Modeling of the arc reattachment process in plasma torches

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Abstract. The need to improve plasma spraying processes has motivated the development of computational models capable of describing the arc dynamics inside plasma torches. Although progress has been made in the development of such models, the realistic simulation of the arc reattachment process, a central part of the arc dynamics inside plasma torches, is still an unsolved problem. This study presents a reattachment model capable of mimicking the physical reattachment process as part of a local thermodynamic equilibrium description of the plasma flow. The fluid and electromagnetic equations describing the plasma flow are solved in a fully-coupled approach by a variational multi-scale finite element method, which implicitly accounts for the multi-scale nature of the flow. The effectiveness of our modeling approach is demonstrated by simulations of a commercial plasma spraying torch operating with Ar-He under different operating conditions. The model is able to match the experimentally measured peak frequencies of the voltage signal, arc lengths, and anode spot sizes, but produces voltage drops exceeding those measured. This finding, added to the apparent lack of a well defined cold boundary layer all around the arc, points towards the importance of non-equilibrium effects inside the torch, especially in the anode attachment region.

Keywords: arc reattachment, plasma torch, finite element method, multi-scale, sub-grid scale

1. Introduction

Plasma spraying, one of the most versatile and widely used thermal plasma applications, suffers from occasional limited reproducibility. A major factor for this limited reproducibility is the lack of understanding of the dynamics of the arc inside the spraying torch, the main component of plasma spraying processes. Figure 1 shows a schematic view of the flow inside a direct current (DC), non-transferred arc plasma torch. After the working gas enters the torch, it is heated by an electric arc formed between a nozzle-shaped anode and a conical cathode to form a plasma, which is ejected as a jet. This flow, despite the axi-symmetry and steadiness of the geometry and boundary conditions, is inherently three-dimensional and transient.

Figure 1. Schematic representation of the flow inside a DC arc plasma torch.
The dynamics of the arc inside a DC plasma torch are the result of the imbalance between the drag force caused by the interaction of the incoming gas flow over the arc attachment and the electromagnetic (or Lorentz) force caused by the local curvature of the arc [1-2]. Because the length of the arc is linearly dependent on the voltage drop across the torch, the variation of the voltage drop over time gives an indication of the arc dynamics inside the torch. This voltage drop signal has allowed the identification of three distinct modes of operation of the torch [1-5], namely: Steady, takeover, and restrike. These modes are schematically depicted in figure 2.

![Figure 2. Schematic voltage drop signals for the different modes of operation of an arc plasma torch.](image)

The need to improve plasma spraying processes has motivated the development of computational models capable of describing the arc dynamics inside DC plasma torches. These models need to describe basically two main features of the arc dynamics: the movement of the arc due to the imbalance between flow drag and electromagnetic forces, and the process of formation of a new arc attachment, in what is called the reattachment process. Progress has been achieved in the development of such models [6-11], but no single model capable of describing the different modes of operation of the torch has been developed yet.

There have been basically two approaches to model the dynamics of the arc: Relying on the anode boundary model to account for the dynamics of the arc (i.e. [6-8]) and the use of an arc reattachment model (i.e. [9-11]). The first approach not only allows the movement of the anode attachment along the anode surface, but also the formation of a new attachment when the arc gets close to the anode surface. This approach, commonly used in steady-state simulations of thermal plasmas [12-14], is capable of describing the steady and takeover modes of operation of the torch; but, as shown in Section 6.3, is not adequate for the modeling of the restrike mode. The second approach is capable of describing the restrike mode by mimicking the physical process by which a new arc attachment is formed in a region upstream of the original attachment when the available voltage in the arc is larger than the breakdown voltage [1]. The major challenge of this approach is that it needs to define where and how to apply the reattachment process in order to reproduce the effect of the physical reattachment process on the flow field.

This paper describes the development and implementation of a modeling approach capable of describing the arc dynamics in plasma torches operating in the restrike mode. This approach combines the above techniques for describing the arc dynamics, and has the potential to describe the steady and takeover modes as limiting cases. Section 2 presents the mathematical model based on local thermodynamic equilibrium approximation, Section 3 its numerical implementation by using a variational multi-scale finite element method, and Section 4 describes the computational domain and boundary conditions. The developed reattachment model is described in Section 5, and numerical results of its implementation applied to the realistic modeling of the flow inside a commercial plasma torch, including comparisons with experimental measurements, are shown in Section 6. Conclusions are drawn in Section 7.
2. Mathematical model

2.1. Model assumptions

Our model is based on the following assumptions: 1, the plasma is considered as a compressible fluid composed of a mixture of perfect gases in Local Thermodynamic Equilibrium (LTE), hence characterized by a single temperature for all its constituent species; 2, the quasi-neutrality condition holds; 3, the plasma is optically thin; 4, the chemical composition corresponds to the equilibrium composition of a perfectly-mixed Ar-He (vol. 75-25%) plasma (i.e. demixing effects [15] are neglected); 5, Hall currents, gravitational effects, and viscous dissipation are considered negligible; and 6, the flow is considered laminar in the sense that no turbulence model is included in the mathematical formulation. Nevertheless, the numerical method is potentially capable of modeling turbulent characteristics in what is called a “residual-based large eddy simulation” if adequate spatial resolution is employed. This has not been pursued in the presented work.

2.2. Thermal plasma equations

According to the above assumptions, the flow of a thermal plasma can be fully described by 5 independent variables. In our model, we chose as unknowns the primitive variables: \( p \) pressure, \( \bar{u} \) velocity, \( T \) temperature, \( \phi \) electric potential, and \( \bar{A} \) magnetic vector potential (a total of 9 components in a three-dimensional model). These variables form the vector \( Y \) of primitive variables:

\[
Y = \begin{bmatrix} p & \bar{u} & T & \phi & \bar{A} \end{bmatrix}
\]

where the superscript \( t \) indicates transpose. For a given vector of unknowns \( Y \), the set of equations describing a thermal plasma flow can be expressed in compact form as a system of \( t \)-\( a \)-\( d \)-\( r \) (TADR) equations as:

\[
\mathcal{R}(Y) = \frac{\partial Y}{\partial t} + (A \cdot \nabla)Y - \nabla \cdot (KVY) - (S_1Y + S_0) = 0
\]

where \( \mathcal{R} \) represents the vector of residuals and \( A_0, A, K, S_1, \) and \( S_0 \) are matrices of appropriate sizes (i.e. for \( nv \) variables and \( nd \) spatial dimensions, the matrix \( A \) is of size \( nv \cdot nd \) by \( nv \)). These matrices are fully defined by the specification of the vector of unknowns \( Y \) and a set of 5 independent equations describing the plasma flow. Our model is based on the equations of: 1, conservation of total mass; 2, conservation of mass-averaged momentum; 3, conservation of thermal energy; 4, conservation of electrical current; and 5, the magnetic induction equation. These equations are shown in Table 1 as a set of TADR equations.

In Table 1, \( p \) represents mass density, \( t \) time, \( \mu \) dynamic viscosity, \( \bar{\delta} \) the identity tensor, \( \bar{J}_q \) current density, \( \bar{B} \) magnetic field, \( C_p \) specific heat at constant pressure, \( \kappa \) thermal conductivity, \( h_e \) electron enthalpy, \( \bar{J}_e \) mass diffusion flux of electrons, \( \bar{E} \) electric field, \( \bar{Q}_r \) volumetric radiation losses, \( \bar{W}_p \) pressure work, \( \sigma \) electrical conductivity, and \( \mu_0 \) the permeability of free space.
Table 1. Thermal plasma equations: \( \text{transient} + \text{advective} - \text{diffusive} - \text{reactive} = 0. \)

<table>
<thead>
<tr>
<th>( i )</th>
<th>( Y_i )</th>
<th>Transient</th>
<th>Adveactive</th>
<th>Diffusive</th>
<th>Reactive</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( p )</td>
<td>( \frac{\partial \rho}{\partial t} )</td>
<td>( \nabla \cdot \rho \ddot{u} )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>( \ddot{u} )</td>
<td>( \rho \frac{\partial \ddot{u}}{\partial t} )</td>
<td>( \rho \ddot{u} \cdot \nabla \ddot{u} - \nabla p )</td>
<td>( \nabla \cdot \mu (\nabla \ddot{u} + \nabla \ddot{u}^T - \frac{2}{3} \nabla \cdot \ddot{u} \ddot{u}) )</td>
<td>( \ddot{J}_q \times \ddot{B} )</td>
</tr>
<tr>
<td>3</td>
<td>( T )</td>
<td>( \rho C_p \frac{\partial T}{\partial t} )</td>
<td>( \rho C_p \ddot{u} \cdot \nabla T )</td>
<td>( \nabla \cdot (\kappa \nabla T - h_e \dot{J}_e) )</td>
<td>( \ddot{J}_q \cdot (\ddot{E} + \ddot{u} \times \ddot{B}) - \dot{Q}_r + \dot{W}_p )</td>
</tr>
<tr>
<td>4</td>
<td>( \phi )</td>
<td>0</td>
<td>0</td>
<td>( \nabla \cdot \sigma (\nabla \phi - \ddot{u} \times \nabla \times \ddot{A}) )</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>( \ddot{A} )</td>
<td>( \frac{\partial \ddot{A}}{\partial t} )</td>
<td>( \nabla \phi - \ddot{u} \times \nabla \times \ddot{A} )</td>
<td>( (\mu_0 \sigma)^{-1} \nabla^2 \ddot{A} )</td>
<td>( \ddot{0} )</td>
</tr>
</tbody>
</table>

The transport of the heavy species enthalpy by diffusion is accounted for in the definition of the thermal conductivity as a reactive component, which is added to the translational conductivity (\( \kappa = \kappa_{\text{translational}} + \kappa_{\text{reactive}} \)). The transport of electron enthalpy by diffusion, which can dominate over the Joule heating term near the anode surface, is accounted for explicitly in the energy equation (see Table 1, diffusive column for \( i = 3 \)) and approximated by:

\[
h_e \dot{J}_e = -\frac{\kappa}{2} k_B T \frac{\ddot{J}_q}{e} \tag{3}
\]

where \( k_B \) is Boltzmann’s constant and \( e \) the elementary charge. Volumetric radiation losses, approximated by the use of a net emission coefficient \( \varepsilon \), for pure argon [16], and the pressure work are given by:

\[
\dot{Q}_r = 4\pi \varepsilon_r, \quad \dot{W}_p = -\frac{\partial \ln \rho}{\partial \ln T} \bigg|_p \left( \frac{\partial p}{\partial t} + \ddot{u} \cdot \nabla p \right) \tag{4}
\]

The set of equations in Table 1 is completed by the following electromagnetic expressions relating the electric and magnetic potentials with the electric and magnetic fields and the current density:

\[
\ddot{E} = -\nabla \phi - \frac{\partial \ddot{A}}{\partial t}, \quad \ddot{B} = \nabla \times \ddot{A}, \quad \ddot{J}_q = \sigma (\ddot{E} + \ddot{u} \times \ddot{B}) \tag{5}
\]

and by appropriate thermodynamic and transport properties. These properties are obtained from a computer code developed in our laboratory, which calculates them based on the kinetic equilibrium assumption (minimization of Gibbs free energy) [16].

As mentioned in 2.1, the plasma is considered as a compressible fluid. Compressibility needs to be taken into account because the Mach number inside the torch could vary from nearly zero at the torch inlet to a value as high as 0.7 at the outlet. To account for compressibility, the plasma density needs to be modeled as a function of both, temperature and pressure (not only function of temperature, as commonly used in thermal plasma simulations). In our model, the plasma mass density is calculated by:

\[
\rho = \frac{p}{R_g T} \quad \text{with} \quad R_g = k_B \sum_s \frac{n_s}{n_s m_s} \tag{6}
\]

where \( n_s \) are the number densities of the heavy species and \( m_s \) their molecular masses.
where \( R_g \) is the gas constant, which is proportional to the compressibility factor and due to the reactive nature of the plasma is a strong function of temperature, \( n_s \) and \( m_s \) are the number density and particle mass of species \( s \) respectively, and the summations are for all the species in the plasma. Even though the number densities in (6) are function of both temperature and pressure, they are calculated as function of temperature for a pressure of 1 atm. This is justified by the fact that the ratio of summations in (6) is a weak function of pressure (i.e. varies by less than 30% for a pressure variation from 1 to 10 atm), and thus \( R_g \) can be well approximated as a function of temperature only.

3. Numerical model

3.1. Preliminaries

Our numerical model is based on the solution of equation (2) for any set of independent TADR equations (i.e. the particular form of the matrices \( A_0, A, K, S_1, S_0 \)) and definition of the vector of unknowns (i.e. set of variables composing \( Y \)). Therefore, any other set of independent equations (i.e. conservation of total energy instead of thermal energy) and/or independent variables (i.e. mass density instead of pressure) could be used in our model. Our selection of variables has been strongly motivated by the work of Hauke and Hughes [17] which indicates the superiority of the use of primitive variables over other sets of variables (i.e. conservative, entropy variables). The equations used in our mathematical model are the ones that have been predominantly used in the thermal plasma literature [6-14]. Furthermore, our numerical approach is strongly coupled, in the sense that the solution of the fluid and electromagnetic equations is sought simultaneously, which adds robustness and accuracy to our model.

The numerical solution of general systems of TADR equations represents an enormous challenge when the equations are strongly coupled, highly non-linear, and present multiple scales; as it is the case for the set of equations describing thermal plasma flows. The strongly coupled and non-linear nature of equation (2) is evident from the inspection of the terms in Table 1. The multi-scale nature of this equation arises when a given term dominates over the others in different spatial and/or temporal regions. This imbalance among terms produces strong spatial and/or temporal gradients in the interfaces between regions and the predominance of distinctive flow features in different regions of the domain. A clear example of the multi-scale nature of (2) is flow turbulence, which occurs when the advective part dominates over the diffusive and reactive parts in the bulk flow, whereas the diffusive part dominates in the regions near the boundaries, where vorticity is produced. Other manifestations of the multi-scale nature of equation (2) are shock waves, reaction layers, boundary layers, and plasma sheaths.

3.2. Sub-Grid Scale Finite Element Method

Variational Multi-Scale (VMS) methods have been developed by Hughes and collaborators [18-19] to model multi-scale phenomena in realistic technological applications. The VMS method uses a variational decomposition of a given field into a large scale component (which is described by the computational mesh) plus a small or sub-grid scale component, whose effect into the large scales is modeled. VMS methods are promising for the modeling of complex multi-scale flows in complex domains, as typically found in industrial applications; offering an improved alternative to traditional Large Eddy Simulation techniques [20]. The interested reader is referred to [19] for a recent review of VMS methods.

The algebraic Sub-Grid Scale Finite Element Method (SGS-FEM) is one of the simplest formulations of the VMS approach, in which the large and small scales are approximated with the same computational grid [21]. The SGS-FEM model of the TADR system given by equation (2) is expressed by:
where \( \mathbf{W} = \mathbf{W}(\mathbf{X}) \) is the weight function typical of every finite element method, and \( \mathbf{X} \) the vector of spatial coordinates; \( \Omega \) represents the spatial domain; the Galerkin term represents the part of the problem solved by the mesh (large scale); the sub-grid scale term represents the modeling of the small scales; \( \Omega' \) represents the spatial domain minus the skeleton of the mesh formed by the elements boundaries; \( \mathcal{P} \) is a differential operator applied to \( \mathbf{W} \), and defined as the negative of the adjoint of the differential operator applied to \( \mathbf{Y} \) in equation (2) \((\mathcal{P} = -\mathcal{L}^* \), and \( \mathcal{L} \) is defined from \( \mathcal{R}(\mathbf{Y}) = \mathcal{L}\mathbf{Y} - \mathbf{S}_0 \); and \( \tau \) is the matrix of intrinsic time scales, the model parameter.

The formulation of the problem given by (7) is consistent with equation (2) as the sub-grid scale term becomes negligible as the discretization mesh becomes finer, and hence more “small scales” are resolved by the computational mesh. To add robustness to the formulation in regions with large gradients, a discontinuity-capturing-operator is added to (7) [22]. More details of our implementation of the SGS-FEM applied to thermal plasmas are found in [7].

3.3. Solution approach

Spatial discretization of (7) leads to the formation of a very large system of time-dependent non-linear algebraic equations expressed as:

\[
\mathbf{R}(t_h, \mathbf{X}_h, \mathbf{Y}_h, \dot{\mathbf{Y}}_h) = \mathbf{0} \tag{8}
\]

where \( \mathbf{R} \) represents the global vector of residuals, the subscript \( h \) indicates the discrete counterpart of a given continuous variable, \( \mathbf{X}_h \) the computational domain, \( \mathbf{Y}_h \) the global vector of unknowns, and \( \dot{\mathbf{Y}}_h \) its time derivative.

The time discretization of system (8) allows us to express the vector \( \mathbf{R} \) as function of \( \mathbf{Y}_h \) only. The multi-scale nature of the plasma equations makes equation (8) very stiff, which makes mandatory the use of time-implicit solution algorithms. We discretize (8) using a second-order, fully-implicit, predictor multi-corrector \( \alpha \)-method [23], whose high frequency amplification factor is the sole parameter, together with an automatic time stepping strategy. The generalized \( \alpha \)-method requires the solution of a non-linear system of equations at each time step. The solution of this non-linear system is accomplished by an inexact-Newton method together with a line-search globalization procedure [24-25]. These techniques form an iterative procedure in which the values of an approximate solution and its residual vector at a given iteration \( k \) are updated according to:

\[
\left\| \mathbf{R}^k + \mathbf{J}^k \Delta \mathbf{Y}_h^{k+1} \right\| \leq \gamma^k \left\| \mathbf{R}^k \right\| \quad \text{and} \quad \left\| \Delta \mathbf{Y}_h^{k+1} \right\| \leq \lambda^k \left\| \mathbf{Y}_h^{k+1} \right\| \tag{9}
\]

where the superindex \( k \) indicates the iteration counter, \( \mathbf{J} \) is an approximation of the Jacobian matrix of the global system (8) \((\mathbf{J} = \partial \mathbf{R} / \partial \mathbf{Y}_h \) ), \( \Delta \mathbf{Y}_h \) represents a correction to the actual solution, \( \gamma \) is a parameter controlling the accuracy required for the linear solve in the current iteration, and \( \lambda \) is the line-search parameter. Equation (9) expresses the inexact-Newton condition whereas equation (10) the updating of the solution according to the line-search procedure.

The approximate solution of a linear system required by the inexact Newton condition is accomplished by the Generalized Minimal Residual (GMRES) method with a block-diagonal
preconditioner. The use of an inexact-Newton method together with a GMRES solver greatly improves the computational efficiency (in terms of memory requirements and computational time) of the solution of the non-linear system of equations. The globalization strategy in (9) together with adaptive time stepping has proven mandatory for attaining convergence when the reattachment model to be described in Section 5 is applied.

4. Computational domain and boundary conditions

The geometry studied corresponds to the commercial plasma torch SG-100 from Praxair Surface Technology, Concord, NH. The computational domain is formed by the region inside the torch limited by the cathode, the inflow region, the anode nozzle, and the torch exit (see figure 1) and is shown in figure 3 together with its finite element discretization using hexahedral elements. The mesh is structured in the z-axis and unstructured in the x-y plane, and refined around the solid boundaries; its total number of nodes and elements is 68482 and 65044, respectively. We have run preliminary simulations of the results shown in Section 6 with a coarser grid (similar to the one used in [7], with 41800 nodes) and, although the results with the finer grid are better resolved, the dynamics of the arc are essentially the same.

Figure 3. Computational domain, finite elements mesh, and boundary sides.

<table>
<thead>
<tr>
<th>variable</th>
<th>$p$</th>
<th>$\vec{u}$</th>
<th>$T$</th>
<th>$\phi$</th>
<th>$\vec{A}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side 1</td>
<td>$p = p_{in}$</td>
<td>$\vec{u} = \vec{u}_{in}$</td>
<td>$T = T_{in}$</td>
<td>$\partial_n \phi = 0$</td>
<td>$A_i = 0$</td>
</tr>
<tr>
<td>Inlet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side 2</td>
<td>$\partial_n p = 0$</td>
<td>$u_i = 0$</td>
<td>$T = T_{cath}$</td>
<td>$\partial_n \phi = 0$</td>
<td>$\partial_n A_i = 0$</td>
</tr>
<tr>
<td>cathode</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side 3</td>
<td>$\partial_n p = 0$</td>
<td>$u_i = 0$</td>
<td>$T = T_{cath}$</td>
<td>$- \sigma \partial_n T = J_{cath}$</td>
<td>$\partial_n A_i = 0$</td>
</tr>
<tr>
<td>cathode tip</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side 4</td>
<td>$\partial_n p = 0$</td>
<td>$\partial_n u_i = 0$</td>
<td>$\partial_n T = 0$</td>
<td>$\partial_n \phi = 0$</td>
<td>$\partial_n A_i = 0$</td>
</tr>
<tr>
<td>outlet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side 5</td>
<td>$\partial_n p = 0$</td>
<td>$u_i = 0$</td>
<td>$- \kappa \partial_n T = h_w (T - T_w)$</td>
<td>$\phi = 0$</td>
<td>$\partial_n A_i = 0$</td>
</tr>
<tr>
<td>anode</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$a$ $\partial_n = \partial / \partial n$ differentiation in the direction of the (outer-) normal to the boundary.

$b$ $i = x, y, z$ Cartesian coordinates defined in figure 3.
Figure 3 shows that the boundary of the computational domain is divided into 5 different *sides* to allow the specification of boundary conditions. Table 2 shows the boundary conditions used in the simulations, where $p_{in}$ represents the inlet pressure equal to 111.325 kPa (10 kPa overpressure), $\bar{u}_{in}$ the imposed velocity profile equal to the profile of a fully developed laminar flow through an annulus, $T_{in}$ the inlet temperature equal to 500 K, $T_{cath}$ the cathode temperature which is approximated by a Gaussian profile along the $z$ axis varying from 500 K at the inlet to 3000 K at the cathode tip, $h_c$ the convective heat transfer coefficient at the anode wall equal to $10^5$ W-m$^{-2}$-K$^{-1}$ [9], $T_e$ a reference cooling water temperature of 500 K, and $J_{cath}$ the imposed current density over the cathode defined by:

$$J_{cath} = J_{cath0} \exp(-r/R_c)^n_c$$

(11)

where $r$ is the radial distance from the torch axis ($r^2 = x^2 + y^2$), and $J_{cath0}$, $R_c$, and $n_c$ are parameters that specify the shape of the current density profile. Typically, $J_{cath0}$ and $n_c$ are chosen to mimic experimental measurements [26], whereas $R_c$ is calculated to ensure that integration of $J_{cath}$ over the cathode tip equals the total applied current. As an example, for a specified current of 800 A, $J_{cath0} = 3.0 \times 10^3$ A-m$^{-2}$, $n_c = 4$, and $R_c = 0.913$ mm.

Due to the thermal equilibrium assumption, the value of the electron temperature is equal to the heavy particle temperature, which is low near the electrodes, especially near the anode surface (i.e. less than 3000 K). Hence the equilibrium electrical conductivity, being mostly a function of the electron temperature, is extremely low (less than 0.01 S/m), which limits the flow of electrical current through the electrodes. To alleviate this, an alternative used in [9-11] is to let the temperature remain high enough (i.e. above 7000 K) at the electrodes. The clear advantage of this approach is that it is consistent with the LTE assumption in the sense that the heavy particle temperature remains equal to the electron temperature, which remains high all the way up to the electrodes. Unfortunately, this approach not only requires unrealistically high heavy particle temperatures at the anode, but also produces anode attachment spots an order of magnitude larger than what has been observed experimentally [9].

A common technique to avoid the above problems consists of specifying an artificially high electrical conductivity in the region immediately adjacent to the electrodes [6-8, 12-14]. The value of this “artificial” electrical conductivity used in the literature is somewhat arbitrary. The only requirement for its value is that it needs to be high enough in order to ensure the flow of electrical current from the plasma to the anode. Typically it has been defined as the harmonic mean between the plasma electrical conductivity and that of the anode material [13] or as the electrical conductivity of the plasma at a given electron temperature (i.e. 15000 K) [7]. This latter approach has been used in the results shown in Section 6. Our experience indicates that a value greater or equal than the value of the plasma electrical conductivity for a temperature of ~12000 K allows smooth current continuity. Higher values, even values of the order of the conductivity of copper, do not affect perceptively the results, except for a slight decrease in the size of the anode spot. Lower values do not allow enough current continuity and makes the numerical solution diverge.

5. Modeling of arc reattachment processes

5.1. Arc reattachment in steady and takeover modes

The high electrical conductivity technique described above allows not only the continuity of the electrical flow between plasma and electrodes, but also the free movement of the arc attachment along the anode surface and the formation of a new arc attachment if some part of the arc gets “close enough” to the anode surface. In this type of reattachment process the required proximity of the arc is given by the thickness of the region in front of the anode specified with high electrical conductivity.
As typically this thickness is very small (i.e. less than 0.1 mm [7, 13]), the dynamics of the arc are not greatly affected by its specific value; the difference between the locations of the attachment for two different values of this thickness being in the order of the difference between the thicknesses used (and therefore typically less than 0.1 mm). This type of arc reattachment does not depend perceptively on the specific value of \( \sigma \) in front of the electrodes; as far as this value allows smooth current continuity.

From the numerical results to be shown in Section 6.3, this approach works well for modeling the dynamics of the arc in a plasma torch operating in steady or takeover mode (as shown in [7-8]), but it is not adequate for simulating the restrike mode of operation, as it leads to solutions displaying exceedingly long arcs and high voltage drops.

5.2. Arc reattachment in restrike mode

In the restrike mode, flow drag forces dominate over electromagnetic forces, causing the arc to be dragged downstream; the arc is very constricted and a thick cold boundary layer can be observed around the arc. At the same time as the arc moves downstream, its length increases and so does the total voltage drop and the magnitude of the electrical field around the arc. If the available voltage across the arc exceeds the local breakdown voltage, a new arc attachment forms somewhere upstream of the original attachment [1, 2]. Even though the exact mechanisms driving the reattachment process are not known, the relatively high electric fields, added to the abundance of excited species around the arc (i.e. due to UV excitation), and the short time scale of the process, suggests that the arc reattachment is initiated by a streamer-like breakdown. This streamer connects the arc with the anode in a region somewhere upstream of the existing arc attachment, creating a conducting channel that allows the establishment of a new arc attachment. The detailed modeling of this process is unfeasible with actual computational methods and computer power, especially when the reattachment process is part of the modeling of a realistic plasma application. Therefore, approximate models are needed which imitate the effects of the reattachment process within the flow field of a given plasma application.

![Figure 4](image_url)

**Figure 4.** Arc reattachment model: A, arc deflected by incoming flow and location where the breakdown condition is satisfied; B, insertion of an electrically conductive channel; C, formation of a new attachment; D, predominance of the new attachment over the old one.

To mimic the physical reattachment process, a model mainly faces the questions of *where* and *how* to introduce the new attachment. *Where* to locate the new attachment translates into the definition of
an adequate breakdown condition, whereas how to introduce the reattachment translates into the definition of adequate modifications of the flow field in order to mimic the formation of an attachment.

Probably the most advanced reattachment model to date is the one developed by Moreau et al [11]. Their model solves the above questions by: 1) using as breakdown criterion the comparison between the voltage drop between the isosurface of 7000 K around the arc and the anode and a pre-specified critical electric field above which a breakdown occurs; and 2) imposing a 8000 K column that connects the arc and the anode at the location where the maximum in 1) is located. A limitation of this model is that the imposition of a high temperature channel connecting the arc and the anode violates global energy conservation, because the amount of energy contained in the channel is added instantaneously to the flow. In this paper we develop a reattachment model that tries to circumvent this limitation. This model is illustrated in figure 4.

Depicted in figure 4-A is the dragging of the arc by the flow field, which causes the local electric field around the arc to increase. The breakdown condition is satisfied when, at a location $x_b$, the maximum of the magnitude of the local electric field in the direction normal to the anode $E_{n,max}$ exceeds the pre-specified breakdown electric field $E_b (E_{n,max} > E_b)$, with:

$$E_{n,max} = \max(\| \vec{E}_n \|), \quad \vec{E}_n = \vec{E} \cdot \vec{n}_a,$$

and $\vec{n}_a$ as the normal to the anode. Centered on $x_b$, a cylindrical channel with radius $R_b$ and connecting the anode surface and the arc in the direction parallel to $\vec{n}_a$ is introduced (figure 4-B). Within this breakdown channel, the value of the electrical conductivity is modified according to:

$$\sigma \leftarrow \max(\sigma, \sigma_b)$$  \hspace{1cm} (13)

Where the $\sigma$ inside the parenthesis is the equilibrium electrical conductivity of the plasma, and $\sigma_b$ is an electrical conductivity that characterizes the breakdown process, which is assumed to be of the form:

$$\sigma_b = \sigma_{b0} \exp(-\beta_b (r_b/R_b)^{n_b})$$  \hspace{1cm} (14)

where $r_b$ is the radial coordinate having as origin the axis of the cylindrical conducting channel (see figure 5). The conducting channel stimulates the growth of a plasma column (figure 4-C), which by reaching the anode surface forms a new attachment that remains over the old attachment, which dies out (figure 4-D). The shape of the $\sigma_b(r_b)$ profile in (14) is defined by the parameters $R_b$, $\beta_b$, and $n_b$. Values used in our simulations are $R_b = 1.25$ mm, $\beta_b = 6$, $n_b = 4$, and $\sigma_{b0} = 10^4$ S/m. The cylindrical channel with $\sigma_b$ is maintained until the maximum electric field within the domain decreases to a value below 0.8$E_b$. The reattachment model is mainly driven by the specification of $E_b$; the parameters defining $\sigma_b$ only control the form of the reattachment process (i.e. $\sigma_{b0}$ controls the speed of the reattachment process, whereas $R_b$ the width of the reattachment column). Moreover, if the physical reattachment process is indeed triggered by the value of the local electric field exceeding a certain “breakdown” voltage (the $E_b$ used in our model), it is reasonable to expect that the value of this breakdown voltage will be a function of the gas composition, and probably only a weak function of the torch characteristics and operating conditions (i.e. nozzle diameter, mass flow rate, total current).
Figure 5. Distribution of the electrical conductivity $\sigma_b$ inside the cylindrical channel connecting the arc and the anode.

The use of $\sigma_b$ to drive the formation of a new attachment modifies the energy equation only weakly, because the Joule heating term will be artificially high only in the region where $E$ is large (i.e. around $\bar{x}_b$). Application of the reattachment model simultaneously with the satisfaction of energy conservation requires a rapid accommodation of energy throughout the domain. This causes severe difficulties for attaining convergence when the reattachment model is just applied. In this regard, utilization of the globalization procedure within the inexact-Newton method (equation 9) and an adaptive time stepping procedure have been mandatory for obtaining the results shown in Section 6.

The reattachment above described is complemented with the use of a high electrical conductivity in the region of thickness $\sim 0.08$ mm in front of the anode surface, as described in Section 5.1. This reattachment model can be applied to general geometries and flow configurations since its only requirement is that the normal to the anode surface needs to be well defined (i.e. it is not suitable for anode surfaces with sharp corners or discontinuities).

Because of the free parameter $E_b$, the described reattachment model cannot predict the operating mode of the torch. The model can only predict the arc dynamics inside a torch operating under given operating conditions and a given value of $E_b$. If the model is used to simulate a torch operating under conditions leading to a takeover mode, a high enough value of $E_b$ should be used in order to ensure that a restrike-like reattachment does not occur. Otherwise, the voltage signal obtained could resemble that of the restrike mode.

6. Modeling results

6.1. Simulation conditions

In this section we present results of our model applied to the simulation of a typical DC arc plasma torch (figure 3) for the cases shown in Table 3. Cases A and B allow the comparison of the arc dynamics with and without reattachment model. The operating conditions of cases C and D are typical of plasma spraying processes, and the different values of $E_b$ permit observing the dominant effect of $E_b$ on controlling the arc dynamics. Case E allows seeing the change of the arc dynamics as the torch operates closer to the takeover mode (see Section 1 and figure 2). In all cases, a value of electrical conductivity equal to $10^4$ S/m has been specified in the region of thickness $\sim 0.08$ mm immediately in front of the electrodes (according to Section 5.1). In all the simulated cases the time step varied adaptively between 0.1 and 1.2 $\mu$s. Comparisons of our modeling results with experimental measurements are presented in Section 6.4.
### Table 3. Cases simulated.

<table>
<thead>
<tr>
<th>Case</th>
<th>Gas</th>
<th>Current [A]</th>
<th>Flow rate [slpm]</th>
<th>Injection</th>
<th>$E_b$ [V/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Ar-He (75-25%)</td>
<td>800</td>
<td>60</td>
<td>straight</td>
<td>$\infty^*$</td>
</tr>
<tr>
<td>B</td>
<td>Ar-He (75-25%)</td>
<td>800</td>
<td>60</td>
<td>straight</td>
<td>$5 \times 10^4$</td>
</tr>
<tr>
<td>C</td>
<td>Ar-He (75-25%)</td>
<td>800</td>
<td>60</td>
<td>$45^\circ$ swirl</td>
<td>$5 \times 10^4$</td>
</tr>
<tr>
<td>D</td>
<td>Ar-He (75-25%)</td>
<td>800</td>
<td>60</td>
<td>$45^\circ$ swirl</td>
<td>$2 \times 10^4$</td>
</tr>
<tr>
<td>E</td>
<td>Ar-He (75-25%)</td>
<td>800</td>
<td>30</td>
<td>$45^\circ$ swirl</td>
<td>$5 \times 10^4$</td>
</tr>
</tbody>
</table>

* no reattachment model.

6.2. Flow fields inside an arc plasma torch

The instantaneous temperature distribution inside the torch for case B is presented in figure 6. It can be observed the marked three-dimensionality of the flow, the formation of a cold flow boundary layer around the plasma (6-2 and 6-3), and the extent of the anode attachment, whose maximum temperature is around 1400 K (6-4). The location and size of the anode spot shown in figure 6-4 is consistent with experimental observations [27], and numerical simulations [13, 27]. As explained in Section 5, the lack of a reattachment model produces excessively long arcs, and hence simulations without a reattachment model produce anode spots further downstream than the one shown in figure 6-4. The excessive lengthening of the arc in the absence of a reattachment model will be shown in the following section.

**Figure 6.** Instantaneous temperature distribution inside a DC arc plasma torch: (1) through a vertical plane, (2) horizontal plane, (3) at different axial cross sections, and (4) over the anode surface, where the location of the anode spot is circled.

Figure 7 shows the distributions of electric potential and electric field normal to the anode surface at the same time instant of the results in figure 6. Due to the cylindrical shape of the anode, the normal to the anode surface is approximated in the whole domain by the radial coordinate, therefore $E_r \sim E_n$. This approximation reduces the computational time of the simulations considerably. It can be observed
that the electric field is negligible within the arc and it is largest in the arc fringes. The arrow indicates the location of the maximum electric field $E_{n,max}$. If this location satisfies the condition $E_{n,max} > E_b$, then it will correspond to the value of $\bar{x}_b$ described in Section 5.2, and subsequently the reattachment model would be applied. It can also be noticed that the location of the anode attachment (at $z \sim 12$ mm in the top part of the anode surface, see figure 6-4) can hardly be deduced from the distribution of electric potential, whereas it can be clearly observed in the distribution of the radial electric field.

Figure 7. Distribution of electric potential and radial electric field (which approximates the electric field in the direction normal to the anode surface) inside the torch at the same time instant of figure 6. The arrow indicates the location of the maximum electric field ($E_{n,max}$).

6.3. Arc reattachment processes

The time evolution of the temperature distribution and total voltage drop during the formation of a new arc attachment when straight gas injection is used are shown in figure 8 for $E_b = \infty$ and in figure 9 for $E_b = 5 \cdot 10^4$ V/m (cases A and B). Figure 8 shows that, at the same time as the arc is dragged downstream, the voltage drop increases (from 1 to 2). The expansion of the plasma downstream added to the effect of the anode jet causes the plasma to get in contact with the anode surface at a location opposite to the original attachment (frame 2). This new connection between the plasma and the anode surface causes a sudden increase in the local temperature, creating a new arc attachment. It can be observed in frames 2, 3, and 4 that two arc attachments coexist, but as the new one is closer to the cathode (and hence has a lower voltage drop, which makes it more thermodynamically favorable) remains over the old attachment, which is dragged away by the flow. Furthermore, frame 3 shows that the newly formed attachment, having an increased curvature and correspondingly a larger electromagnetic force, strongly opposes the flow drag and causes a slight movement of the anode attachment upstream. Frames 5 to 7 show the dragging of the new attachment accompanied by an almost proportional increase in the total voltage drop. The formation of a new attachment at the opposite side of the original one has been observed experimentally in [3] and numerically in simulations of the takeover mode in [7].

The form of the voltage drop signal in figure 8 resembles the voltage signal of the takeover mode of operation of the torch (see figure 2). Unfortunately, the arc length and voltage drop are larger than what is measured experimentally. It seems clear that the described arc reattachment process can be used only to simulate the steady and takeover modes (as done in [7-8]), but not the restrike mode. For the restrike mode, a mechanism that limits the length of the arc is needed. This is accomplished by the use of a reattachment model.
Modeling of the arc reattachment process in plasma torches

Figure 8. Arc reattachment process inside plasma torch for case A (no reattachment model): time sequence of temperature distribution inside the torch and evolution of the voltage drop across the torch.

Figure 9. Arc reattachment process inside plasma torch for case B (with reattachment model): time sequence of temperature distribution inside the torch and evolution of the voltage drop across the torch.

Figure 9 shows the effect of applying the reattachment model in the simulation of the flow inside a plasma torch. When the local electric field is below the pre-specified value of $E_b$, the arc is dragged by the flow, and its length and the total voltage drop increase almost linearly (from 1 to 2). As soon as the breakdown condition is met ($E_{\text{an,max}} > E_b$), the reattachment model described in Section 5.2 is applied automatically. Frame 2 shows the growing of a high temperature appendage in the direction towards the anode, mimicking the formation of a new attachment. This arc reattachment process is in qualitative agreement with experimental observations [1-2]. In frame 3, the new attachment forms, and as seen by the voltage drop between 3 and 4, it rapidly overcomes the old attachment, which is dragged away by the flow. Frames 5 to 7 show the dragging of the new attachment accompanied by a proportional increase of the total voltage drop.
The rapid decrease of voltage drop from 3 to 4 resembles the restrike mode of operation (figure 2). Furthermore, it can be observed that the total voltage drop in figure 9 is lower than in figure 8, and that the voltage signal is sharper in figure 9 than in figure 8. This suggests that, by tuning the value of $E_b$, the principal parameter in the reattachment model, one could be able to match the voltage signal obtained experimentally. This point is discussed in the following section.

Through the conducting channel, temperature and pressure increase very rapidly, causing a radial expansion of the neutral gas, in resemblance to the streamer breakdown processes studied by Marode and collaborators [28]. This sudden gas expansion is observed in figure 10, which shows the velocity distribution in the region where the reattachment model is applied. It can be seen that there is a net flow from the inside of the reattachment column outwards. This is a consequence of at least two effects: The gas expansion due to the rapid heating of the reattachment column, and the formation of an anode jet due to the local constriction of the current path near the new attachment spot. Furthermore, it can be observed that, due to the cathode jet, the flow from the reattachment column is deflected as it approaches the cathode tip.

![Figure 10. Velocity distribution in the region near the reattachment column at the time instant shown in figure 9-2. The new attachment is forming at $z \sim 2$ mm, whereas the old attachment is located at $z \sim 12$ mm.](image)

The problems attaining convergence when the reattachment model is applied (due to the sudden gas expansion and rapid energy accommodation throughout the domain) are to be expected if conservation (of mass/momentum/energy) is enforced within consecutive time steps. Our code, being fully implicit and fully coupled, enforces global conservation in each time step as well as within steps, which made mandatory the use of the globalization technique and adaptive time stepping described in 3.3 in order to attain convergence. These techniques may not be needed if a semi-implicit code is used, because global conservation within consecutive time steps is usually not enforced in such a code.

The time evolution of the temperature isosurface of 14000 K (which resembles the shape of the arc) and the voltage distribution over it during the formation of a new arc attachment for case C are shown in figure 11. The formation of the new attachment occurs in a similar manner as in figure 9; the clear difference being that due to the swirl, the reattachment process is no longer confined to a single plane (plane $y$-$z$ in figures 8 and 9). The swirl causes the arc to remain more centered on the torch axis than when straight injection is used. Furthermore, the stabilizing effect of the swirl causes the arc to be longer than when straight injection is used. The growing of the high temperature appendage from the column towards the anode resembles the high speed camera pictures reported in [1-2].
Modeling of the arc reattachment process in plasma torches

Figure 11. Arc reattachment process inside a DC plasma torch for case C: Electric potential distribution over the 14 kK isosurface at $t = (1) 360, (2) 362, (3) 364, \text{ and (4) } 368 \mu$s. The arrows indicate the locations of the arc attachments; O refers to the old attachment and N to the new one.

6.4. Comparison with experimental measurements

Figure 12 shows the voltage drop signals and their power spectra for the torch operating with swirl injection obtained experimentally, and numerically for cases C and D. (The operating conditions of the experiments are the same as for cases C and D.) The peak frequency $f_p$ in the spectra of the results from the simulation using the reattachment model with $E_b = 5 \times 10^4$ V/m is in good agreement with the experimentally measured ($f_p \sim 3.2$ kHz numerically and $\sim 3.3$ kHz experimentally). But, the magnitude of the voltage drop clearly exceeds the experimental results. Furthermore, the lack of adequate modeling of the plasma sheaths needs to be considered, which makes the obtained voltage drops differ even more from those measured. Reducing the breakdown voltage to $2 \times 10^4$ V/m causes the length of the arc and consequently, the voltage drop, to decrease significantly; but at the same time the peak frequency increases considerably ($f_p \sim 9$ kHz). From this result it seems clear that the tuning of the parameter $E_b$ allows the matching of either the peak frequency or the magnitude of the voltage drop, but not both simultaneously. By tuning the critical field (the model parameter), Moreau’s et al model [11] is able to match approximately the voltage drop and peak frequency, but at the expense of producing an anode spot an order of magnitude larger than what is observed experimentally.
Modeling of the arc reattachment process in plasma torches

The effect of changing the flow rate is appreciated in figure 13, where it can be seen that decreasing the flow rate causes the voltage drop signal to resemble the takeover mode of operation (a smoother and less chaotic signal). As the flow rate decreases from 60 to 30 slpm, the peak frequency increases from 3.23 to 4.29 kHz. Case E shows lower minimum voltages due to a shorter arc. There is no appreciable difference between the maximum lengths of the arc for cases C and E.

The fact that our reattachment model with $E_b = 5 \cdot 10^4$ V/m is able to reproduce the experimentally observed peak frequency, arc length, and size of the anode spot, but not the total voltage drop, indicates that the total resistance of the arc to the current flow is larger in our model than what the experiments suggest. This fact is a clear indication of the limitation of using a LTE model to describe the dynamics of the plasma flow inside DC plasma torches.

The greater electrical resistance of a LTE model, given that the length and width of the arc agree with experimental observations (approximated by the location and size of the anode spot), can be explained by a low electrical conductivity in the arc fringes, especially through the anode attachment. Because $\sigma$ is mostly a function of the electron temperature and generally increases with the degree of thermal non-equilibrium $\theta$ ($\theta = T_e/T_h$, with $T_e$ as the electron temperature and $T_h$ as the heavy particle temperature), it can be deduced that the anode attachment may be characterized by a wider region with high $T_e$ (and hence high $\theta$) than the region currently described by the LTE model ($T = T_e = T_h$). The above argument is also suggested by the comparison of end-on images of the torch with the temperature distribution through different cross sections from our simulation results, as presented in figure 14. The experimental end-on image can be considered typical of similar studies, i.e [29].
Modeling of the arc reattachment process in plasma torches

**Figure 14.** End-on image of the arc inside a DC torch [3] (left) and numerical temperature distribution at different axial locations for case C (right). The arrow indicates the location of the anode attachment. In the numerical results the anode attachment is located at $z \sim 13$ mm (~13 mm from the cathode tip).

It is evident in figure 14 that the numerical results do not display a well defined cold boundary layer all around the arc, as observed in the end-on image. The high temperature of the anode attachment in a LTE model is needed to allow the electrical current flow from the anode to the plasma. A thermal non-equilibrium model (a model that considers $T_e \neq T_h$) should be able to match experimental observations more accurately, by displaying a $T_h$ distribution resembling the end-on image and a $T_e$ distribution resembling the numerical temperature profiles in figure 14. To the best knowledge of the authors, a non-equilibrium model adequate for the simulation of the arc dynamics inside DC arc plasma torches has not been reported in the literature yet.

**Figure 15.** Instantaneous (Inst.) and time-averaged over four reattachment periods (Ave.) velocity, temperature, and mass flow rate per unit area profiles at the torch outlet. The instantaneous profiles correspond to the same instant of the numerical results shown in figure 14.

Figure 14 also shows the elliptical shape of the cross section of the arc column, with the main axis of the ellipse along the direction of the anode attachment (dashed line). This shape of the arc cross section is caused in part by the effect of the anode jet and by the balance of forces over the arc [1-2], and is more pronounced when straight injection is used, as observed in [7]. The elongated shape of the arc shown in the numerical results of figure 14 is not observed in the outlet temperature profile. The
continuous expansion of the arc along the torch axis causes the cross section of the arc to change from being elongated to being more axi-symmetrical, as can be observed in figure 15. Furthermore, figure 15 shows a clear correlation between the temperature and the velocity distribution at the outlet. This correlation has been observed experimentally [3-5]. The distribution of the mass flow per unit area indicates that most of the flow exits the torch through the “cold” boundary layer. It is evident the complexity of the instantaneous outlet profiles, indicating that the observed complex nature of plasma jet is in a significant part due to the forcing caused by the arc dynamics; this complexity is not observed in the time-averaged profiles (figure 15-Ave). The time-averaged profiles are not completely axi-symmetric because of the limited amount of time used in the averaging process (~ 4 reattachment periods), and indicate that the reattachment process has taken place mostly in the direction of the dashed line in figure 14. The large computational cost of the simulations presented makes our ability to study the long-term behavior of the torch very limited. The time-averaged profiles along the x and y axes are shown in figure 16. These results are consistent with the measurements reported in [30] for the same operating conditions used here, but using a nozzle of 5.5 mm diameter, where temperatures of ~15000 K are reported; and with results from [31] for the same torch used here operating with Ar, 450 A, and 23.6 slpm, that show temperatures of ~12000 K; and with the numerical results in [10] for a different torch of 7 mm diameter operating with Ar-H2, 600 A, and 60 slpm, which show temperatures of ~13000 K and maximum velocities of ~2200 m/s.

Figure 16. Time-averaged velocity, temperature, and mass flow per unit area at the torch outlet.

7. Conclusions

The reattachment process is a central part of the arc dynamics in plasma torches. The detailed modeling of this process is unfeasible with actual computational methods and computer power, especially when it is required as a part of the realistic modeling of the plasma flow in an industrial application. Therefore, approximate models that mimic the effect of the reattachment process in the arc dynamics are needed. To mimic the physical reattachment process, a model faces the questions of 1, where and 2, how to introduce the new attachment. In this paper we presented a reattachment model that answers these questions by: 1, forming a new attachment at the location where the local electric field exceeds a certain pre-specified value, and 2, introducing there a high electrical conductivity channel between the arc and the anode. This model has been incorporated into a three-dimensional and transient description of the plasma flow based on the LTE assumption, and implemented numerically in a fully-coupled approach using a variational multi-scale finite element formulation, which implicitly accounts for the multi-scale nature of the flow.

Simulations of the flow inside a commercial plasma spray torch show the effectiveness of our modeling approach. By tuning the breakdown electric field $E_b$, the main parameter of our model, the calculated peak frequencies of the voltage signal, arc lengths, and anode spot sizes agree reasonably well with experimental observations, while the total voltage drops exceed those measured. It is observed that the reattachment model can be tuned to match either the experimentally measured peak frequency or the total voltage drop, but not both simultaneously. This finding, added to the apparent
lack of a well defined cold boundary layer all around the arc, points towards the importance of thermal non-equilibrium effects inside the torch, particularly in the anode attachment region, and therefore shows clear evidence of the limitations of the LTE assumption to describe the plasma flow inside plasma torches.

It is foreseen that a non-equilibrium model will provide better agreement with experimental measurements over a LTE model. But, because a thermal non-equilibrium model will still not be able to describe the restrike mode of operation of the torch (unless detailed excitation mechanisms, charge accumulation, etc. are taken into account), a reattachment model will still be needed. A non-equilibrium model complemented with a reattachment model should be able to simulate the different modes of operation of the torch, and approximately match the measured peak frequency, voltage drop, arc length, and anode spot size, while displaying a cold flow boundary layer all around the arc. A promising alternative to realistically model the reattachment process as part of the simulation of the arc dynamics inside the torch is the combination of a thermal and non-thermal plasma model similar to the one developed by Papadakis et al [32], but suitable for the modeling of atmospheric pressure discharges. But still, the limited understanding of the physics driving the reattachment process will limit the development of such a model.

Our future work includes the development of a non-equilibrium model adequate for the simulation of the arc dynamics in plasma torches and devising a better criterion for identifying the breakdown (i.e. a criterion based on the local electric field and the local electron temperature).

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References

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[27] Sun X and Heberlein J 2004 *J Thermal Spray Tech* 14(1) 39-44
[31] Pfender E, Chen W L T and Spores R 1990 *Proceedings of the Third National Thermal Spray Conference (Long Beach, CA, USA)* 20-25 May