

EFFECT OF SUPERSONIC NOZZLE DESIGN ON JET BEHAVIOR IN BOF STEELMAKING *

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Abstract

The dynamic behavior of oxygen gas flow, determined by the lance nozzle and blow pattern, is a key factor for determining jet efficiency in BOF Steelmaking. The present work compares the performances of Laval and parabolic nozzles with the aid of the Computational Fluid Dynamics (CFD). The Method of Characteristics (MOC) was applied to design a minimum length parabolic nozzle. The results show that the parabolic nozzle generates more uniform and stable jet, with 2% longer potential core and supersonic length and less shock waves. For the parabolic nozzle, the pressure nearby the nozzle wall is higher, which can protect this region from reverse flow of converter gases and offer longer life for the lance tip. Likewise, the flow rate variations would affect less this nozzle. In addition, the nozzle wear was investigated, and the parabolic nozzle has proven relatively less sensitivity to the presence of this deformity.

Keywords: Supersonic nozzle design; BOF; Numerical simulation; Method of Characteristics.

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1 INTRODUCTION

In Basic Oxygen Furnace (BOF) high purity oxygen is pressurized into metal bath surface through supersonic lance what contributes to increasing the reaction surface area and leads to deep penetration and mixing. The supersonic oxygen flow is only possible because of the nozzles and their particular convergent-divergent geometry. As a result, the jet pressure energy is converted in kinetic energy [1]. A combination of standardized blowing patterns and optimum lance tip design are crucial for increasing the metallurgical performance. Besides process optimization, improvements of certain parameters can benefit the production of new steel grades. Therefore, the objective was to evaluate gas expansion and propose a geometry that would optimize the efficiency of the blowing.

Numerical simulation is a well-established method for analyzing the flow inside the reactor [2] [3]. At the present work, mathematical modeling was performed using the commercial software ANSYS FLUENT aiming to compare the influence of nozzles geometry and working pressure on the gaseous turbulence. Due to the high complexity of simulating real bath conditions, this investigation is focused on the jet behavior near the nozzle outlet and do not consider the interaction between gaseous and liquid phases.

After the lance outlet, the jet starts to interact with the furnace environment and is influenced by the pressure, considered as atmospheric and constant. One may observe three main regions in the jet after the nozzle exit, the potential core, the supersonic and the subsonic region, as displayed in Figure 1. The potential core is defined by the region where the turbulent ambient of the furnace has no impact over the jet yet, the velocity and temperature are constant. Thus, for increase the jet efficiency the main objective is to increase the potential core and the supersonic lengths.

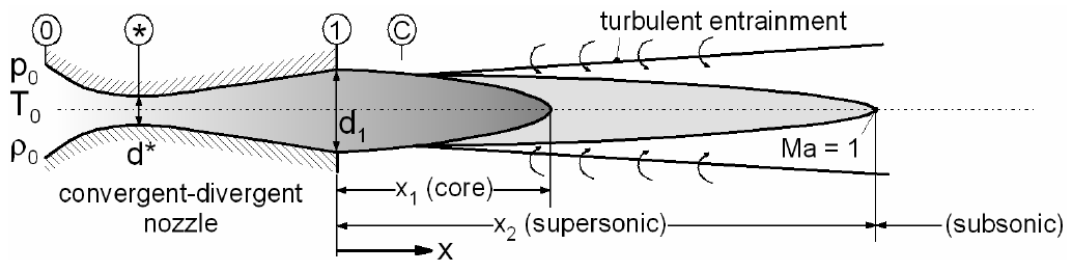


Figure 1: Flow description after nozzle exit. (Odenthal *et al.* [2])

1.1 Nozzle design

Supersonic jet is only possible due to compressibility, which causes variation in the flow properties. According to Anderson [4], for compressible isentropic flow, the relation between area and velocity is given by Equation 1.

$$\frac{dA}{A} = (Ma^2 - 1) \frac{dv}{v} \quad (1)$$

Where A - cross-sectional area, Ma - Mach number, v - velocity.

By analysing equation it is possible to observe that in the convergent section of the nozzle, the flow is subsonic ($0 < Ma < 1$). For the divergent section the supersonic flow ($Ma > 1$) and the sonic behavior happens in the throat ($Ma = 1$). Also by the theory, which considers the fluid as ideal gas, the pressure, temperature and density can be calculated at any location inside the nozzle, according to Equations 2 to 4.

$$\frac{T}{T_0} = \left[1 + \frac{\gamma-1}{2} Ma^2 \right]^{-1} \quad (2)$$

$$\frac{P}{P_0} = \left[1 + \frac{\gamma-1}{2} Ma^2 \right]^{-\gamma/(\gamma-1)} \quad (3)$$

$$\frac{\rho}{\rho_0} = \left[1 + \frac{\gamma-1}{2} Ma^2 \right]^{-1/(\gamma-1)} \quad (4)$$

Where Ma -Mach number, T -temperature, P -pressure and ρ -density. The γ is the adiabatic gas constant.

With information such as BOF size and capacity, its absolute ambient pressure, P_c , the oxygen supply line pressure (P_0), stagnant reservoir temperature (T_0), stagnant reservoir density (ρ_0) and total volumetric flow rate (\dot{V}_0), it is possible to define the nozzle design parameters. The area ratio is defined in Equation 5, where A^* represents the throat cross section area.

$$\frac{A}{A^*} = \frac{1}{Ma} \left(\frac{1 + \frac{\gamma-1}{2} Ma^2}{\frac{\gamma+1}{2}} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \quad (5)$$

The supersonic flow at the nozzle outlet is classified according to the difference between the outlet pressure and the atmospheric pressure. Over-expansion occurs when outlet pressure is lower than atmosphere pressure ($P_1 < P_c$). The ideal behavior is found in the case of equal pressures ($P_1 = P_c$), the flow is fully expanded. In under-expansion, the outlet pressure is higher than the atmosphere ($P_1 > P_c$). All behaviors are schematized in Figure 2 [2] [4].

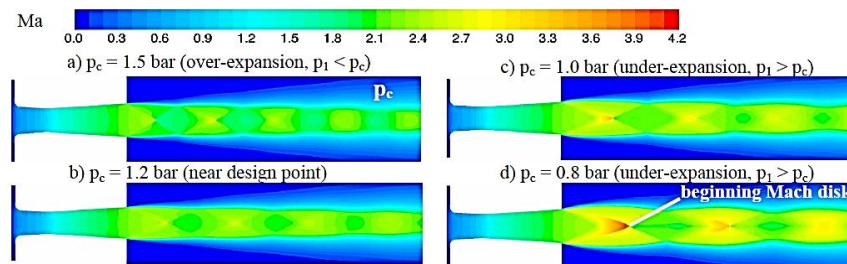


Figure 2: Influence of pressure in jet behavior by CFD Simulation. (Odenthal *et al.*, [2])

The conditions of over and under-expansion generate shock waves after the nozzle outlet. This discontinuity in flow properties is caused by the pressure difference and cause velocity loss, thus kinetic energy loss. The nozzle operates efficiently only at the design point. However, due to blowing pattern, in-blow measurement and constraints such risk of slopping and off-gas system issues, the supply line pressure and BOF pressure change significantly. This implies directly on jet inefficiency and tip deterioration risk [3].

The most unfavorable circumstance is over-expansion as it leads to jet detachment converter hot gases circulation inside the nozzle. Post-combustion reactions may occur inside the nozzles and can provoke melting of copper at the nozzle outlet after several heats. Garajau *et al.* [5] simulated both behaviors and the results are shown in Figure 3.

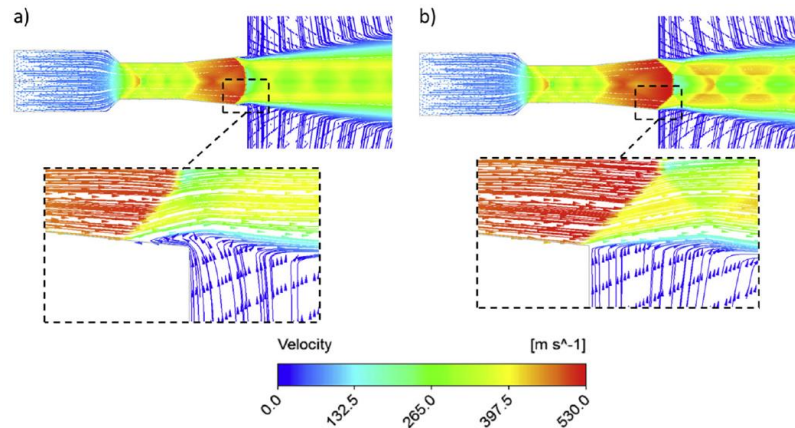


Figure 3: Velocity vectors for a) over-expansion and b) under-expansion. (Garajau *et al.* [5])

Although the isentropic theory is used to design convergent-divergent nozzles, it does not determine the proper contour of the nozzle divergent section [2]. If the nozzle contour is not designed correctly, shock waves may occur inside the nozzle, leading to kinetic energy loss. A topic well established in rocket science has been proved to be useful for optimization of BOF nozzles. Alterations from the traditional conical shape of a nozzle to parabolic shapes seem to be promising to reduce shock waves and nozzle wear. By using the Method of Characteristics, it is possible to develop a nozzle contour free of shock waves. The current work used this method to generate a minimum length contour of the divergent part of the supersonic nozzle. This approach is explained in the next section.

1.2 Method of Characteristics

The method of characteristic (MOC) is a mathematical formulation that can be used to calculate flow properties such as direction and velocity at point in the flow field, satisfying given boundary conditions. The method solves the Euler equations which are a simplification of the Navier-Stokes. The flow is considered two dimensional, steady, inviscid, irrotational and supersonic [4] [6] [7].

A characteristic is a curve across which the flow properties are continuous and the governing partial differential equations (PDEs) are simplified to ordinary differential equations (ODEs) [4]. The intersection of two characteristic lines defines a node and a set of lines creates a mesh. The properties of two nodes are used to calculate the properties of the third node, thus the velocity and cartesian coordinates can be calculated. The objective is that the velocity at the last node of the mesh is equal to the velocity from the node before it, and that both are equal to the velocity defined by the user. An example is Figure 4, the method designed a nozzle for exit Mach equal to 2,4, thus all points from the line 34-35 should have $Ma=2,4$. The expansion waves are cancelled by the compression waves and produce a uniform jet, without shock waves. The contour has the minimum length required for the expansion to be completed [6] [7].

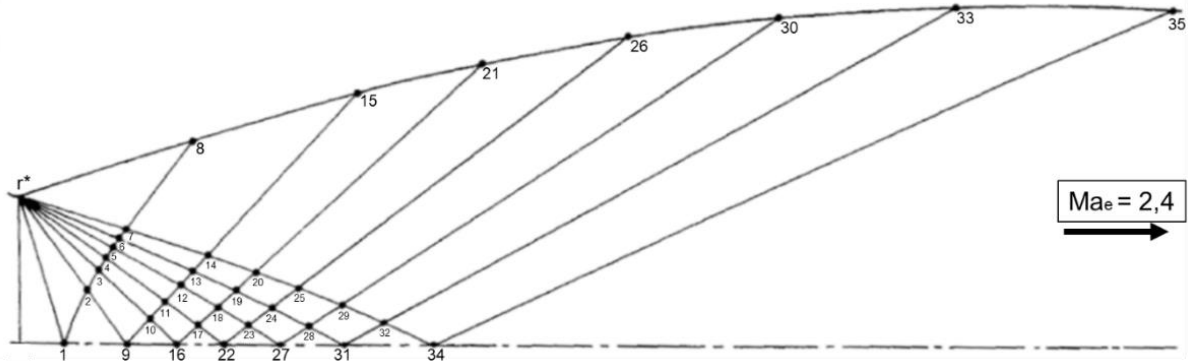


Figure 4: Scheme of a mesh constructed by the method of characteristics for nozzle designing. (Anderson [4])

CFD simulations were used to compare the performance of a Laval and a parabolic nozzle, generated from the Method of Characteristics. Besides that, conditions of nozzle wear were also simulated.

2 DEVELOPMENT

2.1 Materials and Methods

The mathematical simulations were performed on the commercial software ANSYS Fluent 19.1, executed on a Linux cluster with 4 parallel processors. The software uses the finite volume technique, in which the domain is divided into smaller elements of volume and the partial differential equations of global mass conservation, momentum in the three orthogonal directions, turbulence quantities, and energy are solved for the nodal point of each volume element. Due to the high complexity of simulating real bath conditions, this investigation is focused on the jet behavior near the nozzle outlet and do not consider the interaction between gaseous and liquid phases.

To analyze the influence of design on the jet behavior, different nozzle shapes were created in *DesignModeler*. The “Conical” geometry was based on a real nozzle from a conventional 6-hole lance tip. A Visual Basic for Applications (VBA) macro code was written to generate contour of the parabolic nozzle. The program was based on the MATLAB code “Minimum Length Nozzle Design using Method of Characteristics” written by Shubham Maurya (2017) and available in MathWorks website [8]. This geometry was called “Parabolic MOC”, had shorter length and the exit diameter was 0.1mm shorter. According to Bhattacharya *et al.* [9], the convergent section of the nozzles does not have significant effect on the nozzle efficiency, as well as the throat section. Therefore, the dimensions of convergent and throat sections were kept the same.

The second objective was to analyze the influence of nozzle wear on the jet, then, both geometries were adapted for this purpose. For the worn nozzles the outlet diameter was 10mm longer and the erosion height was 5mm. Thus, the diameter increase rate per height of the erosion (D/H) was 2. Since the parabolic nozzles are not commonly used, there is none information regarding the wear. It was considered that the erosion profile would be the same for both nozzles. Figure 5 illustrates the dimensions of the nozzles as a function of throat diameter, respectively: “Conical”, “Conical with wear”, “Parabolic MOC” and “Parabolic MOC with wear”.

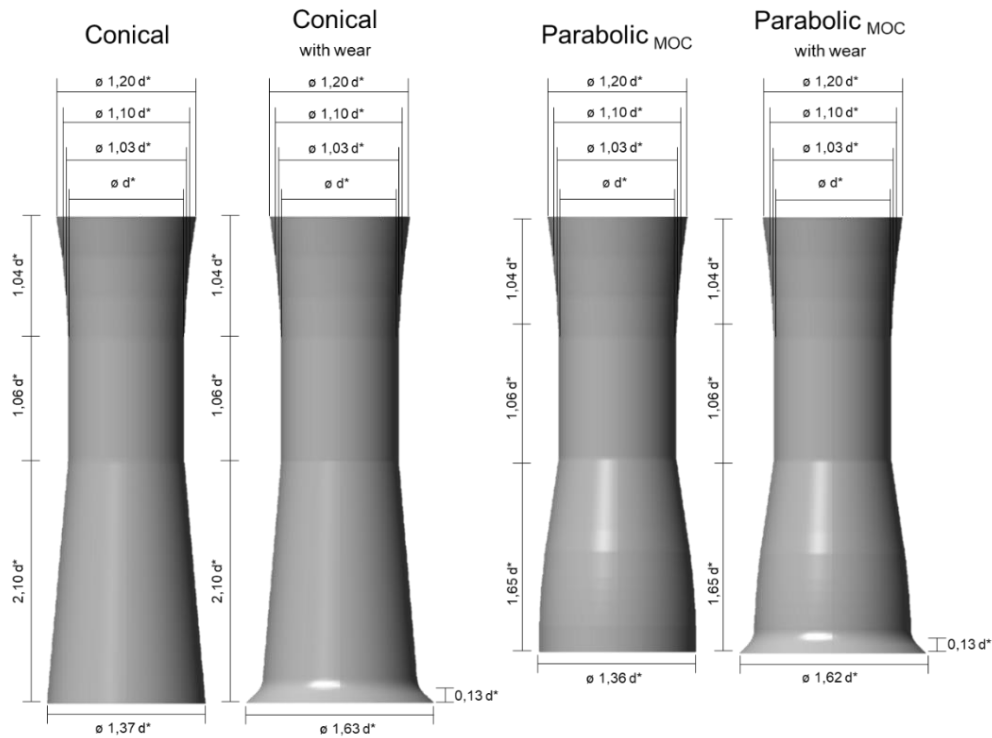


Figure 5: Dimensions of the simulated nozzles as a function of throat diameter.

The domain of the simulations was the same and included the inlet, oxygen reservoir, the nozzle, stationary walls and outlet. Since the domain under study was only one quarter of the nozzle, two symmetry planes were created on the cutting face of the geometry, as illustrated in Figure 6.

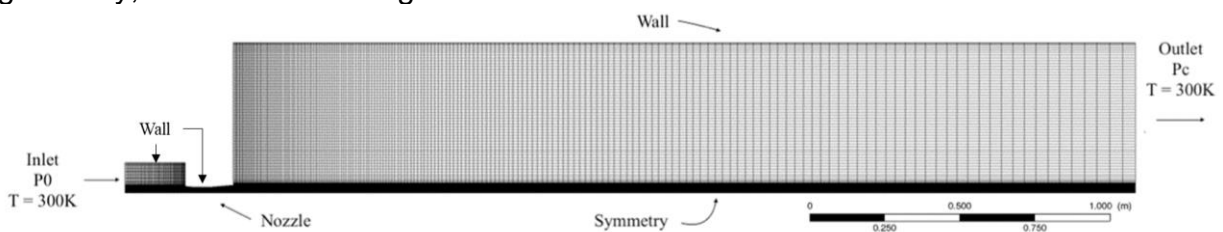


Figure 6: Simulation domain and mesh.

The elements chosen for the all meshes were hexahedral. Boundary layer was considered near the nozzle walls, 10 layers with 10^{-4} m. Mesh refinement was carried in the jet region aiming higher accuracy in the calculation of shock waves and flow turbulence. According to the Fluent Theory Guide [10] the minimum orthogonal quality for all types of cells should be more than 0.01, with an average value that is significantly higher. For “Conical” and “Parabolic_{MOC}” and the minimum orthogonal quality was, respectively, 3.03896×10^{-1} and 3.99695×10^{-1} . Thus, the quality of the mesh was considered satisfactory. The mesh of “Conical” domain had 705200 nodes and 662625 elements. For the “Parabolic MOC” were 1875712 nodes and 1776318 elements.

As informed before, the “Conical” design was based on a real nozzle, for a 345 tons converter with oxygen nominal flow rate of $1100 \text{ Nm}^3/\text{min}$. The design pressure of the stagnant reservoir was 15.5 Bar and the outlet design pressure 1.6 Bar. Thus, this was the first set of pressures for the simulations. Although, the outlet design pressure

was 1.6 Bar it is known that normally, the pressure inside the converter varies from 1 to 1.2 Bar, due to gas generation in the furnace and the constraint imposed by the fume hood. Therefore, the subsequent simulations considered 1.2 Bar for outlet pressure.

Another objective was to study the influence of lance flow rate alterations in the oxygen jet, hence, a new set of pressures was chosen. An inferior limit (8.5 Bar), the stagnant reservoir pressure of design (15.5 Bar) and a superior limit (17 Bar) were tested only under $P_c=1.2$ Bar aiming greater compatibility with real BOF conditions. The lance flow rate is connected with the number of nozzles and throat diameter and it is related with the reservoir pressure. Table 1 summarizes the reservoir pressure, approximated oxygen flow rate correspondent and outlet pressure for the simulations. The same boundary conditions were applied for “Conical” and “Parabolic_{MOC}” geometries. For the worn nozzles solely the two first conditions were reproduced.

Table 1. Boundary conditions for simulations

P_0 (Bar)	Lance flow rate (Nm ³ /min)	P_c (Bar)	Comment
15.5	1100	1.6	Design point
15.5	1100	1.2	Real working point
8.5	600	1.2	Low flow rate
17.0	1200	1.2	High flow rate

The temperature was by default, 300K for all simulations. The oxygen was considered as pure and ideal gas, with thermal conductivity of 0.02674W/m.K and viscosity of 1.919e-05kg/m.s. The adiabatic gas constant was considered 1.4.

In addition to mass and momentum, energy conservation was also considered due to supersonic velocity. Since the flow is turbulent, the Navier-Stokes equations are not enough for modelling the process. The Standard k- ϵ model was used to predict the turbulent viscosity. This model solves two transport equations, one regarding the turbulent kinetic energy k, and the second variable is the dissipation rate of the turbulent kinetic energy, ϵ [10].

To assume convergence of the numerical procedure, the specified residual was in 10^{-6} , i.e., the error cannot be bigger than 0.0001%. For analyzing the results, *CFD Post 18.1* was used.

2.2 Results and discussion

2.2.1 Model validation

The validation of the model was performed for the “Conical” nozzle at design condition, $P_0=15.5$ Bar and $P_c=1.6$ Bar. shows also the alterations in flow properties throughout the nozzle, expressed as a function of A/A^* . The temperature, density, pressure and Mach number were calculated by the isentropic theory and compared with the simulation results (Figure 7).

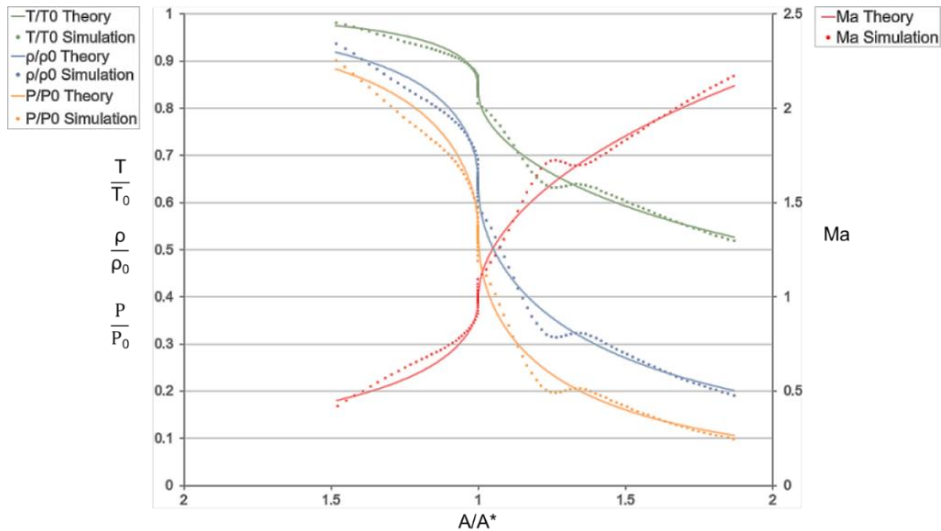


Figure 7: Isentropic theory and simulation for “Conical” nozzle.

Regarding the convergent section, some deviation is observed since the contour of the region in question was not conical. For the divergent segment it is possible to note a disturbance area in the simulation; this problem is associated with the presence of shock waves inside the nozzle. Regardless, the simulation result was considered satisfactory.

2.2.2 Fluid flow analysis

The Mach number contours for all simulations are shown in Figure 8. The potential core and supersonic lengths, express as dimensionless number X/d^* , were measured for each case and summarized. This measurement was performed with the aid of the graphics of Mach number along the jet central axis. The curves corresponding to the primary cases are disposed next.

Ma	Nozzle	P ₀ (Bar)	P _c (Bar)	Mach Number contour	Potential core length (X ₁ /d [*])	Supersonic length (X ₂ /d [*])	Nozzle	P ₀ (Bar)	P _c (Bar)	Mach Number contour	Potential core length (X ₁ /d [*])	Supersonic length (X ₂ /d [*])
	Conical	15.5	1.6		17.6	27.6	Parabolic MOC	15.5	1.6		18.0 (+2%)	28.1 (+2%)
	Conical	15.5	1.2		19.5	32.5	Parabolic MOC	15.5	1.2		20.1 (+3%)	33.3 (+2%)
	Conical	8.5	1.2		13.6	21.6	Parabolic MOC	8.5	1.2		14.7 (+8%)	22.2 (+3%)
	Conical	17	1.2		20.2	34.2	Parabolic MOC	17	1.2		20.8 (+3%)	35.0 (+2%)
	Conical with wear	15.5	1.6		17.1	27.5	Parabolic MOC with wear	15.5	1.6		17.8 (+4%)	27.6 (+0.5%)
	Conical with wear	15.5	1.2		19.2	32.8	Parabolic MOC with wear	15.5	1.2		19.3 (+0.5%)	32.9 (+0.5%)

Figure 8: Contour of Mach number and calculated potential core and supersonic core lengths.

Design point and real working pressure

The first simulations aimed at comparing the “Conical” and “Parabolic MOC” under design pressure and hypothetic real working pressure. Figure 9 shows the results for both conditions and exemplifies how the potential core and supersonic lengths were measured. The graphic origin represents the nozzle outlet.

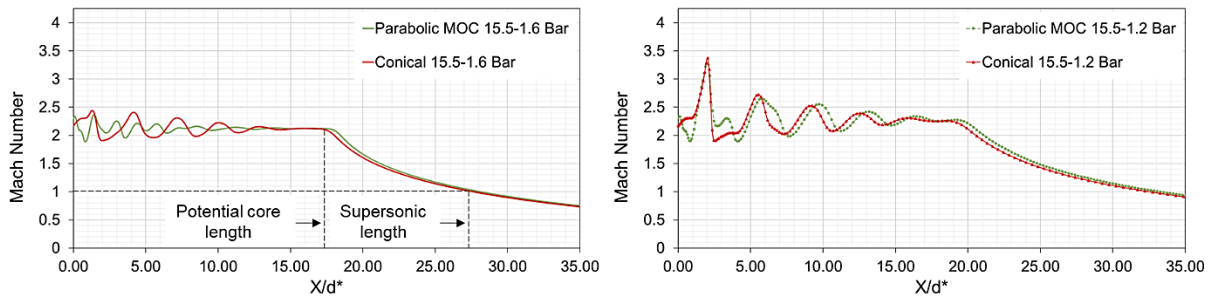


Figure 9: Conical vs Parabolic MOC - Design point and real ambient pressure.

It is possible to see that at the design pressures, both nozzles produce a quite uniform jet, with few shock waves. For this case the potential core was 2% longer for the “Parabolic MOC” and the supersonic 2% longer, in agreement with results find by similar simulation [3] [9]. As expected, under $P_c=1.2$ Bar, both jets presented more shock waves. The potential core length was 3% and supersonic length 2% greater for the parabolic nozzle.

Reservoir pressure variation

As shown in Figure 8, the potential core and supersonic lengths were longer for the “Parabolic MOC” for all tested values of reservoir pressure. The difference was more expressive for the low flow rate case, where the potential core length was 8% longer than the “Conical”. This suggests that even under adverse conditions, the jet of the parabolic nozzle still presents higher efficiency. Figure 10 illustrates the contours of Mach number near the nozzle outlet for a better comprehension of flow rate variation over nozzle wear.

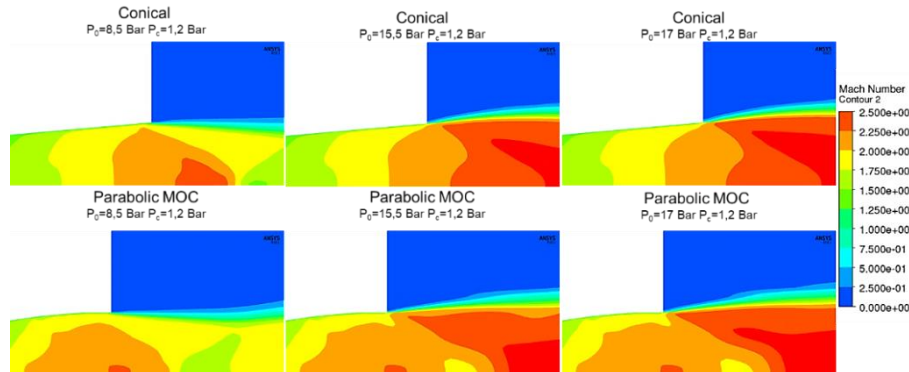


Figure 10: Contours of Mach number for “Conical” and “Parabolic MOC” for different P_0 .

For $P_0=8.5$ Bar over-expansion behavior and first signs of jet detachment were noticed, which promotes faster nozzle erosion. As expected, the rise of reservoir pressure to 17 Bar increased the amount of shock waves, thus higher Mach number and under-expansion are observed.

The contours of pressure were also generated for both nozzles under the same circumstances and are displayed in Figure 11.

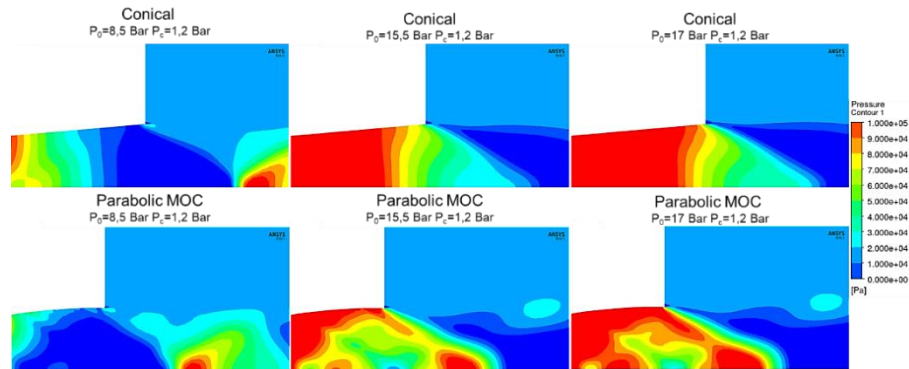


Figure 11: Pressure contours for “Conical” and “Parabolic MOC” for different P_0 .

It is possible to see that the pressure along the radial direction of nozzle is more stable for “Conical” than for the “Parabolic MOC”. For the “Parabolic MOC” there is a low-pressure area close to the nozzle center and high pressure close to the wall. The pressure values in this region were always higher for the “Parabolic MOC” than for the “Conical” and a hypothesis can be elaborated from the analysis of these results. The “Parabolic MOC” might be a better option for preventing nozzle wear. The higher pressure near the wall would protect this region from reverse flow of converter gases, and then, would offer a longer life for the lance tip. Likewise, the flow rate variations would affect less this nozzle.

Nozzle erosion

New vs worn nozzle

The results for the worn nozzles were compared with “Conical” and “Parabolic MOC”, since these represent new nozzles. Figure 12 shows the results at design pressures.

The presence of nozzle erosion increased the shock waves and decreased the potential core and supersonic lengths for both cases. For the “Conical with wear”, the potential core was approximately 3% shorter and the supersonic 1%. As to the “Parabolic MOC with wear” the potential core was 1% shorter and supersonic 2%. The parabolic nozzle presented fewer shock waves and appears to be slightly less sensitive to the presence of erosion.

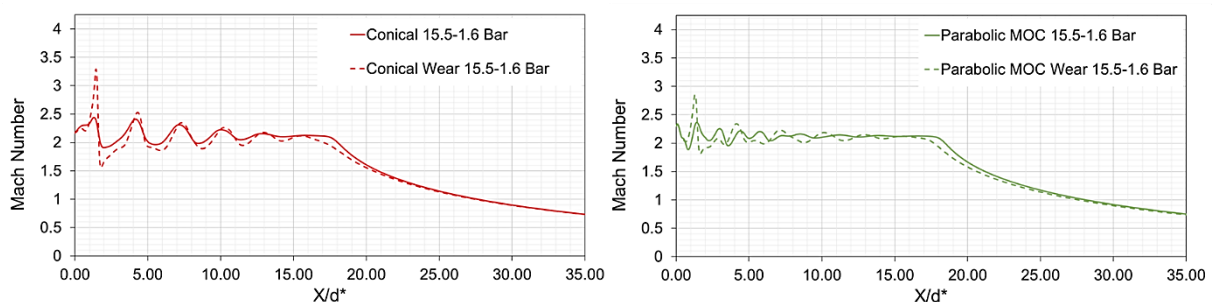


Figure 12: New vs worn nozzles for Conical and Parabolic MOC.

Design pressure and real working pressure

The worn nozzles have also been tested under converter pressure of 1.2 Bar. Figure 13 compares the results for “Conical with wear” and “Parabolic MOC with wear” under design and real working pressure.

Comparing the worn nozzles at design pressures, the potential core was 4% longer and the supersonic 0.5% longer for “Parabolic MOC with wear”. For $P_c=1.2$ Bar no much difference was noticed between the two worn nozzles.

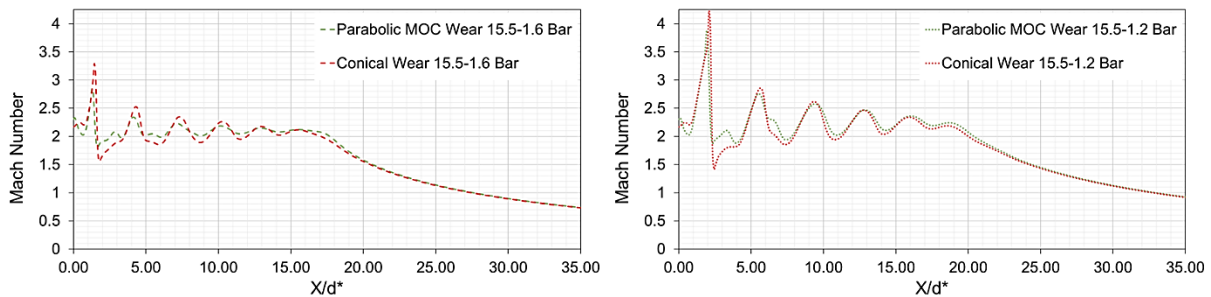


Figure 13: Worn nozzles under design pressure and real working pressure.

Pattern of Mach Number

Different patterns of Mach number were observed for the conical and the parabolic shapes. For the conical nozzles, the Mach number increased after the exit, whereas for the parabolic it decreased. To understand this behavior the Mach number at the central axis of internal part of nozzle is shown in Figure 14.

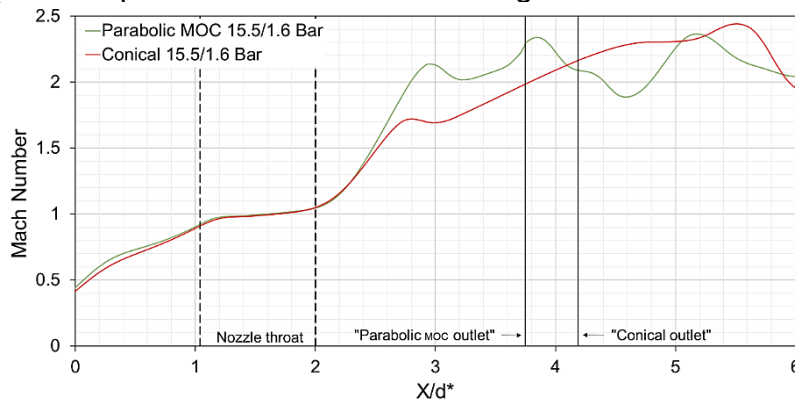


Figure 14: Mach number pattern inside the nozzles.

For both nozzles shock waves can be observed in the divergent section inside the nozzle. The contours of pressure for both nozzles was also taken into account, shown in Figure 15.

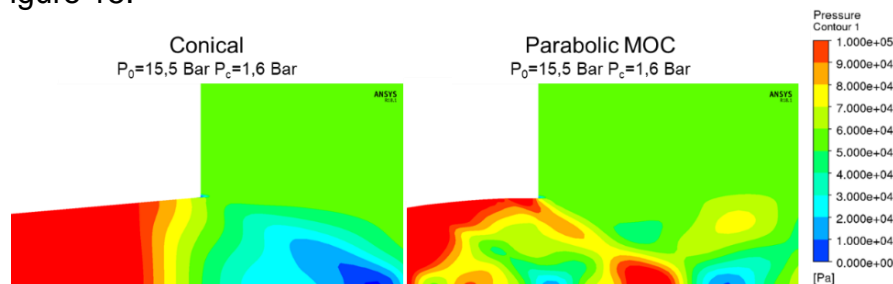


Figure 15: Pressure contours for “Conical” and “Parabolic moc” at design point.

It is possible to notice that for the parabolic nozzle there are two areas of low pressure (blue) and a high pressure (red) area between them. The same region in the conical nozzle exhibits only one low pressure area. The analysis implies that the shock waves occur earlier for the “Parabolic moc”, right after the nozzle outlet. This may be associated with the pressure gradient of the parabolic nozzle. The high pressure near the wall may block the free expansion of the jet, causing shock waves.

3 CONCLUSION

- Even with the presence of shock waves just after the nozzle outlet for “Parabolic MOC”, their intensity was on average lower compared to “Conical” for most of the cases tested;
- Under design pressures, the potential core was 2% longer and the supersonic 2% longer for “Parabolic MOC”.
- The higher pressure near the wall for “Parabolic MOC” may offer longer life for the lance tip. Likewise, the flow rate variations would affect less this nozzle.
- For the worn nozzles, the potential core was 4% longer and the supersonic 0.5% longer for “Parabolic MOC with wear”, thus the parabolic design may be less sensitive to the presence of wear;
- The shorter length of the “Parabolic MOC” might be a positive aspect for reducing material costs;
- More studies regarding the “Parabolic MOC” design should be performed, especially at worn conditions.

Acknowledgments

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