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# SIMULATION OF FLUID FLOW AND HEAT TRANSFER IN PLASMA ARC REGION OF AC ELECTRIC ARC FURNACE

Qipeng Dong, Jiongming Zhang

State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing
No. 30, College Road, Haidian District, Beijing 100083, China

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## Abstract

A mathematical model describing the characteristic of AC plasma arc in electric arc furnace has been developed basing on the model of DC plasma arc. Because of the specificity of AC power, variety of energy in plasma arc region has been considered using varied energy source. Moreover, due to the considerable effect of metal vapor from the vaporization of bath on the transport properties of AC plasma arc, the effect has been taken into account in the simulation. To calculate the velocity and temperature distributions in AC plasma arc region, the time-dependent conservation equations of mass, momentum, and energy are solved in conjunction with the Maxwell's equations of electromagnetic field. The heat transfer from plasma arc to a rigid math surface is calculated.

## Introduction

Electric arcs are widely used for waste disposal, steel-making and welding process, etc. AC plasma arc as well as DC plasma arc is used.[1] In order to improve the using of electric arcs and optimize them, characteristics of them should be known well, such as temperature, velocity, etc. However, because of complex feature and high temperature of plasma arcs, the general way of observation and measurement can hardly apply to the plasma arc. So, numerical modeling has been the principal method for studying and improving electric arc process in past decades.

K.C. Hsu et al[2] presented a two-dimensional model to study the flow fluid and heat transfer in the arc region. A crucial boundary condition for current density in cathode was established, and the predicted temperature distributions showed good agreement with experimental measurement. McKelliget and Szekel[3] developed a mathematical model to predict the velocity, temperature, and current density distributions in inert gas welding arcs. The mechanisms of heat and momentum transfer to the anode were also investigated. Good agreement between the predicted results and experimental data had been obtained. F Lago and JJ Gonzalez[4] developed a two-dimensional numerical model of the interaction between an electric and a solid anode of different types. The anode material vapor in the plasma column and the latent heat of vaporization were taken into account in their work. Larsen and Bakken[5] published their work on the AC arcs in silicon metal furnace. An improved Channel Arc Model for simulation of AC arcs had been presented. Satisfactory agreement between simulated and measured current and voltage waveforms were obtained. However, characteristics of AC arc were not studied. Savarsdottir and Bakken[6] developed a Magneto-Hydrodynamic model for high current AC arcs in submerged-arc furnaces. But the model was almost the same as the model of DC plasma arc, and they didn't consider the differences between AC and DC arcs. Recently, Moghadam and Seyedein[7] et al.

presented a two-dimensional mathematical model to describe the heat transfer and fluid flow in AC arc zone of ferrosilicon submerged-arc furnace. They found that the optimal arc length in furnace is 10cm. However, they didn't notice that energy source will change according to different directions of current.

A lot of works had been done on the electric arc in welding or electric arc furnace, but most of them were concentrated on DC plasma arc. The research on AC plasma arc is very limited and the differences between AC and DC plasma arc aren't considered in previous models. So, not like the DC plasma arc, characteristics of AC plasma arcs are not known well. Because of the different power, the features of AC plasma arc must be different with the DC plasma arc's, and the previous models can't be used in the simulation of AC arc directly. Given this, a mathematical model is developed in this work to study the major characteristics of single-phase AC plasma arc.

**Mathematical model**

The computational domain considered for modeling the AC plasma arc is given in figure 1. When a free-burning arc is not affected by external forces such as magnetic or convective forces, it presents a natural axis of symmetry, and a two-dimensional model is enough for its description.

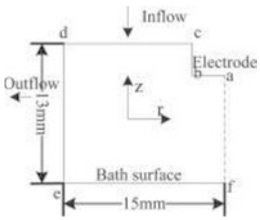



Figure 1. The sketch of calculation domain.

Assumptions

The AC plasma arc is a very complicated physical phenomenon, in order to simplify the mathematical model, the following assumptions have been made in this study:

1) The flow is assumed to be laminar. Characteristic of fluid flow can be classified by the Reynolds number, which can be calculated using the following equation ($Re = \rho \mathbf{v} l /$ ).

The temperature of 15000K was taking into account here, so corresponding parameters were gotten: density $\rho \sim 0.032 kg/m^3$, kinetic viscosity $\sim 7.1\times10^{-5} Pa\cdot s$, arc length $l \sim 0.01m$ and velocity $\mathbf{v} \sim 300 m/s$. The value of Reynolds number was calculated to be 1352. In a free jet, transition from laminar to turbulent flow is found to take place at Reynolds numbers around $1.0\times10^5$.Therefore, a laminar flow regime is expected in the arc.

2) The arc is local thermal equilibrium (LTE), which means that the electron and heavy particle temperatures are similar. Hsu and Pfender[2] have found that this assumption is applicable over most of the arc except in the arc fringes and the regions near the cathode and anode surfaces.

3) The shielding gas of arc is assumed to be pure argon at 1 atm. Due to the considerable effect of metal vapor from vaporization of bath on transport properties of AC plasma arc, the effect has been taken into account basing on the results of previous research[8].

4) Deformation of the bath surface is neglected.

5) The plasma is supposed to be optically thin and an approximate method is used to model the radiation.

Transport equations

Under two-dimensional axisymmetric cylindrical coordinate system, time-dependent transport equations of AC arc are written as follows:

1) Conservation of mass

$$\frac{\partial \rho}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(r\rho v)+\frac{\partial}{\partial z}(\rho u)=0 \quad (1)$$

where, $\rho$ is the density, $t$ is time, $r$ is the radial distance and $z$ is the axial distance, **v** and **u** are the velocity components in the radial and axial directions, respectively.

2) Conservation of axial momentum

$$\frac{\partial(\rho u)}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(r\rho vu)+\frac{\partial}{\partial z}(\rho uu)=-\frac{\partial P}{\partial z}+\frac{\partial}{\partial z}\left(2\mu\frac{\partial u}{\partial z}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left\{r\mu\left(\frac{\partial v}{\partial z}+\frac{\partial u}{\partial r}\right)\right\}+F_z \quad (2)$$

The source of momentum is Lorentz force which is produced by self-induced magnetic field. The Lorentz force component (**Fz**) is given as: $F_z=j_rB_\theta$.

where, $P$ is static pressure,   is the viscosity, **j** is the current density and $B_\theta$ is the azimuthal magnetic field.

3) Conservation of radial momentum

$$\frac{\partial(\rho v)}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(\mathrm{r}\rho vv)+\frac{\partial}{\partial z}(\rho uv)=-\frac{\partial P}{\partial r}+\frac{2}{r}\frac{\partial}{\partial r}\left(r\mu\frac{\partial v}{\partial r}\right)+\frac{\partial}{\partial z}\left\{\mu\left(\frac{\partial v}{\partial z}+\frac{\partial u}{\partial r}\right)\right\}-\frac{2\mu v}{r^2}+F_r \quad (3)$$

The Lorentz force component (**Fr**) is given as: $F_r=-j_zB_\theta$.

4) Conservation of energy

$$\frac{\partial(\rho h)}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(r\rho vh)+\frac{\partial}{\partial z}(\rho uh)=\frac{\partial}{\partial z}\left(\frac{k}{c_p}\frac{\partial h}{\partial z}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{k}{c_p}\frac{\partial h}{\partial r}\right)+S_h \quad (4)$$

The energy source ($S_h$) in the energy equation may be composed of three components, the first one is the Joule heating caused by arc resistance, the second term is the enthalpy which is transported by electrons due to the fact that velocity of electrons is generally much higher than heavy particles'[2], and the final term is optically thin radiation loss per unit volume. In DC arc model, the source will not change due to the fixed current. However, for the AC arc, direction and value of the current will change with time, the enthalpy which is transported by the electrons will be different. This is the major difference between AC and DC plasma arc model. And different energy sources are the key point of AC plasma arc model. The difference was not taken into account in the previous papers,[1,6,7] and the unsatisfactory results were obtained. The source in the energy equation can be expressed as follows:

$S_h=\frac{j_z^2+j_r^2}{\sigma}+\frac{5k_B}{2e}\left(\frac{j_z}{c_p}\frac{\partial h}{\partial z}+\frac{j_r}{c_p}\frac{\partial h}{\partial r}\right)-S_R$, the ab in figure1 is cathode;

$S_h=\frac{j_z^2+j_r^2}{\sigma}-\frac{5k_B}{2e}\left(\frac{j_z}{c_p}\frac{\partial h}{\partial z}+\frac{j_r}{c_p}\frac{\partial h}{\partial r}\right)-S_R$, the ab in figure1 is anode.

The radiation loss for argon plasma is taken from the study of D.L.Evans and R.S.Tankin[9].

In order to calculate the momentum source and energy source, current density and azimuthal magnetic field should be known first. So, it is necessary to solve the equations of electromagnetic field. In this study, three equations are defined in the generalized form (equation (5)) suggested by Patankar[10] for electric potential ($V$), radial and axial potential vector components (**Ar** and **Az**).

$$\frac{\partial(\rho\phi)}{\partial t}+\nabla\cdot(\rho v\phi)=\nabla\cdot(\Gamma_{\phi}\nabla\phi)+S_{\phi} \quad (5)$$

The equations in the generalized form of Patankar for the three scalars are given as follows:

Table I. Transport equations for the three user-defined scalars.

| Conservation equations | Φ | $\Gamma_\Phi$ | $S_\Phi$ |
|---|---|---|---|
| Current (equation (6))* | V | σ | 0 |
| Axial vector potential (equation (7))* | $\mathbf{A_z}$ | 1 | $_0\mathbf{j_z}$ |
| Radial vector potential (equation (8))* | $\mathbf{A_r}$ | 1 | $_0\mathbf{j_r}$-$\mathbf{A_r}/r^2$ |

*The general equation can be used to calculate the three scalars by taking the convection term equal to zero.

where, $_0$ is the permeability of vacuum and is given by the value of $4\pi\times10^{-7}Hm^{-1}$.

The current density can be deduced from the electric potential:

$$\begin{cases} j_z=-\sigma\left(\dfrac{\partial\phi}{\partial z}-v_r B_\theta\right) \\ j_r=-\sigma\left(\dfrac{\partial\phi}{\partial r}+v_z B_\theta\right) \end{cases} \quad (9)$$

Boundary conditions

Table II. Boundary conditions for the model

| boundary | P/Pa | $\mathbf{v_z}/ms^{-1}$ | $\mathbf{v_r}/ms^{-1}$ | T/K | Φ/V | $\mathbf{A_z}$ | $\mathbf{A_r}$ |
|---|---|---|---|---|---|---|---|
| ab | - | 0 | 0 | T=3000 | Equation(12) | | |
| bc | - | 0 | 0 | T=3000 | | | |
| cd | 1atm | Δ | Δ | T=1000 | | | |
| de | 1atm | Δ | Δ | T=1000 | | | |
| ef | - | 0 | 0 | T=1800 | 0 | | |
| fa | - | | | | | | |

Boundary conditions for the model of AC plasma arc are listed in Table II. Where, Δ represents that the value is derived from the internal computation, represents that the flux is zero. Symmetrical boundary condition is used for the axis a-f. No-slip conditions (zero velocities) are applied for the anode and cathode surfaces. For the boundary condition of electric potential, the current density distribution expressed by the equation (12) is imposed on the surface a-b, which is different with the DC plasma arc model.

$$J = \begin{cases} -2J_c(1-(r/R_c)^2)\sin(2\pi\omega t), r \le R_c \\ 0, r > R_c \end{cases} \qquad (12)$$

where, $R_c$ is the radius of the cathode spot, which is defined as:

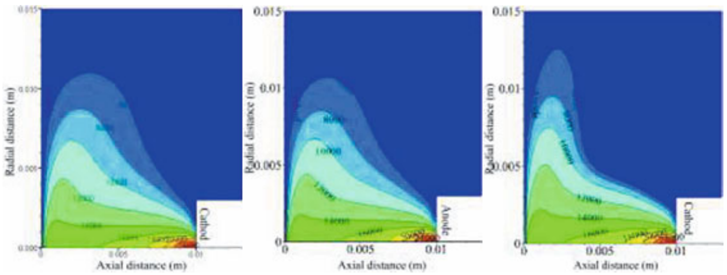
$$R_c = \sqrt{I/(\pi J_c)} \qquad (13)$$

And in this study, $R_c$ is taken to be a constant which is corresponding to the maximum current. $I$ is the total current in the system. $J_c$ is the average current density, it is assumed to be $6.5\times10^7$ $A/m^2$[3].

No matter what kind of plasma arc, AC or DC, the major function of them is to supply heat for the bath or work-piece efficiently. In the previous researches about the DC plasma arc[11,12], four major mechanisms for the heat transfer from arc to the metal were taken into account: heat transfer by convection, Thompson effect, condensation of electrons, and heat transfer by radiation. The four different mechanisms for the heat transfer are also considered for the single-phase AC plasma arc here.

## Results

The CFD commercial code FLUENT is used to solve the transport equations for the single-phase AC plasma arc model. The program-developing tools (user-defined-function and user-defined-scalar) are used to realize the coupling of the electromagnetic and hydrodynamic equations. Arc length is taken to be 10mm in this study. Electrical current should be dependent on the time, $I=200\cdot sin(2\pi\omega t)$ is adopted in this work. Where ω is the frequency of the AC current, 50Hz is used here. Uniform grid with minimum cell of $0.2\times0.2mm^2$ is adopted in the calculation, which is carried out for one and a half period.




(a) t=0.005s (b) t=0.015s (c) DC arc

Figure 2. Temperature field of the AC arc at two specified times and DC arc.

Since the single-phase alternating current is time-dependent, the characteristics of the AC plasma arc will vary with time. So the distribution of temperature, velocity, electric potential of AC plasma arc will change all the time, while the direction of the current and polarity of the plasma arc change with the time periodically. Figure 2 shows temperature distributions of AC arc at $t$=0.005s and $t$=0.015s, corresponding to the maximum current in opposite direction, respectively. The temperature distribution of DC arc with the value of maximum current is also presented for comparison. As seen in the figure, the temperature distributions of the AC arc at different times are very similar with each other. Comparison between the calculated temperature distribution with the DC arc shows that the shape of AC arc is similar with the DC arc's. Although the temperature distribution of the AC arc will change with the time, the highest temperature is always found at the central location closing to the graphite electrode. The highest temperatures are nearly the same at 0.005s and 0.015s.

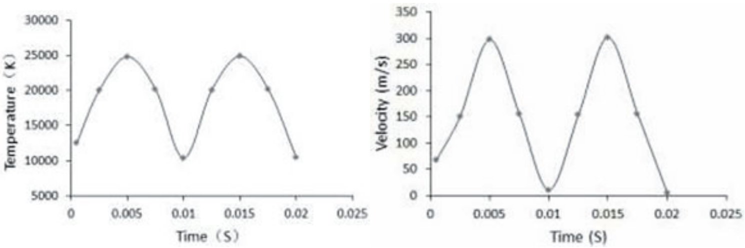


Figure 3. Highest temperatures and maximum velocities of AC arc at different times.

Figure 3 presents the predicted highest temperatures and maximum velocities of AC plasma arc at nine different times in a period. The current imposing on the electrode changed with time in sine form here. As shown in the figure, shape of the curve which composed of nine highest temperatures at different times is semi-sinusoidal. The transformation of AC arc temperature is connected with the change of current. The highest temperature of AC arc is varying periodically with time, just like the alternating current. And because the temperature has no direction, the period of temperature is half of the current's. Temperatures at 0.005s and 0.015s are the most highest which are corresponding to the maximum absolute values of current in a period. The shape of time-velocity curve is similar to the time-temperature curve. So, the law of the temperature is appropriate to the velocity of AC arc.

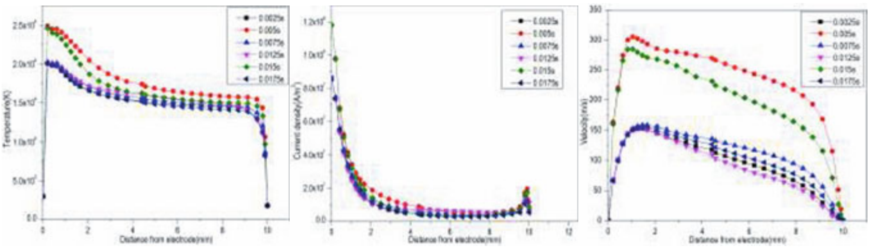


Figure 4. Simulated results of axial characteristics.
(a) temperature profiles, (b) current density profiles, (c) velocity profiles

Figure 4 presents the predicted results for the axial characteristics of AC arc at different times. As we can see from it, not like DC arc, the temperature of AC arc varies with time. As the only variable changing with time is current, so, we can say that, the temperature of AC arc varies with the change of currents, and greater the current, higher the temperature. Although the highest temperatures are changing with the time, distributions of the axial temperature of AC arc are similar to each other. For the characteristic of the AC electric current, we can know that the absolute values of current at four specified times (t=0.0025s, 0.0075s, 0.0125s and 0.0175s) are the same. Just as expected, the predicted temperatures at the four times are almost in agreement with each other. In figure 4(b) and (c), the predicted results for the current density and plasma velocity along the symmetric axis are presented respectively. The results show that the law of the temperature is appropriate to the current density and the velocity of the AC arc. So, for the AC arc, although the direction of current will change, the characteristics will not change for the equal values of current.

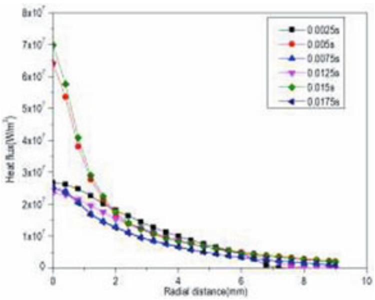


Figure 5. Heat flux on the bath surface.

The mechanism of heat transfer from arc to the melt surface is very complicate. The predicted heat flux from the AC plasma arc to the metal is presented in figure 5. As shown in figure 5, the greatest heat flux for AC arc appears at the central of arc, and the effective region of heating is very small, just around the central of arc. The heat flux of AC arc will vary with the time, and this is connected with temperature. The difference of the heat fluxes at different times is very evident, and higher current lead to higher heat flux. Although the direction of current will change with time, the heat fluxes will be similar as long as the absolute values of current are equal.

## Conclusion

1. The characteristics of the AC plasma arc will vary with the time, for the current is time-dependent.
2. Although the temperature distribution of the AC arc will change with the time, the highest values of temperature, current density and plasma velocity are always found at the central location closing to the graphite electrode, and so do for the heat flux.
3. The highest temperature and velocity of AC arc are varying periodically with time, just like the alternating current. And the periods of them are both half of the current's.
4. Just like DC arc, greater the current, higher the temperature and velocity. The distribution law of temperature at different times is very similar to each other. And so it is with the current density and velocity.

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**References**


1. J.A. Bakken, L. Gu, H.L. Larsen, and V.G. Sevastyanenko, "Numerical modeling of electric arcs," *Journal of engineering physics and thermophysics*, 70 (1997), 530-543.

2. K.C. Hsu, K. Etemadi, and E. Pfender, "Study of the free- burning high- intensity argon arc," *Journal of Applied Physics*, 54 (1983), 1293-1301.

3. J. McKelliget, and J. Szekely, "Heat transfer and fluid flow in the welding arc," *Metallurgical Transactions A*, 17 (1986), 1139-1148.

4. F. Lago, J. J. Gonzalez, P. Freton, and A. Gleizes, "A numerical modelling of an electric arc and its interaction with the anode: Part I. The two-dimensional model," *Journal of Physics D: Applied Physics*, 37 (2004), 883-897.

5. H.L. Larsen, G.A. Saevarsdottir, and J.A. Bakken, "Simulation of AC arcs in the Silicon Metal Furnace" (Paper presented at the $54_{th}$ Electric Furnace Conference Proceedings, Dallas, Texas, 9 December 1996), 157.

6. G.A. Saevarsdottir, J.A. Bakken, V.G. Sevastyanenko, and L.Gu, "Modeling of AC arcs in submerged-arc furnaces for production of silicon and ferrosilicon," *Iron & steelmaker*, 28 (2001), 51-57.

7. M.M. Moghadam, S.H. Seyedein, and M.R. Aboutalebi, "Fluid Flow and Heat Transfer Modeling of AC Arc in Ferrosilicon Submerged Arc Furnace," *Journal of Iron and Steel Research International*, 17 (2010), 14-18.

8. G.J. Dunn, T.W. Eagar, "Metal vapors in gas tungsten arcs: Part II. Theoretical Calculations of Transport Properties," *Metallurgical and Materials Transactions A*, 10 (1986), 1865-1871.

9. D.L. Evans, R.S. Tankin, "Measurement of emission and absorption of radiation by an argon plasma," *Physics of Fluids*, 10 (1967), 1137-1144.

10. S. Patankar, *Numerical heat transfer and fluid flow* (Boca Raton. CRC Press, 1980).

11. J. Alexis, M. Ramirez, G. Trapaga, and P. Jönsson, "Modeling of a DC Electric arc furnace: Heat transfer from the arc," *ISIJ international*, 40 (2000), 1089-1097.

12. R.T.C. Choo, J. Szekely, and R.C. Westhoff, "Modeling of high-current arcs with emphasis on free surface phenomena in the weld pool," *Welding Journal*, 69 (1990), 346-361.