Journal of the Korean Society of Marine Engineers. Vol.28, No.8, pp.1251~1257, 2004. 11 (ISSN 1226-9549)

# Numerical Analysis of an Arc Plasma in a DC Electric Furnace

Jong-Hoon Lee* · Yeon-Won Lee†

(Manuscript : Received OCT. 11, 2004 ; Revised NOV. 18, 2004)

**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 onto account, that is radiation, convection and energy transported by electrons. The finite volume method and a SIMPLE algorithm are used for solving the governing MHD equations, that are 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, MHD (Magneto-Hydro Dynamics), Lorentz force

## 1. Introduction

The Plasma means the gas phase that is separated positive and negative charges at high temperature of above 6,000~30,000$K$. The plasma has been used to make the steel in an electric arc furnace as shown in Fig. 1. So it is quite important to analyze the heat transfer mechanism in the plasma flame.

J.Szekely et. al. have investigated heat transfer and fluid flow in the electric arc furnace. But, they treated properties of fluid as constants at their study in 1983[1]. B. Liu and T. Zhang et. al studied the influence of process parameters on the fluid flow of a plasma jet with a viewpoint of the flow characteristics in 2000[2]. In Korea, there are few papers in this field. D. E. Lee and S. J. Kim studied the heat transfer phenomena in the plasma flames and published in their internal report in 2002[3].

When the electric current flows between the cathode and anode, magnetic field is

---

† Corresponding Author(School of Mechanical Engineering, Pukyong National University)
E-mail : ywlee@pknu.ac.kr, Tel : 051-620-1417

* School of Mechanical Engineering, Graduated School of Pukyong National University

generated simultaneously in the periphery of the plasma column. At that time, Lorentz force is created by the interaction between electric field and magnetic field as shown in Fig. 2. This force drives the plasma jet in a downward direction.

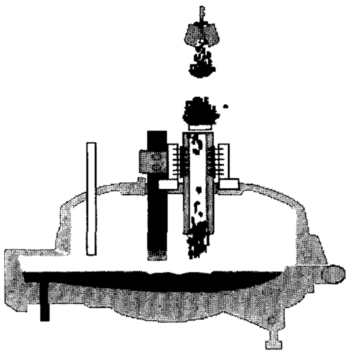


**Fig. 1 Schematic diagram of an electric furnace**

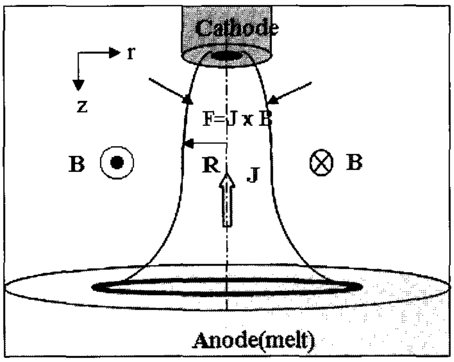


**Fig. 2 Schematic diagram of a plasma**

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

## 2. Numerical Analysis

Figure 3 shows the computational domain that is consisted of cathode, air and anode region. In order to add the heat flux obtained from the experimental information, the special attentions are given to the nearest cells from the cathode and anode surface respectively.

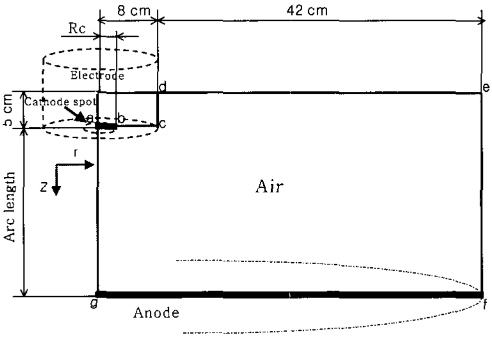


**Fig. 3 Computational domain in a DC arc furnace**

The plasma is considered as the air with the electric conductivity and its thermodynamic properties are the functions of the temperature. The following assumptions were used in this study.

① The plasma is axis symmetric 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

Governing equations needed to solve this problem are as follows.

The continuity equation

$$\nabla \cdot (\rho \vec{v}) = 0 \tag{1}$$

The momentum equation

$$(\vec{v} \cdot \nabla)\rho \vec{v} = -\nabla \vec{p} + \nabla \tau + \vec{J} \times \vec{B} \tag{2}$$

where, $\vec{p}$ is the pressure, $\vec{J}$ is the current density, $\vec{B}$ is the magnetic density, $\vec{J}\times\vec{B}$ is the generated Lorentz force by the interaction between the electric and magnetic field.

The energy equation

$$c_p(\vec{v}\cdot\nabla\rho T)=\nabla\cdot(k_{eff}\nabla T)+\vec{J}\cdot\vec{E}-S_R+\frac{5}{2}\frac{k}{e}\vec{J}\cdot\nabla T \tag{3}$$

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

For the detailed boundary conditions and properties of fluid, refer to the related references. Thermodynamic properties of the plasma were studied by M. Capitelli et. al., who calculated theoretically viscosity, thermal conductivity and electric conductivity from $50K$ to $100,000K$ using the pertabative Chapman-Enskog method [4]. And the perfect gas law of state was used in this study.

### 2.2 Electro-Magnetic field Computation

The Lorentz force is given by

$$\vec{F}=\vec{J}\times\vec{B} \tag{4}$$

where, $\vec{J}$ is the current density and its components $J_z$, $J_r$ are calculated using the current definition, MHD approximation $\nabla\cdot\vec{J}=0$ and assuming that $J_z$ is the parabola. $\vec{B}$ is the magnetic density and the azimuthal magnetic density $B_\theta$ is as follow in the axis symmetry.

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

where, $\mu_p$ is the magnetic permeability.

### 2.3 Source term in the cathode region

The heat energy needed to ionize the plasma in the cathode region is given to the boundary cells as source terms. It is considered as equation (6) from the previous experimental studies.

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

where, $T_c$ is the temperature in the cathode region, $T_{cathode}$ is the temperature on the cathode surface, $k_b$ is the Boltzmann constant and $e$ is the electron discharge.[5]

### 2.4 Source terms in the anode region

In the anode region, the heat energy will be absorbed into the bath 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.

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

$$Q_{Thompson}=\frac{5}{2}\frac{k_b}{e}J_A(T_a-T_w) \tag{8}$$

$$Q_A=J_A(V_A-q_A) \tag{9}$$

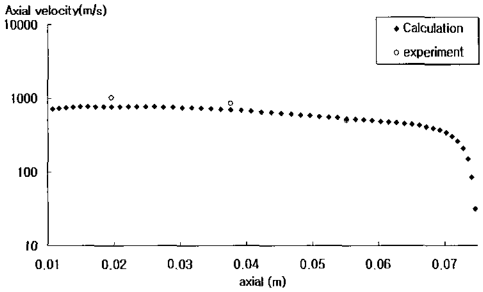
where, suffix $w$ is the anode surface, suffix a is the anode region, $J_A$ is the current density on the anode surface, $T_w$ is the temperature on the anode surface and $V_A$, $q_A$ were assumed as 4V of work function respectively.[1][6]

For radiation model, the validity will be scrutinized in the near future.

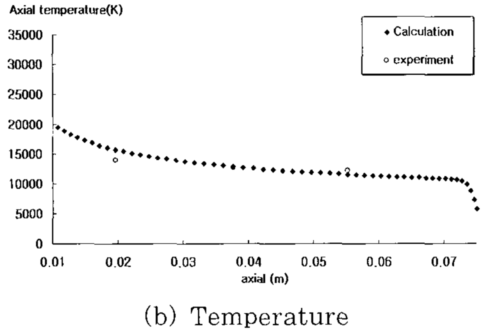
## 3. Results and Discussion

### 3.1 preliminary study

In order to check the validity of arc modeling, the preliminary computation was carried out. The results of numerical calculation in the case of 2.16*kA* current and 7cm arc length were compared with the experimental results as shown in Fig. 4. The maximum velocity and temperature were indicated as 770*m/s* and 30,826*K* in the cathode region respectively. These results mean that the numerical computation is in accord with the experiment.



(a) Velocity

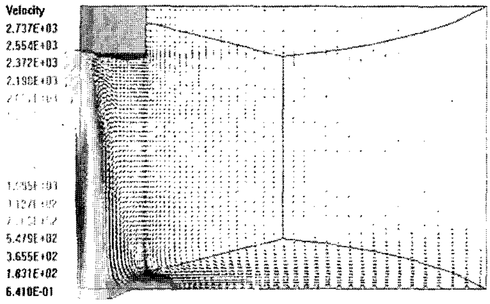


(b) Temperature

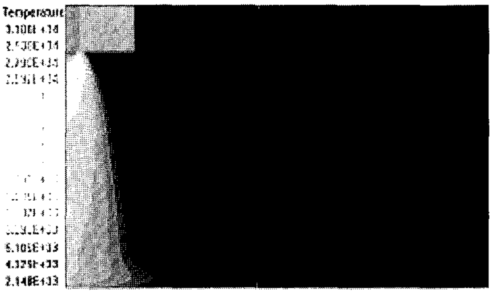
**Fig. 4 Comparison between the experiment and the numerical computation**

### 3.2 Present study

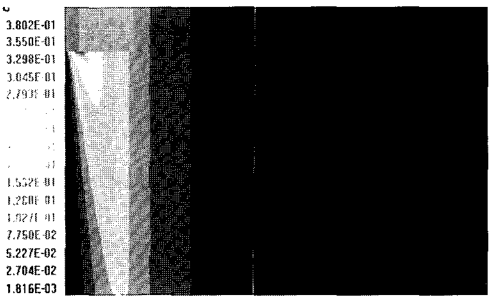
In this study, we have investigated the influences of the arc length and the electric current that are the most important factors in the arc plasma. The arc length and electric current were changed in the range of 15~30*cm* and 32~44 *kA* respectively.



(a) Velocity Field

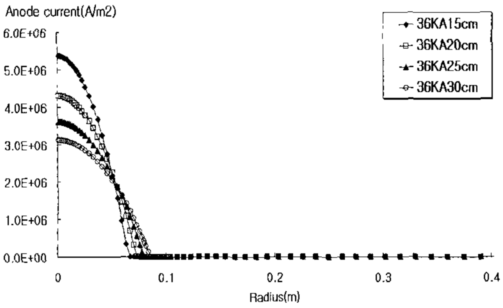


(b) Temperature Field

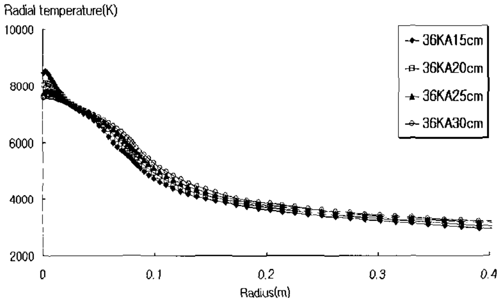


(c) Magnetic Field

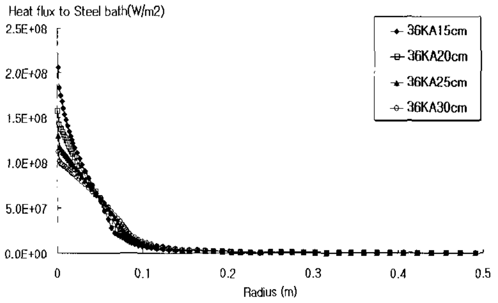
**Fig. 5 Characteristics of 36 kA and 25 cm arc length**



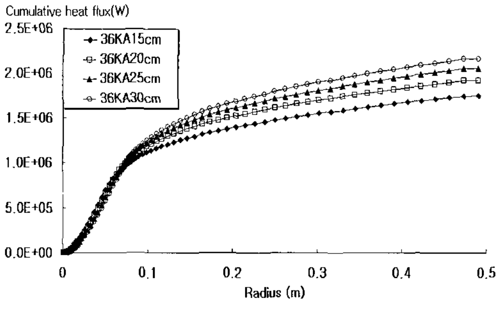
(a) Anode Current



(b) Temperature



(c) Total Heat Flux



(d) Cumulative Heat Flux

**Fig. 6 Characteristics of various arc lengths**

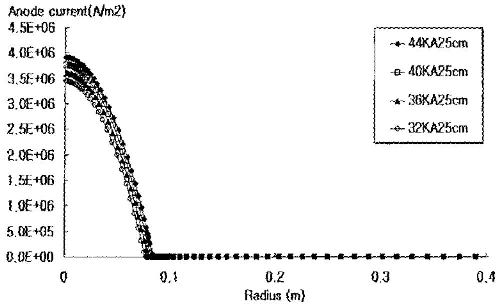
Figure 5(a) and 5(b) show the velocity and temperature field of the standard model (36 kA current and 25 cm arc length) which is the middle size in the working place. It appears that the maximum temperature is 31,860*K* in the cathode region and the velocity is 2,737*m/s* at 6.1*cm* away from the cathode surface. Figure 5(c) is the magnetic field. The maximum magnetic density appears in the cathode region, because the electric current density is the highest.

As the arc length increases, the arc radius widens and the maximum current density on the anode surface decreases because the total current does not change regardless of the change of the arc length as shown in Fig. 6(a).

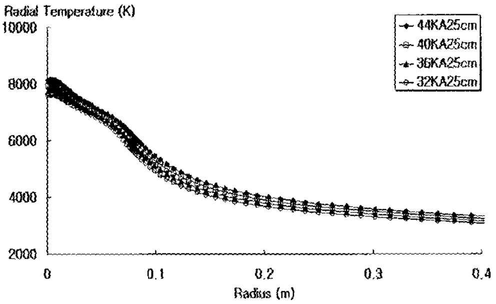
Figure 6(b) is the temperature on the bath. Although the highest temperature appears near the center of arc in the case of 15 *cm* arc length, actually, the long arc length has high temperature over the wide range of bath surface as the arc length increases.

Figure 6(c) shows that the maximum total heat flux increases at the center of arc as the arc length shortens. But the cumulative heat flux which is integrated all over the anode surface increases in proportion to the growth of the arc length as shown in Fig. 6(d).

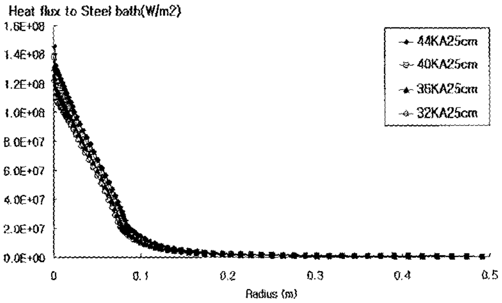
Figure 7(a) shows that anode current is directly proportional to the increase of the input electric current. Also, temperature, total heat flux and cumulative heat flux on the anode surface simply increase in proportion to input current as shown in Fig. 7(b), (c) and (d).



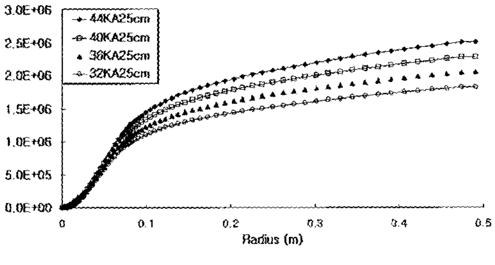
(a) Anode Current



(b) Temperature



(c) Total Heat Flux



(d) Cumulative Heat Flux

**Fig. 7 Characteristics of various input currents**

## 4. Conclusions

This study was numerically performed 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 numerical results have a good agreement with the experimental results.
(2) The cumulative heat flux increases as the arc length increases
(3) The cumulative heat flux increases as the input current increases

## Acknowledgement

This work was supported by the BK21 Group of Pukyong National University.

## References

[1] J. Szekely, J. Mckelliget and M. Choudhary, "Heat transfer fluid flow and bath circulation in electric arc furnaces and DC plasma furnaces", Ironmaking and Steelmaking, Vol. 10, No. 4, pp. 169-179, 1983

[2] B. Liu, T. Zhang and D. T. Gaven, "Computational analysis of the influence of process parameters on the flow field of a plasma jet", Surface and Coating Technology 132, pp. 202-216, 2000

[3] D. E. Lee and S. J. Kim, "Analysis of Heat transfer phenomena in the plasma flames", RIST, No. 16-3, pp. 303-310, 2002

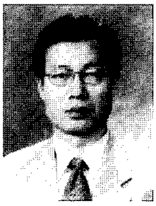
[4] M. Capitelli, G. Colonna, C. Gorse and

A. D′Angola, ″Transport properties of high temperature air in local thermodynamic equilibrium″, Eur. Phys. J. D 11, pp. 279-289, 2000

[5] P. Josson, PhD Thesis, MIT, Boston, USA, 1993

[6] J. W. McKelliget and J. Szekely: Metall. Trans. A, 17A, 1139, 1986

## Author Profile



### Yeon-Won Lee

He graduated from Kyungpook National University (B.A. 1981, M.S. 1983) in Korea. He received his Ph.D. degree from the University of Tokyo (Doctor of Engineering 1993) in Japan. He worked at POSCO E&C for 3 years as a Team Leader of Division of Mechanical Design. He visited the Institute of Industrial Science of the University of Tokyo as a visiting professor in 1997. He has severed as a professor of the School of Mechanical Engineering in Pukyong National University since 1993. His research interests are CFD, various natural energy problems including wave energy conversion, and MEMS technology.

### Jong-Hoon Lee

He graduated from Pukyong National University (B.A. 1999). At present, he is studying about CFD in Master Course of same university. He obtained three technical certificates for general machine, construction machinery and welding in 1998. He is interested in aircraft and space science.