Numerical Simulation of Heat Transfer and Fluid Flow in a DC Plasma-Arc Reactor for the Thermal Treatment of Hazardous Wastes

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Abstract

In this work, Magnetic Hydrodynamic (MHD) model is used to simulate heat transfer and fluid flow in a DC Plasma-Arc reactor for waste thermal treatment. Through the coupled iterative computation about electromagnetic equations (using magnetic vector potential) and hydrodynamic equations, the temperature and velocity distributions are solved, which are the most valuable information for industrial application.

The simulation results clearly describe the phenomenon of high temperature cathode jet of plasma-arc. The gas around arc region is heated and driven to flow by cathode jet. The situation of heat transfer and fluid flow is obtained, which is expected to meet the requirements for industrial application of hazardous waste treatment with the plasma-arc technology.

Keywords: Modeling, Plasma Arc, thermal plasma, Magnetic hydrodynamic model

1. Introduction

Plasma technology has been widely used to destroy the hazardous wastes. In a plasma-arc reactor, the distributions of temperature and velocity have important influence on the mass transfer of harmful elements, and directly determine the destruction efficiency of the hazardous wastes. Because it is very difficult to directly measure the temperature and velocity fields inside the arc region, numerical simulation is a necessary method to realize the inner situation of the reactor. The MHD model is an effective model for simulating heat transfer and fluid flow in Plasma-Arc reactor. [1,2]

In the MHD model, plasma gas is treated as electrical conductive fluid, whose conductivity changes with temperature. Take argon for example, its conductivity is close to zero when temperature is below 3000 K, however, when temperature increases from 5000K to 10000K, its conductivity will quickly rise, from 1.03 to 2730 S/m. This phenomenon can reflect the ionization process of gas with temperature increasement. Furthermore, the plasma density, specific heat, viscosity and thermal conductivity are all the functions of temperature. Through the coupled iterative computation about electromagnetic equations and hydrodynamic equations, temperature and velocity distributions can be solved. More details are in the next part of this paper.

Traditional approach of the plasma arc modeling usually uses magnetic inductive intensity parameter B to describe magnetic field. [1,2] In this work, magnetic vector potential A is used instead of B. With this innovation, it is more convenient to modeling the electrical and magnetic field of plasma-arc by commercial CFD code FLUENT with UDS method[3], which is a second development method of FLUENT.

2. MODELING OF DC PLASMA ARGON ARC

2.1 Assumptions

The Assumptions used in the present modeling include:

(1) The plasma flow is steady, laminar and axially symmetric;

(2) In the arc column region, it is assumed to be in local thermodynamic equilibrium (LTE) state;

(3) The plasma is optically thin;

(4) The arc plasma density, specific heat, viscosity and thermal and electrical conductivities are the functions of temperature only;

(5) The gravity and viscous dissipation are negligible.

2.2 Governing equations and Numerical method

Under the steady and axial symmetric conditions, the MHD equations describing arc plasma motion are as follows (the subscripts r and z representing radial direction and axial direction, respectively. expressions in the panes are special momentum and energy source terms concerning with plasma):

Mass conservation:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r)+\frac{\partial}{\partial z}(\rho v_z)=0 \tag{1}$$

Radial momentum conservation:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r^2)+\frac{\partial}{\partial z}(\rho v_r v_z)=-\frac{\partial P}{\partial r}+\frac{1}{r}\frac{\partial}{\partial r}(2r\mu\frac{\partial v_r}{\partial r}) +\frac{\partial}{\partial z}[\mu(\frac{\partial v_z}{\partial r}+\frac{\partial v_r}{\partial z})]-2\mu\frac{v_r}{r^2}-\boxed{j_z B_\theta} \tag{2}$$

Axial momentum conservation:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r v_z)+\frac{\partial}{\partial z}(\rho v_z^{\,2})=-\frac{\partial P}{\partial z}+\frac{\partial}{\partial z}(2\mu\frac{\partial v_z}{\partial z}) +\frac{1}{r}\frac{\partial}{\partial r}[r\mu(\frac{\partial v_z}{\partial r}+\frac{\partial v_r}{\partial z})]+\boxed{j_r B_\theta} \tag{3}$$

Energy conservation:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho c_p v_r T)+\frac{\partial}{\partial z}(\rho c_p v_z T)=\frac{1}{r}\frac{\partial}{\partial r}(rk\frac{\partial T}{\partial r})+\frac{\partial}{\partial z}(k\frac{\partial T}{\partial z}) \boxed{+\frac{j_r^{\,2}+j_z^{\,2}}{\sigma}+\frac{5k_B}{2e}(j_r\frac{\partial T}{\partial r}+j_z\frac{\partial T}{\partial z})-U} \tag{4}$$

The basic four variables defined by Eqs. (1)-(4) are temperature T, pressure P, radial velocity v_r and axial velocity v_z. The plasma property functions are density ρ, viscosity μ, specific heat c_p, thermal conductivity k and electrical conductivity σ.

For high power arc, the radiation term U in Eqn. (4) can't be neglected. The radiation loss model adopted is then:[4]

$$U = -c[\frac{1}{r}\frac{\partial}{\partial r}(r\sigma_0 T^4) + \frac{\partial}{\partial z}(\sigma_0 T^4)] \quad (5)$$

Where $c \leq 1$ is the gas gray scale, and σ_0 is Stefan–Boltzmann constant. The current density components j_r, j_z and the magnetic inductive intensity B_θ (the value of ***B***) required in Eqs. (3) and Eqn. (4) are obtained by Maxwell's equations in magnetic vector potential format:

$$\vec{E} = -\nabla\varphi - \frac{\partial\vec{A}}{\partial t}$$

$$\vec{B} = \nabla\times\vec{A}$$

Where **E**, φ, **B**, **A** are electrical intensity vector, electrical potential, magnetic inductive intensity vector, magnetic vector potential. Under the steady and axial symmetric conditions, equations below are derived:

Current continuity equation:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\sigma\frac{\partial\varphi}{\partial r}) + \frac{\partial}{\partial z}(\sigma\frac{\partial\varphi}{\partial z}) = 0 \quad (6)$$

Maxwell's equation:

$$\begin{aligned}\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial A_z}{\partial r}) + \frac{\partial}{\partial z}(\frac{\partial A_z}{\partial z}) &= -\mu j_z \\ \frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial A_r}{\partial r}) + \frac{\partial}{\partial z}(\frac{\partial A_r}{\partial z}) &= -\mu j_r\end{aligned} \quad (7)$$

Ohm's law:

$$\begin{aligned}j_z &= -\sigma\frac{\partial\varphi}{\partial z} \\ j_r &= -\sigma\frac{\partial\varphi}{\partial r}\end{aligned} \quad (8)$$

For converting ***A*** to ***B***, which is necessary in Eqs. (2) and (3), an equation is need:

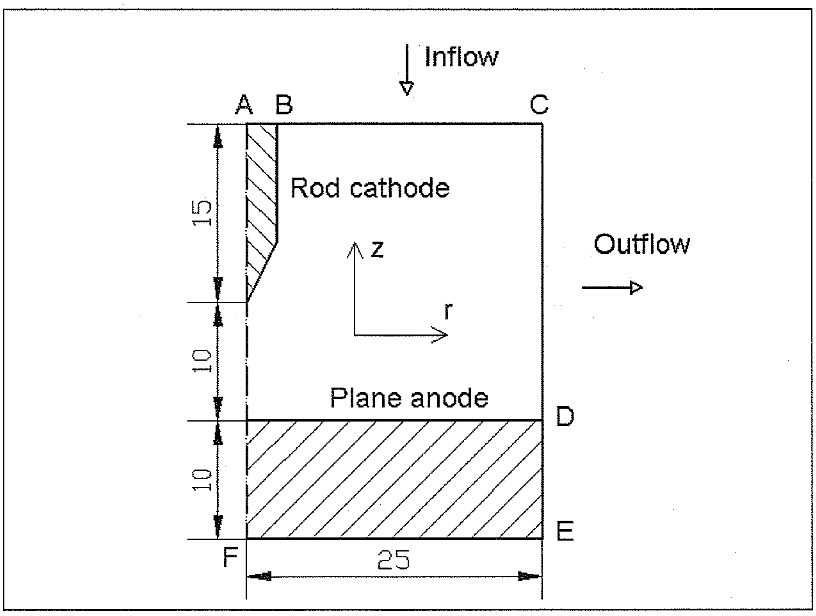
$$B_\theta = \frac{1}{r}\left(\frac{\partial A_r}{\partial z} - \frac{\partial A_z}{\partial r}\right) \tag{9}$$

All the previous Eqs. (1)-(4), (7) and (8) are elliptical partial differential equations (PDE), which could be solved by using CFD commercial code FLUENT. Besides basic hydrodynamics equations (Eqs. (1)-(5)) contained by FLUENT, Eqs. (7) and (8) have to be added into FLUENT by using UDS method.[3] The special source terms in Eqs. (2), (3), (4) and (8) are treated by using UDF method.[3]

2.3 Boundary conditions

The calculation domain of the DC plasma arc is shown in Fig. 1. The rod cathode is made of graphite, and the cone angle of its tip is 60 degree. The plane anode is made of copper. Argon is chosen as the plasma working gas. The modeling domain contains 22574 cells.

Figure 1. Geometry of the arc model (mm)



The boundary conditions used in the present modeling are summarized in Table 1 with: [5]

$$\Upsilon \equiv \frac{\partial \Omega}{\partial n} = 0$$

$\Lambda \equiv$ extrapolation from the interior of the domain

The use of the lambda (Λ) boundary is typical when the outflow at the boundary is not at a high Peclet number ($Pe = RePr$ where Re is the Reynolds number and Pr the Prandtl number). That particular boundary condition was chosen because the flow at the frontiers of the numerical domain might not be fully developed, and also because it enables the solver to easily treat any occurring backflow.[3] It is assumed that cathode and anode is cooled to 2000 K. The boundary condition of electrical potential equation is given by voltage rather than current density.

Table 1. Boundary conditions for arc model.

	AB	BC	CD	EF	AF
P	--	1 atm	1 atm	--	Υ
T	2000 K	Λ	Λ	2000 K	Υ
φ	-40 V	Υ	Υ	0	Υ
$\vec{A}$	0	0	0	0	Υ
$\vec{v}$	--	Λ	Λ	--	Υ

2.4 Numerical Results

Through the coupled iterative computation about previous equations (1)-(9), numerical results are obtained. It can be seen from Fig. 2 that the isotherms form a shape of bell, which is typical pattern of arc isotherms. The point of maximum temperature appeared on the tip of cathode as same as real arc.[1] Compared with the isotherms measured and calculated by K.C. Hsu *et al.* in Fig. 3 (P=1 atm, I=100 A, Argon),[1] it can be found that they are essentially similar. Velocity vectors of argon arc are shown in Fig. 4, maximum of velocity is 38.4 m/s, and there is lack of accurate experiment data that can be referred. It is indicated in Fig. 4 that plasma jet flow impacts on the plane anode and form vortex.

Figure 2. Isotherms of argon arc

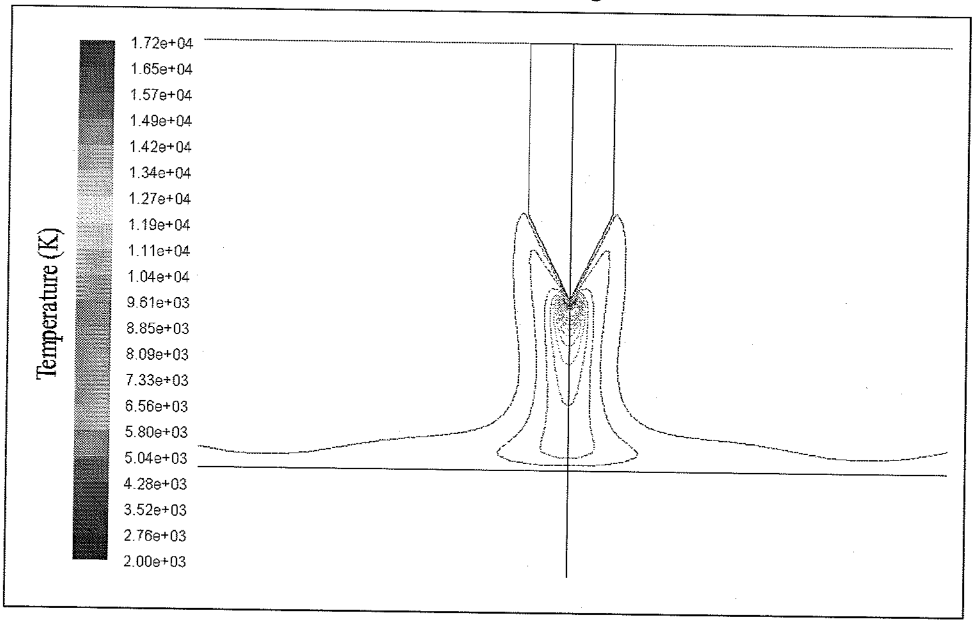
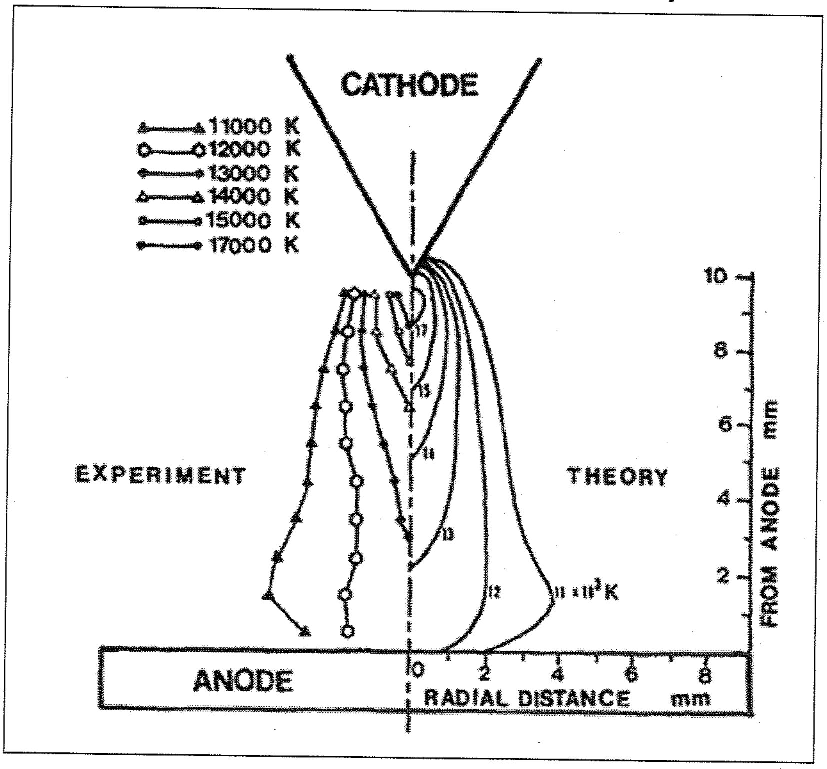
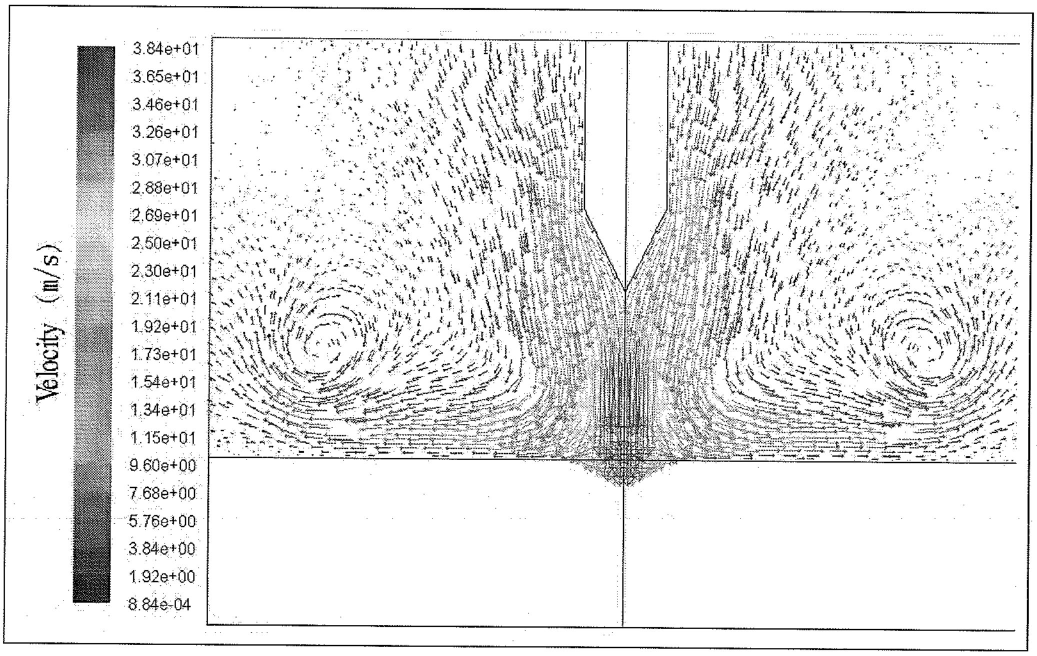


Figure 3. Isotherms of argon arc measured and calculated by K.C. Hsu *et al.*[1]



Argon is ionized in the electric field, and then heated by Joule heat. Its temperature increase to more than 10000K, get into the temperature range of plasma. Actually, electrons in plasma are driven by Lorentz force, and then generate a cathode jet. However, in the MHD model, plasma is not considered as a mixture of electrons and ions, but a kind of single component electrical conductive fluid whose conductivity varies with temperature. So plasma in the MHD model can be driven by Lorentz force to generate a "cathode jet".

Figure 4. Velocity vectors distribution of argon arc

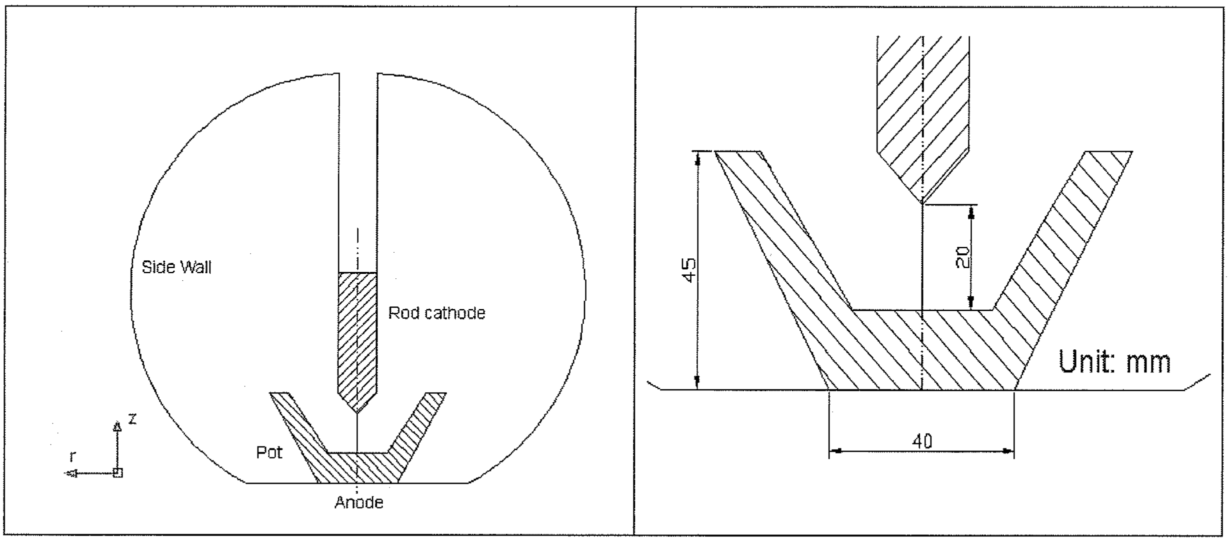


3. MODELING OF THE PLASMA-ARC REACTOR

The reactor shown in Fig. 5 is an experimental plasma-arc reactor developed in the laboratory of Waste Treatment Technology, Institute of Mechanics, Chinese Academy of Sciences (CAS). It is used for pyrolysis of hazardous organic compounds or vitrification of inorganic wastes with high content of heavy metals. Those assumptions in the previous section are still suitable for this case.

This reactor is simplified as a closed axial symmetric model. Actually, there should be an inlet and an outlet on the side wall of the reactor.

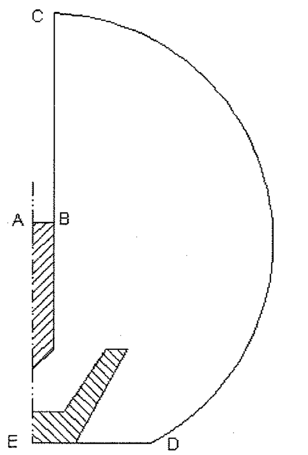
Figure 5. Plasma-Arc reactor model



3.1 Boundary conditions

Boundary conditions used in the present modeling are summarized in Table 2. These boundaries are either solid walls or axis, so it is unnecessary to set pressure boundary condition. The electrical potential difference between the two electrodes is 40 V. The rod cathode and melting pot are both made of graphite.

Table 2. Boundary conditions for Plasma-Arc reactor.



	AB	BC	CD	DE	AE
T	2000 K	Λ	1500 K	1500 K	ϒ
φ	-40 V	-40 V	ϒ	0	ϒ
$\vec{A}$	0	0	0	0	ϒ
$\vec{v}$	--	Λ	Λ	--	ϒ

3.2 Numerical Results

Numerical results are obtained by the same method as that of previous case.

Isotherms are shown in Fig. 6. Compared with previous case, because the distance between the two electrodes increases from 10 mm to 20 mm, the maximum temperature decreases evidently.

Figure 6.a. Isotherms of Plasma-Arc reactor

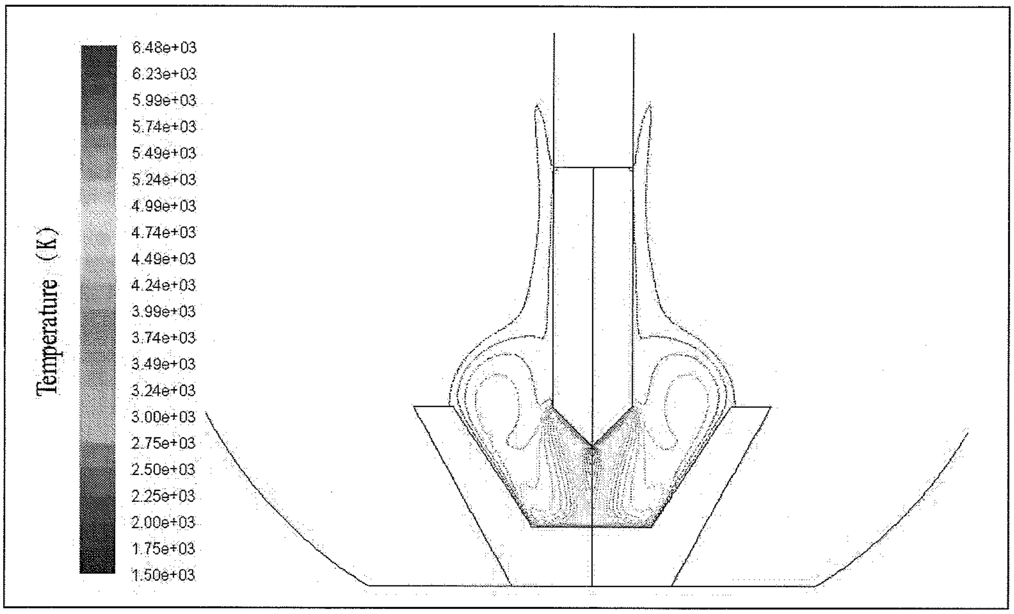


Figure 6.b. Isotherms of Plasma-Arc reactor

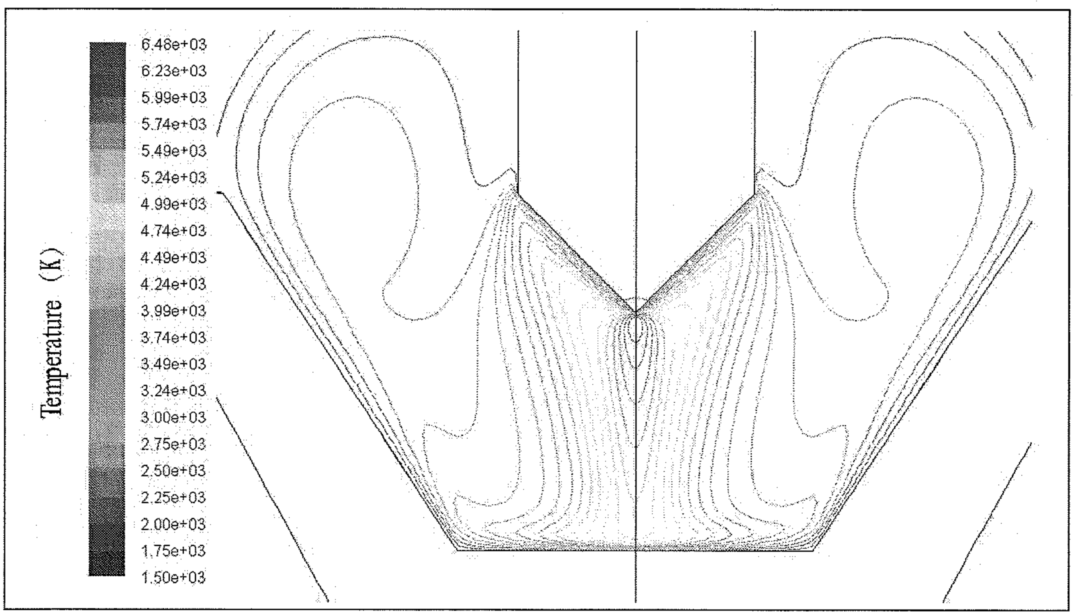


Figure 7.a. Velocity vector distribution in the plasma-arc reactor

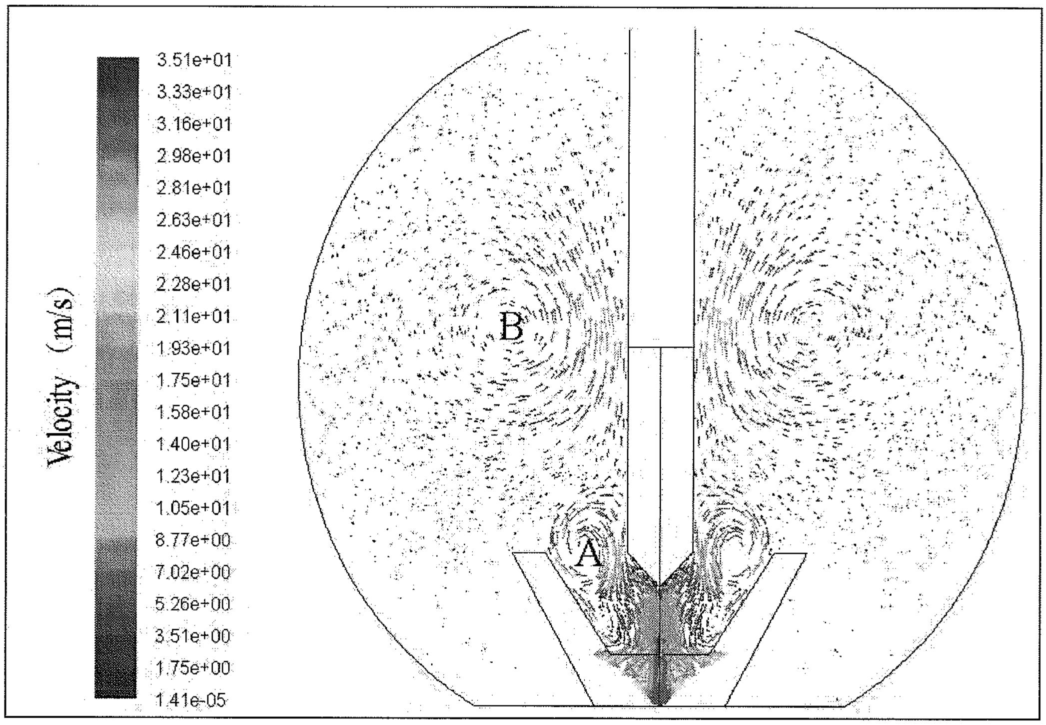
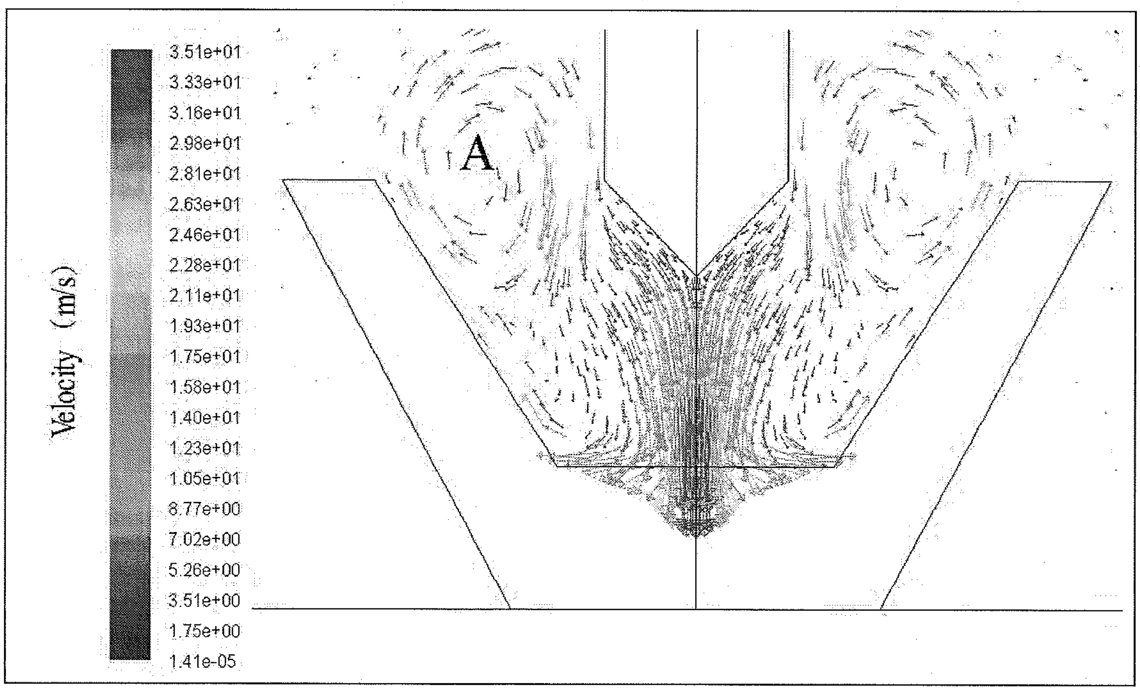


Figure 7.b. Velocity vector distribution in the plasma-arc reactor



The velocity vector distribution in the plasma-arc reactor is shown in Fig. 7. As the same, driven by Lorentz force, a cathode jet forms, and then carries the gas around to flow. In Fig. 7.a, it is indicated that two vortex cores (A and B in Fig. 7) are generated by gas flow. This is important for hazardous waste treatment, because existence of vortex can increase the residence time of gas in the high temperature reaction zone and result in higher destruction efficiency of hazardous waste.

4. CONCLUSIONS

In this paper, it has been proved that the use of a combination of MHD model and magnetic vector method is an effective way to modeling arc plasma. A similar attempt was made by A Blais *et al.*[5] The difference between Ref. 5 and this paper lies in the electromagnetism equations' usage. In Ref.5, electrical vector potential is selected instead of magnetic vector potential in this paper.

The simulation results clearly describe the phenomenon of high temperature cathode jet of plasma-arc. The gas around arc region is heated and driven to flow by cathode jet. The situation of heat transfer and fluid flow is obtained, which is expected to meet the requirements for industrial application of hazardous waste treatment by plasma-arc technology. With the numerical simulation results, optimization of the plasma-arc reactor can be made to increase the destruction efficiency of hazardous waste in the future.

5. ACKNOWLEDGEMENTS

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