Project of a New Experimental Installation for the Investigation of Rocket Nozzle Flows

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Abstract. Here, the project of a new experimental facility to be installed at the Aerodynamics Division of the Institute of Aeronautics and Space is presented. The new facility will provide means to perform experimental campaigns to analyze the flow behavior at different rocket nozzle concepts using cold gas flow, that will be obtained from a modification of the Pilot Transonic Wind Tunnel compressed air system. The new installation will enable safer and cheaper experiments, since the cold gas experimental procedures do not demand fuel storage and burn and security measures are much less severe. Furthermore, experiments can be carried out with different types of sensors and instrumentation, typically used in wind tunnel tests, and the optical access is greatly improved enabling the use of optical techniques for the characterization of flow properties inside the nozzles, such as schlieren optics, pressure (PSP) and temperature (TSP) sensitive painting.

Keywords: nozzle flows, transonic wind tunnel, cold gas facility

Introduction

Research on the gas dynamics inside rocket nozzles is an essential step for improving the launching capability of different kinds of rockets. The Aerodynamics Division of the Institute of Aeronautics and Space (IAE) is working in order to provide a new experimental cold gas facility to analyze and investigate the flow behavior inside small scale nozzles with different geometries, both in transient and steady flow regimes.

Here, the main issues concerning the investigation of nozzle internal aerodynamics are described, while defining the conceptual project of the cold gas facility, from an adaptation of the aerodynamics circuit of the existing Pilot Transonic Wind Tunnel (TTP), and detailing the design of optimum nozzles that are initially planned to be tested.

Rocket nozzles are usually designed to operate under high pressures, typically reaching pressure ratios about 60 in normal operation conditions. However, sometimes, during the booster ignition procedure at low altitude or cutoff at high altitudes, back pressure effects can induce a local significant decreasing in the pressure ratio causing flow separation from the nozzle walls and the formation of shock waves inside the nozzle giving rise to strong random side loads in the nozzle geometry, as observed by Hagemann and Frey, 2007.

Nowadays, the best way to avoid these phenomena is by using low area ratio nozzles, at the expense of performance. Thus, the study of flow patterns inside nozzles is essential to prevent failures, particularly during the transient start-up and shut-down operations, as also to improve nozzle performance. Additionally, the development and calibration of numerical models capable of capturing steady and transient flow behavior at different conditions is of great interest for comparison with the experimental results and for future developments using reliable computational tools, so that experimental information about the flow behavior at different pressure ratios is essential.

In order to have a cold gas facility capable of conducting experimental campaigns to analyze the gas dynamics inside rocket nozzles, an adaptation of the existing Pilot Transonic Wind Tunnel (TTP) installation of the Institute of Aeronautics and Space (IAE) is proposed. While the concept of a cold gas test facility for nozzle flows is not new, there are well known operating facilities at the German Aerospace Center at Lampoldshausen (Frey, *et al*., 2000) and the NASA Marshall Space Flight Center at Huntsville (Ruf *et al*., 2009), for example, the main objective in building a facility of this kind in the IAE is to enable studies concerning nozzle flows in a friendly environment, where one can take advantage of different kinds of instrumentation to carefully characterize the flow inside various nozzle geometries in different modes of operation, as different experimental tools, such as pressure transducers, commonly used in wind tunnels, and optical techniques as PSP and TSP can be used in the friendly environment of the cold gas flow.

The investigations of the flow physics inside these devices is extremely important for the improvement of performance and the evaluation of unsteady phenomena as, for example, the appearance of side loads and flow transition phenomena driven by the interaction between the boundary layer and shock waves (Dumnov, 1996). These unsteady phenomena can impose severe difficulties for the engine operation as reported, for example, by Watanabe *et al.*, (2002), that describe the problems in the development of the Japanese LE7-A engine due to the appearance of significant side loads during the transient modes of operation.

We expect that the new facility will assist the IAE for the development of future efficient launchers for the Brazilian Aerospace Program and also in the research of alternative and new rocket nozzle designs and flow control strategies. After the installation of the facility is completed, experiments and numerical simulations of the inviscid and

viscous internal flow under the same design configuration parameters will be performed providing a synergy between numerical and experimental investigations.

Project of the new installation

The project of the new experimental installation is derived from an adaptation on the main compressed air circuit of the TTP, shown in Fig. 1. The TTP is a modern installation, able to perform tests in a continuous Mach number range from 0.1 to 1.1 and intermittently, by means of mass injection system, up to Mach number 1.3. The tunnel is equipped with a test section of 0.25 m high and 0.30 m wide and automatic control subsystems that perform actions to settle Mach number, stagnation pressure (from 50 kPa to 125 kPa), stagnation temperature and humidity in the tunnel test section.

Figure 1. View of the Pilot Transonic Wind Tunnel of the Institute of Aeronautics and Space

The existing mass injection system will be used to supply compressed air up to 40.10^5 Pa by means of two alternative high pressure compressors with 92 kW each, two reservoirs with 10 m^3 each, distribution tubing and control valves. The main modifications consisting of a new pressure line, stagnation section, structural section, rupture disc and the nozzle installation are represented in Fig. 2, where the CAD project of the new installation is shown in detail.

Figure 2(a) shows the actual configuration of the TTP facility, with the two reservoirs connected to the tunnel by the tubing system, with a valve, in red, to control the pressure of the reservoir, while Figure 2(b) presents the new configuration proposed for the TTP to allow the experimental investigation of nozzle flows, where one can observe that the tubing system will be modified by the addition of a derivation that drives the flow to the nozzle structure, detailed in Fig. 3, but the main structure of the TTP will not be affected by the modifications.

The nozzle exit will be open to atmosphere, what imposes a restriction to the experiments, as exit pressure cannot be varied. A way to circumvent this restriction is to use a vacuum chamber with optimum pressure control, allowing pressure variation from sea level conditions, or higher, to very high altitude, low pressure conditions. The usage of a vacuum chamber is not present in the initial project but is being planned for future upgrades in the cold gas facility.
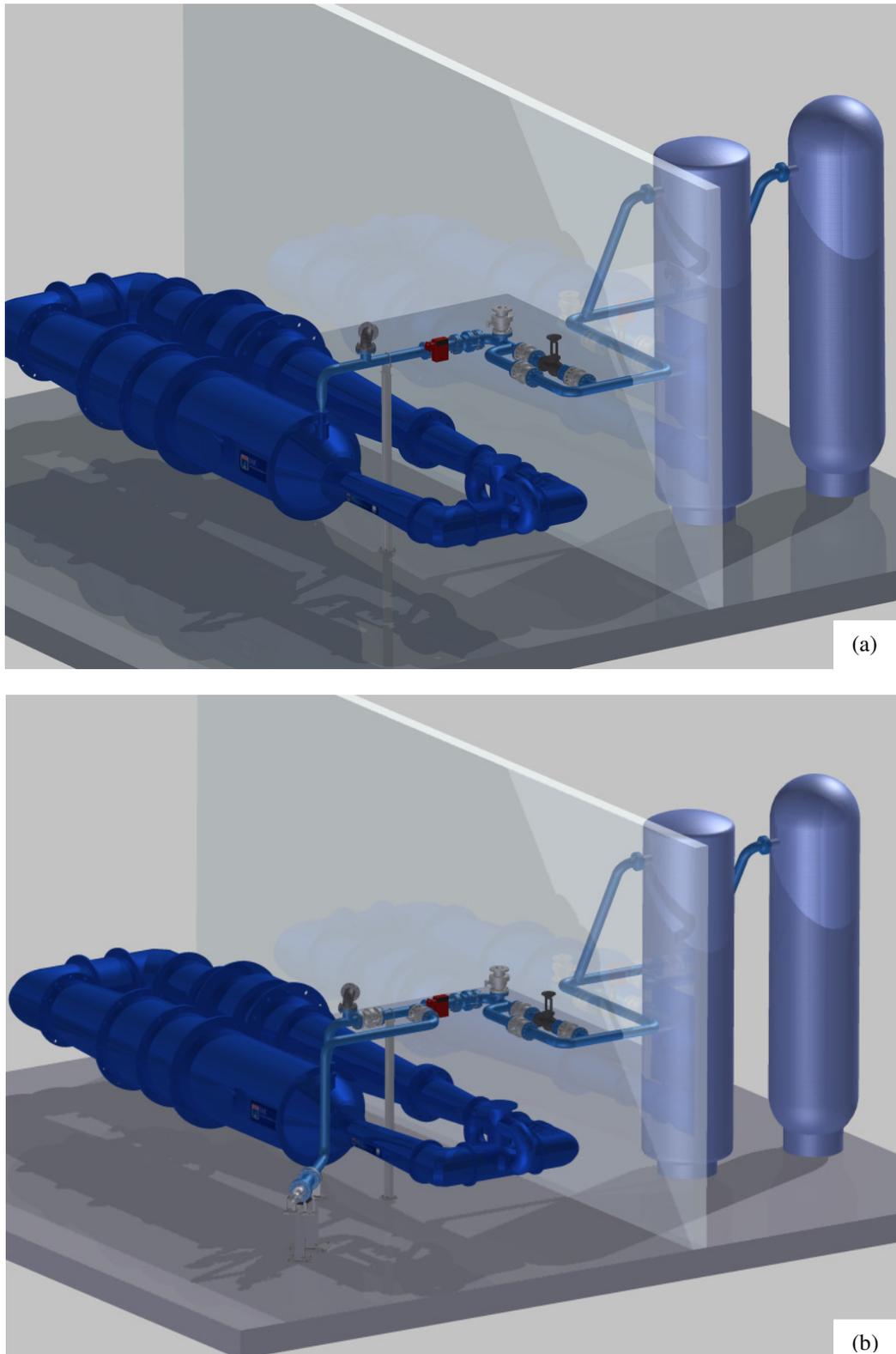
Figure 2. Spatial three dimensional view of the actual configuration of the TTP (a) and the proposed adaptation for the nozzle experimental facility (b)

Figure 3(a) presents the detailed system configuration for the nozzle cold gas facility, with the new configuration depicted in red, where the line system, the supporting structure and the nozzle can be seen. The flow will get through the line system, controlled by an automatic valve, and will reach a stagnation chamber that will be connected to the nozzle by a flange. The stagnation chamber will be equipped with pressure and temperature transducers to characterize the flow properties at this region.

In Fig. 3(b) a generic nozzle is shown mounted over the supporting structure, with the line system mounted over a rigid structure, projected to avoid strong vibrations due to pressure variations, which will be connected to the different kinds of nozzles by a flange that will be propped on a column (Fig. 3b).
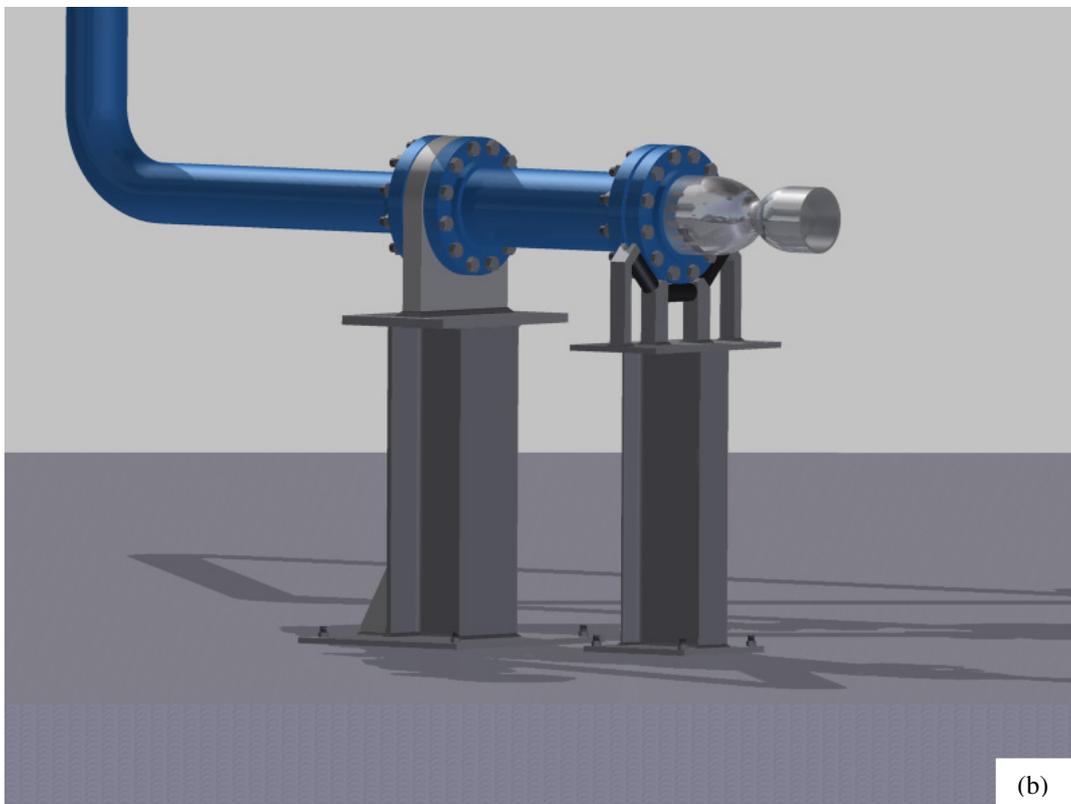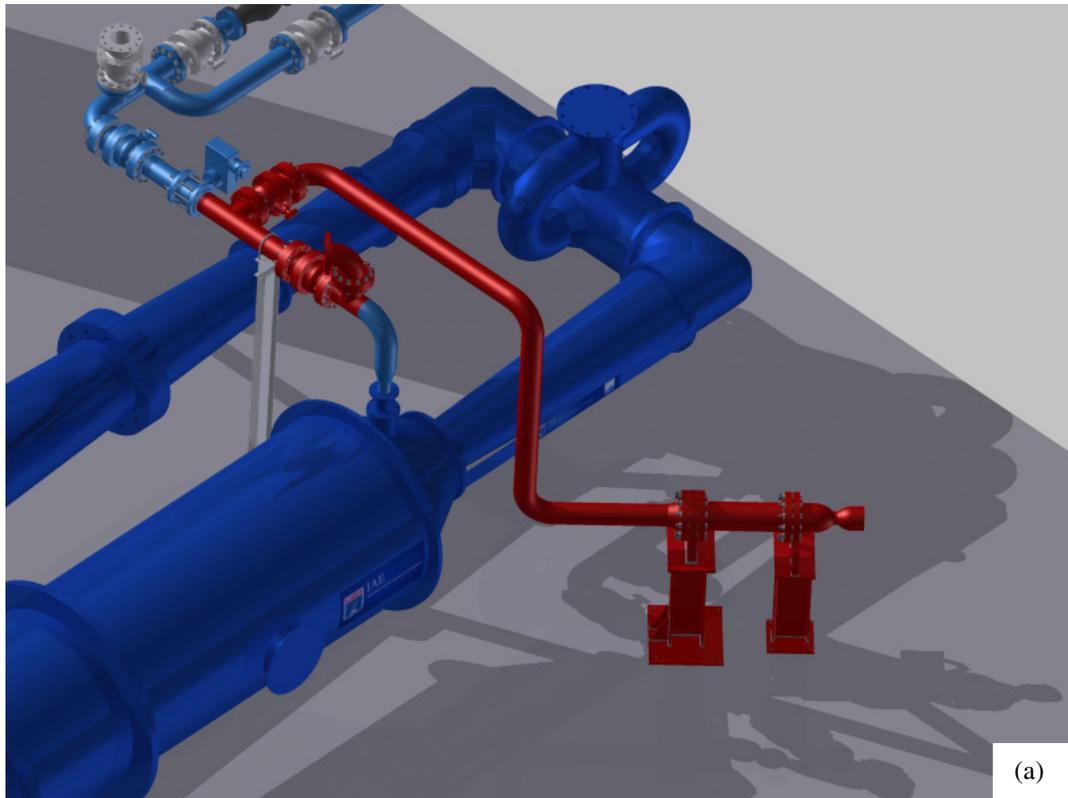

(a)

(b)

Figure 3. Three dimensional view of the tubing system adaptation and nozzle facility structure (a) and detailed view of the nozzle installation and supporting system showing the flange connections and a generic nozzle.

Experiments will be performed through the opening of the valve connecting the pressurized reservoirs to the small plenum chamber connected to the nozzle. The operation of the nozzles is going to be intermittent with a running time depending on the nozzle geometry and operational parameters. Moreover, there is a time lag in the opening of the valve of about 4 s and this time lag will be neglected in order to perform the experiments.

Another experimental procedure proposed is the use of a rupture disc to investigate transient flow behavior at a sudden start of the flow, with the rupture disk projected to open when a certain, predetermined, pressure is achieved at the stagnation chamber.

Experimental tools for the investigation of steady and transient flow inside the nozzles and its effects on nozzle performance will include pressure taps and pressure transducers, pressure sensitive painting, schlieren photography and strain gauges.

Experimental range of test parameters

The range of parameters for the experimental tests is presented in Fig. 4 and Fig. 5, where the experimental conditions for the tests of different nozzle geometries are calculated using the isentropic relations for a calorically perfect gas (Anderson, 2002) and, as such, represent theoretical approximations for the experimental conditions.

$$\frac{p}{P} = \left[1 + \frac{(\gamma - 1)M^2}{2} \right]^{-\gamma/(\gamma-1)} \tag{1}$$

$$\dot{m} = A M P \left(\frac{\gamma}{RT} \right)^{1/2} \left(1 + \frac{\gamma-1}{2} M^2 \right)^{-(\gamma+1)/2(\gamma-1)} \tag{2}$$

$$\frac{A}{A_*} = \frac{1}{M} \left[\left(\frac{2}{\gamma+1} \right) \left(1 + \frac{\gamma-1}{2} M^2 \right) \right]^{(\gamma+1)/2(\gamma-1)} \tag{3}$$

In these equations, γ is the ratio of specific heats, R is the universal gas constant, A is the area of the duct in a given axial positition, M is the Mach number, p is the static pressure and P is the stagnation pressure. The starry quantities refer to sonic conditions that occur in the smallest area section, that are reached at the nozzle throat.

Thus, Eq. (1) gives pressure ratio as a function of the Mach number, Eq. (2) is a special form of mass flow rate convenient for dealing with steady one-dimensional isentropic flow and Eq. (3) is the critical flow area ratio for a given Mach number.

Figure 4 shows the isentropic flow characteristics for a wide range of parameters, where from the knowledge of stagnation pressure, Mach number and the time interval for a constant pressure flow can be obtained. For example, for a throat diameter of 0.04 m, an experiment where the reservoir is initially at 39.10^5 Pa and the chamber stagnation pressure will be 24.10^5 Pa can be maintained during 50 s, with an exit Mach number of 2.6, although, in practice, these values will present small deviations from the theoretical ones because of head losses and the valve response time.

The largest nozzle planned for the experiments will have a throat diameter of 0.07 m, allowing, with an initial reservoir pressure of 39.10^5 Pa, 8 seconds of operation at 30.10^5 Pa or 24 seconds of operation at 20.10^5 Pa. The system will attain in this case, for example, Mach numbers of 2.62 at 20.10^5 Pa and 2.9 at 30.10^5 Pa chamber stagnation pressure. Initially, the operational capability of the installation will be limited by an operation pressure of the reservoirs of 30.10^5 Pa for steady flows using the actual valve system, however, this pressure can be increased up to 40.10^5 Pa for unsteady experiments by using a rupture disk instead of the valve.

Figure 5 presents the relation among area ratio, pressure ratio and Mach number considering, again, the isentropic flow of a calorically perfect gas. So, for example, to reach a Mach number 3.0 a pressure ratio of 36.7 is required with an area ratio of 4.23. The same analysis can be directly performed for other Mach numbers. Although the Mach numbers and nozzle pressure rates to be achieved are not very high, the experimental campaigns will enable tests on different geometries as, for example, bell, dual bell, truncated ideal contoured and even spike small scale nozzles operating at sea level mode.

As stated above, the air exiting the nozzle will flow directly to the atmosphere limiting the range of nozzle pressure ratios that will be possible to achieve and is our intention to expand, in the future, the experimental capability by the use of a vacuum chamber in order to determine nozzle efficiency, steady flow conditions and unsteady shock dynamics in a wider range of nozzle pressure ratios to simulate different altitudes and the transitional behavior during ambient pressure variations, which represents an essential aspect in nozzle design as shown, for example, by the works of Hagemann and Frey (2007) and Génin et al., 2013.
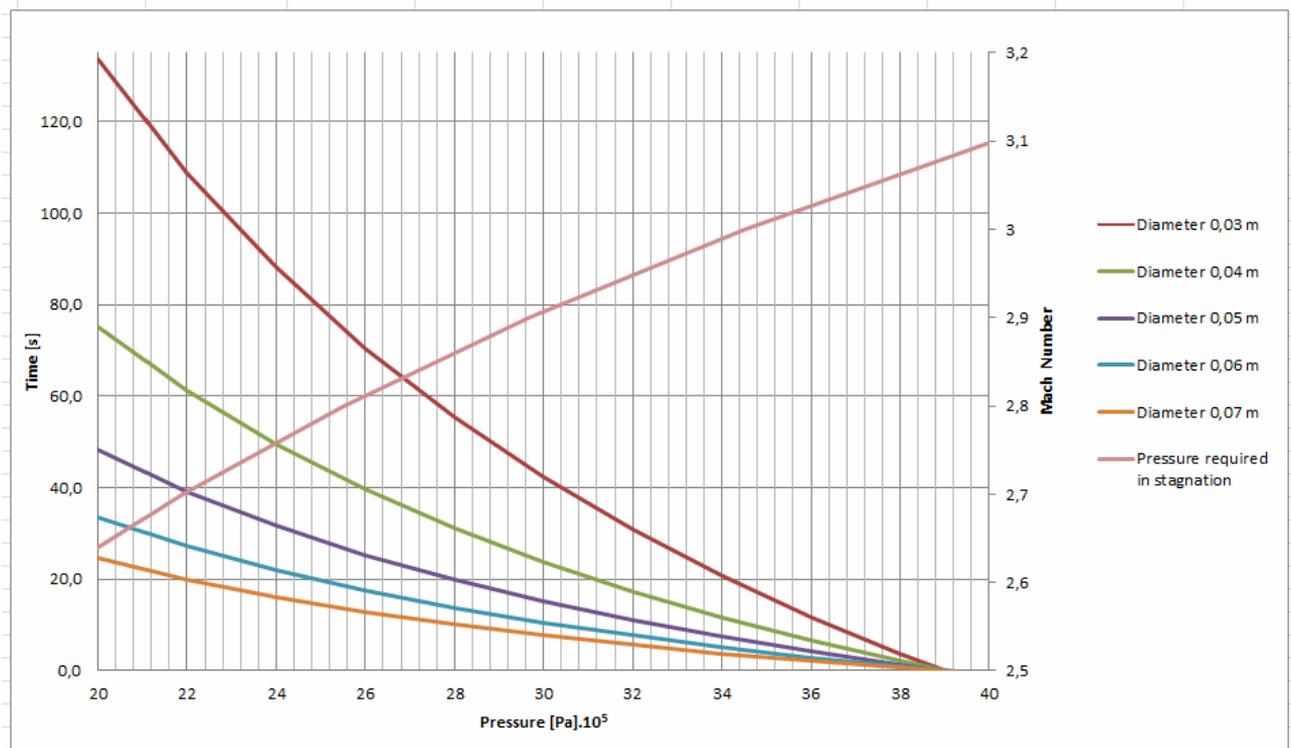
Figure 4. Theoretical isentropic calculation of the nozzle flow exit Mach number and experiment duration, considering an initial reservoir pressure of 39.10^5 Pa, for different nozzle throat diameters.
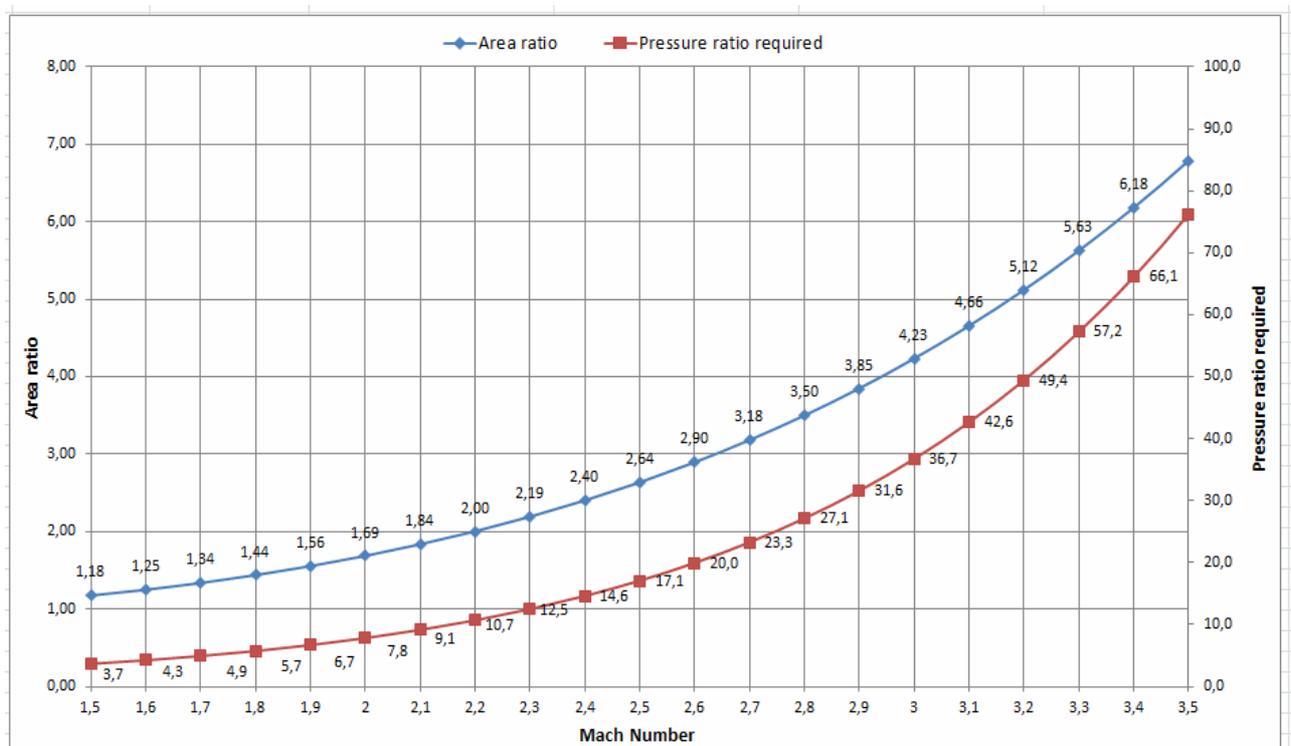

Figure 5. Relation among Mach number, area ratio and pressure ratio for an isentropic flow of a calorically perfect gas.

Initial nozzle design

Different types of nozzles, with distinct geometries, will be investigated throughout the project by means of experimental and numerical tools. Nozzle types will include bell, dual bell, spike, and plug nozzles.

The initial design for the different nozzle types can be performed using the classical method of the characteristics, or other methods derived from it, for the most common type of nozzles. As an example, the design of an optimized parabolic nozzle is shown in Fig. 6, where it is calculated following Hetem *et al.*, 2012. These authors used the method of Rao, 1958, where a thrust optimized bell nozzle is calculated relative to a 15° conical nozzle for different ratios between nozzle exit and throat diameters, ε, called the expansion rate.

The nozzle contours are calculated specifying the fractional nozzle length of a 15° conical nozzle and the expansion rate. Using these parameters a parabola giving the exit flow angle and initial turning angle is found, where the subsonic and supersonic radius of curvature are calculated using the throat radius, such that the subsonic radius is 1.5 times the throat radius and the supersonic radius is 0.4 times the throat radius.

Figure 6(a) shows the results of the initial and final angles of the parabolic nozzle obtained for different expansion rates, where the equivalent lengths, L_f , are given as a percentage of the total length, measured as the distance between throat and nozzle exit relative to the 15° conical nozzle. Figure 6(b) shows the initial design for an optimized nozzle with nozzle throat, d^*, of 0.02 m, a relative length, L_f, of 80% and an expansion rate, ε, of 10.
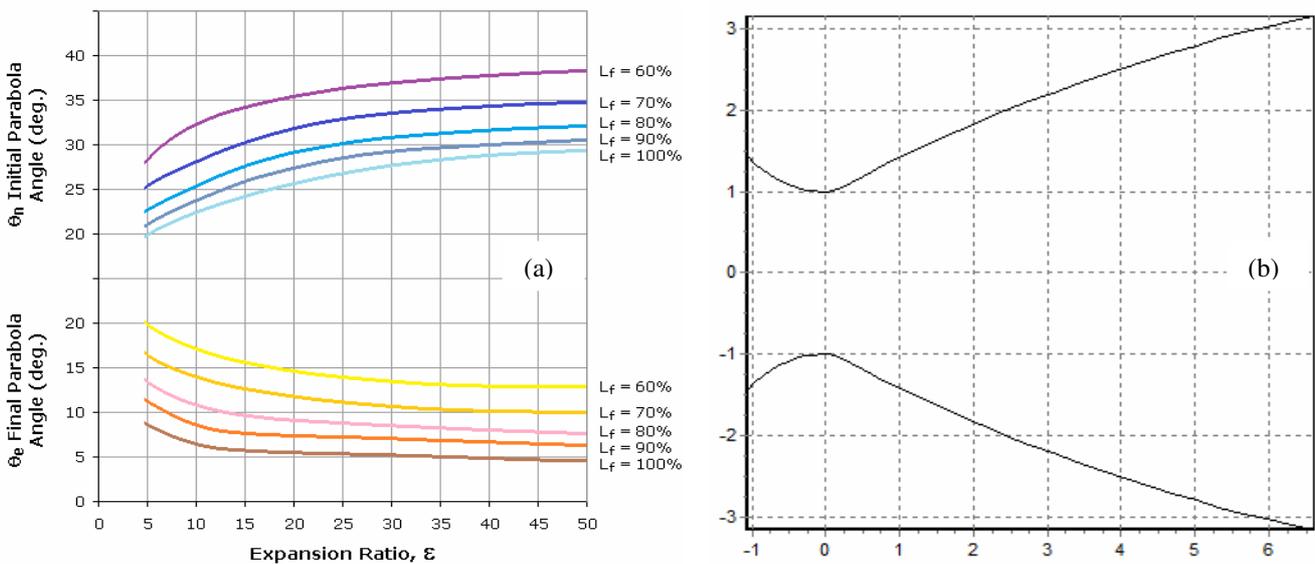

Figure 6. Design parameters for an optimized parabolic nozzle, using the method of Rao, 1958, for different values of the expansion rates (ε) and equivalent lenghts (L_f) (a) and the optimized parabolic nozzle contour for the parameters $d^* = 0.02$ m, $L_f = 80\%$ and ε = 10 (b).

Conclusions

Here, a new experimental installation is proposed for the investigation of the gas dynamics inside different nozzle geometries. The new facility will utilize a cold gas, pressure driven flow, to simulate steady and unsteady nozzle operation in sea level mode.

In steady experiments the flow will be controlled by a valve system that will maintain a constant pressure flow during a time that will depend on nozzle geometry and initial conditions. For unsteady flow experiments, measurements can be performed during the valve system adjustment, where pressure is expected vary in a time interval of approximately 7 s, or using a rupture disc to simulate the sudden start of the flow.

As there are no combustion processes involved, the new facility will enable a safe experimental environment, where flow diagnostics can be performed using conventional instrumentation as, for example, pressure transducers, hot wire anemometry, PSP, TSP and other experimental techniques that would be very difficult, if not impossible, to implement in a harsh environment. Additionally, experiments involving new technologies or innovative nozzle designs can be initially tested with a considerable reduction in costs, before a full hot gas experiment is performed.

Finally, the possibility to perform a detailed characterization of the flow and the comparison between experimental and numerical data will enhance the simulation capabilities of in house numerical codes for future developments of launching vehicles by IAE.

Acknowledgements

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