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NUMERICAL ANALYSIS OF AN ARC PLASMA IN A DC ELECTRIC FURNACE

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Abstract

In order to analyze the heat transfer phenomena in the plasma flames, a mathematical model describing heat and fluid flow in an electric arc has been developed and used to predict heat transfer from the arc to the steel bath in a DC Electric Arc Furnace. The arc model takes the separate contributions to the heat transfer from each involved mechanism into account, i.e. radiation, convection and energy transported by electrons. The finite volume method and a SIMPLE algorithm are used for solving the governing MHD equations, i.e., conservation equations of mass, momentum, and energy together with the equations describing a standard k-ϵ model for turbulence. The model predicts heat transfer for different currents and arc lengths. Finally these calculation results can be used as a useful insight into plasma phenomena of the industrial-scale electric arc furnace. From these results, it can be concluded that higher arc current and longer arc length give high heat transfer.

Key Words : Plasma, Electric Arc Furnace, Computational Fluid Dynamics, Lorentz Force

1. INTRODUCTION

The Plasma means the gas phase that was separated positive and negative charges. The plasma has been used to make the steel in an electric arc furnace. So it is quite important to analyze the heat transfer mechanism in the plasma flame.

The purpose of this study is to understand the heat transfer of the plasma in an electric arc furnace, in addition to give some information of the optimum process variables and the system design.

2. MODELING OF AN ELECTRIC ARC

Figure 1 shows the computation domain. The domain is divided into three parts named cathode, air and anode region to add the heat flux in the nearest cell from the cathode and anode surface respectively. The arc length and current were changed in the range of 15~30cm and 32~44KA individually.

The following assumptions were used in this study. The plasma is the air has the electric conductivity and its thermodynamic properties are the function of the temperature.

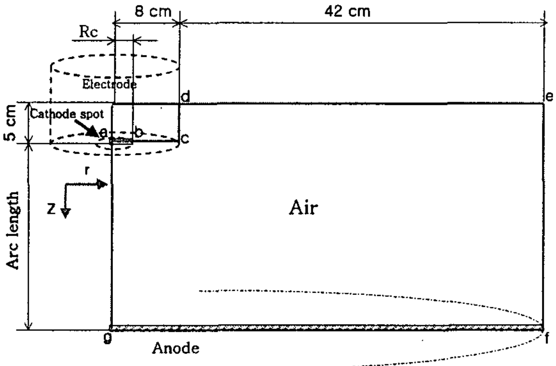

Fig.1. Calculation domain in a DC arc furnace

① The plasma is axis symmetry and its operation is steady state.
② The plasma is in the local thermal equilibrium (LTE).
③ The deformation of the anode surface by the collision of the plasma jet is ignored.

2,1 Governing Equations

The continuity

$$\nabla \cdot (\rho \mathrm{V}) = 0 \qquad (1)$$

The momentum equation

$$(\mathrm{V} \cdot \nabla)\rho \mathrm{V} = -\nabla \mathbf{p} + \nabla \tau + \mathbf{J} \times \mathbf{B} \qquad (2)$$

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where, p is the pressure, , $\mathbf{J}$ is the current density, $\mathbf{B}$ is the magnetic density, $\mathbf{J}\times\mathbf{B}$ is the generated Lorentz force by the interaction of the electro-magnetic field.

The energy equation

$$c_p(\mathrm{V}\cdot\nabla\rho T)=\nabla\cdot(k_{eff}\nabla T)+\mathrm{J}\cdot\mathrm{E}-S_R+\frac{5}{2}\frac{k}{e}\mathbf{J}\cdot\nabla T \qquad (3)$$

where, T is the temperature, $\mathbf{J}\cdot\mathbf{E}$ is Joule heating , S_R is the radiation loss and the last term is Thompson effect.

For the detailed boundary conditions, refer to the reference[1]. Thermodynamic properties of the plasma studied by M. Capitelli et. al., who calculated theoretically viscosity, thermal conductivity and electric conductivity from 50K to 100,000K[2], have been used. Also the density was calculated using the perfect gas law of state.

2.2 Electro-Magnetic field Computation.

The Lorentz force is given by

$$\mathbf{F}=\mathbf{J}\times\mathbf{B} \qquad (4)$$

where, $\mathbf{J}$ is the current density and its components J_z, J_r is calculated using the current definition, MHD approximation $\nabla\cdot\mathbf{J}=0$ and assumption that J_z is the parabola. $\mathbf{B}$ is the magnetic density and the azimuthal magnetic density B_θ in axis-symmetry is the follow.

$$B_\theta=\frac{\mu_p}{r}\int_0^r J_z r\,dr \qquad (5)$$

where, μ_p is the magnetic permeability.

2.3 Source term in the cathode region

In the cathode region, the heat energy is needed to ionize the plasma.

$$Q_c=|J_c|\frac{5}{2}\frac{k_b}{e}(T_c-T_{cathode}) \qquad (6)$$

where, T_c is the temperature in the cathode region, $T_{cathode}$ is the temperature on the cathode surface, k_b is the Boltzman constant and e is the electron discharge. [3]

2.4 Source terms in the anode region

In the anode region, the heat energy will be absorbed through the anode surface by the convection, radiation, Thompson effect and anode fall. In this computation, we described the heat transfer which occurs due to the convection, Thompson effect and anode fall. The radiation loss is solved using the IMMERSOL model.

$$Q_{con}=\frac{0.915}{k_w}\left(\frac{\rho_a\mu_{la}}{\rho_w\mu_{lw}}\right)^{0.43}\left(\frac{\rho_w\mu_{lw}v_a}{r}\right)^{0.5}c_p(T_a-T_{anode}) \qquad (7)$$

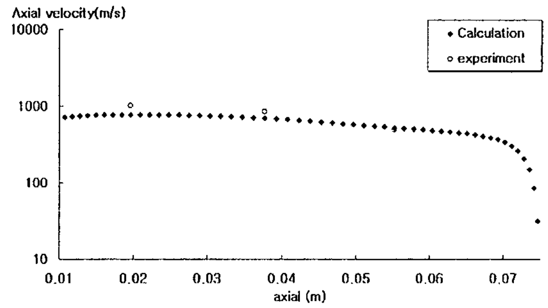
$$Q_{Thompson}=\frac{5}{2}\frac{k_b}{e}J_A(T_a-T_{anode}) \qquad (8)$$

$$Q_A=J_A(V_A-q_A) \qquad (9)$$

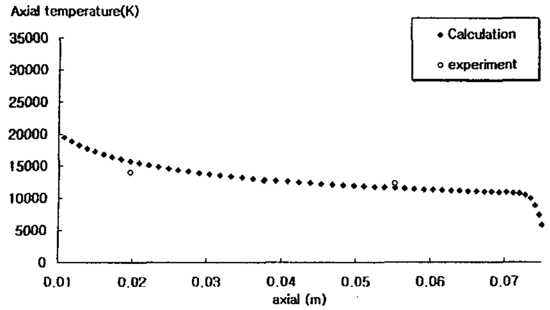
where, suffix w is the anode surface, suffix a is the anode region, J_A is the current density on the anode surface, T_{anode} is the temperature on the anode surface and V_A, q_A was individually assumed 4V of work function.[4][5]

3. RESULTS AND DISCUSSION

In order to check the validity of arc modeling, the previous computation was carried out. The results of numerical calculation (2.16KA current and 7cm arc length) were compared with the experimental results as shown in Fig 2.[6] The maximum velocity and temperature were indicated as 770m/s and 30,826K in the cathode region respectively. These results mean that the numerical computation is in accord with the experiment.



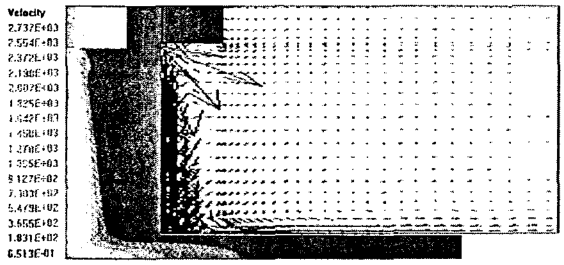
(a) Axial velocity



(b) Temperature

Fig 2. Comparison between experiment and computation

Figure 3 shows respectively the velocity and temperature field of the standard model (36KA current and 25cm arc length) which is the middle size in the working place. It appears that the maximum temperature and velocity are 31,860K in the cathode region and 2,737m/s at a 6.1cm position away from the cathode surface individually.



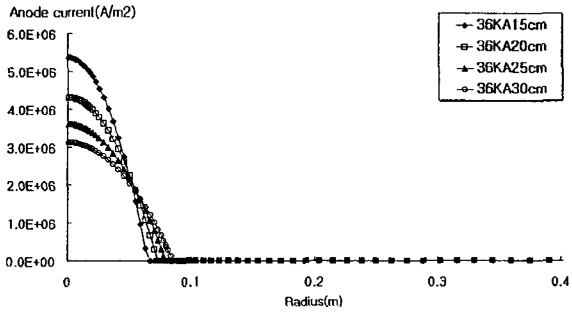
(a) Velocity Field

(b) Temperature Field

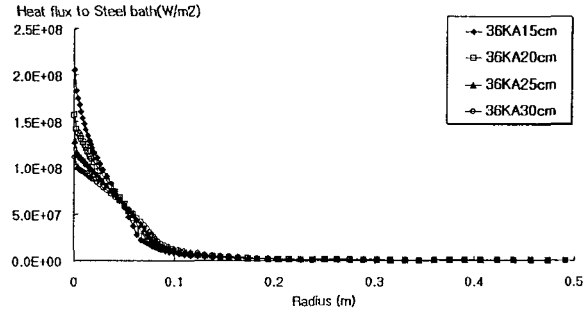
Fig 3. Characteristics of 36KA and 25cm arc length

As the arc length increases, the arc radius widens and the maximum current density on the anode surface decreases because that total current does not change regardless of the change of the arc length.

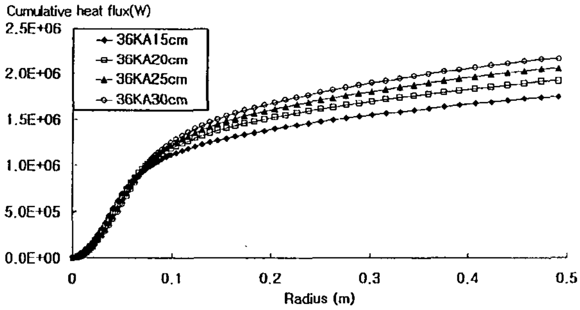
Figure 4(b) shows that the maximum total heat flux increases as the arc length shortens. But the cumulative heat flux integrated all over the anode surface increases in proportion to the growth of the arc length. Figure 5 shows that total heat flux and cumulative heat flux on the anode surface simply increased in proportion to input current.



(a) Anode Current

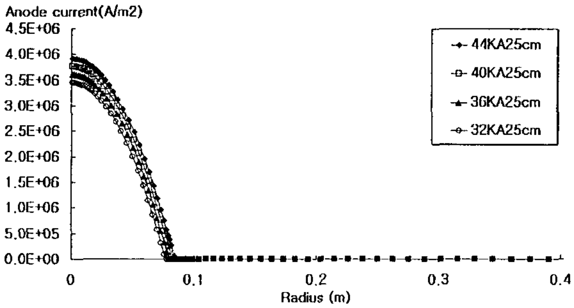


(b) Total Heat Flux

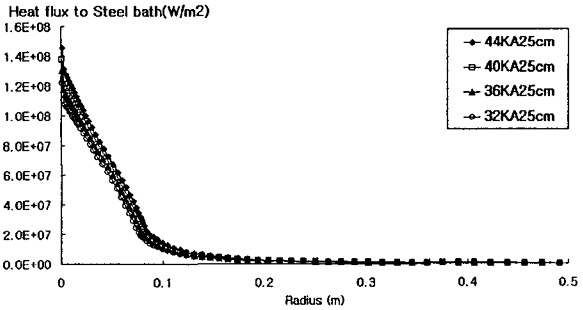


(c) Cumulative Heat Flux

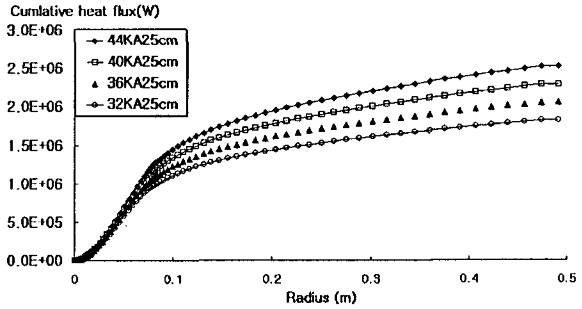
Fig 4. Characteristics of various arc lengths



(a) Anode Current



(b) Total Heat Flux



(c) Cumulative Heat Flux

Fig 5. Characteristics of various input currents

4. CONCLUSIONS

This study was performed numerically with two parameters i.e. arc lengths and currents to analyze the DC electric arc furnace. The results can be summarized as follows.

(1) The computational results have a good agreement with the experimental results.

(2) The cumulative heat flux increases as the arc length grows.

(3) The cumulative heat flux increases as the input current increases.

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