Role of the Diffusion Current in Nonequilibrium Modelling of Welding Arcs

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Abstract: 2D self-consistent nonequilibrium model of a free-burning arc in argon has been developed. The model is based on the COMSOL Multyphysics platform and describes in a self-consistent manner the fluid dynamics, the heat transfer, the magneto-electrodynamics, and species conservation. The governing equations are solved applying the COMSOL interfaces Laminar flow, Electric currents, and Magnetic fields, which are complemented by Weak form PDE for the temperatures of electrons and heavy particles, and species conservation for the ions. The work is focused on physically justified description of the effects in the regions of the arc plasma in the vicinity of the electrodes.

Keywords: arc plasma, nonequilibrium, TIG arc welding, generalized Ohm's law.

1. Introduction

The free-burning arc can be seen as an idealized representative of DC arc encountered in many applications: tungsten-inert gas (TIG) welding, DC plasma torches for cutting and spraying, switching, etc. The electrodes are essential constituents of the corresponding plasma devices and determine the characteristics of the arc discharge. The near-electrode regions ensure the current transfer and control the heat load to the electrodes and hence their lifetime. Modelling of the arc plasma based on multiphysics approach enables the physically relevant description of the processes. In many works, the arc plasma is treated as being in local thermodynamic equilibrium (LTE). However, it has been already recognized that in the near-electrode regions of the arc plasma and also in the bulk plasma deviations from LTE are present. Therefore, in general a nonequilibrium description of the plasma seems to be more adequate.

Results obtained using a nonequilibrium model are capable of predicting beside the typical arc plasma characteristics (e.g. temperatures of electrons and heavy particles, particle densities, electric current density, electric potential, flow velocity) the role played by the diffusion current in the near electrode regions. In the near-cathode region of the arc plasma, the diffusion current causes a repel of the electrons coming from the bulk plasma to the edge of the space-charge sheath adjacent to the electrode. On the anode side, the diffusion current enables a reversal of the electric field so that a part of the electron flux from the bulk plasma is suppressed to ensure current continuity.

2. Physical model

The schematic of the arc geometry is shown in Figure 1. The system is of axial symmetry and includes the arc region, the electrodes, and a part of the nozzle for gas inflow. The cathode is a cylindrical rod with a conical tip made of tungsten. The anode is a plate made of copper and it is water cooled. The arc is operated in argon at atmospheric pressure with a gas inflow of 12 slpm and arc current of 100 A.

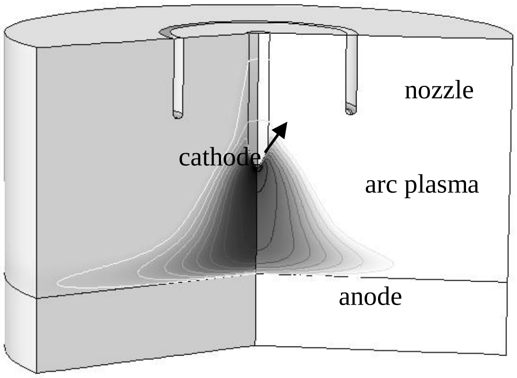

Figure 1. Geometry of the arc.

The model is based on the hydrodynamic approach assuming that the collision times of the particles in the plasma are much shorter than the time constants of the flow. The plasma behaves like a fluid which is considered to contain electrons and argon atoms and singly charged ions. The bulk plasma model considers the simplest reaction scheme and a two-level representation of the argon atom as a first step for the implementation in COMSOL. An extension of the reaction scheme has been applied in a former model developed on a computational platform based on finite volume formulation [1]. It has been found that the simplest reaction scheme is capable of predicting the main arc plasma characteristics.

3. Use of COMSOL Multiphysics

The mathematical description of the problem includes the equations of conservation of mass and momentum, energy balance of electrons and heavy particles, species balance, conservation of mass and momentum, current continuity, generalized Ohm's and Ampére's law [2, 3].

$$
\begin{aligned}
&\nabla \cdot \rho \vec{u} = 0 \\
&\rho\left(\vec{u} \cdot \nabla\right)\vec{u} = \nabla \cdot \left(-p\hat{I} + \hat{\tau}\right) + \vec{j} \times \vec{B} \\
&\nabla \cdot \vec{J}_{\varepsilon} = -e\vec{j}_e \cdot \vec{E} + S_{\varepsilon}, \\
&\nabla \cdot \vec{J}_h = e\vec{j}_i \cdot \vec{E} - \rho C_p \vec{u} \cdot \nabla T + S_h, \\
&\nabla \cdot \vec{J}_i = S_i - \rho \vec{u} \cdot \nabla y_i, \\
&\nabla \cdot \vec{j} = 0, \\
&\frac{\vec{j}}{e} = \vec{j}_i - \vec{j}_e, \\
&\nabla \times \left(\mu_0^{-1} \vec{B}\right) = \vec{j}.
\end{aligned}
\tag{1}
$$

In the equations listed above, ρ is the mass density, p – the gas pressure, $\hat{I}$ and $\hat{\tau}$ - the identity matrix and the viscous stress tensor for Newtonian fluid. $\vec{J}_{\varepsilon}$ and $\vec{J}_h$ denote the energy flux of electrons and heavy particles, $\vec{j}_i$ and $\vec{j}_e$ – the particle fluxes of ions and electrons, $\vec{j}$ – the electric current density, $\vec{E}$ – the electric field strength, S_{ε} and S_h – source terms of energy of electron and heavy particles, C_p – the specific heat, $\vec{u}$ – the mean velocity, T – the temperature of heavy particles, $\vec{J}_i$ and S_i – the diffusive mass flux and source term of production/loss of species, $\vec{B}$ – the magnetic field.

The Stefan-Maxwell equations describing the multi-component diffusion in the arc plasma are considered in order to express the diffusive mass flux of species [4-6]

$$\vec{J}_k = \vec{G}_k \frac{\rho y_k}{z_k} D_k^{eff} + D_k^{eff} y_k \sum_{l \neq k} \frac{z_l}{y_l \hat{D}_{kl}} \vec{J}_k. \tag{2}$$

Equation (2) presents a set of n equations with n being the total number of species in the mixture. The requirement of zero total mass flux reduces the system to n-1 independent equations. In Eq. (2), $\vec{G}_k$ denotes the volumetric friction force, y_i and z_i – the mass and pressure fraction of species, D_k^{eff} – the effective diffusion coefficient, $\hat{D}_{kl}$ – the binary diffusion coefficient of species k and l.

The corresponding equations are strongly coupled and a special attention has to be paid to the initial and solver conditions. The governing equations are solved applying the COMSOL interfaces Laminar flow, Electric currents, and Magnetic fields, which are complemented by Weak form PDE for the temperatures of electrons and heavy particles, and species conservation for the ions.

The boundary conditions employ Dirichlet condition for the gas temperature and mass fractions on the inlet and outlet boundaries, Neumann condition for the electron temperature. Normal current density and fixed temperature are applied at the cathode base. The outer anode boundary is grounded and kept at fixed temperature. The rest of the outer boundaries are isolated.

4. Results

Results concerning the temperatures of electrons and heavy particles and the electron density are presented in Figures 1 and 2. The highest temperatures are obtained on the arc axis and in front of the cathode tip (notice the individual scales of the temperatures). In the arc core, the temperatures of electrons and heavy particles are close and even almost equal to each other, i.e. the core of the arc plasma is close to local thermodynamic equilibrium. Deviations from equilibrium are obtained in the near-electrode regions and in the arc fringes. The arc plasma is strongly ionized. Electron density values in the order of 10^{23} m^{-3} are obtained.

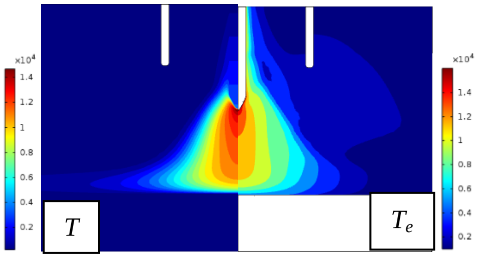

Figure 2. Distribution of the temperatures of heavy particles and electrons (in Kelvin).

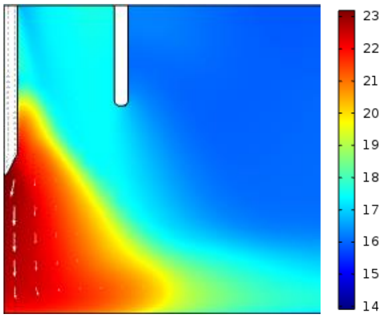

Figure 3. Distribution of the electron density (in m^{-3}, logarithmic scale).

Figure 4 clearly shows the thermal equilibrium in the core of the plasma column and the nonequilibrium between electrons and heavy particles in the near-electrode regions. While the temperature of heavy particles equals the temperature of the adjucent solid, the electron temperature remains significantly higher so that the current transfer can be ensured. In contrast, models based on the asumption of LTE need an artificial condition (enhancement of the electrical conductivity) in these regions.

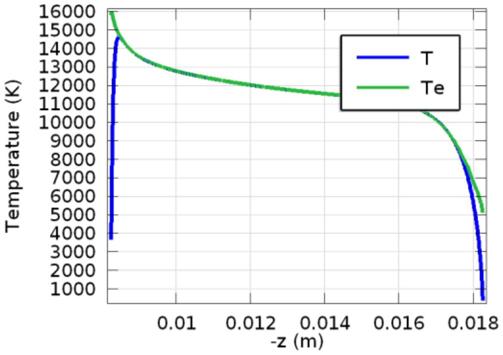

Figure 4. Axial distribution of the electron and heavy particle temperature along the inter-electrode distance.

The understanding of the physical processes in the near-electrode regions is of great importance. The nonequilibrium model developed allows to study the role played by the diffusion of electrons and ions in these regions. The axial components of the electron particle flux to the cathode are shown in Figure 5 for a distance of about 60 µm away from the cathode. It can be seen that the components due to diffusion and drift in the electric field get almost equal in the vicinity of the cathode. Since they have oposite signs, the total of both is small and a consequence the electrons coming from the bulk plasma to the cathode are repelled. In the free-burning arc, the most of the electric current on the cathode surface is due to thermionic emission from the cathode. The emitted electrons are accelerated in a sheath of space charge which has a thickness of the Debay length. This region is not resolved in the model. However, the energy balance of the sheath is considered locally in global and proper boundary conditions are derived for the density of charged particles and the electron temperature. For the bulk plasma, the asumption of quasineutrality is still valid. Considering the energy balance in the space-charge sheath allows to determine the heat fluxes to the cathode which are needed to sustain the arc operation. Each electron released from the cathode takes away energy equal to the work function of the cathode material. Therefore, the thermionic emission is cooling the cathode. Then, the heating is ensured by the ion current. Other heating/cooling mechanisms, e.g. by the electrons coming from the bulk plasma, radiative heating by the plasma, and black-body radiation are much weaker.

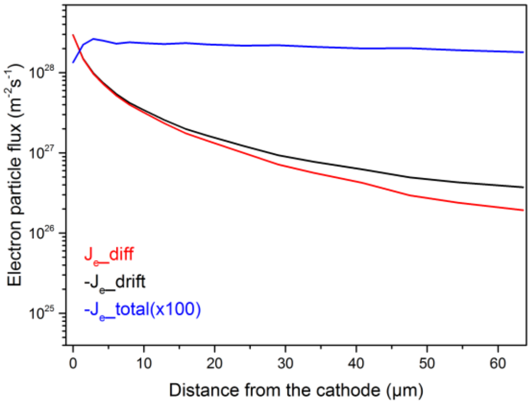

Figure 5. Axial component of the electron particle flux to the cathode.

On the anode side, the situation is different from physical point of view. As it can be seen in Figure 6, a negative voltage drop (the curve V_{cond}) is built in front of the anode. The explanation of this phenomenon is related again to the diffusion current. In this case, the electron particle flux is so strong that a part of it has to be suppressed in order to ensure current continuity. Correspondingly, the electric field undergoes a reversal. Also in Figure 6, the axial distribution of the electric potential resulting from electric conduction and diffusion is presented (the curve V_{eff}). It should be mentioned that the course of the effective potential is similar to that of the conductive one in models which account only for the drift component of the electric current. Nevertheless, a physically justified picture of the near-electrode effects cannot be obtained.

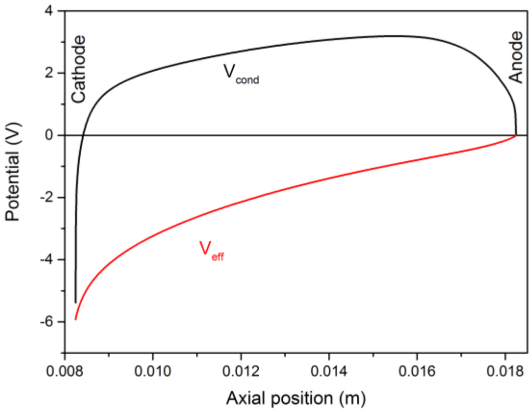

Figure 6. Axial distribution of the electric potential.

5. Conclusions

A self-consistent nonequilibrium model of a free-burning arc plasma in argon has been developed based on the computational platform COMSOL Multiphysics. The model is capable of describing and predicting not only the main plasma characteristics but also the effects provoked by the diffusion of electrons and ions in the near-electrode regions, where also a strong deviation from local thermodynamic equilibrium is observed. For the sake of stability and more flexibility in the formulation of the governing equations and boundary conditions, the arc plasma model has been set up applying Weak form PDE for the temperatures of electrons and heavy particles, and species conservation for the ions. Further optimization of the model is aimed at reducing the computational effort of the simulations.

9. References

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