Effect of Asymmetrical Distribution of Current Density on the Three-Dimensional Non-Transferred Arc Plasma Torch

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Abstract: In this study, three-dimensional steady-state non-transferred arc plasma torch was investigated by computational fluid dynamics (CFD) method with user defined function (UDF). Two-equation current density profile was developed to simulate the complex plasma flow inside the torch. The effect of asymmetric distribution of current density (ADCD), particularly the deviation distance (distance between the cathode tip center and the current density profile center), on the characters of the plasma arc flow was systematically investigated for the first time. It is found that as the deviation distance increases, the temperature and velocity inside the plasma column reduce, but the temperature near the arc-root attachment increases. In addition, the arc length decreases with increasing the deviation distance.

Keywords: Non-transferred arc, plasma torch, two-equation current density profile, arc-root attachment, computational fluid dynamics (CFD)

1. Introduction

Plasma spray technique has been attracting more and more attentions over the years due to its great ability to coat high melting-point metal and ceramic powders. Experiments have been used to show the non-transferred arc inside the plasma torch[1-2]. However, experimental observation and measurement always cost too much money and it is difficult to well understand the insight of the

plasma flow by experiment due to the technique limitation. Numerical simulation, therefore, is becoming a good option to study the thermal dynamic features of plasma arc.

Both two-dimensional [1-7] and three-dimensional [8-17] models have been adopted to study the plasma spray inside the torch. In some cases for steady-state simulation, zero electrical potential was imposed to the anode spot and zero gradient electrical potential was imposed to the rest region of anode, which can lead to the current passing through the anode[8,13]. Although steady-state simulation can provide sufficient information of the plasma flow field, it is not applied to all circumstances because the real arc always moves on the anode wall and operates in different modes depending on the working conditions. Therefore, time-dependent plasma flow was numerically studied in some works [18-24], where Trelles et al. [22-23] developed a transit model to simulate the arc reattachment by using an artificially high electrical conductivity near the anode wall. The models successfully predict the arc break down and reattachment processes inside the plasma torch.

In previous works, one can notice that the maximum current density are always located at the center of the cathode tip[8-24], particularly for transient models concerning the time-dependent plasma [21-23]. Actually, the maximum value of the current density profile imposed on the cathode surface may not be located on the center of the cathode. Therefore, it is meaningful to well understand the effect of ADCD (here, asymmetrical distribution of current density means the maximum value of current density is not at axis of the cathode tip) on the plasma flow fields. In this study, the F4 APS torch (a common torch for thermal spray) with 3mm nozzle size that is also stated in [13] is adopted. The main goal of the paper is to study the effect of deviation distance r_c shown in Fig.1, so the shape of ADCD profile is the same as that of axisymmetric case.

2. Mathematical model

2.1. Model assumptions

The model is based on the following assumptions:

- 1) The gravity effect and viscous dissipation are neglected.
- 2) The flow is incompressible and turbulent[8,15].

3) The plasma flow is in steady state satisfying the conditions for local thermodynamic equilibrium (LTE). The plasma is treated as a single continuous fluid characterized by a single temperature for all species.

4) The plasma is optically thin.

5) The working gas is injected into the plasma torch in axial direction at the torch inlet.

2.2. Governing equations

The governing equations are solved by the commercial computational fluid dynamics (CFD) software ANSYS-FLUENT 14.5 with user defined function (UDF), which includes the mass conservation equation, momentum equations, energy equation, and electromagnetic equations given by Maxwell's equations in the form of electric potential and magnetic vector potential. The equations to be solved are presented as follows:

$$\nabla \cdot \rho \vec{u} = 0 \quad (\text{Eq.1})$$

$$\nabla (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot \vec{\tau} + \vec{j} \times \vec{B} \quad (\text{Eq.2})$$

$$\nabla (\rho C_p \vec{u} T) = -\nabla \cdot (\kappa \nabla T) + \vec{j} \cdot (\vec{E} + \vec{u} \times \vec{B}) - 4\pi \epsilon_r + \frac{5}{2} \frac{k_B}{e} \vec{j} \cdot \nabla T \quad (\text{Eq.3})$$

$$\nabla \cdot (\sigma \nabla \phi) = 0 \quad (\text{Eq.4})$$

$$\nabla^2 \vec{A} = -\mu_0 \vec{j} \quad (\text{Eq.5})$$

where $\vec{j} \times \vec{B}$, $\vec{j} \cdot \vec{E}$, $4\pi \epsilon$ and $\vec{j} \cdot \nabla T$ represents the Lorentz force, the Joule heating term, the volumetric radiation losses and the diffusion of electron enthalpy respectively. The radiation emission coefficients of Ar and H₂ are taken from Ref. [25] and [26]. Thermodynamic and transport properties of the plasma gases are taken from Ref. [27-29]. The radiation loss of Ar-H₂ mixture is calculated through mole-average method expressed as the following equation [16],

$$S_R = \epsilon_{Ar} x_{Ar} + \epsilon_{H_2} x_{H_2} \quad (\text{Eq.6})$$

Besides, the following additional relations are introduced to close the equation set (Eq. 1 – Eq. 5),

$$\vec{\tau} = -\mu(\nabla \vec{u} + \nabla \vec{u}^T - \frac{2}{3} \nabla \cdot \vec{u} \vec{\delta}), \quad \nabla \times \vec{A} = \vec{B}, \vec{E} = -\nabla \phi, \text{ and } \vec{j} = \sigma \vec{E} \quad (\text{Eq.7})$$

It is reported that the large gas acceleration, shear velocity and temperature gradient together with the electromagnetic force inside the plasma torch cause the flow to become unstable and turbulent [30, 31]. Therefore, the standard k- ϵ model combined with standard wall function for the near-wall treatment is employed to describe the turbulent flow inside the plasma torch. The equations of the turbulent model can be found in Ref [32].

2.3. Computational domain and boundary conditions

The computational domain is defined based on the standard F4 plasma torch, which consists of cathode tip, gas flow inlet, anode, and outlet. The schematic and dimensions of the computational model are given in Fig. 2 and Tab. 1, respectively [13]. The computational domain is meshed into 319,756 hexahedral cells with the refined mesh at the near-wall region. According to our own experimental data and previous studies [13], the mass flow rate is given as 40 slpm of Ar and 8 slpm of H₂, and the current is set as 400 A. The arc core radius $R = 1.6$ mm is used because it is close to the real arc core radius through minimum entropy production method [13].

At the anode surface, the convective boundary condition is employed with the convective heat transfer coefficient of 10^5 W/(m² K) and the cooling water temperature of 300 K [13]. The temperature-dependent electrical conductivity is employed to accurately predict the electrical field inside the plasma torch. For this reason, the current passing through the electrodes is blocked due to the quite low temperature at the near-anode region. In order to properly deal with this problem, an artificially high electrical conductivity layer with the value of 10^4 1/($\Omega \cdot m$) and thickness of 0.1 mm is imposed in front of the anode wall to allow the current passing through the cool near-anode region [23]. However, according to experimental observation of the small erosion part burnt at anode wall [8, 17], only part of the anode wall with the angle of 10° (Fig.2, ϕ) is imposed with artificially high electrical conductivity layer. The location of the arc-root attachment can be calculated from the computation procedure because the arc core radius has already been known (1.6 mm). The determination of the arc-root attachment can be well explained by the balance between magnetic body force on the anode-arc column and gas dynamic drag force in the axial direction [26].

At the cathode surface, the exponential current density profiles were commonly used in the previous literatures [5, 23, 24, 33]. The results obtained by the exponential profiles are proved to be sufficient accurate, but the current density at the end of the profile is not strictly zero. In this work, a two-equation current density profile is developed. This is an improved format of exponential current

density profiles, which can guarantee both the zero current density at the end of profile ($r = R$) and also the smooth transition at the maximum point ($r = r_c$). The maximum current density of $J_{cath} = 1.493 \times 10^8$ A/m² is chosen to ensure that the integration of the density current is equal to 400A. This current density profile can be expressed as follows,

$$J_1(r) = J_{cath} \exp\left(-b(r - r_c)^2\right) \quad r \leq 0.5 + r_c \quad (\text{Eq.8})$$

$$J_2(r) = J_{inlet} \left(1 - \frac{(r - r_c)^n}{R^n}\right) \quad r > 0.5 + r_c \quad (\text{Eq.9})$$

where n is 0.57, $J_{inlet} = 2.275$ and $b = 1.212 \times 10^8$ A/m². The distribution of the current density is shown in Fig.1 and the detailed boundary conditions of the computational model are given in Tab. 2.

3. Results and discussion

3.1. Temperature and velocity fields with symmetrical current density profile

Fig. 3 shows the temperature field inside the plasma torch at different cross-sections. It is immediately seen that strong heating effect of the plasma arc results in a high temperature region behind the cathode. When gas flow passes through the plasma arc, it is significantly heated up and maintains a relatively high temperature at the nozzle downstream. The arc-root is found to be located at a spot on the anode wall and a high temperature region is also developed locally near the anode root attachment due to the current passing through the anode spot. In addition, the gas heated near the anode spot develops an anode jet and then mixes with the cathode jet. The velocity fields inside the plasma torch are shown in Fig. 4. As can be seen, the high-velocity region is located at the center of the plasma torch as a result of the rapid temperature rise and the consequent expansion of the gas flowing through the plasma arc which generates significantly accelerating effects (Lorentz force).

Tab. 3 gives the comparison of torch power efficiency (P_{exit}/W [17]) between the simulation results obtained based on the two-equation profile and previous numerical as well as experimental results [13]. It is found that the simulation results in the paper are consistent with the previous results, which partly confirms the accuracy of the two-equation current density profile.

3.2. Effect of asymmetric current density profile on the temperature and velocity fields

The effect of deviation distance on the torch power is studied and the results are given in Fig. 5. It is seen that torch power decreases gradually with increasing the deviation distance. The reason for this

phenomenon is given as follows. When the deviation distance increases, the distance between the anode wall and center of the current density profile is shortened. This process can be roughly considered as reducing the electric resistance. Hence, in order to maintain the same current passing through the electric resistance, the torch power must decrease. This is can also be supported by the voltage distributions shown in Fig.6, which shows that the voltage reduces as deviation distance increases, resulting in the reduction of the input power under the same current.

Fig. 7 shows the effect of deviation distance on the temperature field inside the torch. As the deviation distance increases, the temperature at the arc column region exhibits significantly decreasing trend as a result of the decreased torch power. Besides, the location of the arc-root attachment is found to move towards the upstream, which implies that arc length decreases gradually. This phenomenon can be well explained by the following equation [13],

$$L = \pi R_{arc}^2 \sigma \frac{W}{I^2} \quad (\text{Eq.10})$$

for convenient explanation, the increasing process of deviation distance from 0.1 to 0.5 mm is taken as an example. According to Eq. 10, it is found that only electrical conductivity and torch power can affect the arc length at a given current. As the deviation distance increases from 0.1 to 0.5 mm, the averaged temperature of plasma arc increases by 1000K and the consequent electrical conductivity decreases by 14%, the torch power decreases by 10% which can be calculated from Fig. 5. Therefore, the final reduction of arc length can be calculated as approximate 23%. For comparison, the predicted arc length by simulation as a function of deviation distance is also provided in Fig. 8 in which the arc length reduction is calculated as approximate 30% when deviation distance increases from 0.1 to 0.5 mm. This result is quite close to the analytical result from Eq. 10. Besides, it is also noticed from Fig. 7 that the temperature around arc-root attachment increases gradually with increasing the deviation distance. This fact can be explained by the following relations applied at the arc-root region,

$L \sim \rho^{5/4} V / I^2$, reported in [18] based on the experiment. At a given current, gas flow velocity around the arc-root is insensitive to the deviation distance, which can be seen in Fig. 9 showing the effect of deviation distance on velocity field. In this case, one can notice that arc length is proportional to the temperature-dependent arc density that decreases as the temperature rises. Hence, it is not difficult to deduce that the increase of the deviation distance results in the reduction of arc length (Fig. 7 and 8) and then the increase of arc temperature. For further investigation, Fig. 10 shows the effect of deviation

distance on the temperature distribution at the nozzle exit. As can be seen, the temperature in plasma torch considerably reduces as the deviation distance increases due to the reduction of torch power. In this case, with increasing the deviation distance, the voltage reduces and then less heat energy can be taken away and transferred to the nozzle exit by the gas flow, the consequence to that fact is the lower temperature at the nozzle exit. Furthermore, it is also seen from Fig. 10 that the location of the temperature peak seems to move toward to the arc-root direction due to the corresponding movement of the maximum current density at the cathode tip and inlet.

The effect of deviation distance on the velocity field shown in Fig. 9 is further discussed. With increasing the deviation distance, the magnitude of the velocity field decreases gradually and the high velocity zone moves to upstream, which arises from the shortened arc length and decreased arc column temperature. Both changes can reduce the acceleration capability of plasma arc to the gas flow. For the same reason, the velocity at the nozzle exit exhibits a decreasing trend with increasing the deviation distance which can be observed from Fig. 11 showing the effect of deviation distance on the velocity distribution at the nozzle exit. Finally, the effect of deviation distance on the torch efficiency is studied, and the result is provided in Fig. 12. As can be seen, the torch efficiency shows a downward trend as the deviation distance increases, which suggests that deviation of the maximum current density from the cathode tip can cause more energy loss.

Conclusions

The simulation of three-dimensional non-transferred arc inside the plasma torch was carried out by a steady-state CFD model. Two-equation current density profile was developed to simulate the complex plasma flow inside the torch, which can guarantee both the zero current density at the end of profile ($r=R$) and also the smooth transition at the maximum point ($r=0$). The comparison of the simulation results with the experimental measurement proves the accuracy of two-equation profile. Besides, the effect of ADCD on the plasma flow was systematically investigated. Based on the numerical results, it is found that as the deviation distance increases, the overall temperature and velocity inside the torch reduce, but the temperature near the arc-root attachment increases. The arc length is found to decrease gradually with increasing the deviation distance.

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Appendix

Determination of the constants in two-equations current density profile

In order to get a smooth transition at $r=0.5\text{mm}$, Eq. 8 and 9 must satisfy the following relations,

$$\begin{aligned} J_1 \Big|_{r=r_1=0.5} &= J_2 \Big|_{r=r_1=0.5} \\ J_1' \Big|_{r=r_1=0.5} &= J_2' \Big|_{r=r_1=0.5} \end{aligned} \quad \text{Eq. 11}$$

Then, the following relations can be obtained by solving Eq. 8, 9 and 11.

$$b = \frac{nr_1^{n-2}}{2(R^n - r_1^n)} \quad \text{Eq. 12}$$

$$J_{inlet} = J_{cath} \exp\left(-br_1^2\right) \left(\frac{R^n}{R^n - r_1^n}\right) \quad \text{Eq. 13}$$

Substitute Eq. 8, 9, 12 and 13 into Eq. 14, the constants (n, b and J_{inlet}) can be obtained.

$$\int_0^{r_1} 2\pi J_1 r dr + \int_{r_1}^R 2\pi J_2 r dr = I \quad \text{Eq. 14}$$

Nomenclature	
L	arc length (m)
W	torch power (W)
P_{exit}	the total thermal power delivered to the plasma jet at the nozzle exit(W)
Q	mass flow rate (kg/s)
I	current (A)
C_p	specific heat at constant pressure (J/kg K)
T	temperature (K)
J	current density (A/m ²)
J_1	linear current density (A/m ²)
J_2	parabolic current density (A/m ²)
J_3	exponential current density (A/m ²)
J_4	current density profile at inlet (A/m ²)
J_5	current density profile at cathode tip (A/m ²)
j_0	maximum value of J
j_{max}	maximum value of J_3
j_{inlt}	maximum value of J_4
j_{cath}	maximum value of J_5
R	arc core radius
r	radial position of current density profile (mm)
r_1	radius of the cathode tip (mm)
r_c	deviation distance(mm)
a, b, a_0 , m, n	real number
ρ	density (kg/m ³)
P	pressure (Pa)
$\vec{J}$	current density (A/m ²)
$\vec{u}$	velocity (m/s)
$\vec{E}$	electric field (V/m)
$\vec{A}$	magnetic potential (T m)
$\vec{\tau}$	stress tensor (Pa)
$\vec{\delta}$	identity tensor
$\vec{B}$	magnetic field (T)
h_{conv}	convective heat transfer coefficient (W/m ² K)
κ	thermal conductivity (W/m K)
ϵ_r	net emission coefficient (W/m ³ sr)
k_B	Boltzmann constant (J/K)
e	elementary charge (C)
σ	electrical conductivity (1/ Ω m)
ϕ	electric potential (V)
S_R	radiation loss
ϵ_{Ar}	net radiation emission coefficient of argon
χ_{Ar}	mole fraction of argon
ϵ_{H2}	net radiation emission coefficient of hydrogen
χ_{H2}	mole fraction of hydrogen

Tables:

Tab.1. Dimensions of the computational model

Configuration	Dimensions
Inlet radius	3.8 mm
Outlet radius	3.0 mm
Convergent length	7mm

Barrel length	20 mm
Cathode tip radius	0.5 mm

Tab. 2. Boundary conditions of the computational model used in the simulations

	$\vec{u}$	T	φ	$\vec{A}$
Inlet	Q, kg/s	3500 K	$-\sigma \cdot \partial \varphi / \partial n = J_{inlet}$	$\partial A_i / \partial n = 0$
Cathode tip	0	3500 K	$-\sigma \cdot \partial \varphi / \partial n = J_{cath}$	$\partial A_i / \partial n = 0$
Anode	0	$-\kappa \cdot \partial T / \partial n = h_{conv} \cdot (T - T_{water})$	0	$\partial A_i / \partial n = 0$
Outlet	$\partial u_i / \partial n = 0$	$\partial T / \partial n = 0$	$\partial \varphi / \partial n = 0$	0

Tab. 3.Comparison of torch efficiency with previous works

	Exp. in [13]	Cal. in [13]	Current	Error
400 A	49.0%	55.6%	53.5%	9.18%
500 A	49.6%	56.4%	50.2%	1.2%

Figures

Fig. 1 Pattern of the two-equations current density

Fig. 2 Schematic of the computational domain

Fig. 3 Temperature field inside the plasma torch

Fig. 4 Velocity flow field at the vertical plane inside the plasma torch

Fig. 5 Torch power as a function of deviation distance

Fig.6. Voltage distribution for each deviation distance

Fig. 7 Effect of deviation distance on the temperature field inside the plasma torch

Fig. 8 Arc length as a function of deviation distance

Fig. 9 Effect of deviation distance on the velocity field inside the plasma torch

Fig. 10 Effect of deviation distance on the temperature distribution at the nozzle exit

Fig. 11 Effect of deviation distance on the velocity distribution at the nozzle exit

Fig. 12 Torch efficiency as a function of deviation distance