A 2D Model of a Plasma Torch

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Abstract: Plasma torches are used in processing of materials and in energy industry for producing plasma. In this work we use the Equilibrium Discharge interface of COMSOL Multiphysics® 5.1 to model a 2D DC non- transferred arc plasma torch, under hypothesis of local thermodynamic equilibrium. The steady state equations of conservation of fluid mechanics, heat transfer and electromagnetics are implemented by using the multiphysics couplings options available in the software. The plasma is considered optically thin and a net emission coefficient is used for the heat transferred by radiation mechanisms. A laminar flow, with a free vortex at the inlet, has been simulated for an axisymmetric plasma torch with argon as working gas. Furthermore, a parametric study of the heat source term of the energy equation has been carried out in order to improve the convergence of the computational model. The numerical results of temperature and velocity patterns in the plasma torch compare well with results of other works carried out under similar assumptions.

Keywords: plasma torch, LTE, multiphysics, magneto-hydrodynamics equations.

1. Introduction

Plasma torches are used in processing of materials and in energy industry for producing plasma [1]. Direct currents (DC) arc plasma torches represent the primary components of thermal plasma processes (plasma spraying, metal welding and cutting, waste treatment, biogas production, etc.). In a non-transferred arc plasma torch, an electric arc can be glowed by applying a direct current (DC) between the cathode and anode, both placed inside the torch. Then, the plasma is obtained by heating, ionizing and expanding a working gas, introduced into the chamber of the torch upstream of the cathode. Due to the cooling of the anode, the gas close to the anode surface is cold, electrically no conductive, constricting the plasma.

Experimental works carried out by observation and measurements techniques are difficult to apply owing to the specific properties of these physical processes. Hence, the computational techniques could represent a useful tool to investigate the plasma processing, although the computational work is extremely challenging, because the phenomena are not independent among them and are simultaneous.

The modeling of a DC plasma torch has to take into account many mechanisms. The plasma is constituted by different species (molecules, atoms, ions and electrons) and several coupled phenomena, due to the interaction between electric, magnetic, thermal and fluid flow fields, characterize the highly nonlinear plasma flow. The presence of strong gradients and chemical and thermodynamic nonequilibrium effects make the modelling work very complex. Trelles et *al.* [2] (prof. Heberlein´s group) presented the fundamentals of arc plasma modelling and reviewed the mechanisms of the main aspects involved, such as turbulent and radiative transport, thermodynamic and transport properties, boundary conditions and reattachment models.

Under hypothesis of local thermodynamic equilibrium (LTE), the electrons and heavy particles temperatures are approximately equal and the plasma can be modeled by using the magneto-hydrodynamics (MHD) equations. However, the LTE approximation is not valid near the plasma boundaries, where the plasma may interact with refrigerated solid walls or cold gas streams. Since the plasma properties strongly depend on the temperature, an important deviation from the true plasma behavior is obtained when the electron temperature is restricted to be equal to the low heavy species temperature [2]. For instance, a peculiar aspect is the low plasma electric conductivity σ for temperatures T below a critical value (for argon gas $\sigma \leq 1$ S/m if $T < 4600$ K). As a consequence, near the cooled anode wall of the torch, the electric current is not guaranteed by using LTE. To overcome the problem, different methods have used artificial values of σ [2, 3] near the anode walls. This approach might also be required when the task is to predict the arc-root attachment position on the anode and the arc shape [3], as well as arc reattachments in transient studies [2]. Selvan et *al.* [4] applied instead the minimum entropy production for determining the real size of arc radius and arc length.

To reduce the complexity of the modeling work relating the highly coupled plasma flow, stationary two and three dimensional models have been developed by many authors. However, from the physical point of view, this approach is not strictly correct, because the dynamic operating modes of the arc inside the torch (takeover and restrike modes) could not be simulated. Only the steady operation mode, which leads to a rapid erosion of the anode torch in proximity of the arc spot, can be represented and computed. Furthermore, in an axisymmetric two dimensional model, the arc spot is represented by a circumferentially uniform arc attachment, in some cases giving unrealistic behavior of the plasma [3]. Using a commercial software, Deng et *al.* [5] have proposed a MHD model to simulate the electromagnetic field, heat transfer and fluid flow in a DC torch under laminar and turbulent conditions. By including the cathode and anode in their calculation domain, they used a fluid-solid coupled method to guarantee the continuity of the electric current and heat transfer at the interface plasma-electrodes. The circumferentially arc root attachment is automatically calculated as the position of the maximum value of the currents density at the internal surface of the anode. Mendoza et *al*. [6] modeled a DC thermal plasma torch using the same MHD equations of Deng et *al*. [5] but in a three dimensional domain. By developing a parametric study of the inlet velocity in the torch, they were able to simulate the arc root attachment and showed how the increasing injection rate shifted downstream the arc attachment on the anode wall.

Starting from the work of Deng et *al*. and continuing a previous our work [7], we have developed in COMSOL Multiphysics® 5.1 a steady state two-dimensional model of a DC non-transferred arc plasma torch, under hypothesis of LTE. The modeling work is given in the next sections of the paper and is structured in the following way. The description of the physical and mathematical model is given in Section 2, while Section 3 deals with the use of Comsol Multiphysics®. Finally, the computational results are presented in Section 4 and the conclusions in Section 5.

2. Model description and equations

2.1 Physical model

By applying axisymmetric conditions, the DC plasma torch is modeled as a 2D region (Fig. 1).

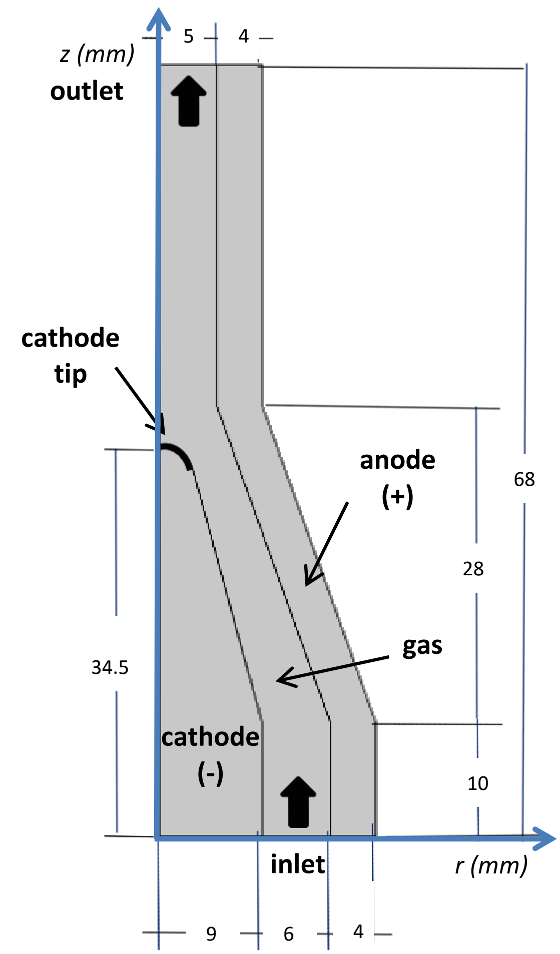

Figure 1. Schematic of a 2D DC plasma torch.

The plasma flow is studied by using the magnetohydrodynamics equations in the system of cylindrical coordinates *r*,*z*, of Fig 1. Gravity forces are not considered and by assuming conditions of LTE, the electrons and heavy particles temperatures are equal. Argon is the working gas with physical properties obtained from the Comsol Multiphysics® material data base. The anode and cathode, including the rounded cathode tip are made up of copper. Due to the steady state assumption, the arc´s reattachment processes on the anode surfaces is not modeled. For the radiation transfer mechanism in the torch, the plasma is considered optically thin and a net emission coefficient is used. Moreover, the gas flow is assumed weakly compresible with a Mach number < 0.3. Finally, to set specific swirling vortex flow regimes at the inlet, we vary the intensity of the vortex inflow and therefore of the azimuthal velocity v_θ.

2.2 Mathematical model

For the laminar and weakly compressible argon flow, the continuity and momentum Navier-Stokes equations modeled in Comsol Multiphysics® are the following [8]:

$$\nabla \bullet (\rho \mathbf{u}) = 0 \tag{1}$$

$$\rho (\mathbf{u} \bullet \nabla)\mathbf{u} = \nabla \bullet [-p\mathbf{I} + \eta (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2\eta}{3}(\nabla \bullet \mathbf{u})\mathbf{I}] + \mathbf{F} \tag{2}$$

In the above equations, the scalar magnitudes ρ and η are the fluid density and the dynamic viscosity, respectively. On the other hand **u** is the fluid velocity, p is the pressure and **I** is the identity tensor. **F** represents the body forces, including the Lorentz force $\mathbf{F}_L$.

The conservation of the thermal energy in the torch is represented by the Fourier equation with convective terms and source terms [9]:

$$\rho C_p \mathbf{u} \nabla T = \nabla \bullet (k \nabla T) + Q \tag{3}$$

where T is the temperature, while k, C_p and Q, are the thermal conductivity, specific heat capacity at constant pressure and heat source, respectively. The term Q accounts for the Joule heating Q_J, volumetric net radiation loss defined by a total volumetric emission coefficient and enthalpy transport, which is the energy carried by the electric current.

For the stationary electromagnetic phenomena in the plasma torch, we use the definitions of the magnetic vector **A** and electric scalar V potentials:

$$\nabla \times \mathbf{A} = \mathbf{B} \tag{4}$$

$$\mathbf{E} = -\nabla V \tag{5}$$

where **B** is the magnetic flux density and **E** is the electric field intensity. Afterwards, the equations of Maxwell:

$$\nabla \times \mathbf{H} = \mathbf{J} \tag{6}$$

$$\nabla \times \mathbf{E} = \mathbf{0} \tag{7}$$

$$\nabla \bullet \mathbf{D} = 0 \tag{8}$$

$$\nabla \bullet \mathbf{B} = 0 \tag{9}$$

and the conservation of the charge:

$$\nabla \bullet \mathbf{J} = 0 \tag{10}$$

are formulated in terms of these potentials [10]. In the Maxwell equations, $\mathbf{J} = \sigma (\mathbf{E} + \mathbf{u} \times \mathbf{B})$ is the current density, $\mathbf{H} = \frac{1}{\mu}\mathbf{B}$ is the magnetic field intensity and $\mathbf{D} = \varepsilon \mathbf{E}$ is the electric flux density. Again **u** is the velocity field of the electromagnetic conductor, while the properties σ, μ and ϵ are the electric conductivity, magnetic permeability and electric permittivity of the material, respectively.

Additionally, in order to complete the coupled thermo-fluid-electromagnetic model of the plasma torch, the magnitude **F** and Q are expressed in terms of the electromagnetic variables **J**, **E** and **B**, by defining the next terms:

$$\mathbf{F}_L = \mathbf{J} \times \mathbf{B} \tag{11}$$

$$Q_J = \mathbf{J} \bullet (\mathbf{E} + \mathbf{u} \times \mathbf{B}) \tag{12}$$

Eqs. 1 to 12 constitute the system of partial differential equations of the model, for which boundary conditions have to be defined.

3. Solution with COMSOL Multiphysics

The axisymmetric model of the DC arc plasma torch is implemented in Comsol Multiphisics® by using the physics of the following modules: CFD module (*Laminar flow)* [8], Heat Transfer module (*Heat transfer in fluids/solids*) [9], AC/DC module (*Electric currents, Magnetic fields*) [10] and Plasma module *(Equilibrium Discharges Interface)* [11]. Also, the coupling phenomena of the plasma multiphysics flow in the DC torch are modeled by setting in Comsol Multiphisics® [4]: plasma heat source (*electric→heat*), static current density component (*electric→magnetic*), induction current density (*magnetic→electric*), Lorentz forces (*magnetic →fluid flow*), boundary plasma heat source (rounded cathode tip) (*electric→*

heat), boundary plasma heat source (anode) (*electric*→*heat*), temperature couplings (*heat*→*electric, magnetic, fluid flow*).

As boundary conditions for the thermal energy equation, we assume: temperature of 300 K at the inlet; an anode externally cooled (setting h = 10^4 W/(m^2 K) and T_{ext} = 500 K) and internally transferring energy by radiation (gray body); cathode tip with a temperature of 3500 K (thermionic emission); radiative heat transfer on the cathode walls (gray body); thermal insulation on the other surfaces of the torch. i.e. $-\mathbf{n} \bullet \mathbf{q} = 0$, where **q** is the heat flux and **n** is the normal direction.

For the evolution of the velocity field computed by the Navier-Stokes equations, we set at the inlet a radial velocity v_r equal to 0 and an axial velocity v_z of 4 m/s giving approximately an argon mass flow of 0.175x$10^{(-2)}$ kg/s. Afterwards, defined the azimuthal velocity v_θ of the free vortex flow as $v_\theta = k_1 / r$, we consider the following three distinct values of k_1 for the swirling inflow: 81x$10^{(-3)}$ m^2/s, 67.5x$10^{(-3)}$ m^2/s and 54x$10^{(-3)}$ m^2/s. Furthermore, the other usual boundary conditions for the flow equations are no slip on the walls and pressure equal to zero at the outlet.

To solve the Maxwell equations in terms of the potentials V and **A**, we define the next characteristic values on the DC torch boundaries:

a) a constant current density of -10^7 A/m^2 on the rounded cathode tip; electric insulation, i.e. $\mathbf{n} \bullet \mathbf{J} = \mathbf{0}$, on the remaining surface of the cathode, at the inlet and outlet; grounded anode by fixing an electric potential of 0 V on the anode's outer surface; b) magnetic insulation in all the boundaries, with the magnetic potential **A** fulfilling the condition $\mathbf{n} \times \mathbf{A} = \mathbf{0}$.

Additionally, a gauge fixing Ψ_0 = 1 A/m is used for a **A**.

Then, in the Equilibrium discharges interface, which handles the complicated coupling between the individual physics interfaces of the model, we specify the physical values for the electrodes of the plasma torch. Both the copper cathode tip and copper anode wall are modeled as boundary plasma heat sources, mapping the electromagnetic surface losses as heat sources on the boundary. In this case, a surface work function of 4.15 V is the default value for copper electrodes in Comsol Multiphysics®.

Lastly, for all the equations we use a condition of axial symmetry on the z axis of the torch model.

The resulting system of partial differential equations is numerically solved with Comsol Multiphysics® 5.1 by dividing the 2D region of the torch in three different domains, i.e. cathode, fluid (plasma) and anode. Then, electric and magnetic fields are computed in the fluid and anode, the fluid flow is simulated only in the plasma, while the heat transfer equations are solved in the three regions. The computational domain is accomplished by meshing the torch with nearly 7x10^4 triangle elements and refining the discretization in the plasma region and close to the walls. The number of degrees of freedom to be solved for is 9.2x10^5. Fig. 2 depicts a partial view of the mesh between the cathode tip and anode wall. By using a fully coupled approach,

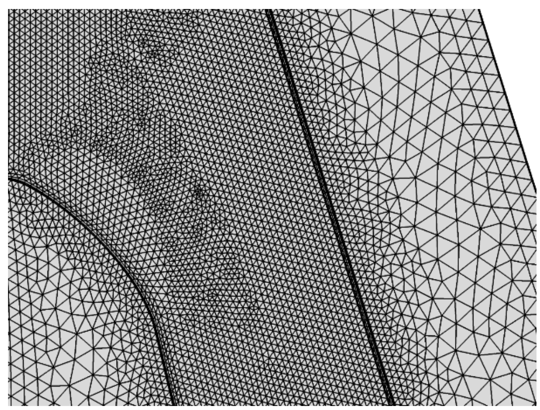

Figure 2. Partial view of the mesh between the cathode tip and anode wall.

the MUMPS direct solver is selected to numerically integrate the equations of the model. Simultaneously, a parametric sweep study of the heat source term is set in order to improve the convergence of the computations. The computational model was run in a workstation with Intel Xenon CPU E5-2687W v2 16 cores, 3.40 GHz (2 processors), 216 GB RAM, 64bit and Windows 7 Operative System. The solution time was approximately of 34600 s.

4. Results and discussion

For a free swirling flow at the inlet of the torch with k_1 = 81x$10^{(-3)}$ m^2/s, Fig. 3 and 4 show the temperature and velocity field, respectively. In particular, Fig. 3 reveals the arc column of argon gas that, introduced into the chamber of the torch upstream of the cathode, is heated, ionized and expanded by the Joule heating effect of Eq. 12. On the other hand, Fig. 4 shows the velocity distribution resulting from both the gas expansion and acceleration, the latter one due to the Lorentz force $\mathbf{F}_L$ acting over the electrically charged gas. According to Eq. 11, $\mathbf{F}_L$ depends on the cross product of the fields **J** and **B**, which is higher in the fluid region behind the cathode tip, as shown in Figs. 5 and 6. Hence, the significant accelerating motion acquired by the fluid is

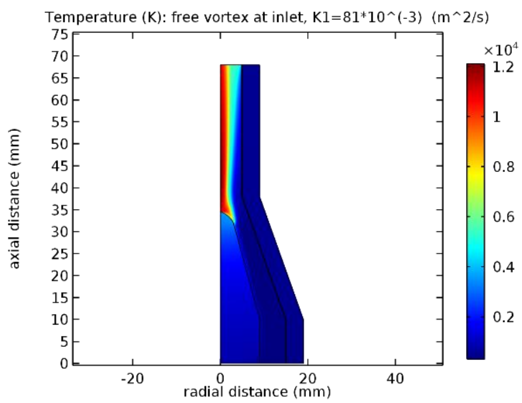

Figure 3. Temperature field in the DC torch (k_1 = 81x10$^{(-3)}$ m^2/s).

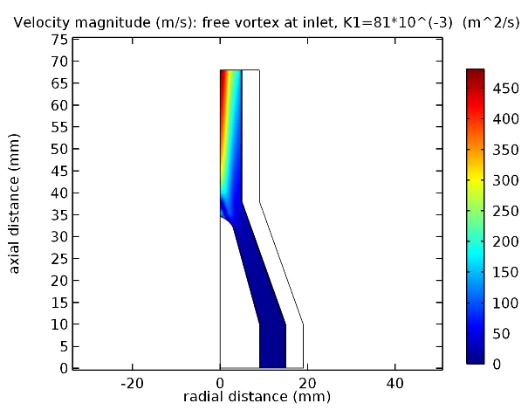

Figure 4. Velocity field in the DC torch (k_1 = 81x10$^{(-3)}$ m^2/s).

clearly evident in Fig. 7 where the magnitude of the axial velocity increases with increasing distance from the cathode tip. These profiles correspond to axial velocities respectively, behind the cathode tip (z= 40 mm), close to the torch outlet (z=65 mm) and in between (z=52.5). The temperature profiles for the same axial coordinates are plotted in Fig. 8. Both for the temperature profiles and axial velocity profiles, our computational results agree well with the ones obtained by other authors under similar conditions [5,12,13].

The evolution of the current density normal to the anode wall, computed with the parametric study for the heat source term of Eq. 3, is shown in Fig. 9. The numerical results have been obtained by proportionally reducing the heat source term, which accounts also for the Joule heating effect in the energy conservation equation. In Fig. 9 the maximum current density would correspond to the arc root attachment at the

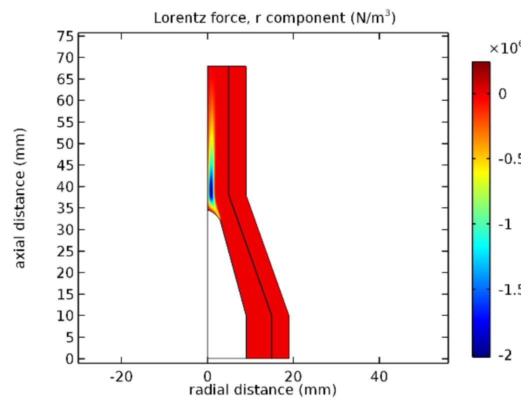

Figure 5. Radial component of the Lorentz force in the DC torch (k_1 = 81x10$^{(-3)}$ m^2/s).

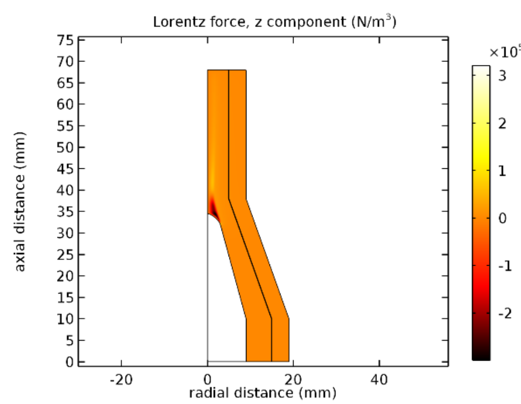

Figure 6. Axial component of the Lorentz force in the DC torch (k_1 = 81x10$^{(-3)}$ m^2/s).

inner anode walls. From the same plot it is observed that, with increasing heat source term the electric current moves forward. Based on computational results of this parametric study, Fig. 9 and 10 depict respectively the electric potential and electric displacement field for the reduced heat terms 10$^{(-5)}$ Q and 10$^{(-2)}$ Q. Again, the

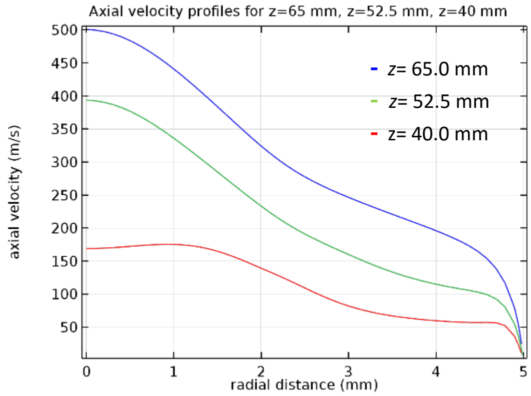

Figure 7. Axial velocity values at three distinct heights in the DC torch ($k_1 = 81x10^{(-3)}$ m^2/s).

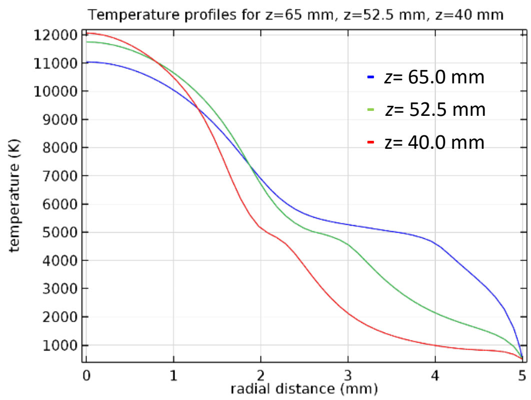

Figure 8. Temperature values at three distinct heights in the DC torch ($k_1 = 81x10^{(-3)}$ m^2/s).

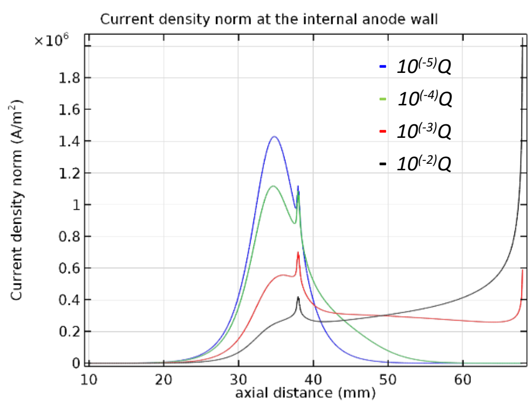

Figure 9. Current density norm at the internal anode wall of the DC torch for the parametric study of *Q*.

dependence of electric phenomena on the simulated heat source term is made evident.

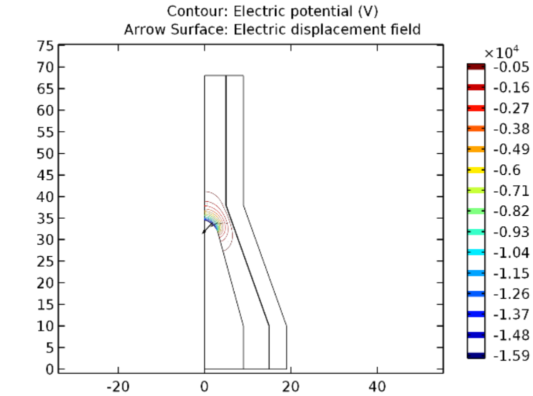

Figure 10. Electric potential and electric displacement field in the DC torch, for the reduced heat source term $10^{(-5)}$ *Q*.

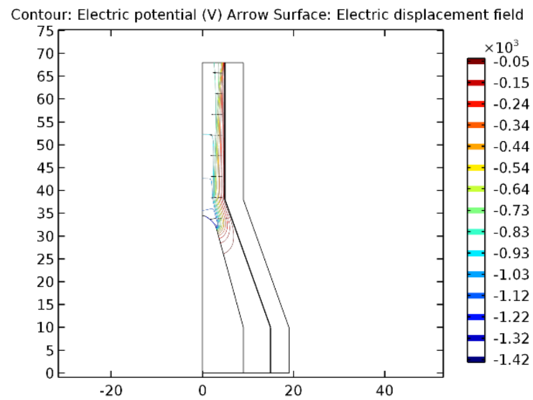

Figure 11. Electric potential and electric displacement field in the DC torch, for the reduced heat source term $10^{(-2)}$ *Q*.

5. Conclusions

A DC plasma torch has been modeled and simulated by developing a 2D axisymmetric model of laminar flow and heat transfer coupled to electromagnetic fields. In order to solve the partial differential equations of electric currents and magnetic fields, both in the gas than in the anode region, we have contemplated appropriate boundary conditions in the modeling work. Lorentz forces and Joule heating effects have been modeled, coupled to the physical model of the plasma torch and finally computed. The numerical results of the gas temperature and axial velocity result to be quite satisfactory. We foresee to develop a more complete reproduction of the thermal and fluid phenomena in a future three dimensional model, which might include the modeling of other issues. However, computational requirements and computing times should be also taken into account.

6. References

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