EFFECT OF EXTERNAL MAGNETIC FIELD ON ARC PLASMA FLOW

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Abstract

On assumption that axisymmetric one-fluid MHD equations are good approximation to describe arc plasma flow in a water-stabilized plasma torch, we found earlier numerically that the equations predict a recirculation of the plasma near the torch cathode. In the present study we show that the same equations provide a remedy how to remove the reverse flows which are potential source of damages of the electrode. A weak external DC magnetic field parallel to the symmetry axis.

1. Introduction

In this paper we summarize governing equations and the most relevant results which demonstrate a visible effect of an applied DC magnetic field on water plasma flow. Specifically, the source of the plasma is a water stabilized plasma torch whose principle and basic experimental data are described in [1]. Let us note that for arc currents of 600 A, axial temperatures and velocities of the plasma at the torch nozzle exit can be about 28 000 K and 7 km/s, respectively.

As shown numerically in [2], 2D axisymmetric MHD equations coupled with Ampere's and Ohm's laws used to describe arc plasma flow in the water-vortex stabilized plasma torch admit solutions containing a recirculation zone in the near-cathode region. This region extends up to 3-4 mm downstream of the cathode and is caused by pinch effect of weak, about 0.02 T, induced magnetic field of the arc. Depending on the distribution of plasma temperature near the cathode, the lines of electric current density may converge slightly towards the symmetry axis downstream of the cathode. At low arc currents, such as 300 A, the resulting Lorentz force is not strong enough to enforce a reverse plasma flow. However, for currents of 400, 500 and 600 A there are reverse flows present and can, amongst other phenomena, be the source of faster consumption of graphite cathodes.

It is thus important to control the plasma temperature near the electrode since the temperature dependent electric conductivity influences the current density which, in turn, induces the magnetic field and pinch effects. The control can be done in different ways; for example, one can change the shape of the cathode or impose boundary conditions (equivalent to a suitable cooling of the cathode surface) for which the current lines diverge downstream of the cathode [3].

To remove the recirculation zones, we apply to the arc a uniform external DC magnetic field whose lines are parallel to the symmetry axis. Theoretical and experimental evidence for effective control of plasma jets with the help of external magnetic fields is given in [4]. In arc plasmas, where arc current densities are much higher than in the plasma jets, we anticipate that even weak applied fields may have a non-negligible effect on the flow.
Using the Lorentz force and coupling between azimuthal and radial velocity components of the plasma, we increase the azimuthal component with the help of a DC external magnetic field whose intensity is about 0.06 T. The increase of the azimuthal velocity induces variations of the radial component which result either in a complete removal of the recirculation zones (at arc currents about 400 A) or in shifting the zones towards colder regions apart the symmetry axis (at arc currents of 500 – 600 A).

In next sections we outline the governing MHD equations, summarize and comment computational results obtained.

2. Physical assumptions

We assume 2D, steady (or steady-periodic), axisymmetric, laminar, viscous, subsonic, compressible flow of thermal water plasma at atmospheric pressure. Phenomena taken into account in the plasma are the Joule heating, radiative losses (given by net emission coefficient), viscous heat dissipation (negligible, however), enthalpy transport due to electron diffusion, and the Lorentz force due to the induced and applied magnetic field. Plasma is supposed to be optically thin and in LTE. The Reynolds number based on the radius of the discharge chamber (3.3 mm) is several hundreds but for the outer region and its typical radius of 2 cm the Reynolds number can be a few thousands, which suggests that a transition to turbulence can be expected. The current density in the arc has the predominant \( j_z \)-component, \( j_z \gg j_r \), \( j_z \sim 10^7 \text{ A/m}^2 \), but near the torch cathode \( j_z \) may become \( \sim 0.1j_r \) due to the plasma temperature distribution in this region. The plasma is supposed to issue from the discharge chamber into water steam and the rotating anode is approximated by virtual anode to preserve axial symmetry of the model. Figure 1 shows the computational domain \( \Omega \) for standard configuration (except for the solid wall EF) of the torch with a straight nozzle.

Thermal and transport parameters of the plasma are temperature dependent \( (\mu, \lambda, \sigma, c_p, R, Q_{\text{rad}}, \nu, \tau) \) viscosity, thermal and electric conductivity, specific heat at constant pressure, gas constant, and the net emission coefficient, respectively). Pressure dependence of these quantities is neglected, only the values tabulated for the pressure of 101.325 Pa (= \( p_0 \) below) are assumed with the effect of chemical reactions of the plasma species taken into account. For further details, numerical method (PE-FVM) and results related to the modelling of water plasma flow, see [2].

![Diagram](image)

Figure 1: Computational domain \( \Omega \). All lengths are in millimeters.
3. Governing equations

The assumed governing equations for the plasma flow are, in vector form, the following:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0
\]  

(1)

\[
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) = -\nabla p + \nabla \cdot \left[ \mu \left( \nabla \mathbf{v} + (\nabla \mathbf{v})^T - \frac{2}{3} \mathbf{1} \nabla \cdot \mathbf{v} \right) \right] + \mathbf{j} \times \mathbf{B}
\]  

(2)

\[
\rho \frac{\partial \mathbf{v}}{\partial t} + \rho \mathbf{v} \cdot \nabla \mathbf{v} = \frac{\partial p}{\partial t} + \mathbf{v} \cdot \nabla p + \nabla \cdot (\lambda \nabla \mathbf{v}) + \mu \mathbf{F} + \frac{\mathbf{j} \cdot \mathbf{E}_{\text{eff}}}{\sigma} - Q_{\text{rad}} + \frac{5k}{2c} \nabla T
\]  

(3)

\[
\mathbf{j} = \sigma (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \equiv \sigma \mathbf{E}_{\text{eff}} \quad \mathbf{E} = -\nabla V
\]  

(4)

\[
\nabla \cdot \mathbf{j} = \nabla \cdot (\sigma (\mathbf{E} + \mathbf{v} \times \mathbf{B})) = -\nabla \cdot (\sigma \nabla V) + \nabla \cdot (\sigma \mathbf{v} \times \mathbf{B}) = 0
\]  

(5)

\[
\nabla \times \nabla \times \mathbf{b} = \mu_0 \nabla \times \mathbf{j} \quad \nabla \cdot \mathbf{b} = 0 \quad \nabla \cdot \mathbf{B} = 0
\]  

(6)

\[
\mathbf{B} = \mathbf{b} + \mathbf{B}^{\text{ext}} = (B_x, B_y, B_z) \quad \mathbf{b} = (b_x, b_y, b_z) \quad \mathbf{B}^{\text{ext}} = (B_x^{\text{ext}}, B_y^{\text{ext}}, B_z^{\text{ext}})
\]  

(7)

\[
p = \rho RT
\]  

(8)

In the above equations, \( \mathbf{j} \) is the electric current density in the plasma, \( \mathbf{b} \) is the induced, by \( \mathbf{j} \), magnetic field, \( \mathbf{B}^{\text{ext}} \) is the applied DC magnetic field, \( \Phi_0 \) is the dissipation function, \( k \) is the Boltzmann constant, \( \epsilon \) is the electric permittivity, \( \mu_0 \) is the vacuum permeability, \( \rho \) is the density, \( \mathbf{E} \) is the electric field. Axial symmetry means \( \partial / \partial z = 0 \).

There are 9 unknowns \( v_x, v_y, v_z, T, p, \mathbf{v}, \mathbf{b}, \mathbf{b}_r, \mathbf{b}_z \) - velocity components, temperature, pressure, electrostatic potential, and components of the induced magnetic field \( \mathbf{b}_r, \mathbf{b}_z \) can be neglected, respectively, for which boundary conditions are prescribed [2] (symmetry on the axis, \( \partial / \partial z = 0 \) on DE, no slip for \( \mathbf{v} \) and Newton’s law on solid walls, zero potential on CK, \( \nabla V / \partial z = \text{const} \) on the cathode where \( \text{const} \) is adjusted at each time step to preserve given current \( I = p \rho \omega \) on DE, given \( b_y \) on EF...). Zero normal derivatives \( \partial / \partial n \) for all variables where necessary, on the water wall given \( T = 3735 \) K, \( v_r = 0 \) m/s, \( v_z = 5 \) m/s, uniform \( v_r \approx 0.46 (0.38) \) m/s for given mass flow rate of 0.34 (0.28) g/s and given current \( I = 600 \) (400) A. The initial conditions: \( \Omega \) given zero \( \mathbf{v}, b_r, \phi \), parabolic and/or flat profile of sufficiently high temperature (above 20 K on the axial).

The \( v_x, v_y, v_z \) velocity components coupling and the Lorentz force effect follow from \( \partial (\rho \mathbf{v}_r) / \partial t = \cdot \cdot \cdot + \rho v_r^2 / r + (j_r B_z - j_z B_r) \) and \( \partial (\rho \mathbf{v}_z) / \partial t = \cdot \cdot \cdot - \rho v_r v_z / r + (j_z B_r - j_r B_z) \).

4. Results

We assumed the applied DC magnetic field uniform, \( \mathbf{B}^{\text{ext}} = (0, 0, \pm B_z^{\text{ext}}) \) with a given constant \( B_z^{\text{ext}} \geq 0 \) in \( \Omega \) (thus not a nonzero value only in a vicinity of the cathode). A FE mesh of approx. 34 000 points was used as the finest mesh in a solution procedure.

4.1 Arc current of 600 A

Figures 2(a,b,c) show respectively the lines of current density (converging towards the axis downstream of the cathode), isolines of the induced magnetic field \( \mathbf{b}_r \) (which is stronger in front of the cathode and at the exit nozzle where the hot conductive core is narrower), and isolines of \( v_y \) for no applied magnetic field. Figure 2(d) shows the isolines of \( v_y \) in the presence of the applied magnetic field \( B_z^{\text{ext}} = -0.02 \) T which produces a non-negligible change of the plasma streamlines near the cathode - see Figs. 3(a,b). Stronger applied field \( B_z^{\text{ext}} = \pm 0.20 \) T was also used for comparison purposes - see Figs. 3(c,d). The
solutions found are numerically stable but rather than steady they are steady-periodic or unsteady ones. In all cases studied, the temperature field in front of the cathode is changed in the presence of the applied magnetic field, with a flux of colder gas along the cathode surface. The relatively colder gas insulates the hot one from the surface (Fig. 4).

Figure 2: From above for $B_{ext} = 0.00$ T. (a) Lines of electric current density, (b) isolines of $b_\phi$, (c) isolines of $v_\phi$. For $B_{ext} = -0.02$ T: (d) isolines of $v_\phi$. 

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Figure 3: "Streamlines". The plasma flow is from left to right and from top to bottom. The $v_r$ velocity component is not assumed in these figures.

Figure 4: Plasma temperature in front of the cathode.
4.2 Arc current of 400 A

The applied DC magnetic field $B^\text{ext} = -0.06$ T is the weakest field which leads to a complete removal of the reverse flow near the cathode for $I = 400$ A – see the steady state streamlines in Fig. 5. The temperature field is altered; a colder gas flows along the cathode surface from the water wall towards the symmetry axis and then, more importantly, away from the cathode. Since the plasma density is higher at lower currents such as 400 A, stronger applied magnetic field is needed to overwhelm inertial forces.

(a) $B^{\text{ext}} = 0.00$ T

(b) $B^{\text{ext}} = -0.06$ T

Figure 5. Streamlines. The plasma flow is from left to right and from top to bottom.

5. Conclusions

The most important conclusion as regards the possibility to remove the reverse flow near the cathode is that the intensity of the applied uniform DC magnetic field can be of the order of $10^{-2}$ T, a value substantially lower than that for, e.g., magnetic control of plasma jets. While at arc currents about 400 A the reverse flows could be completely removed and steady state flows obtained, at higher currents the recirculation zones could only be moved away from the cathode and for stronger applied fields unsteady solutions were found.

The present construction of the plasma torch studied does not enable to observe the plasma flow near the cathode which is hidden in a discharge chamber. We do not have thus an experimental evidence both for the predicted recirculation zone and its behaviour in the presence of an applied magnetic field.

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References