Some numerical simulation results of swirling flow in d.c. plasma torch

C L Felipini and M M Pimenta
Polytechnic School, University of São Paulo, São Paulo, Brazil
E-mail: celsofelipini@gmail.com

Abstract. We present and discuss some results of numerical simulation of swirling flow in d.c. plasma torch, obtained with a two-dimensional mathematical model (MHD model) which was developed to simulate the phenomena related to the interaction between the swirling flow and the electric arc in a non-transferred arc plasma torch. The model was implemented in a computer code based on the Finite Volume Method (FVM) to enable the numerical solution of the governing equations. For the study, cases were simulated with different operating conditions (gas flow rate; swirl number). Some obtained results were compared to the literature and have proved themselves to be in good agreement in most part of computational domain regions. The numerical simulations performed with the computer code enabled the study of the behaviour of the flow in the plasma torch and also study the effects of different swirl numbers on temperature and axial velocity of the plasma flow. The results demonstrated that the developed model is suitable to obtain a better understanding of the involved phenomena and also for the development and optimization of plasma torches.

1. Introduction
Thermal plasma torch designs using electric arc (usually called plasma torches) should be specifically developed according to their applications [1]. Therefore, the optimization of electrothermic processes involving thermal plasmas is closely related to the proper conception of plasma torches, mainly concerning to geometry/dimensions of electrodes (anodes and cathodes) and to operating parameters: working gas (plasmogenic gas), electric current intensity, electric voltage, gas flow rate and temperature range [2]. Besides the experimental procedures used in the development of plasma torches, the Computational Fluid Dynamics (CFD) is an interesting tool for torch design and optimization because it allows reducing the development costs and it helps to understand the related phenomena [3].

The model of this work approaches non-transferred arc torches (torches where the electric circuit closes among electrodes, cathodes and anodes, inside the torches themselves and the plasma jet does not conduct the current to their outer part), specifically the ones destined to industrial applications (thermal spraying, advanced material production, etc.) and the solutions for garbage, contaminated residues, toxic material and pollutants which affect the environment (figure 1).

We should highlight that in many non-transferred arc plasma torch, the gas is introduced with swirl in order to reduce the anode erosion rate through the arc rotation [4, 5]. It also shows that the swirling in plasma jet is useful for the synthesis of some materials [4]. This way, the effect of swirling flow in the behavior of plasma arc and plasma jet is an important investigation aspect which is a little divulged in literature motivating its insertion into the goals of this work.
This article presents a mathematical model for the numerical simulation of swirling flow in thermal plasma torches and, besides that, in some results obtained with initial simulations.

2. The model
A magnetohydrodynamic model (MHD model) was adapted to thermal plasma torches based on [3-17]. Its main characteristics are: two dimensional mathematical model (axisymmetric) of swirling flow in non-transferred arc thermal plasma torches which operate in direct current (d.c.), involving all regions of study interest and influence in phenomena (gas inlet; inside torch– where there is arc/flow interaction; plasma jet free in the environment).

2.1. Assumptions
The following assumptions have been adopted for this model: (1) plasma (electrons; heavy particles) has a Newtonian and single-species fluid behavior; (2) flow is approached in a continuum, two dimensional (axisymmetric), laminar, with incompressible behavior and steady state; (3) the local thermodynamic equilibrium (LTE) prevails in the study domain; (4) plasma is optically thin (black body radiation emitted by plasma is not absorbed by it); (5) heat dissipation due to viscous tensions may not be taken into consideration (constituted by second order terms); (6) MHD approach is applicable: displacement current is not considered when compared to the conduction current; the electrostatic field strength is not considered; (7) gravity effects are not considered; (8) the external environment is formed by the same gas as the work one.

2.2. Model equations
By taking into consideration the assumptions previously adopted, the governing equations for the axisymmetric (2D), laminar flow in stationary status with plasma torch swirl may be presented in cylindrical coordinates as follows:

Mass conservation equation:

$$\frac{1}{r} \frac{\partial}{\partial r} (r \rho u) + \frac{\partial}{\partial z} (\rho u) = 0$$

(1)
Momentum conservation equations in $z$ (axial), $r$ (radial) and $\theta$ (azimuthal) directions, respectively:

$$
\frac{1}{r}\frac{\partial}{\partial r} (rp\mu v) + \frac{\partial}{\partial z} (p\mu v^2) = \frac{1}{r}\frac{\partial}{\partial r} \left[ r\mu \left( \frac{\partial u}{\partial r} + \frac{\partial v}{\partial z} \right) \right] + \frac{\partial}{\partial z} \left( 2\mu \frac{\partial u}{\partial z} \right) - \frac{\partial p}{\partial z} + j_B \theta
$$

(2)

$$
\frac{1}{r}\frac{\partial}{\partial r} (rp\nu^2) + \frac{\partial}{\partial z} (p\nu v^2) = \frac{1}{r}\frac{\partial}{\partial r} \left[ 2r\mu \frac{\partial v}{\partial r} \right] + \frac{\partial}{\partial z} \left( \mu \left( \frac{\partial u}{\partial r} + \frac{\partial v}{\partial z} \right) \right) + \frac{\partial}{\partial r} \left( \frac{1}{r^2} \mu \nu - \frac{\partial p}{\partial r} - j_z B_\theta \right)
$$

(3)

$$
\frac{1}{r}\frac{\partial}{\partial r} (rp\nu w) + \frac{\partial}{\partial z} (p\nu w^2) = \frac{1}{r}\frac{\partial}{\partial r} \left( r\mu \frac{\partial w}{\partial r} \right) + \frac{\partial}{\partial z} \left( \mu \frac{\partial w}{\partial z} \right) - \frac{1}{r^2} \mu \nu w - \frac{\partial p}{\partial r}
$$

(4)

where $u, v$ and $w$ are the velocity components in $z$ (axial), $r$ (radial) and $\theta$ (azimuthal) directions, respectively; $\mu, \rho$ and $p$ are the following gas properties: dynamic viscosity, specific mass and pressure, respectively; $j_z$ and $j_r$ are the axial and radial components of the electric current density vector $\mathbf{j}$, respectively and $B_\theta$ is the azimuthal component of the of magnetic induction intensity vector (self-induced) $\mathbf{B}$ (note: “magnetic field inducted by the arc electric field”). Observe that $j_z B_\theta$ and $j_r B_\theta$ terms are components of Lorentz force vector: $\mathbf{F} = \mathbf{j} \times \mathbf{B}$.

Energy conservation equation (“written” in function of the gas specific enthalpy, $h$: $h = \int C_p dT$):

$$
\frac{1}{r}\frac{\partial}{\partial r} (rp\nu h) + \frac{\partial}{\partial z} (p\nu h^2) = \frac{1}{r}\frac{\partial}{\partial r} \left( r k \frac{\partial h}{C_p \partial r} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial h}{C_p \partial z} \right) + \frac{j_z^2 + j_r^2}{\sigma} - S_r + \frac{5 k_h}{2}\frac{1}{e} \left( \frac{j_r}{C_p \frac{\partial h}{\partial r}} + \frac{j_z}{C_p \frac{\partial h}{\partial z}} \right) + u \frac{\partial p}{\partial z} + v \frac{\partial p}{\partial r}
$$

(5)

where $C_p$ is the gas specific heat at constant pressure; $k$ is the gas thermal conductivity and $\sigma$ is the gas electric conductivity. One should observe that besides the terms which represent the enthalpy transport through convection and diffusion, the energy conservation equation is constituted by the following source terms: $\frac{j_z^2 + j_r^2}{\sigma}$, heating through Joule effect; $S_r$, heat dissipation through radiation per unit of plasma volume ($S_r = 4\pi e_N$), where $e_N$ is NEC emissivity NEC - plasma is considered optically thin – experimental values [12]); $\frac{5 k_h}{2}\frac{1}{e} \left( \frac{j_r}{C_p \frac{\partial h}{\partial r}} + \frac{j_z}{C_p \frac{\partial h}{\partial z}} \right)$ (electron drift) is the enthalpy transport through electron current which is directed to the anode ($k_h$ is Boltzmann constant; $e$ is the elementary electric charge); $u \frac{\partial p}{\partial z} + v \frac{\partial p}{\partial r}$, energy variation due to pressure variation.

The reference [2] presents the thermodynamic and plasma transport properties for some gases (air; argon; others).
The current densities and the azimuthal component of the magnetic field are obtained through the electric current conservation equation solution, and through the third Maxwell equation, with the help of the “adapted" Richardson-Dushmann equation (applicable for thermionic emission).

Electric current conservation equation (in the form of electric potential):

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \sigma \frac{\partial \Phi}{\partial r} \right) + \frac{\partial}{\partial z} \left( \sigma \frac{\partial \Phi}{\partial z} \right) = 0
\]

(6)

where \( \Phi \) is the electric potential.

Third Maxwell equation (in differential form):

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r B_0 \right) = \mu_0 J_z
\]

(7)

where \( \mu_0 \) is the magnetic permeability in free space (vacuum).

One should observe that this equation is applicable only for symmetric current distributions (in this specific case, symmetry related to axis: axisymmetry).

The current density vector \( \mathbf{j} \) is related to the electric field intensity vector \( \mathbf{E} \), or to \( \Phi \) electric potential, through \( \mathbf{j} = \sigma \mathbf{E} = -\sigma \nabla \Phi \). So, for such case (2D model): \( j_z = -\sigma \frac{\partial \Phi}{\partial z} \) and \( j_r = -\sigma \frac{\partial \Phi}{\partial r} \).

2.3. Computational domain and boundary conditions

The computational domain used for the simulations of this work is schematized in figure 2 and the employed boundary conditions are summarized in table 1.

Figure 2. Computational domain.
Table 1. Summary of the boundary conditions.

|   | \( u \) | \( v \) | \( w \) | \( h \) | \( \Phi \) |
|---|---|---|---|---|---|
| AB | \( \partial u / \partial r = 0 \) 0 0 0 \( \partial h / \partial r = 0 \) \( \partial j_z / \partial r = j_r = 0 \) |
| BC | \( \partial (\rho u) / \partial z = 0 \) \( \partial v / \partial z = 0 \) \( \partial w / \partial z = 0 \) \( \partial h / \partial z = 0 \) |
| CD | 0 0 \( \partial (\rho v) / \partial r = 0 \) 0 300K |
| FG | \( u = u(r) \) 0 \( w = w(r) \) 500K |
| AA' | \( j_z(r) \) (specified) |
| EE' | \( j_z = j_r = 0 \) |
| Anode | 0 0 0 1000K 0 |
| Cathode | 0 0 0 300K |

The description of the boundary conditions is presented as follows:

Inlet (FG line): in the inlet section, the axial velocity presents a parabolic profile and depends on the specification of the gas flow rate. Radial velocity is zero at the inlet. Azimuthal velocity presents a profile partially formed by the behavior of free vortex and forced vortex. The azimuthal velocity depends on the swirl number in torch inlet. The definition of the swirl number used in this work is presented by [4]: ratio of the axial flux of the azimuthal momentum to the axial flux of the axial momentum, normalized by an appropriate/characteristic radius \( R_0 \). In this work, \( R_0 \) radius is the torch nozzle radius. Therefore, the swirl number is given by:

\[
S_w = G_\theta / G_z R_0
\]

where the axial flux of the azimuthal momentum is

\[
G_\theta = \int_0^\infty \rho u w r^2 dr
\]

and the axial flux of the axial momentum is

\[
G_z = \int_0^\infty \rho u^2 r dr
\]

Other conditions: on the surfaces of electrodes (anode and cathode) the non-slip conditions are assumed (\( u = v = w = 0 \)). In the symmetry axis (line AB): \( \partial u / \partial r = 0 \) and \( v = w = 0 \). Conditions of free boundary are assumed for BC and CD. For BC: \( \partial (\rho u) / \partial z = 0 \), \( \partial v / \partial z = 0 \) e \( \partial w / \partial z = 0 \). And for CD: \( u = w = 0 \) and \( \partial (\rho v) / \partial r = 0 \). The boundary conditions for enthalpy are provided in temperature and converted to gas enthalpy. For the torch inlet, the temperature is 500K and for CD line the temperature is 300K. The temperatures of cathode and anode surfaces are assumed 3000K and 1000K, respectively. In the symmetry axis (line AB): \( \partial h / \partial r = 0 \); and in line BC, \( \partial h / \partial z = 0 \). Lines AA’ and EE’ are internal boundary conditions and are known as “fictitious” or “porous” boundary conditions (in these lines the boundary conditions for the electric potential \( \Phi \) are
assumed). In line AA', the electric potential is determined by assuming a axial current density profile [7, 18], adapted from Richardson-Dushmann equation (applicable for thermionic emission): 

\[ j_z(r) = j_0 e^{-r/r_c} \]

where \( j_0 \) and \( r_c \) are constants which depend on the electric current and are experimentally obtained. In line AB: \( \frac{\partial j_z}{\partial r} = 0 \) and \( j_r = 0 \). In ED: \( j_r = j_z = 0 \). In anode: \( \Phi = 0 \).

2.4. Numerical method

The model was implemented in the Computer Code for Simulation of the Swirling Flow in Thermal Plasma Torches (CTP), developed in order to enable the numerical solution of governing equations. CTP code uses the Finite Volume Method (FVM) and it is based on [9, 10, 19]. CTP was elaborated in FORTRAN 90 language (Microsoft FORTRAN Powerstation 4.0) and the simulations were executed in a microcomputer with INTEL CORE i7 processor and 6GB of RAM memory. The average computing time for each simulation is 15min, for meshes of 120x80 nodes and approximately 20000 iterations.

3. Initial results and comments

This article presents some results of initial simulations executed with CTP code. The results are categorized according to their goals: comparison with experimental results described in literature; study of the behavior of swirling flow in plasma torches.

3.1. Comparison with literature experimental results

In order to verify the quality of results of simulations with CTP, there were researches in literature to find experimental results obtained in plasma torches similar to the ones of this work and, also, in comparable operating conditions. In fact, there are a few experimental results in literature due to technical difficulties to execute the measurements of temperature and, mainly, velocity. Besides that, in general, there are considerable differences between the torches experimentally researched and the one used in this work.

The results of the performed experiences in Idaho National Engineering Laboratory (INEL) were chosen for the comparisons due to the similarity between its torch and the torch simulated in this work and, also, because the swirl was generated in it, enabling a proper comparison for the interest of this work in the study of the effects of swirl in the behavior of arc and plasma jet. The results obtained in INEL were published by [20].

The experimental apparatus used in INEL consisted of a non-transferred arc plasma torch and a chamber for pure argon atmosphere control. The torch operated in laminar mode, so that the flow in its interior part and in the jet, near its nozzle outlet, may be assumed as laminar (once the number of Reynolds at outlet is in the range of 100-200) [20]. An emission spectroscopy technique was used to measure the temperature of the plasma jet coming outside the torch. Investigators estimated the following measurements errors: ±0,2% for 12000K and ±1,5% for 9000K [20].

The numerical simulations were executed for two operating conditions of INEL torch and they are presented in table 2. The comparisons between the experimental results and the temperature calculated results for both operating conditions are showed in figures 3, 4, 5 and 6. In these figures, it is possible to observe that discrete figures denote experimental results and the lines indicated the calculated results.

Figure 3 refers to BES23-INEL case and presents the temperature values of plasma jet coming out of the torch. The values were experimentally obtained (measured) in function of the axial distance (origin of the graph coincides with the origin (0) of the computational domain) for the radial position: torch symmetry axis (r=0). The temperature profile which was numerically obtained (calculated) through computer code (CTP), for the same operating conditions, is also presented.

The comparison presents the following differences: the biggest difference between the measured temperature values (experimental ones) and the calculated values (simulation with CTP code) is -5.4% (Texp=11196 K; Tclc=11800 K), in the axial distance z=33 mm. From the distance z=41 mm, the
Table 2. Operating conditions of INEL torch.

| INEL Code | Plasma Gas | Gas Flow (l/min) | Gas Flow (scm/h) | Electric Current (A) | Electric Voltage (V) | Input Power (kW) | Swirl Number |
|-----------|------------|-----------------|-----------------|----------------------|---------------------|------------------|--------------|
| BES23     | Argon (Ar) | 9,83            | 0,59            | 250                  | 19,16               | 4,79             | Sw=5         |
| BES24     | Argon (Ar) | 13,83           | 0,83            | 250                  | 19,44               | 4,86             | Sw=5         |

Figure 3. Temperature profiles in function of axial distance in the radial position: symmetry axis (r=0). Comparison between experimental results (BES23-INEL case) and calculated results (simulation-CTP).

measured values are bigger than the calculated values and the biggest difference between them is +4,3%, in the axial distance z=69 mm. In other axial distances, the differences are between +2,8% and +3,4%.

The comparison between the radial temperature values that were measured and the temperature radial profiles that were obtained with CTP for BES23-INEL case is shown in figure 4, for axial positions: z=33 mm, z=45 mm, z=57 mm, z=69 mm and z=80 mm.

The differences between the experimental and calculated values are the following ones:

Axial position z=33 mm: in the torch symmetry axis, r=0, the difference between the experimental and the calculated value is -5,4%, already showed in figure 3 as well. The biggest difference, -5,5%, occurs in r=0,5 mm. Between r=0,5 mm and r=2,3 mm, the difference varies between -3,7% and -2%, and between r=2,7 mm and r=4,4 mm the differences vary from -1,3% to +1,3%.

Axial position z=45 mm: the differences vary from +1,0% to 3,1%.

Axial position z=57 mm: between r=0 and r=3,4 mm, the differences are between +3,4% and +4,3%. In r=3,8 mm the difference decreases to 1,3%.

Axial position z=69 mm: between r=0 and r=2,7 mm, the differences are between +4,3% and +1,5%. In r=3,0 mm the difference is -1,5%. Axial position z=80 mm: in the torch symmetry axis (r=0) the difference between the experimental and the calculated value is +3,0% (already showed in figure 3 as well). Between r=0,2 mm and r=0,9 mm, the differences vary from +2,2% to 1,4%. Between r=1,1 mm and r=1,4 mm, the differences vary from +1,1% to 0,5%. In r=1,5 mm the difference is -1,0%.
Figure 4. Temperature profiles in function of the radial distance in axial positions (plasma jet): 33 mm; 45 mm; 57 mm; 69 mm; 80 mm. Comparison between experimental results (BES23-INEL case) and calculated results (simulations-CTP).

The comparisons between experimental results and calculated ones for BES24-INEL case are showed in figures 5 and 6.

Figure 5 presents the temperature in function of the axial distance for the radial position r=0 (torch symmetry axis). The comparison between the measured and the calculated values shows the following differences: in z=33 mm the difference is -2,7%. From the axial distance z=37 mm, the measured values are bigger than the calculated ones and the biggest difference between them is +4,8% (Texp=10390 K; Tcalc=9890 K), in axial distance z=45 mm. In other axial distances, the differences are between +1,5% and +3,5%.

Figure 5. Temperature profiles in functions of the axial distance in radial position: symmetry axis (r=0). Comparison between the experimental results (BES24-INEL case) and the calculated results (simulation-CTP).

Figure 6 presents the temperature in function of the radial distance for the axial positions: z=33 mm, z=45 mm, z=57 mm and z=69 mm.
Figure 6. Temperature profiles in function of the radial distance in axial positions (plasma jet): 33 mm; 45 mm; 57 mm; 69 mm. Comparison between the experimental results (BES24-INEL case) and the calculated results (simulations-CTP).

The differences between the experimental values and the calculated values are the following ones:

Axial position $z=33$ mm: in the torch symmetry axis ($r=0$) the difference between the experimental and the calculated value is -2.7% (showed in figure 5 as well). The biggest difference, -10.0%, occurs in $r=4.8$ mm. Between $r=0.5$ mm and $r=2.9$ mm, the difference is around -2.5%. Between $r=3.4$ mm and $r=4.4$ mm the differences vary from -4.5% to -7.2%.

Axial position $z=45$ mm: between $r=0$ and $r=1.9$ mm the differences vary from +4.8% to +3.0%. From $r=3.4$ mm, the measured values are smaller than the calculated values and the biggest difference between them is -6.0%, in $r=4.7$ mm. Axial position $z=57$ mm: the differences vary from +2.4% to +1.9% between $r=0$ and $r=4.4$ mm. In $r=4.8$ mm, the difference is -1.6%. Axial position $z=69$ mm: between $r=0$ and $r=4.4$ mm the difference are between +2.4% and +1.3%.

Although the biggest differences between the experimental values and the calculated values are negative (-5.5% for BES23 case and -10.0% for BES24 case), that is, experimental values are smaller than calculated values, a systematic tendency is not characterized in this sense because there are also several regions where the experimental values are bigger than the calculated values (positive differences).

The predominance of the biggest differences in one of the two investigated cases in relation to each other is not characterized either. Considering that the average of differences is approximately ±3.2% and also considering the simplifying assumptions of the developed mathematical model, the concordance of the results of the numerical simulations with the results of measurements is good and, therefore, the model is adequate to the intended investigations in this work and in future ones as well.

3.2. Results of simulations of swirling flow in plasma torches

The numerical simulations carried out until the moment with CTP code for different plasma torches and operating conditions have enabled the study of behavior of flow in torches, as well as the study of effects of different swirl intensities in temperature and axial velocity in plasma flow. This paper presents (figure 7 to figure 12) some results of simulations of an academic torch operating with the conditions of BES23-INEL case (table 2).

Figure 7(a) presents the temperature axial profiles in the radial position $r=0$ (torch symmetry axis), obtained with different swirls numbers and figure 7(b) presents the temperature radial profiles in the axial position $z=33$ mm, also obtained with different swirl numbers.
**Figure 7.** Temperature profile and swirl effect: (a) temperature axial profiles (radial position: symmetry axis (r=0)); (b) temperature radial profiles (axial position: 33 mm).

Figure 8 shows the temperature radial profile, for each swirl number, in the axial positions \( z=45 \) mm (a) and \( z=57 \) mm (b) and figure 9 in the axial positions \( z=69 \) mm (a) and \( z=80 \) mm (b).

**Figure 8.** Temperature radial profiles and swirl effect: (a) axial position: 45 mm; (b) axial position: 57 mm.

**Figure 9.** Temperature radial profiles and swirl effect: (a) axial position: 69 mm; (b) axial position: 80 mm.
Figure 10(a) presents the axial velocity profiles in function of axial distance, in the radial position \( r=0 \) (torch symmetry axis), obtained with different swirl numbers and figure 10(b) presents the axial velocity profiles in function of the radial distance, in the axial position \( z=33 \) mm, also obtained with different swirl numbers.

Figure 10. Axial velocity profile and swirl effect: (a) in function of the axial distance (radial position: symmetry axis \((r=0)\)); (b) in function of the radial distance (axial position: 33 mm).

Figure 11 shows the axial velocity profile in function of the radial distance, for each swirl number, in the axial positions \( z=45 \) mm (a) and \( z=57 \) mm (b) and figure 12 in the axial positions \( z=69 \) mm (a) and \( z=80 \) mm.

Figure 11. Axial velocity profile in function of the radial distance and swirl effect: (a) axial position: 45 mm; (b) axial position: 57 mm.

Through the analysis of figures it is possible to verify the following phenomenological characteristics:

Due to gas ionization and, consequently, to its increased electric conductivity, in the region next to the cathode (where there is the maximum current density), there is a big increase of the gas temperature due to its heating through Joule effect.

Still inside the torch (up to the distance \( z=13 \) mm), there is a big decrease of the plasma temperature due to the convection with the anode cooled surface. When the plasma jet comes out of the torch, it presents a less intense reduction of temperature, in function of the axial distance, due to the convection with the environmental gas. Next to the cathode there is plasma acceleration due to its expansion (caused by the temperature increase) and due to Lorentz force effect (resulting from the
interaction between the arc current and the inducted magnetic field). Then, there is a continuous deceleration of the velocity of plasma jet when in contact with the environmental gas.

![Figure 12. Axial velocity profile in function of the radial distance and swirl effect: (a) axial position: 69 mm; (b) axial position: 80 mm.](image)

It is also possible to observe the “flattening” of the radial profile of the axial velocity of plasma jet and of the temperature radial profile, in the axial direction, due to the dragging with the environmental gas. Such behavior is also reported by [4, 6, 7].

The temperature profiles (figure 7 to figure 9) with Sw=0 and Sw=1 practically coincide, which indicates that a bigger swirl number is required to modify the arc behavior. Only for Sw>3, the swirl significantly affects the temperature profiles (axial and radial ones). The increase in the azimuthal momentum of plasma jet due to an increase in swirl intensifies the jet heat exchange with the environmental gas and, consequently, it causes a more intense decrease in temperature (that can be confirmed in the axial and radial profile figures).

Concerning the axial velocity (figure 10 to figure 12), its decrease is significantly intense for Sw≥3 due to the increase in the jet energy dissipation interacting with the environmental gas.

The determination of the relationship between the swirl number which is appropriate to rotate the arc and significantly reduce the anode erosion rate and its effects on the profiles of temperature and velocity of plasma jet, which are important for the efficient work of torches in determined applications, requires both the experimental surveys and the numerical simulations.

4. Conclusion
This work presented and discussed the results of some numerical simulations of thermal plasma torch flow carried out with the developed computer code (CTP), which was concisely presented. The mathematical model was also presented including the swirl in order to enable the study of its effect on the arc behavior inside the torch and in the free plasma jet.

With the purpose of verifying the quality of the simulation results, part of them was compared to the experimental results and was observed that -10% is the biggest difference obtained between the experimental temperature values and the calculated ones, and ±3.2% is the average obtained from the differences between the values.

Simulations were made for this study with the following characteristics / operating conditions: conic cathodes; current intensities of 100 and 250 A; argon at atmospheric pressure; gas flow of 9.83 and 13.83 l/min; flow with and without swirl (swirl numbers, Sw= 0 to 7). Through the analysis of the results, it is possible to point out the following remarks: the flow temperature curves with Sw=0 and Sw=1 practically coincide, which indicates that a bigger swirl number is required to modify the arc behavior. Only for Sw≥ 3, the swirl significantly affects the temperature profile. The increase in the azimuthal momentum of plasma jet due to an increase in swirl intensifies the jet heat exchange with the environmental gas and, consequently, it causes a more intense decrease in temperature. Concerning
the axial velocity, its decrease is significantly intense for Sw≥3 due to the increase in the jet energy
dissipation interacting with the environmental gas. Therefore, it is possible to conclude that the model
is able to carry out numerical investigations of flow in plasma torches and swirl effects in the arc/flow
interaction.

Acknowledgements
The authors acknowledge the support from Escola Politécnica da Universidade de São Paulo and
Centro de Pesquisa da Universidade São Judas Tadeu.

References
[1] Feinman J 1987 Plasma technology in metallurgical processing (Feinman and Associates, USA)
[2] Boulos M I, Fauchais P and Pfender E 1994 Thermal plasma: Fundamentals and applications
vol 1 (New York: Plenum Press)
[3] Gleizes A, Gonzalez J J and Freton P 2005 J. Phys. D: Appl. Phys. 38 153
[4] Westhoff R and Szekely J 1991 J. Appl. Phys. 70 3455
[5] Sun X and Heberlein J 2005 Journal of Thermal Spray Technology 14(1) 39
[6] Scott D A, Kovitya P and Haddad G N 1989 J. Appl. Phys. 66 5232
[7] Murphy A B and Kovitya P 1993 J. Appl. Phys. 73 4759
[8] Bauchire J M, Gonzalez J J and Gleizes A 1997 Plasma Chem. Plasma Process. 17 409
[9] Favalli R C 1997 Master Dissertation, Universidade de Sao Paulo
[10] Bianchini R C 2000 Master Dissertation, Universidade de Sao Paulo
[11] Klinger L 2002 PhD Thesis, L’école Polytechnique de Lausanne
[12] Baudry C 2003 PhD Thesis, Universite de Limoges
[13] Li H P, Pfender E and Chen X 2003 J. Phys. D: Appl. Phys. 36 1084
[14] Yuan X Q, Li H, Zhao Z, Wang F, Guo K and Xu P 2004 Plasma Chem. Plasma Process. 24(4) 585
[15] Li H P and Pfender E 2007 Journal of Thermal Spray Technology 6(2) 245
[16] Trelles J P, Chazelas C, Vardelle A and Heberlein J V R 2009 Journal of Thermal Spray
Technology 18(5-6) 728
[17] Huang R, Fukanuma H, Uesugi Y and Tanaka Y 2013 Journal of Thermal Spray Technology 22 183
[18] Hsu K C, Etemadi K and Pfender E 1983 J. Appl. Phys. 54 1293
[19] Vatavuk P 1996 PhD Thesis, Universidade de Sao Paulo
[20] Dilawari A H, Szekely J, Batdorf, J, Detering R and Shaw C B 1990 Plasma Chem. Plasma
Process. 10 321