STUDY OF AN Ar-H₂ PLASMA TORCH SUBMITTED TO AN EXTERNAL COOLING

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Abstract
A three dimensional (3D) Ar-H₂ arc plasma at atmospheric pressure is presented. The model is developed using the commercial code Fluent. The model is then used to study the hydrodynamic flow and the influence of air injectors on the plasma jet. The injectors are situated symmetrically from the nozzle torch. They produce change on the temperature fields following their plane position. On the plane injectors the plasma is constricted, and it expands on the perpendicular plane.

1. Introduction

Thermal plasma models of increasing sophistication which approximate realistic conditions more and more closely, have been reported in the literature. Many two dimensions studies are developed on free burning arc or plasma torch configurations, where numerous experimental results are available. Nevertheless some physical points, like the influence of the vortex injection, arc attachment in a nozzle or complex geometry need to be studied with a 3D model. But the literature is very poor in real three dimensional plasma configurations.

The aim of this study is to show in a real three dimensional configuration without any symmetric plane, the effect of the flow air injection in a Ar-H₂ plasma torch configuration. The model is developed using the Fluent software based on the finite volume method (version 4.4.8). This code is modified to take the arc plasma into account, and all the electromagnetic equations are written in 3D (potential vector, scalar potential, magnetic field). The arc attachment situated in the nozzle torch is not directly described and the attachment is represented by a fictitious porous electrode. The model uses in Ar-H₂ plasma mixture discharging in an air environment. The natural symmetry of the geometry is broken by the presence of the two air injectors, and by the powder injector. The last one is not taken into account in this paper and corresponds to future developments. The subtract position is situated 120mm from the nozzle exit.

The device configuration is described, then the mathematical model is presented with the equations, the boundary conditions and the hypothesis. In the last part the main results which could influence the thermodynamic state of the powders before their impact on the subtract are discussed : temperature and mass fraction fields.

2. Device description

The geometry is presented in figure 1. Two parts must be distinguished, the upper one where the torch and the two injectors are implanted and the second one represented by a cylinder corresponding to the jet expansion and to the subtract localization (Wall 3). The torch
is constituted by the cathode electrode (wall c) and the nozzle (wall 2). The two injectors used for the subtract protection are named inlet 2 and inlet 3. This configuration is particularly designed for plasma spraying application. The torch can support high intensity (up to 600A) and presents a convergent – divergent nozzle. Its mean diameter is about 8mm and the distance from the cathode tip to the exit nozzle is equal to 25 mm. The plasma gas on inlet 1 is axially injected. Its a mixture of argon 89.7% and hydrogen 10.3%. The plasma jet expands in an air environment. Air gas is also used for the two injectors. The injectors have a symmetric position in regard to the nozzle center. The injectors are positioned at 15° with the vertically direction in order to intercept the plasma jet 120mm below the torch exit. In the experimental configuration the subtract is located 100mm from the nozzle exit. The pulsed air cuts the plasma jet and cools it in the plane of the injectors. Due to the presence of the two secondary air flows, the problem is highly three dimensional. In this study step only the influence of the complex hydrodynamic flow behavior is studied and we do not take into account any particles injection. The distance between the nozzle exit and wall3 is about 120mm and the radius geometry about 6 cm (distance from the nozzle center to the inlet4).

Figure 1: Geometry configuration
3. Mathematical model

**Assumptions:**

The plasma is assumed to be a fluid at local thermodynamic equilibrium described only by one temperature for all the species. The transport coefficients of the melt Ar-H₂-Cu are calculated by Cressault [1]. This program allows us to calculate the transport and thermodynamic properties for the different Ar-H₂ plasma mixtures and to take into account the fraction of copper introduced by the particles. As no particle is added in the injectors and as the plasma flow expands in a surrounding air environment Ar-air-H₂ mixture must by considered. The transport coefficients of the air are those of the literature [2]. At the nozzle exit, in the free jet, the transport coefficients of the mixture are deduced from proportionally laws following the mass or the molar fraction between Ar-H₂ and the air. The radiation term in the energy equation is treated by the net emission coefficient [1]. The flow is assumed to be stationary and laminar. In this paper we focus on the influence of the flow injectors on the plasma jet in a 3D configuration, so the cathode and anode sheaths regions are not treated and the arc attachment assumes a porous anode [3].

**Equations**

We solve the equations of the mass, momentum (vₓ, vᵧ, vₗ), and of the static enthalpy conservation (h) to deduce the temperature (T). The electrical characteristics of the plasma are taken into account by solving the electrical potential (V) and potential vector components equations (Aₓ, Aᵧ, Aₗ). All these equations are written with the Patankar formulation [4]:

\[
\frac{\partial}{\partial z} (\rho v_z \Phi) + \frac{\partial}{\partial x} (\rho v_x \Phi) + \frac{\partial}{\partial y} (\rho v_y \Phi) = \frac{\partial}{\partial z} \left[ \Gamma_x \frac{\partial \Phi}{\partial z} \right] + \frac{\partial}{\partial x} \left[ \Gamma_x \frac{\partial \Phi}{\partial x} \right] + \frac{\partial}{\partial y} \left[ \Gamma_x \frac{\partial \Phi}{\partial y} \right] + S_{\Phi} \tag{1}
\]

The system solution is obtained with the commercial Fluent program. We have shown in precedent works [5] the aptitude of this numerical code to solve thermal plasma flows in two and three dimensions. The geometrical domain is divided in 92x92x73 grids. The mesh in the nozzle is particularly fine with a 30x30x43 grid definition. One week CPU time is needed to obtain a converged solution on a HP C3000.

At the cathode tip an exponential profile of the current density is used:

\[ j(r) = j_{\text{max}} \exp(-br) \tag{2} \]

where \( j_{\text{max}} \) is chosen equal to 1.2E8 A/m² and \( b \) in order to verify the equation (3):

\[ l = 2\Pi \int_0^{\infty} j(r) r \, dr \tag{3} \]

We choose for our study a current intensity equal to 500A. The length of the arc is taken equal to 1.44 cm to obtain a potential difference equal to 49V which is the experimental value. Using a pressure value, the inlet mass flow rate of Ar-H₂ is imposed to 2E-3kg/s. The pressure condition for the injectors is chosen to have a total air mass flow rate equal to 3.4E-3kg/s.
### Boundary conditions

<table>
<thead>
<tr>
<th>Wall/Cover</th>
<th>Pressure $P$</th>
<th>Velocity components $V_i$</th>
<th>Ar-H$_2$ Molar fraction</th>
<th>Temperature $T$</th>
<th>Potential $V$</th>
<th>Potential vector components $A_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall 1</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>300 K</td>
<td>0</td>
<td>$\frac{\partial A_i}{\partial n} = 0$</td>
</tr>
<tr>
<td>Wall 2</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>500 K</td>
<td>0</td>
<td>$\frac{\partial A_i}{\partial n} = 0$</td>
</tr>
<tr>
<td>Wall 3</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>300 K</td>
<td>0</td>
<td>$\frac{\partial A_i}{\partial n} = 0$</td>
</tr>
<tr>
<td>Wall C</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>3500 K</td>
<td>$J(t)$</td>
<td>$\frac{\partial A_i}{\partial n} = 0$</td>
</tr>
<tr>
<td>Inlet 1</td>
<td>1.2 atm</td>
<td>$\frac{\partial V}{\partial n} = 0$</td>
<td>1</td>
<td>300 K</td>
<td>0</td>
<td>$\frac{\partial A_i}{\partial n} = 0$</td>
</tr>
<tr>
<td>Inlet 2</td>
<td>3 atm</td>
<td>$\frac{\partial V}{\partial n} = 0$</td>
<td>0</td>
<td>300 K</td>
<td>0</td>
<td>$\frac{\partial A_i}{\partial n} = 0$</td>
</tr>
<tr>
<td>Inlet 3</td>
<td>3 atm</td>
<td>$\frac{\partial V}{\partial n} = 0$</td>
<td>0</td>
<td>300 K</td>
<td>0</td>
<td>$\frac{\partial A_i}{\partial n} = 0$</td>
</tr>
<tr>
<td>Inlet 4</td>
<td>1 atm</td>
<td>$\frac{\partial V}{\partial n} = 0$</td>
<td>0</td>
<td>300 K</td>
<td>0</td>
<td>$\frac{\partial A_i}{\partial n} = 0$</td>
</tr>
</tbody>
</table>

Table 1: boundary conditions

4 Results

Figure 2: Constant velocity value (100 m/s).
In the cathode and nozzle regions, due to the natural symmetry of the geometry and to the assumption made on the arc attachment, all the fields present a cylindrical symmetry. In figure 2, we show a general result found by the 3D model in the total domain. On the upper part of the picture we can see the cathode and the nozzle. The iso-value 100 m/s of the velocity magnitude is plotted. We can observe the three-dimensional aspect of the problem. The cylindrical symmetry is broken by the injectors, nevertheless the changes are weak on the velocity value near the axis. The maximum of velocity is about 2500 m/s.

In the paper we want to focus on the influence of the injector, so the other results will be presented only for the plasma jet region. Using the operating conditions given above in the paper, the temperature maximum is found near the cathode and is about 28000 K.

Figure n° 3 : Temperature fields at the nozzle exit in the planes Y=0 and X=0.

Figure 3 shows the temperature fields at the nozzle exit for two planes: the plane of the air injectors (X=0 - right side) and the perpendicular one (Y=0 - left side). At the nozzle exit, the temperature is about 16000 K on the axis and presents a cylindrical symmetry. While the pulsed air does not intercept the plasma jet, the symmetry is conserved. Towards 90 mm from the nozzle exit, we can see that the flows air injectors influence the plasma jet. In the plane X=0, the plasma jet is pinched and in the plane Y=0, the plasma jet is flattened.

On the figure 4, we present the Ar-H$_2$ mass fraction for the two previous planes. The black color represents pure Ar-H$_2$ and the white one the air. We can observe that the air penetrates in the plasma jet at 90 mm from the nozzle. The two conjugate effects: the presence of air and the changes on the temperatures can influence the plasma transport properties and so the thermal transfer to the particles.
5 Conclusion

A general 3D model is developed and used to study the influence of the air injector in a spraying process. The 3D model uses the commercial Fluent software previously validated in a simple free burning arc configuration. The results show the great influence of the air injectors on the temperature and mass fraction fields, so on the thermodynamic state of the particle on the subtract depending to their trajectories in the plasma. The air injector have two roles : a pinching effect but also a distortion of the plasma jet. We have also studied the influence of the injector on the velocity magnitude, on the plasma edges. The high velocity could also lead to unsticking effects on the subtract depending to the deposit orientation in regard to the plane of injectors.

References