Simulation of magnetically dispersed arc plasma

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Abstract: Magnetically dispersed arc plasma exhibits typically dispersed uniform arc column as well as diffusive cathode root and diffusive anode root [1, 2]. In this paper magnetically dispersed arc plasma coupled with the solid cathode is numerically simulated by using simplified cathode sheath model of Lowke’s [3]. The numerical simulation results under argon ambiance and 200A arc current show that: the average current density of arc root at the cathode is $1.85 \times 10^7$A/m$^2$, which is less than the value of a contracted arc. The result exhibit characteristics of diffusive cathode arc root. The maximum plasma temperature and temperature gradient of diffusive arc root plasma are less than the contracted arc root plasma. Plasma volume is much larger and almost fills the generator, the plasma dispersed uniformly.

Keywords: magnetically dispersed arc plasma, diffusive arc root, thermionic cathode

1. Introduction

Generally, arc plasma is of concentrated energy and the inhomogeneous parameters. The magnetic dispersed arc plasma in Large Area Dispersed Arc Plasma Source (LADPS[1]) is of uniform distribution of density and energy. Beside the dispersed arc column, the magnetic dispersed arc plasma shows a diffusive arc root at the cathode as well as at the anode. Figure 1[4] show the development of cathode arc root diffusing. There is only one arc root at the cathode end surface while arc ignition at 0.00 second. As time goes, the cathode root splits into multiple roots, and till 109.89s, no conspicuous arc root is seen by the highlight point but a diffused arc root around the cathode end surface.

![Figure1](image)

Figure1, diffusive process of arc root on the end of cathode ($\Phi 18$) in LADPS, arc current: 300A, axial magnetic field: 0.21T

Li al. [5] simulated dispersed arc plasma with fixed cathode temperature and the current density. Li’s results exhibit dispersed arc column and diffusive anode arc root, they are at variance with the experimental results, especially at the cathode arc root and the nearby region, however it should take the cathode into account in researching magnetic dispersed arc plasma with thermionic cathode.

There have been several papers giving models of the near cathodes region. Benilov[6] take the near cathode region as sheath and ionized layer. The electron density is obtained by solving the Poisson equation and the Boltzmann equation. In the space charge ionized layer, multicomponent hydrodynamic equations are employed to get the space-charge distribution. In Hsu’s paper[7], the cathode region is divided into two subzones: the ionization zone and the space-charge zone. The ionization zone is used to calculate the generation of ions and electrons with electron Boltzmann equation. The latter is used for accounting the sheath formation.

The models introduced above only contrapose the near cathode region. Lowke al. [3] proposed a simplified model of arc and the cathode. The method of calculation omits any account of the space-charge sheath at the cathode. The electron density and thus the electrical conductivity within the cathode sheath region are evaluated by assuming ambipolar diffusion. Current density values are derived from
the current continuity equation. M Tanaka et al.[8] have employed this model to calculate the molten pool formation and thermal plasma with metal vapour in gas tungsten arc welding, and the calculations appear to be consistent with the experiments.

In this paper, magnetically dispersed arc plasma coupled with cathode is simulated in Fluent by using the developed Lowke’s model. Dispersed arc plasma as well as diffusive arc roots is obtained. The arc roots’ properties such as the current density distribution and the energy flux on the cathode surface are discussed.

2. Simulation model

2.1 Equations

MHD equations are applied in the plasma column, which can be found in [10]

2.2 Energy flux at the cathode surface

Except the heat conduction to the cathode surface, simulation of arc plasma coupled with cathode should include the additional energy transfer processes occurring at the surfaces: cooling process due to the thermionic emission, and heating process due to ion current and radiation. Heating by radiation from the plasma is neglected. So the additional energy flux \( F \) to the cathode is as follow:

\[
F = -\varepsilon \sigma T_c^4 - |j_e| \Phi_c + |j_i| V_i
\]

\( \varepsilon \) is the emissivity of the surface, \( T_c \) is the surface temperature, \( \sigma \) is the Stefan–Boltzmann constant. \( j_e \) is the electron current density. \( \Phi_c \) is the work function, it depends on the Cathode material. \( j_i \) is the ion current density which is assumed to be \( j_i = |j| - |j_R| \) at the cathode surface. And \( V_i \) is the ionization potential of the plasma. \( j = j_e + j_i \) is the current density at the surface of the cathode obtained from the current continuity equation. \( j_R \) is the theoretical thermionic emission current density given by the Richardson equation:

\[
|j_R| = AT_c^2 \exp \left( \frac{\Phi_c}{k_B T_c} \right)
\]

\( A \) is the thermionic emission constant for the surface of the cathode, \( e \) is the electronic charge, \( k_B \) is Boltzmann’s constant. In computation if \( |j_R| \) is greater than\(|j|\), we take \( j_i \) to be zero.

2.3 Effective electrical conductivity

The temperature of the near cathode region is 3000K~4000K. The LTE electrical conductivity and electron density are approximately 0, but the ambipolar diffusion and the ionization make the near cathode region highly conducting. Therefore, we introduce the effective electric conductivity to enable the Ohm's Law in this region.

The electron continuity equation as below:

\[
\nabla \cdot (D_A \nabla n_e) = \gamma (n_e^2 - n_{eq}^2)
\]

Where: \( D_A \) is the ambipolar diffusion coefficient for the local temperature \( D_A = \frac{2kT \mu_i}{e} \). \( \mu_i \) is the ion mobility, define by the Langevin mobility. \( n_e \) is the electron number density and \( \gamma = 1.1 \times 10^{-12} n_e T^{-4.5} \text{ cm}^3 \cdot \text{s}^{-1} \) is the electron–ion recombination coefficient, \( n_{eq} \) is the equilibrium plasma value of electron density for the local plasma temperature.

Then the effective electrical conductivity of near cathode region \( \sigma_{eff} \) is derived:

\[
\sigma_{eff} = \frac{n_{eq} \sigma}{n_0/(n_T \mu_e) + (2\pi n_e n_{eq})/(\pi_T \sigma)}
\]

Where \( n_0 \) is the equilibrium neutral particle density, \( \mu_e \) is the electron mobility \( \mu_e = \frac{e}{m_e v} \nu \) is the collision frequency of the electron \( v = \frac{\lambda_e}{v_e} \), \( v_e \) is the electron velocity define by the local temperature, \( \lambda_e \) is the electron mean free path, \( n_T = n_0 + n_e + n_{eq} \) is the total particle density.

Figure 2 shows the two-dimensional cylindrical coordinate axle diagram of the coaxial plasma generator. A-C-D-E-F-G-H is the computational domain. A-C is the symmetry axis. A-H-J-B is the graphite cathode region. G-F-E is the anode surface. G-H is the gas inlet, where there was an imposed argon gas flow around the cathode. And E-D-C is the external environment with argon at 1 atmosphere pressure. A uniform axial magnetic field is present in the plasma area.
3 Calculation results

Figure 3 shows the temperature distribution of this simulation (figure (a), (b)) and compared with fixed cathode root (figure (c) [9]).

Compared to the fixed contracted arc root plasma, the plasma column of the simulation is dispersed into a large region: the plasma volume is 0.014m long in the x direction, much greater than 0.004m of the contracted arc root plasma. The temperature gradient of the former’s is much smaller than that of the later. Both of them exhibit uniformity at the cross section.

The maximum temperature on the cathode surface in figure 3(b), (from figure 3 to 7: the distance of the x axis from 0 to 11.5 means from H(x=0) to J(x=10) to B (x=11.5) in figure 2), appears at the edge of the end (at “J”), which is 3428K, less than the sublimation temperature of graphite. The high temperature region is in good agreement with the cathode ablation zone in experiment. Except at the edge, gently declining uniform temperature more than 3200K appears at the cathode end from the edge to the center.
density in the contracted arc root plasma which is \(1.1 \times 10^8 A/m^2[5,9]\). The profile of the current density is smooth from 10.2mm to 11.5mm. The current area from 9.6mm to 11.5mm is about 10.81mm\(^2\). According to the current density, we conclude that the cathode root diffuses.

4 conclusions

A cathode has been taken account in the simulation. Compared with Li’s simulation results [9] in which the current density on the cathode is fixed and contracted, we conclude that:

The average and maximum current density on the cathode surface of this simulation is smaller, and currents distribute in a large area. Those show arc root diffusing at the side near by the edge and whole end of the cathode.

The maximum and average temperature of plasma of the diffusive arc root plasma in this simulation is 14990K, less than 22000K in plasma of the contracted root arc. The plasma volume exhibits larger.

References

[2] Lin-Cun Li, Quan Chen, He-Ling Zhou, and Wei-Dong Xia, IEEE TRANSACTIONS ON PLASMA SCIENCE, Vol 36, No. 4, 2008, 1080–1081