Modeling and Experimental Validation of a 1.2MW DC Transferred Well-Type Plasma Torch

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Abstract

This paper discusses the numerical modeling and experimental validation of a 1.2 MW DC transferred plasma torch, which is equipped with a well-type cathode (WTC). In order to investigate the complicated thermal and flow characteristics due to the interaction between the working gas and electric arc, the flow filed inside the plasma torch is modeled by the magnetic-hydrodynamic (MHD) equations. The governing equations are solved numerically using a finite volume discertization for both cold and hot flow simulations. The numerical simulations are then validated by experimental measurements at a specfic operation condition. The predicted results successfully reflect some important features of the studied transferred WTC plasma torch.

Key words: transferred plasma torch; well-type cathode; numerical simulation

1. Introduction

Because plasma torch plays an important role in the hot plasma technology, it is therefore, from the industrial point of view, of great interests. This technology has been adopted in numerous industrial applications, such as plasma spray, plasma welding, plasma cutting and plasma waste disposal etc. [1,2]. Scientific studies are devoted to simulating different types of plasma torch flows due to the experimental difficulties of high temperature flows. For example, in several references [3-9] numerical methods were employed to investigate the two-dimensional non-transferred DC plasma torch. The magneto-hydrodynamic (MHD) equations were used to calculate current density and to take the influences of Joule heat and Lorentz force into account. Recently, three-dimensional simulations of non-transferred DC plasma torch are conducted [10-12], which are believed to reveal more three-dimensional characteristics of plasma flows. In this paper, we simulate the flow field inside a transferred plasma torch with the well-type cathode and validate our numerical predictions with experimental measurements.

2. Method

The fundamental assumptions of plasma flow in a two-dimensional transferred DC plasma torch are given as follows: The plasma is optically thin, the plasma is assumed in local thermal equilibrium, only the steady state characteristics are interested and the gravity is neglected, the turbulent effect is at present time ignored it the present study, the external magnetic field is absent, and the flow field is axial-symmetric. Based on aforementioned assumptions, the MHD equations consisting of the continuity equation, momentum equation, energy equation, and current continuity equation are ex-

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pressed as follows:

Continuity equation

$$\frac{\partial(\rho u)}{\partial x} + \frac{1}{r}\frac{\partial(\rho r v)}{\partial r} = 0 \tag{1}$$

Momentum equation (axial-direction)

$$\frac{\partial(\rho u^2)}{\partial x} + \frac{1}{r}\frac{\partial(\rho r u v)}{\partial r} = -\frac{\partial p}{\partial x} + 2\frac{\partial}{\partial x}[\mu(\frac{\partial u}{\partial x})] + \frac{1}{r}\frac{\partial}{\partial r}[r\mu(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial x})] + j_r B_\theta \tag{2}$$

Momentum equation (radial-direction)

$$\frac{\partial(\rho u v)}{\partial x} + \frac{1}{r}\frac{\partial(\rho r v^2)}{\partial r} = -\frac{\partial p}{\partial y} + \frac{2}{r}\frac{\partial}{\partial r}[\mu r(\frac{\partial v}{\partial r})] + \frac{\partial}{\partial x}[\mu(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial x})] - \mu(\frac{2v}{r^2}) - j_x B_\theta \tag{3}$$

Energy equation

$$\frac{\partial(\rho u h)}{\partial x} + \frac{1}{r}\frac{\partial(\rho r v h)}{\partial r} = u\frac{\partial p}{\partial x} + v\frac{\partial p}{\partial r} + \frac{\partial}{\partial x}(\frac{k}{c_p}\frac{\partial h}{\partial x}) + \frac{1}{r}\frac{\partial}{\partial r}(\frac{rk}{c_p}\frac{\partial h}{\partial r}) + \frac{j_x^2 + j_r^2}{\sigma} - S_R + \frac{5}{2}\frac{k_b}{e}(\frac{j_x}{c_p}\frac{\partial h}{\partial x} + \frac{j_r}{c_p}\frac{\partial h}{\partial r}) \tag{4}$$

Current continuity equation

$$\frac{\partial}{\partial x}(\sigma\frac{\partial E}{\partial x}) + \frac{1}{r}\frac{\partial}{\partial r}(\sigma r\frac{\partial E}{\partial r}) = 0 \tag{5}$$

where ρ denotes the fluid density, σ the electrical conductivity, u the velocity component in the axial direction (x), v the velocity component in the radial direction (r), E the electrical potential, p the pressure, S_R the radiation loss, k the thermal conductivity, c_p the specific heat, h the enthalpy, μ the fluid viscosity, j_x the axial component of current density, j_r the radial component of current density, k_b the Boltzmann constant, e the electric charge, B_θ the self-induced magnetic field in the radial direction. The current density j_x and j_r are determined by the Ohm's law:

$$j_x = -\sigma\frac{\partial E}{\partial x} \qquad j_r = -\sigma\frac{\partial E}{\partial r} \tag{6}$$

where σ denotes the electrical conductivity. The magnetic field B_θ is calculated according to the following expression:

$$B_\theta = \frac{\mu_0}{r}\int_0^r j_x\,\xi\,d\xi \tag{7}$$

A finite volume method [13] is employed to discretize the governing differential equations and a integral form of governing equation over an arbitrary control volume V is obtained:

$$\int_S \rho\phi(\vec{v}\cdot\vec{n})\,dS = \int_S (\vec{T}_\phi\cdot\vec{n})\,dS + \int_V \rho f_\phi\,dV \tag{8}$$

where the controal volume V is defined by the control surface S with an outer normal vector $\vec{n}$, ϕ the generalized variable, $\vec{v}$ the velocity vector, $\vec{T}_\phi$ the generalized surface force, f_ϕ the generalized source term. Using the value of neighboring nodes to approximate each term appearing in the governing equations, a linearized equation is obtained for every governing equation. Then a SIMPLE-like algorithm is employed to solve the coupling of dependent variables iteratively. Because the studied plasma flow paroblem is highly nonlinear, an under-relaxation strategy is necessary to stablize the numerical calculation and get a converged solution, as conducted in [14]. The numerical solution is considered as converged, when all residual of governing equations have been reduced by three orderos in magnitude.

The most important boundary condition is the determination of current density at electrodes. For the current density distribution at cathode, we assume an exponential profile as follows [15]:

$$j_c(\xi) = J_{max}\,e^{-b\xi} \tag{9}$$

where J_{max} denotes the maximum current density, ξ the decreasing direction of current density and the constant b is decided by the system current I and the area of hot spot A:

$$I = 2\pi\int_A j_c(\xi)\,dA \tag{10}$$

Table 1 summarizes the boundary conditions adopted in our numerical simulations. Figure 1 illustrates the employed computaional domain to calculate the flow filed of the investigated transferred WTC plasma torch.

	$\overline{abc},\overline{de},\overline{fg}$	$\overline{cd}$	$\overline{ef}$	$\overline{ij}$	$\overline{jk}$	$\overline{ak}$
u	$u=0$	$u=0$	$u=0$	$\frac{\partial u}{\partial r}=0$	$u=0$	$\frac{\partial u}{\partial r}=0$
v	$v=0$	$v=0$	$v=0$	$\frac{\partial v}{\partial r}=0$	$v=0$	$v=0$
T	$1000K$	$3000K$	$300K$	$\frac{\partial T}{\partial r}=0$	$\frac{\partial T}{\partial x}=0$	$\frac{\partial T}{\partial r}=0$
E	$-$	$j_c(r)$	$-$	$-$	$E=0$	$\frac{\partial \phi}{\partial r}=0$

Table 1. Numerical boundary conditions.

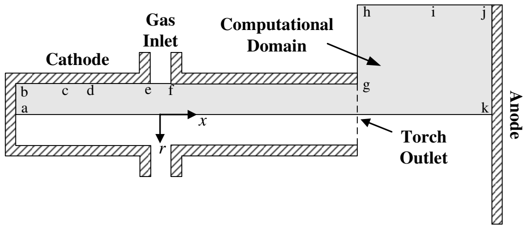

Fig. 1. Schematic illustration of computational domain.

3. Results

The proposed numerical scheme is applied to simulate a DC transferred plasma torch installed at the Institute of Nuclear Energy Research (INER). The studied plasma torch is designed to deliver a maximum power of 1.2 MW, where a well-type cathode (WTC) and swirler inlets are equipped. The working gas is a mixture of air and nitrogen. The studied condition is at the thermal output power of 0.78 MW, where the system current is 845 A and the flow rate is 1000 L/min with an air-nitrogen ratio of 0.25. Because the oxygen component in the gas mixture is quite few, we use pure nitrogen as the working gas in our numerical computation. The location of cathode on torch wall is determined by a cold flow analysis, similar to the practice demonstrated in [14], which is close to the erison region in the investigated torch. The anode location is fixed at the furnace bottom, as depicted in Fig. 1. For our transferred WTC torch, the cathode attachment radius is chosen as 1.0 mm, where the maximum current density J_{max} is selected as 7.4×10^7 Am^{-2}. After an grid-dependence test, the final grid used in the numerical simulation comprises of about 20000 cells to discrtize the computation domain shown in Fig. 1. The grid is clustered near the gas inlet and cathode to resolve the large gradient of field variables to avoid diffusion errors.

Figure 2 shows the plasma temperature disturbution and velocity plot inside and outside the studied transferred WTC torch. Different from root-type cathde (RTC) torches, the numerical simulation confirms the feature of cold cathode in WTC torches, where the predicted temperature near cathode is about 5000K $\sim$ 7000K. Another important themal characteristic in the studied transferred WTC torch is that there is a very hot plasma core along the central axis, which stretches out of torch oulet and attaches to the furnace bottom. Figure 3 gives the image of buring arc generated by the transferred WTC torch in our experiments. After comparing these two figures, the experimentally observed flame outline is very close to the temperature contour of 10000 K, where high current density exists. Additionally, the temperature distribution of the attachment region at furnace bottom varies from 10000 K to 15000 K, while a very large temperature gradient occures inside the torch, which is mainly due to the effects of injected gas. As indicated by the vector plot in Fig. 1, the plasma flow has high velocity in the inner region and the flow velocity quickly decreases along the radial direction, showing a jet flow feature outside the torch. The calculated arc voltage in our simulation is 911 V, while the measured arc voltage is read as 921 V.

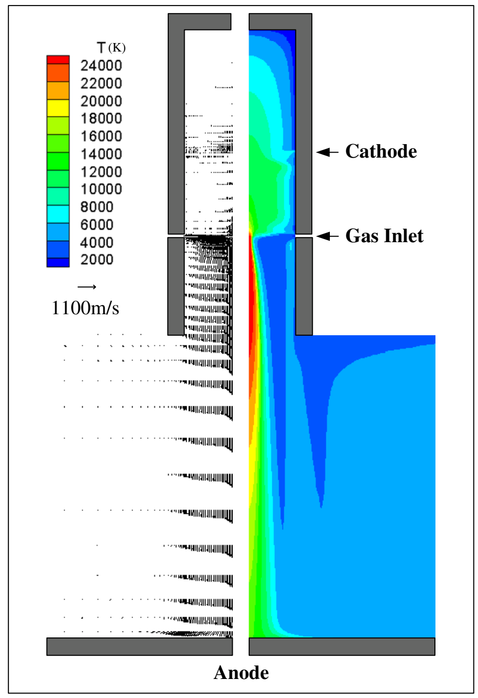

Fig. 2. Predicted temperature distribution and velcoity vectors for the 1.2 MW transferred WTC torch.

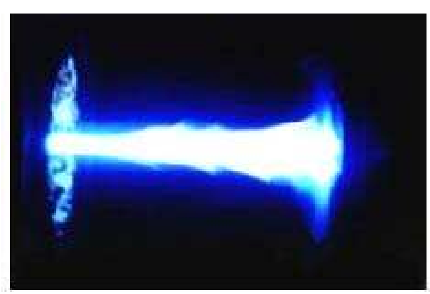

Fig. 3. Burning arc during torch operation.

Figure 4 depicts the temperature and axial velocity distribution along center line in the numerical simulation. In our transferred WTC torch, the predicted temperature and axial velocity at the center line increase rapidly across the gas inlet loaction, and reach a maximum value of 25000 K and 1100 m/s, respectively. Figure 5 depicts the temperature and axial velocity distribution at the torch outlet along radial direction. The temperature at torch outlet exhibits a significant drop approximately at 1/3 of the torch radius, while the axial velocity quickly decreases near the center line, and remains a constant value of 400 m/s in the outer region.

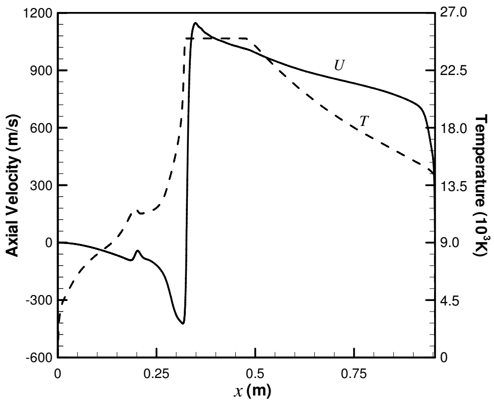

Fig. 4. Predicted temperature and axial velocity distribution along center line.

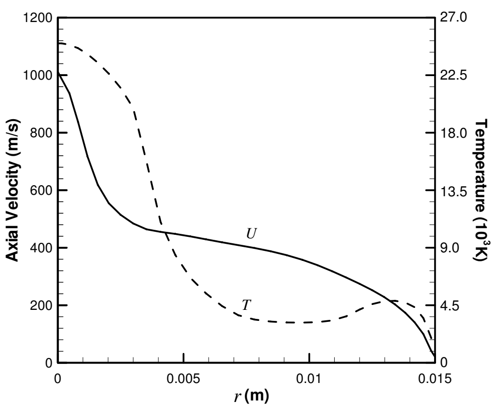

Fig. 5. Predicted temperature and axial velocity distribution at torch outlet.

4. Summary

This paper discusses the numerical modeling and experimental validation of a 1.2 MW DC transferred plasma torch, where a well-type cathode is installed. A numerical approach solving the MHD equations to calculate the plasma flow is proposed to investigate the complicated thermal and flow characteristics of the transferred plasma torch. A finite volume discertization is employed to solve the governing equations. The numerical simulations are then validated by experimental measurements. The predicted results successfully reflect some important features of the studied 1.2 MW transferred WTC torch.

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