3 bar.

All results obtained so far are serving as a baseline for future nominal runs. Furthermore, this commissioning phase has been essential for verifying the functionality of T5 systems, including instrumentation, ignition, hydraulic, and vacuum systems, DAQ, loading and triggering sequences, and other components, ensuring we will be operationally ready for our high-enthalpy hypersonic flow tests.

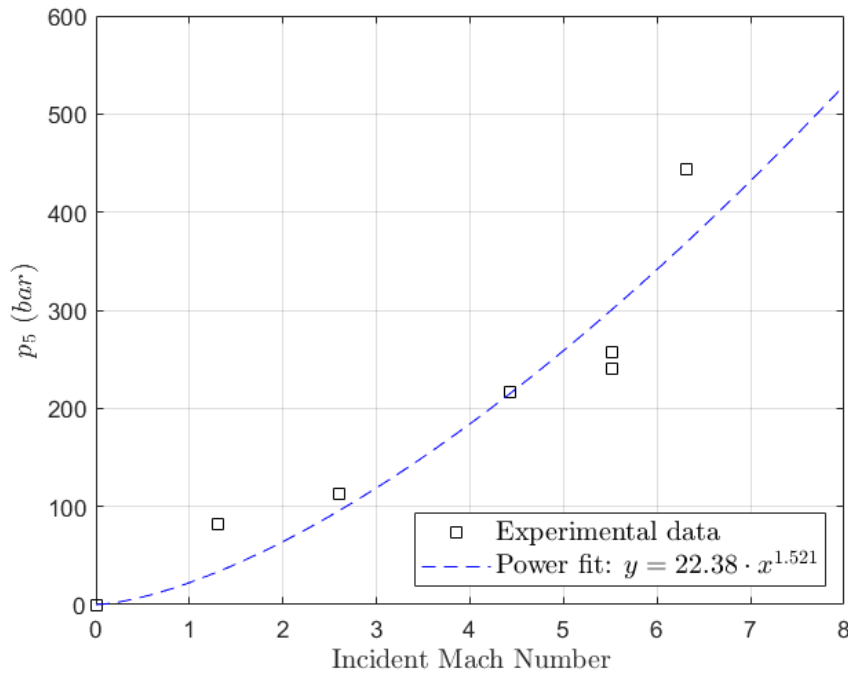


Fig. 14. Performance curve of the T5 shock tube, showing the relationship between the incident shock Mach number and the measured stagnation pressure, defining its operational envelope and structural limits.

Conclusions

The ongoing development of the T5 combustion-driven shock tunnel at IEAv marks a major milestone in establishing a high-capacity hypersonic test facility in Brazil. This work has successfully moved from the design and fabrication stages to a comprehensive verification campaign, demonstrating the facility's readiness for high-enthalpy hypersonic flow tests. The design and integration of all main components, such as the combustion driver, driven section, reinforced reservoir, contoured nozzle, and large test section, have been completed to strict specifications, ensuring safe operation under extreme dynamic loads (mechanical and thermal). The auxiliary systems for diaphragm clamping, gas mixing, ignition, vacuum, and data acquisition have been validated and are working as intended. Our current results from confined combustion and initial shock tube tests confirm the fundamental operational principles of the T5 facility. Using a fixed stoichiometric H_2-O_2 mixture diluted with 75% helium has proven effective in producing controlled deflagration, with an average pressure amplification factor of around 6.88, while preventing deflagration-to-detonation transition (DDT) across the tested loading pressure range. The T5 combustion driver successfully generates a high-temperature, high-pressure driver gas (75% hot helium and 25% water vapor), enabling the creation of strong incident shock waves with Mach numbers up to 6.3 and, in turn, reflected stagnation conditions with pressures up to 445 bar, along with estimated temperatures exceeding 3000 K in the current off-design operation. Additionally, the tests have been crucial in characterizing T5 system behavior, such as ignition jitter and diaphragm burst dynamics, as well as validating the performance of our codes.

The relationship between incident shock strength and diaphragm pressure ratio, and resulting stagnation pressure has been verified, mapping the facility's current off-design operational envelope and confirming our predictions. Completing this commissioning phase has provided several insights into system performance, refined operational and safety procedures, and set a baseline for routine operations to be done in the near future.

Additional tests with the 18 spark plugs and the soon-to-be-commissioned heavy section are already scheduled to enable a complete evaluation of T5 capability of achieving its nominal operating conditions (see Table 1). They will focus on reaching the target stagnation conditions needed to produce a Mach 10 freestream with 4.4 MJ/kg total enthalpy, supporting hypersonic technology research and development on a representative scale in Brazil.

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