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G. M. Di Cicca
Department of Mechanical and Aerospace Engineering
Politecnico di Torino
Turin, Italy
gaetano.dicicca@polito.it

J. Hassan
Department of Mechanical and Aerospace Engineering
Politecnico di Torino
Turin, Italy
jehangir.hassan@polito.it

E. Resta
Department of Mechanical and Aerospace Engineering
Politecnico di Torino
Turin, Italy
emanuele.resta@polito.it

R. Marsilio
Department of Mechanical and Aerospace Engineering
Politecnico di Torino
Turin, Italy
roberto.marsilio@polito.it

M. Ferlauto
Department of Mechanical and Aerospace Engineering
Politecnico di Torino
Turin, Italy
michele.ferlauto@polito.it

***Abstract*—In the present work cold (without high temperature effects) flow test experiments on a linear aerospike nozzle are carried out using the test rig available at Politecnico di Torino. Mean pressure distributions are measured in order to characterize the flow evolution along the nozzle plug. First results show a good agreement between the measurements in the present experiment and those reported in literature.**

***Index Terms*—aerospike, pressure transducers**

I. Introduction

Key requirements of future space transportation systems are a drastic reduction of Earth-to-Orbit launch costs and the increase in launcher reliability. Interest in reusable space launchers has dramatically increased in recent years thanks to their intrinsic capability of driving down manufacturing and operation costs, compared to traditional launcher vehicles. Moreover, reusable propulsion systems may allow the designers to adopt more complex and advanced design solutions, further reducing costs and increasing reliability. In this perspective, Single-Stage-to-Orbit (SSTO) and Two-Stage-to-Orbit (TSTO) configurations are currently being studied as possible architectures of future launchers. However, the possibility of realization of these vehicles heavily depends on the performance of the employed engines.

Performance data of existing rocket engines are always lower than the theoretical values because of the presence of several loss mechanisms. Some examples of these well known phenomena are: the imperfect mixing of oxidizer and fuel in the combustion chamber, losses due to the irreversible process of combustion, losses for divergence and non-uniformity of the exiting flow and a non-ideal expansion of the propellants [1]. The latter source of losses is the most important by a large margin. In fact, as is the case with the Space Shuttle Main Engine (SSME), the non-adaptation of the exhaust gases causes up to a 15% decrease in performance during certain phases of the mission [2]. The SSME is equipped with traditional bell nozzles that are designed to operate from sea-level conditions at lift-off, to nearly vacuum conditions, and therefore the Nozzle Pressure Ratio (NPR) for the design conditions had to be chosen as a compromise between the performances at high altitudes and the necessity to avoid uncontrolled separation and side loads at lift-off. In fact, under these conditions, shock waves form inside the divergent, and the walls of the nozzle would be subjected to huge pressure gradients and vibrational loads, with the risk of destruction of the whole launcher [3]. This compromise in the choice of the design NPR becomes even more limiting when SSTO vehicles are concerned, so that advanced nozzle concepts as an alternative to bell nozzles have been eagerly and intensively investigated up to the present day.

A possible solution for the design of the engine of SSTO vehicles may be found in plug nozzles or aerospikes, which represent a valid alternative to conventional bell nozzles. In contrast to the classical nozzle concepts, plug nozzles provide, at least theoretically, a continuous altitude adaptation up to their geometrical area ratio. For high area ratio nozzles with relatively short length, plug nozzles perform better than conventional bell nozzles [2]. While in a conventional nozzle the expansion of the propulsive fluid is constrained by the geometry of the nozzle, for the aerospike nozzle the expansion takes place around a plug (truncated or not) without a flow confinement. The resulting expansion jet has the capability to adjust itself to the external pressure changes, i.e. it has self altitude compensation capabilities [4].

Performance behaviors and flowfield development of linear plug nozzles as function of ambient pressure are in principle similar to circular plug nozzle. However, special attention must be addressed to the influence of both end sides from where the ambient disturbs the expanding flowfield, resulting in an expansion of the flow normal to the main flow direction and therefore in an effective performance loss. Especially for truncated plug nozzles, the change of wake flow behavior may be strongly influenced by the penetration of ambient pressure through both end sides. In fact, this phenomenon has already been observed in a comparative study, where the differences in flowfield between a 2D and a 3D linear plug nozzle configuration have been assessed. For instance, the variation of the pressure value at the base of the plug, within the recirculation zone, can be related to the variation of some parameters of the aerospike, such as the truncation length, and the NPR. For the 2D nozzle, it is possible to have a range of working conditions in which the value of plug base pressure is constant, and does not change in response to a variation in the ambient pressure. This regime is defined as ”closed wake”. On the contrary, another range of NPR values can be identified, for which the acoustic disturbances from the external pressure can propagate towards the base of the plug and induce a change in pressure value. This regime is defined as ”open wake”. For the 3D linear plug configuration it was found that the flow is always in ”open wake” regime, with a stronger or weaker influence of the external conditions, depending on the value of the nozzle NPR. Additionally, 3D effects directly influence the formation of flow structures, also depending on truncation length, leading to different vortical patterns [5].

For these reasons, experimental, analytical and numerical research on plug nozzle have been performed since the 50s worldwide. Some examples of recent and historical aerospike engine projects and prototypes are, for instance, the linear aerospike engine XRS-2200, which was selected as a candidate propulsion system for the Venture Star/X33 SSTO spaceplane in the 1990s. After these pioneering contributions, the research effort on aerospikes was reduced because of the cancellation of several research programs. More recently, research in the field has been taken on by universities and private companies. An example is the project CALVEIN (California Launch Vehicle Education Initiative). Within this project, a truncated plug nozzle was analyzed during a thorough test campaign [6]. Other private companies have proposed designs of aerospike engines for the propulsion of both SSTO and TSTO configurations. For example, Firefly Aerospace and RocketStar Space proposed a TSTO vehicle, while ARCA Space Corporation proposed a SSTO design [7]. Additionally, the use of linear aerospike nozzles has also started to spark interest regarding the propulsion of high-speed aircraft. [8]–[11]

In the recent years, the aerospike has received renewed attention due to the advantageous performance compared to classical bell nozzles, and the capability of generating thrust vectoring with different approaches [12]–[14]. The use of an aerospike nozzle limits the possibility to perform thrust vectoring by means of a gimballed joint, as it is done conventionally with bell nozzles. This is due to the large diameter/extension of the aerospike nozzle which prevents the possibility of moving the entire nozzle. However, thrust vectoring has become a key requirement for space launchers, allowing for increased safety and maneuverability of the aircraft during all phases of the mission. For these reasons, several alternative thrust vectoring strategies have been investigated since the conception of aerospike nozzles [7]. Among them, some possible strategies are represented by movable plugs, flaps on the plug, differential throttling and fluidic thrust vectoring. Differential throttling and fluidic thrust vectoring are promising approaches, since their advantage compared to more traditional methods is the absence of movable parts, which results in simpler and more reliable systems. Differential throttling is a simple control strategy which can be applied in the presence of clustered aerospike engines with multiple independent combustion chambers. Since the mass flow rate and the pressure can be controlled independently in each chamber, it is possible to generate a lateral thrust component which can be used for maneuvering. This solution is suitable for large engines, whereas for small-scale engines the use of multiple combustion chambers would not be convenient. Another possible solution could be the adoption of Fluidic Thrust Vectoring techniques, one of which consists in injecting a secondary flow from the plug wall. This creates an obstacle for the primary flow during its expansion along the wall, generating a shock followed by a zone of separation downstream to the injection point. As a result, the pressure distribution on the nozzle walls becomes asymmetric, generating a lateral thrust component. Moreover, with the introduction of suitable thrust vectoring methods, the size of the aerodynamic control surfaces needed for flight within the atmosphere can be reduced. For all these reasons, given the general and renewed interest in academia and industry for the aerospike nozzle technology, the present work aims to lay the foundations for future studies on advanced propulsion systems through the construction of a test rig for cold flow experiments. This experimental system will be able to be fitted with different types of nozzle geometries. The first type of nozzle chosen for our analyses is a linear aerospike scale model, for which an experimental characterization of the evolution of the flow is carried out in this work. The mean pressure is measured along the nozzle walls on the symmetry plane, and is compared with experimental results from the literature. The experimental test rig is located at the Politecnico di Torino and its design process has been described in a previous work [15]. The aim of the research group in the future is to further explore the characteristics and capabilities of advanced aerospace propulsion systems and control strategies, for which experimental testing is always a necessary step.

II. Test Rig Set-Up and Preliminary Results

The test-rig is composed of two subsystems: the air-supply control system and the nozzle model. The first subsystem must provide the prescribed inlet flow conditions and is able to manage interchangeable nozzle models that may be either axisymmetric, e.g., bell/dualbell nozzle, or two-dimensional, e.g., converging-diverging nozzles and aerospikes. An interfacing duct may be required to generate the correct inlet flow conditions and stream redistribution in the axisymmetric or 2D/3D case. The test rig is positioned on a frame, as shown

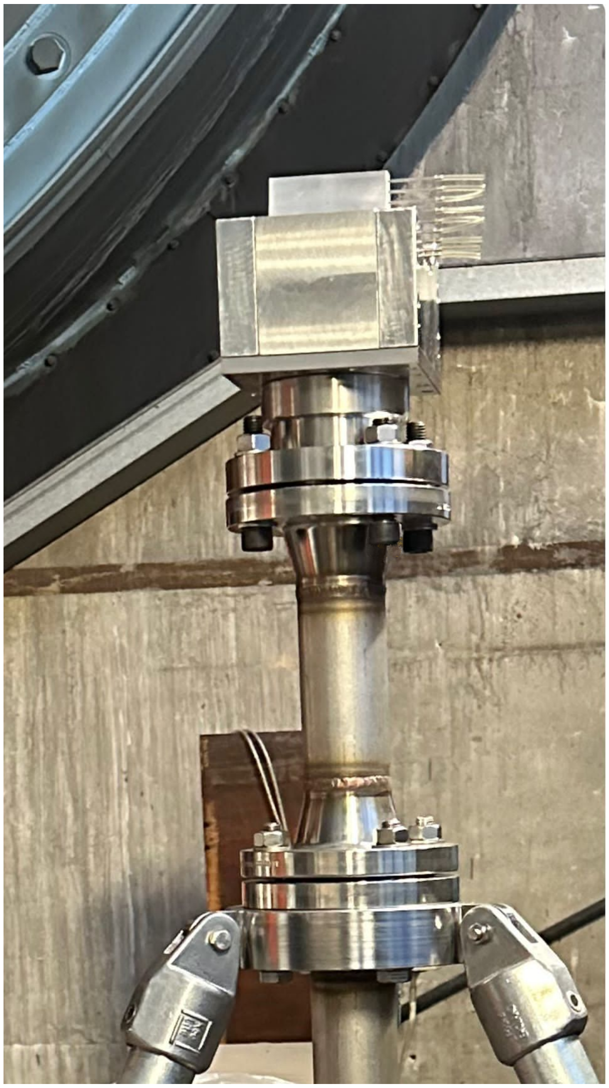

Fig. 1. Test rig.

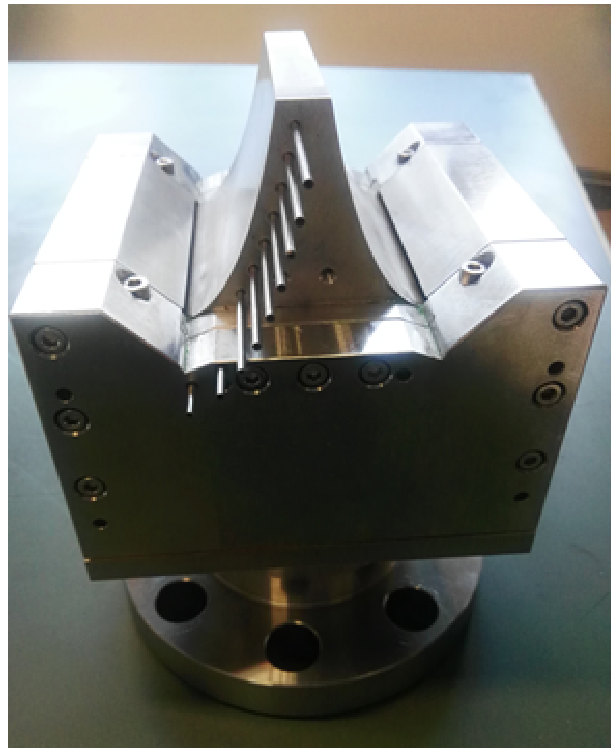

Fig. 2. Linear plug nozzle with $b/h_t = 30.41$ and 40% plug truncation.

TABLE I
CHARACTERISTIC DIMENSIONS OF THE NOZZLE

Quantity		Value
Throat height	h_t	2.55 mm
Throat width	b	77.55 mm
Width/height throat ratio	b/h_t	30.41
Throat area	A_t	395.51 mm^2
Exit area	A_E	5003.21 mm^2
Area ratio	A_E/A_t	12.65

in figure 1. A corrugated metal hose with an inner diameter of 25mm provides the feeding gas (air) and is connected to a diffuser, followed by a flow straightener.

A linear plug nozzle with a width to height throat ratio (b/h_t) equal to 30.41 (see figure 2) is connected to the flange at the exit of the downstream conduct. The exit Mach number, M_e, is equal to 1 and the design nozzle pressure ratio $\mathrm{NPR_d}$ is equal to 200. The main characteristic dimensions of the nozzle are reported in table I.

The splines describing the plug surfaces of the nozzle have been designed using the method proposed by Angelino [16] and a tilt angle ϑ equal to $68.1°$ has been evaluated at the throat. The aerospike plug geometry is truncated at 40% of the ideal length.

Mean pressure distributions are measured in order to characterize the flow evolution along the nozzle plug. For this purpose a Scanivalve® DSA5000 pressure scanner (see figure 3) is used. This unit is capable of obtaining up to 16 individual pressure measurements at different locations along the plug, and incorporates 16 temperature compensated piezo-resistive pressure transducers. Also, 24-bit A/D converters and microprocessors are included in the unit. The DSA5000 pressure scanner utilizes an individual A/D converter for each pressure sensor. This feature allows fully synchronous data collection and data stream up to 5000Hz (samples/channel/second). One resistance temperature detector (RTD) per pressure sensor is integrated in the unit and each RTD utilizes its own 24-bit A/D converter. The system accuracy is ±0.04% FS for a pressure range from 0 up to 250 psi (from 0 up to 17.2 bar).

The static wall pressures are measured via orifices (with a diameter is equal to 0.6 mm) drilled perpendicularly to the nozzle plug wall (see figure 4). The distance between two adjacent pressure ports is equal to 7 mm. These ports are connected through small steel tubes and Teflon tubes to the Scanivalve® pressure scanner.

Figure 5 shows preliminary results with a comparison in

Fig. 3. Scanivalve® DSA5000 pressure scanner [17].

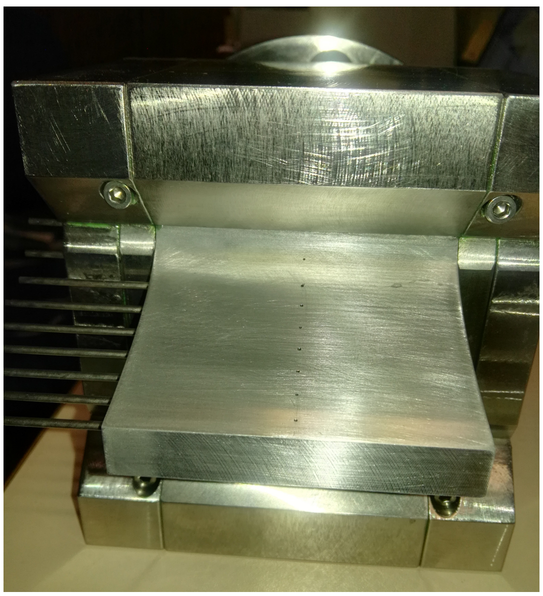

Fig. 4. Pressure ports on the nozzle plug wall.

terms of wall static pressure between the measurements in the present experiment and those reported in [2] (Festip in the figure). The measurements were performed for different ratios between the static pressure in the nozzle chamber p_c and the ambient pressure p_{amb}, with the nozzle working in over-expanded conditions. The waviness of the pressure distributions highlights the presence of compression and expansion waves in the region close to the plug surface.

III. Conclusions

An aerospike nozzle flow has been experimentally characterised in the present work. The experiments have been carried out in cold flow conditions using pressurised air at different values of NPR. The results are presented in terms of wall

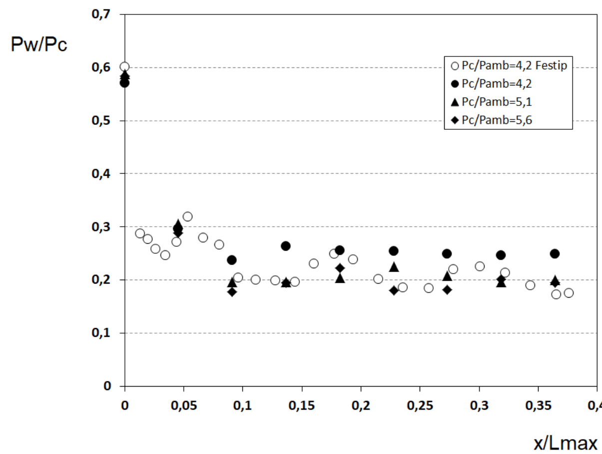

Fig. 5. Aerospike wall pressure distributions.

pressure distributions, and good agreement with experimental results available in the literature has been observed.

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