Numerical Simulation of Temperature Field and Temperature Control of DC Arc Plasma Torch

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Abstract. In order to study and analyze the internal heat transfer process of DC arc plasma torch, a two-dimensional axisymmetric model of DC arc plasma torch was established based on magnetohydrodynamics and heat transfer theory. The finite element analysis software COMSOL was used to simulate the temperature field under different conditions. The results show that when the terminal current is constant, the DC plasma arc voltage and the average temperature of the torch outlet increase with the increase of nitrogen standard flow rate, and the maximum temperature in the plasma torch decreases with the increase of nitrogen standard flow rate. When the standard flow rate of nitrogen is constant, the arc voltage decreases with the increase of arc current, and the average temperature of plasma torch exit and the maximum temperature in the torch increase with the increase of arc current. The analysis of simulation data provides theoretical guidance for the temperature control of experimental DC plasma torch.

1. Introduction

DC arc plasma torch can produce jet with high temperature, high enthalpy and high chemical activity, which is widely used in various industrial fields, such as ignition, thermal spraying, cutting, new material manufacturing, chemical manufacturing, hazardous waste solid treatment\cite{1-5}. With the development of society, the production of urban garbage is increasing, and the impact on the environment is increasingly serious. Compared with the traditional waste treatment methods, such as sanitary landfill, composting, incineration and pyrolysis, the outlet reaction temperature of the plasma torch can be as high as 2000 °C \cite{6}, and all kinds of harmful waste or gases can be effectively pyrolyzed at high temperature. The treatment method of plasma pyrolysis gasification waste has the advantages of high resource utilization and the most thorough harmlessness, and has great potential in protecting the environment, recycling energy and promoting sustainable development\cite{5}. However, the short working life of the DC arc plasma torch, the core equipment, limits the promotion of this technology. In order to study and analyze the internal heat transfer process of DC arc plasma torch, it is difficult to effectively measure the internal temperature of the torch in reality. It is necessary to establish a reliable mathematical model for numerical simulation and analysis, which is helpful to the actual temperature control of DC plasma torch jet.

In this paper, the DC arc plasma model is constructed based on the theories of electromagnetism, fluid mechanics and heat transfer. The finite element software COMSOL is used to conduct the two-dimensional axisymmetric modeling according to the equal proportion of the actual equipment. Based
on the finite element (FEA) algorithm, the temperature field of DC arc plasma torch in this paper is numerically calculated.

2. Numerical models

2.1 Basic assumptions

In order to simplify the calculation model and accurate numerical solution, this paper makes the following assumptions for the model:

1) The plasma is in the local thermodynamic equilibrium state, that is, the electron temperature is approximately equal to the heavy particle temperature, and the physical parameters are only the function of temperature.
2) Plasma flow is steady, laminar and compressible.
3) The plasma torch is a two-dimensional axisymmetric structure.
4) Plasma is optical thin.
5) The arc attachment process on anode surface is not modeled.
6) Gravity is not considered [6-8].

2.2 Control equations

Based on the steady-state assumption in the previous section, the control equations are as follows:

\[ \nabla \cdot ( \rho \mathbf{u} ) = 0 \]  

(1)

Navier-Stoke equation:

\[ \rho \left( \mathbf{u} \cdot \nabla \right) \mathbf{u} = \nabla \cdot \left[ -p \mathbf{I} + \eta \left( \nabla \mathbf{u} + \left( \nabla \mathbf{u} \right)^\top \right) - \frac{2\eta}{3} \left( \nabla \cdot \mathbf{u} \right) \mathbf{I} \right] + \mathbf{F} \]  

(2)

The conservation of heat energy is expressed by Fourier equations with convection and source terms:

\[ \rho C_p \cdot \nabla T + \nabla \cdot \mathbf{q} = \mathbf{Q} + \mathbf{Q}_p + \mathbf{Q}_{vd} \]  

(3)

\[ \mathbf{q} = -k \nabla T \]

Current continuity equation:

\[ \nabla \cdot \mathbf{J} = 0 \]  

(4)

Electromagnetic field equation:

\[ \nabla \times \mathbf{H} = \mathbf{J} \]  

(5)

\[ \mathbf{B} = \nabla \times \mathbf{A} \]  

(6)

\[ \mathbf{J} = \sigma \mathbf{E} + \sigma_v \times \mathbf{B} + \mathbf{J}_e \]  

(7)

\( \mathbf{u} \) is the velocity vector. \( \rho \) and \( \eta \) are fluid density and fluid dynamic viscosity coefficient respectively. \( p \) is pressure. \( \mathbf{I} \) is a constant tensor. \( \mathbf{F} \) is the volume force vector. \( C_p, k, T \) are constant pressure specific heat, thermal conductivity and temperature respectively. \( \mathbf{J}, \mathbf{H}, \mathbf{B}, \mathbf{A}, \mathbf{E} \) are current density vector, magnetic field intensity vector, magnetic flux density vector, magnetic vector and electric field intensity vector, respectively.

2.3 Calculation area and boundary conditions

Since the equations of fluid mechanics and electromagnetics described in the previous section are nonlinear equations, and the thermodynamic physical parameters of carrier gas change with temperature, it is necessary to reasonably set the boundary conditions of the model to solve the special solution of the above combined equations. The two-dimensional axisymmetric structure of plasma studied in this paper
is shown in Fig. 1, where the calculation area of high-temperature plasma is the area surrounded by ABCDEFGHIJK, the ABCDO area is the cathode, FGHIMNQ is the small anode, and IJLM is the large anode. In reality, the small anode and the large anode are isolated by insulating materials. The model is directly simplified to a plane, and EFOP is the support. DE is the carrier inlet, KJ is the outlet.

In numerical simulation, the boundary conditions of temperature field are as follows: the inlet temperature of carrier gas is 300K, the AB temperature of cathode tip is 3500K, the boundary condition of anode outer wall is convective heat flux, and the LMNOP temperature of torch outer wall is 500K.

3. Analysis of calculation results

3.1 Numerical simulation results under the same terminal current and different carrier gas standard flow rate

When the cathode terminal current is 180 A, the working carrier gas is nitrogen, and the standard flow rate of carrier gas is 30.54m/h, 30.7m/h, 30.9m/h, 31.1m/h, 31.3m/h, and the temperature field simulation results are shown in Figs. a)~e). It can be found from the figure that with the increase of the standard flow rate of carrier gas, the maximum temperature of the plasma appearing in the throat channel of the small anode decreases, and the maximum temperature borne by the inner wall of the whole anode decreases. However, the high temperature part of the plasma at the outlet of the torch is more concentrated to the central region of the axis, so the average temperature of the plasma at the outlet is also increasing. The specific numerical simulation results are shown in Table 1.

![Fig. 2 Simulation results of plasma torch temperature distribution under different standard flow rates with the same input current](image)

| Table 1 Simulation results under the same cathode terminal current and different flow rates |
|---------------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Cathode terminal current /A | Maximum plasma temperature/K | Average export temperature /K | Inlet gas flow / (m³/h) | Maximum temperature of anode inner wall /K | Arc power /W |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 180             | 10202.0         | 5175.1          | 0.54            | 760.02          | 10000.80        |
| 180             | 9866.6          | 5347.1          | 0.70            | 752.30          | 10793.88        |
The highest temperature is located in the throat of small anode, and decreases with the increase of carrier gas. The reason for this phenomenon is that nitrogen is a diatomic molecule, and its ionization process is a process of absorbing heat. The increase of carrier gas rate will bring more nitrogen molecules to be ionized and the absorbed energy increases. The maximum temperature of plasma torch anode decreases because of the increase of carrier gas standard flow rate, which accelerates the flow of plasma energy, strengthens the cooling effect of plasma on arc boundary and improves the protection of anode. However, the increase of carrier gas rate will reduce the ionization rate of carrier gas and break the thermal equilibrium state of arc center.

![Graph](image)

**a) Arc power curve**

**b) Curves of maximum temperature at anode wall and average temperature at plasma outlet**

Fig. 3 Parameter changes under different carrier gas standard flow rates

Figure 3 a) shows that the arc power increases linearly with the increase of carrier gas flow rate, and the volt-ampere curve of DC arc is hyperbolic characteristic curve. In order to expand the application range, the mathematical expression of volt-ampere characteristics of DC arc modified by Nottingham (8) shows that the increase of carrier gas flow rate leads to the extension of arc length. A, B, C and D are constant under the determined operating conditions. Under the constant terminal current, the arc voltage is proportional to the arc length, increases and increases, and the arc power increases.

\[
U_{arc} = A + BL + \frac{C + DL}{I^n}
\]  

where \( U_{arc} \) is arc voltage, in unit of voltage (V). \( I \) is the current through the arc, unit is ampere (A). \( L \) is arc length, unit is millimeter (mm). A, B, C and D are constants. \( n \) is an index, changing from 0.35 (Zinc) to 1.38 (Tungsten), which is related to the electrode material[9].

In Fig. 3 b), it is observed that the average temperature at the outlet of the plasma torch increases with the increase of the carrier gas flow rate. The reason is the increase of the carrier gas flow rate accelerates the heat transfer process of the fluid inside the plasma torch, and also accelerates the heat flow. More heat balance plasma heat energy flows to the outlet. The increase of the carrier gas flow rate weakens the convective heat transfer process of the high-temperature plasma on the inner wall of the anode, so the maximum temperature of the inner wall of the anode decreases with the increase of the carrier gas flow rate.

3.2 Analysis of numerical simulation results under the same carrier gas standard flow and different terminal currents

For the same model structure, the standard flow rate of carrier gas is 1.3m³/h, and the temperature field of DC arc plasma torch is numerically simulated under different cathode terminal currents. The simulation results are shown in Fig. 4.
Fig. 4 Temperature field simulation results of different cathode terminal currents with the same flow rate

Fig. 5 Air flow rate and parameter changes under different cathode terminal currents

4. Conclusions
In this paper, the non-transfer arc plasma torch with large and small anode structure is analyzed according to the theory of magnetohydrodynamics, and the numerical simulation is carried out by COMSOL finite element simulation software. According to the simulation results, the following conclusions can be drawn:

1) When the cathode terminal current is constant, increasing the airflow rate of the DC plasma torch, the arc voltage increases, and the increase of the arc voltage will lead to the increase of the power
of the plasma torch and the increase of the average outlet temperature. Therefore, by increasing the standard flow rate of carrier gas, the power of torch can be increased and the average temperature of export can be increased, which is more conducive to the full decomposition of solid waste, but at the same time, the cost of working carrier gas can be increased.

2) Under the condition of constant carrier gas standard flow rate, the maximum temperature in the plasma torch increases with the increase of terminal current, resulting in the increase of plasma physical conductivity and the decrease of arc voltage in a hyperbolic curve, but the arc power increases, the average temperature at the outlet of the plasma torch and the maximum temperature at the inner wall of the anode increase. Therefore, the power of the plasma torch can be increased by increasing the input current of the plasma torch, so as to improve the average outlet temperature of the torch and the waste treatment efficiency. However, at the same time, it will increase the maximum temperature to be borne by the anode, increase the anode loss rate and reduce the anode service life.

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