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Effect of the deviation of the current density profile center on the three-dimensional non-transferred arc plasma torch

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ABSTRACT

In this study, the three-dimensional steady-state non-transferred plasma arc was investigated using computational fluid dynamics (CFD) with user defined functions (UDFs). A two-equation current density profile was developed to simulate the complex plasma flow inside the torch. The effect of the deviation distance (distance between the cathode tip center and the current density profile center) on the plasma flow features was systematically investigated for the first time. It is found that the temperature and velocity inside the plasma column reduce as the deviation distance increases, but the temperature near the arc-root attachment shows an increasing trend. Besides, it is also found that the arc length decreases with increasing the deviation distance.

1. Introduction

Plasma spray has been attracting more and more attention over the years due to its great ability to produce thermal barrier coatings. The core component of a plasma spray system is the torch, which is used to generate the plasma arc. Fig. 1 shows a schematic overview of a typical plasma torch. As can be seen in the figure, the torch consists of a cathode and an anode. The plasma arc is generated between two electrodes as a result of the very high voltage. As the high-velocity inlet working gas flows through the plasma arc, it is rapidly heated up to an extremely high temperature and then forms the plasma jet out of the nozzle. The temperature of the plasma jet influences the melting degree of the metal and ceramic powers. Therefore, well understanding of the flow features inside the plasma torch is of great importance to produce high-quality thermal barrier coatings. Some experiments are presented in literature that study the non-transferred arc inside the plasma torch [1,2]. However, experimental observation and measurements are costly. Furthermore, it is difficult to get the insight of the plasma flow by experiment due to technical limitations. Numerical simulation, therefore, is becoming a good option to study the thermal dynamic features of the plasma arc.

In literature, both two-dimensional (2D) [1–7] and three-dimensional (3D) [8–17] models have been used to study the plasma flow inside the plasma torch. However, 2D models are known to result in unrealistic predictions of the arc attachment due to the axisymmetric assumption of the plasma torch. Therefore, 3D models were more frequently used in recent publications. Among these publications, a large number of studies focused on the steady-state solution of the plasma flow. In order to allow the current passing through the anode spot, zero electrical potential and zero gradient electrical potential were given to the anode spot and the other anode wall area, respectively [8,13]. In other studies, an artificially high electrical conductivity layer (AHECL) was imposed near the anode wall to realize the same objective [2]. Besides, simulations of the transient process of the plasma flow were performed in the past decade [18–24]. The AHECL technique was also used to simulate the arc reattachment, which successfully predicts the arc break down and reattachment processes inside the plasma torch [22,23]. Therefore, this method is also used in the current study.

Furthermore, in previous simulation studies, symmetrical profiles were widely used to describe the current density at the cathode surface, in which the maximum current density is located at the center of the cathode tip [8–24]. However, in reality, the maximum value of the current density may not strictly be located at the cathode tip center. Therefore, in this study, the effect of the deviation distance, which is defined as the distance between the cathode

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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)
$\overleftrightarrow{\tau}$	stress tensor (Pa)
$\overleftrightarrow{\delta}$	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
$\varepsilon_{\mathrm{Ar}}$	net radiation emission coefficient of argon
χ_{Ar}	mole fraction of argon
$\varepsilon_{\mathrm{H_2}}$	net radiation emission coefficient of hydrogen
$\chi_{\mathrm{H_2}}$	mole fraction of hydrogen

tip center and the peak of the current density profile on the plasma flow, is investigated for the first time. The patterns of the current density profiles as used in this study are shown in Fig. 2.

2. Numerical methodology

2.1. Model assumptions

The CFD model is based on the following assumptions:

(1) The gravity effect and viscous dissipation are neglected.
(2) The plasma flow is quasi-compressible, turbulent [8,15] and in local thermodynamic equilibrium (LTE).
(3) 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 axially injected into the plasma torch at the inlet.

2.2. Governing equations

The governing equations, including the mass conservation equation, momentum equations, energy equation, and electromagnetic equations given by Maxwell's equations in the form of electric potential and the magnetic vector potential are solved by the commercial CFD software ANSYS-FLUENT 14.5 with UDFs. The equations to be solved are listed as follows:

$$\nabla\cdot\rho\vec{u} = 0 \tag{1}$$

$$\nabla\cdot(\rho\vec{u}\vec{u}) = -\nabla p + \nabla\cdot\overleftrightarrow{\tau} + \vec{j}\times\vec{B} \tag{2}$$

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

$$\nabla\cdot(\sigma\nabla\phi) = 0 \tag{4}$$

$$\nabla^2\vec{A} = -\mu_0\vec{j} \tag{5}$$

where $\vec{J}\times\vec{B}$, $\vec{J}\cdot\vec{E}$, $4\pi\varepsilon$ and $\vec{J}\cdot\Delta T$ represent 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 H_2 are taken from Ref. [25] and [26]. The thermodynamic and transport properties of the plasma gases are taken from Ref. [27–29]. The radiation loss of the Ar–H_2 mixture is calculated through the mole-average method which is expressed in the following equation [16],

$$S_R = \varepsilon_{\mathrm{Ar}}\chi_{\mathrm{Ar}} + \varepsilon_{\mathrm{H_2}}\chi_{\mathrm{H_2}} \tag{6}$$

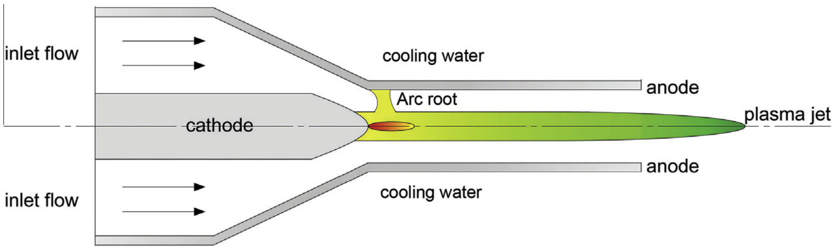

Fig. 1. Schematic picture of the plasma torch.