Studies on the convergent-divergent nozzles for simulation of reentry aerodynamic flows on the plasma system of the Laboratório de Plasmas e Processos of the Instituto Tecnológico de Aeronáutica (LPP-ITA)

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Abstract. *In this work, we report on convergent-divergent nozzles that have been designed and manufactured to be used in a plasma torch to accelerate argon plasma to Mach numbers higher than two under a pressure difference existing between a vacuum chamber and a plasma torch. The nozzles were produced with aluminum using a mechanical technique. The nozzles characterizations were performed using air as working fluid instead plasma.The total conditions were assumed to be the atmospheric ones. The flow measurements show that all convergent-divergent nozzles produce supersonic air flows inside the vacuum chamber. The smallest Mach number was found to be (2.1 ± 0.4) and the bigger, (5.01 ± 0.02). The critical mass flow rate was found to be in the range of (1.5x10^{-4} – 7.2x10^{-4})kg/s.*

Keywords*. Nozzles, Mach number, plasma torch, reentry flows*

1. Introduction

Testing of the thermal protection system materials on reentry ambient needs simulation of the thermal fluxes, and the aerodynamic conditions existing in high velocity flows during atmospheric reentry. Both of the conditions can be simulated by a plasma torch providing that a convergent-divergent nozzle exists to accelerate plasma from its stagnation conditions to supersonic velocities producing an uniform flow. A DC argon plasma torch (Aquino, 2002) has been developed at the Instituto Tecnológico de Aeronáutica (ITA) to produce high enthalpy flows without concerning aerodynamic conditions, so studies on De Lavall nozzles have been made to supply the need of aerodynamic characteristics on the flows generated by the plasma torch.

The objective of these studies was to design convergent-divergent nozzles, based on the Characteristic Method (Shapiro, 1956), to accelerate an argon plasma to Mach numbers higher than two under the pressure difference existing between the stagnation chamber, in the torch, and the vacuum system, to produce a complete isentropic jet at the nozzles exits.

The vacuum chamber is equipped with a proper pumping system that reaches a vacuum of 10^{-4}Pa, vacuum pressures sensors, an automatic control valve, and a mass flow controller for 5 different gas lines.

The development of this work was based on rough calculations to estimate the exit and throat areas of the nozzles depending on the mass flow allowed by the vacuum system, and considering the governing equations for quasi-one-dimensional inviscid, steady, adiabatic, isentropic flow (Anderson, 1991,1990).

The mass flow reaches its maximum value when the Mach number flow is one at the throat, so for the isentropic condition, Eq (1) allow us to predict the throat area of the convergent-divergent nozzles.

$$\frac{\dot{m}}{A_t} = \frac{\dot{m}}{A^*} = P_0 * \sqrt{\frac{\gamma}{R\,T_0} * \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{1}$$

Where: $\dot{m}$, A_t, A^*, R, γ, P_0 are respectively the maximum mass flow, the area throat, the critical area for which M is one, the specific gas constant used, the Poisson coefficient and the stagnation pressure at the reservoir.

The Mach number at the nozzle exit can be found using Eq. (2), considering the stagnation and back pressures P_b allowed by the vacuum system. The exit area is calculated by Eq. (3).

$$M^2 = \frac{2}{\gamma-1} * \left[\left(\frac{P_0}{P_b}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \quad A^* \tag{2}$$

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

2. Experimental procedures

The method used to fabricate the axis-symmetrical convergent-divergent nozzles is based on three steps. In the first one, calculations are made using the mass flow and the background pressure conditions allowed by the vacuum system and considering the governing equations for quasi-one-dimensional nozzles flows to estimate the relation between the throat and exit area of the nozzles. The second one consists in calculations using a numerical code (Grümmer; Paglione, 1976, 1988), based on the Characteristic Method, to describe the nozzles walls contours. These shapes are made to produce an axis-symmetrical and uniform flow at the nozzles exits. The last step consists in using the nozzles walls contours cotes to produce two-dimensional convergent-divergent curve profiles. A mechanical lathe is then used to manufacture three-dimensional nozzles. The final finish is made with fine mass for polish of the internal surfaces of the axis-symmetrical nozzles. The external parts of the nozzles were made by conventional mechanical process.

A second method, called Conical Method, was used for the production of the convergent-divergent nozzles, in which the shapes of the nozzles were approximated by conical ones Fig (1).

Figure 2 shows conical drills used to manufacture both the convergent and the divergent sections of the nozzles. This method is cheaper than the former but a little more complicated of being implemented.

The characterization of the axis-symmetrical convergent-divergent nozzles has been performed using air at atmospheric pressure and ambient temperature at the inlet. The outlet backpressure ranged from $2.0e^2$ to $1.0e^3$ Pa (1.5 to 7.5 Torr). The backpressure was maintained by the vacuum system showed by Fig (3). The total flow conditions were obtained from data of the Centro Técnico Aeroespacial (CTA).

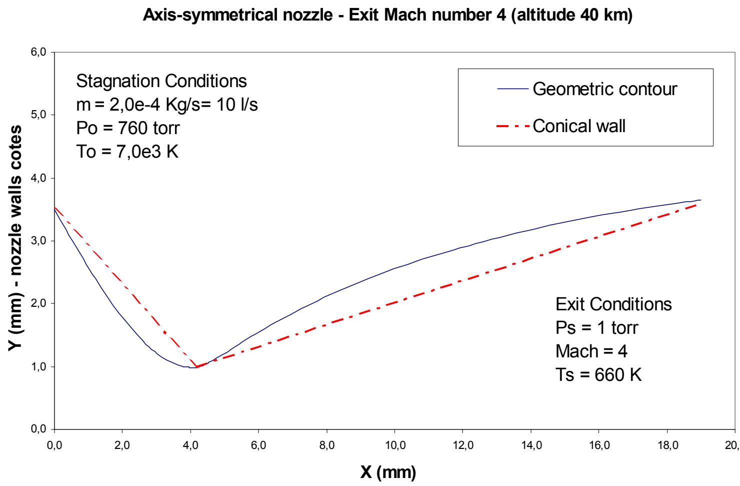
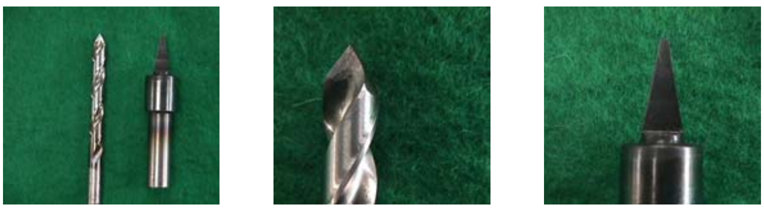


Figure 1 – Conical shapes from calculated walls contours.



(a) (b) (c)

Figure 2 – a) Conical drills, b) divergent conical drill, c) convergent conical drill.

Figure 3 – Vacuum system

An U tube manometer coupled with a Pitot tube measured the total pressure at the exit of the nozzles. A capacitance manometer with a pressure range from $1.3x10^3$ to 1.3 Pa measured the backpressure.

The mass flow was obtained from the volumetric flow assuming steady state at the vacuum system by a simple vacuum throughtput calculation method using a recipient of constant volume full of water and a chronometer.

3. Results and discussion

The results of the experimental procedures are presented in this section. A set of four convergent-divergent nozzles was produced with aluminum by the foremost technique described above with theoretical exit Mach numbers in the range of 6 to 3. Table 1 shows the geometric parameters used and obtained by the mechanical procedure.

Table 1. Geometric parameters calculated by quasi-one-dimensional theory (QOT) and obtained by the mechanical code.

Nozzles	Inlet Radius (±0.05mm)	Throat Radius (±0.05mm)	Outlet Radius (±0.05mm)	Mach number	Mass flow (kg/s)
QOT	3.5	0.5	2.0	6	$2.00x10^{-4}$
BCD2b	3.5	0.5	3.6	6	$1.87x10^{-4}$
BCD7	3.5	0.5	2,57	5	$1.87x10^{-4}$
BCD8	3.5	0.5	1,67	4	$1.87x10^{-4}$
BCD9	3.5	0.5	1,03	3	$1.87x10^{-4}$

It can be seen that the procedure is quite precise, what gives a good agreement with the desired parameters to be found in the nozzles geometries.

Other four nozzles were produced starting from theoretical geometries by the second method. Their geometries are presented in Tab (2). Although the geometries used are the same as used in the first method, the throat regions of the nozzles are difficult to be made just because the drills couldn't made a soft turn from the convergent to divergent regions. This causes a change in the geometry of the region and so in the flow.

Table 2. Geometric nozzles parameters obtained by the Conical Method.

Nozzles	Inlet Radius (±0.05mm)	Throat Radius (±0.05mm)	Outlet Radius (±0.05mm)	Mach number	Mass flow (kg/s)
TOQ	3.5	1.0	3.5	4.15	$7.5x10^{-4}$
BCD1	3.5	1.0	3.5	4.15	$7.5x10^{-4}$
TOQ	3.5	0.5	2.0	6	$2.0x10^{-4}$
BCD2	3.5	0.5	3.5	5.89	$1.87x10^{-4}$
BCD13	3.5	0.65	1,64	3.43	$3.16x10^{-4}$
BCD14	3.5	0.65	1,03	2.45	$3.16x10^{-4}$

The results of the measurements of the values of the ratio between total pressure at the exit and total pressure at the inlet of the nozzles (P_{02}/P_{01}) and the corresponding calculated Mach numbers at the exit for each one are shown in Tab (3). It's important to notice that all Mach numbers are higher than one. It means that the flows produced by the convergent-divergent nozzles are supersonic as expected.

Table 3. Experimental results for nozzles exit Mach numbers characterization

Nozzles	**P_{02}/ P_{01}**	**Mach number**
BCD1	0.20 ± 0.01	3.56 ± 0.08
BCD2	0.06 ± 0.002	5.01 ± 0.02
BCD2b	0.07 ± 0.005	4.82 ± 0.10
BCD7	0.07 ± 0.001	4.82 ± 0.02
BCD8	0.16 ± 0.01	3.85 ± 0.09
BCD9	0.67 ± 0.17	2.1 ± 0.4
BCD13	0.28 ± 0.01	3.19 ± 0.05
BCD14	0.43 ± 0.01	2.68 ± 0.03

Table 4 presents the comparison among the theoretical and experimental Mach numbers values. Although they are not equal one can say that theoretical values were obtained by considering the governing equations for quasi-one-dimensional inviscid, steady, adiabatic, isentropic flow and further corrections for viscous or turbulent effects are necessary. Boundaries layers corrections were made by the numerical code.

The Mach numbers found in the characterization of the nozzles are of the same order of magnitude to those theoretical calculated.

Unfortunately a perfect characterization of the flow uniformity could not be done and the Mach numbers values only represent medium values at the exit because the relation between Pitot tube diameter and the nozzles exit were not as small as necessary to do a punctual investigation of the total pressure at the exit of the convergent-divergent nozzles.

Table 4. Comparison among the theoretical and experimental Mach numbers values.

Parameters	Theoretical Mach number	Experimental Mach number
BCD1	4.15	3.56 ± 0.08
BCD2	5.89	5.01 ± 0.02
BCD2b	5.89	4.82 ± 0.10
BCD7	5.07	4.82 ± 0.02
BCD8	4.05	3.85 ± 0.09
BCD9	3.0	2.1 ± 0.4
BCD13	3.43	3.19 ± 0.05
BCD14	2.45	2.68 ± 0.03

The mass flow measurements for the nozzles are presented in Tab (5). They are compared to the theoretical values for the chocked flow at the nozzles throats. It's shown that the values are almost the same. That means that all the nozzles were working with chocked flow. These results are good to validate to the values found for the Mach numbers. It would be impossible to obtain a supersonic flow without a Mach number of unit at the throat.

Table 5. Experimental results for nozzles mass flows.

Parameters	Theoretical Mass flow (kg/s)	Mass flow (kg/s)
BCD1	7,5 x10^{-4}	$(7,2 \pm 0,8)$x10^{-4}
BCD2	1,9 x10^{-4}	$(1,6 \pm 0,8)$x10^{-4}
BCD2b	1,9 x10^{-4}	$(1,8 \pm 0,8)$x10^{-4}
BCD7	1,6 x10^{-4}	$(1,5 \pm 0,7)$x10^{-4}
BCD8	1,6 x10^{-4}	$(1,7 \pm 0,8)$x10^{-4}
BCD9	1,6 x10^{-4}	$(1,7 \pm 0,8)$x10^{-4}
BCD13	3,2 x10^{-4}	$(2,9 \pm 1)$x10^{-4}
BCD14	3,2 x10^{-4}	$(2,9 \pm 1)$x10^{-4}

4. Conclusions

Convergent-divergent nozzles have been manufactured to accelerate a plasma flow from its stagnation conditions to supersonic velocities.

The Mach numbers of the nozzles were obtained at the exit by using total pressure measurements. These measurements shown that the method used to produce the nozzles by lathe or drills gives approximately the same results and that these technique will be useful to produce the titanium nozzles to run argon plasma flows experiments at the Laboratório de Plasmas e Processos of the Instituto Tecnológico de Aeronáutica.

The flows were all chocked at the throat nozzles once the experimental values were in agreement with theoretical value and the conditions at the vacuum chamber were all steady.

The next stage of the works will involve the producing of the convergent-divergent nozzles with titanium to generate a supersonic plasma jet and their fully characterization.

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