Simulation of arc root fluctuation in a DC non-transferred plasma torch with three dimensional modeling

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It has been well known that the coating quality of plasma spraying is strongly influenced by instability of jets in plasma spray due to the arc root fluctuation. A three dimensional (3D) unsteady modeling was employed in the research to analyze the arc root fluctuation in a DC non-transferred plasma torch. Numerical calculations on the distribution of gas temperature and velocity in plasma torch were carried out using argon as plasma gas. The electrical current density and potential were also discussed. The results indicate that the fluctuation of arc inside the plasma torch is mainly induced by the movement of the arc root on the anode surface. The arc root moves downstream with the flow of gas, and the arc will wraped caused by the electromagnetic force simultaneously. While the arc wraped closed enough to anode boundary, a new arc root is formed somewhere upstream of the original attachment. This article represents nature of fluctuation of arc root, also in this paper we will present that the voltage-drop calculated is larger than that measured experimentally based on the hypothesis of local thermodynamic equilibrium.

1 Introduction

The plasma spraying is the injection of metal or ceramic powder into hot gas plasma which melts and projects the molten droplets at high velocity onto a substrate to form coatings. Gases such as argon or hydrogen are passed through as electric arc inside a torch [1]. Plasma spraying, one of the most widely used in industrial fields based on thermal plasmas, is commonly employed to provide coatings for protection of materials against wear, erosion, corrosion, and thermal loads. Despite its versatility, the limited reproducibility of the processes is a major limitation for its wider application. A major factor for this limited reproducibility is the lack of understanding and control of the dynamic behaviours of the arc inside the spraying torch and, the effect of erosion of the anode on the forcing of the plasma jet [2-6].

A conventional DC non-transferred plasma torch (more than 90% of industrial torches) with a stick type cathode is shown schematically in **Fig. 1** [7-8]. After working gas enters into the torch, it is heated by an electric arc formed between a nozzle-shaped anode and a conical cathode, which is ejected as a jet. The arc inside the torch has been characterized experimentally [4, 6, 9] and numerically [1-3, 8]. Unfortunately, experiments have been limited by involvement of high cost equipments and lack of understanding of the results obtained.

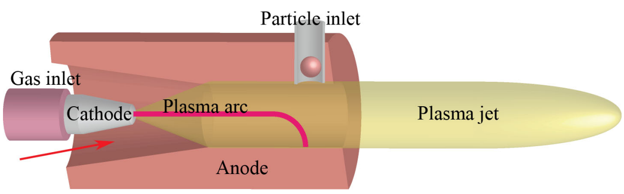


Fig. 1. Schematic of a conventional dc arc spray torch.

Fortunately, the numerical calculation provides a valid way to understand the arc behavior inside plasma torch. The modelling of DC arc plasma torches is an extremely challenging task because the plasma flow is highly nonlinear and presents strong property gradients. It is characterized by a wide range of time and length scales, and often includes chemical and thermodynamic non-equilibrium effects, especially near its boundaries [8]. Despite of the complexity of the subject, over the past few decades, many papers concerning numerical studies of the characteristics of DC arc plasma torches have been published [2-3, 8, 9-22]. At the initial stage, two-dimensional (2D) modeling method was employed in the research to predict the heat transfer and flow patterns inside the plasma torch [10-14]. The predicted arc voltage of the torch in the turbulent regime is much higher than the measured value; in addition the predicted axial location of the arc attachment at the anode surface is also much farther downstream than that observed in experiments [15]. With the rapid development of computer technology, the calculation of heat transfer and fluid flow for a 3D thermal plasma torch with axisymmetrical geometries become feasible [2-3, 15-22]. The models most frequently used for simulation of plasma spray torch rely on the LTE approximation, and regard the plasma flow as a property-varying electromagnetic reactive fluid in chemical equilibrium in which the internal energy of the fluid is characterized by a single parameter of gas temperature [2-3, 15-21]. Selvan et al. developed a steady 3D LTE model to describe the temperature and velocity distributions inside a DC plasma torch. Moreover the arc length and radius were also discussed. But the model overestimated the plasma gas temperature near the arc-root due to the assumption that all the electric current transferred to the anode only through a fixed arc-root [3, 16]. Klinger L. et al. also developed a steady 3D LTE model simulation of the plasma arc inside a DC plasma torch. However, the position of arc-root was determined arbitrarily [17]. A. Vardelle and J. P. Trelles developed a time-dependent 3D LTE model representing the fluctuant of plasma arc [2, 18-21]. The voltage drop for the LTE model was larger compared with the experimental ones due to the

hypothesis of LTE, resulted in less estimation of the electrical conductivity especially near the electrode boundary. A non-equilibrium (NLTE) model was developed for the non-transferred arc plasma torch, which showed better agreement with the experimental results [22]. However, to solve the NLTE model is extremely difficult due to the fact that the two-temperature chemical equilibrium need to be considered compared with the LTE mode.
In this research, an 3D LTE model was developed to mimic the non-transferred DC plasma torch. The plasma gas temperature and velocity distributions were obtained with the LTE model. The fluctuation of arc inside the torch was also presented.

2 Description of the Mathematical Model

2.1 Model Assumptions

The model developed in this study is base on the following main assumptions for simulating the heat transfer and flow patterns inside a plasma torch.

(1) The continuum assumption is valid and the plasma can be considered as a compressible, perfect gas in Local Thermodynamic Equilibrium (LTE).
(2) The plasma is optically thin.
(3) Gravitational effect and viscous dissipation are considered negligible.
(4) The induced electric field is negligible in comparison with the applied electric field intensity in the plasma arc region.
(5) The transport properties of plasma gas were only determined by the plasma gas temperature.
(6) Because of the lower electric conductivity near the cold boundary of electrode, the vicinity of anode, distance of 0.1 mm, is artificially considered as a high electrical conductivity of 10^4 S/m, so that a new arc-root can be formed if the arc is closed enough to the inside surface of anode.

2.2 Governing Equations

Based on the forgoing assumptions, the governing equations for the 3D time-dependent for the arc plasma can be written as follows:

Conservation of mass:
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0$$

Conservation of momentum:
$$\rho\left(\frac{\partial \vec{V}}{\partial t} + \vec{V}.\nabla\vec{V}\right) = \vec{j} \times \vec{B} - \nabla\left[P + \frac{2}{3}\mu(\nabla \cdot \vec{V})\right] + 2\nabla \cdot (\mu \bar{\bar{S}})$$

Conservation of energy:
$$\rho c_p\left(\frac{\partial T}{\partial t} + \vec{V}.\nabla T\right) - \frac{DP}{Dt} = \vec{j}.\vec{E} - S_r + \nabla \cdot (\lambda \nabla T)$$

Maxwell electromagnetism equations:
$$\nabla \cdot (-\sigma \nabla \emptyset) = 0$$
$$\vec{E} = -\nabla \emptyset$$
$$\Delta \vec{A} = -\mu_0 \vec{J}$$
$$\vec{B} = \nabla \times \vec{A}$$

Ohm law:
$$\vec{j} = \sigma \vec{E}$$

Where ρ is gas mass density, t time, $\vec{V}$ velocity, $\vec{j}$ electric current density, $\vec{B}$ magnetic induction vector, P gas pressure, μ dynamic viscosity, $\bar{\bar{S}}$ strain rate tensor, c_p specific heat at constant pressure, $\vec{E}$ electric field, S_r volumetric net radiation losses, λ gas thermal conductivity, σ electric conductivity, $\emptyset$ electric potential, $\vec{A}$ magnetic vector potential and μ_0 permeability of free space.
For the gas flow calculation, the K- ε model is employed in this study. The thermodynamic and transport properties of the plasma gas are taken from Ref. [23,24].

2.2 Computational Domain and Boundary Conditions

The geometry used in the current study corresponds to the SG-100 plasma torch from Praxair. The computational domain formed by the region inside the torch limited by the cathode, the gas flow inlet, the anode and the outlet as shown in **Fig. 2**. The computational domain is meshed using 217600 hexahedral cells with 224567 nodes. The governing equations are solved by the SIMPLE algorithm using the commercial CFD software of FLUENT 6.3.

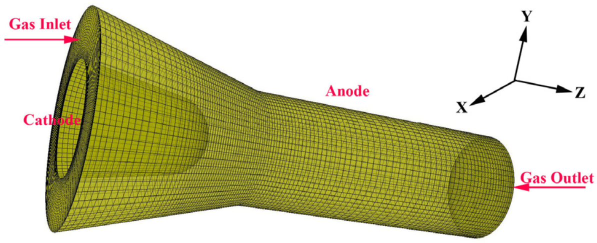


Fig. 2. Geometry of the computational domain

As seen in **Fig. 2**, the boundary of the computational domain is divided into 4 different faces to allow the specification of boundary conditions. Table 1 shows the boundary conditions used in the simulation, where P_{in} represents the inlet pressure equal to 111325 Pa (10 kPa overpressure), h_w the convective heat transfer coefficient at the anode wall equal to 1×10^5 W.m^{-2}.K^{-1} [19-22], T_w a reference cooling water temperature of 500 K. The current density of cathode was defined by:
$$j(r) = J_{catho} \exp\left(-\left(\frac{r}{R_c}\right)^{n_c}\right)$$
Where r is radial distance from the torch axis ($r^2 = x^2 + y^2$), and J_{catho} and n_c are parameters that specify the shape of current density profile. The R_c is

calculated to ensure that integration of *j(r)* over the cathode equals the total applied current. According to the reference 20 and 23, J_{cath0} of 2.08×10^{8} A/m^2, n_c of 4 and R_c of 0.913 mm were used in this study for the applied electric current of 500 A.

Table 1. Boundary conditions

Boundary	P	V	T	Ø	A
Inlet	P_{in}	50 SLM	300 K	$\partial \phi/\partial n=0$	0
Cathode	$\partial P/\partial n=0$	0	3000 K	*j(r)*	$\partial A/\partial n=0$
Anode	$\partial P/\partial n=0$	0	$h_w(T-T_w)$	0	$\partial A/\partial n=0$
Outlet	1 atm	$\partial V/\partial n=0$	$\partial T/\partial n=0$	$\partial \phi/\partial n=0$	$\partial A/\partial n=0$

Argon gas was employed as the plasma gas in this study. As the table 1 showed, the spray conditions is 500 A of current and 50 SLM of gas flow rate.

3 Results and Discussions

3.1 Flow fields inside the torch

The distribution of electric field strength inside plasma torch calculated by the LTE model is shown in the **Fig. 3**. The maximum electric field strength is about 0.78×10^{5} V/m near the anode boundary. **Figure 4** shows the time-evolution of the electric current distributions. It reveals that the arc-root moved downstream for the time of 858 μs to 868 μs. At the same time, a new electric current “path” will be formed if the electric field strength is strong enough to break down between the arc and anode boundary. Consequently, electric current will go through the old arc-root and the new one simultaneously. With the time elapsed, the old arc-root will be disappeared and only the new one maintained as shown in the Fig. 4.

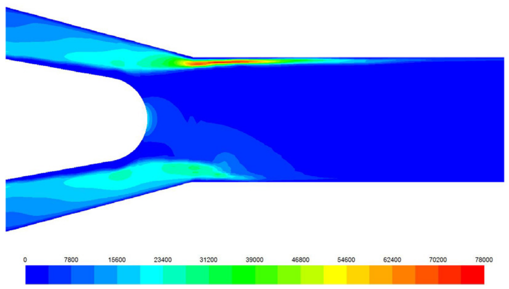


Fig. 3. Electric field strength distribution inside plasma torch at the time of 858 μs.

With the arc-root movement and transition, the arc should be fluctuated. The time-evolution of gas temperature and velocity distributions inside plasma torch are showed in the **Fig. 5**. While the attachment of arc to the anode at the underside surface at the time of 858 μs as shown in the Fig. 4, the arc was warped and deviated to the contrary side. The deviation of arc resulted to rise of the electric field strength at the fringe of the arc so that a new arc-root formed. As the old arc-root disappeared, the arc will deviate to the other side too in order to generate the next attachment as shown in the Fig. 5 (a). The gas velocity distributions inside plasma torch show that the gas velocity inside plasma torch has also a significant fluctuation with the arc-root movement and transition as shown in the Fig. 5 (b). The fluctuations of plasma gas temperature and velocity are the main reason to caused the plasma jet fluctuated, consequently influencing on the reproductivity of coatings. The maximum gas temperature more than 30000K and velocity more than 1000 m/s are obtained under the current spray conditions of argon gas, 500 A electric current and 50 SLM gas flow rate.

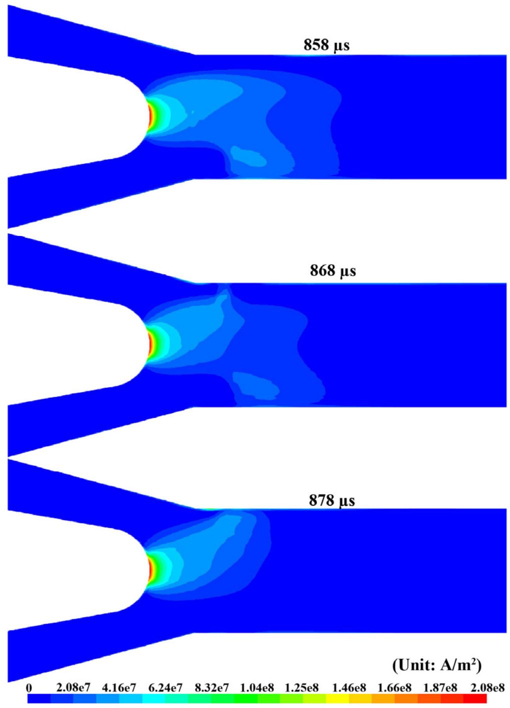
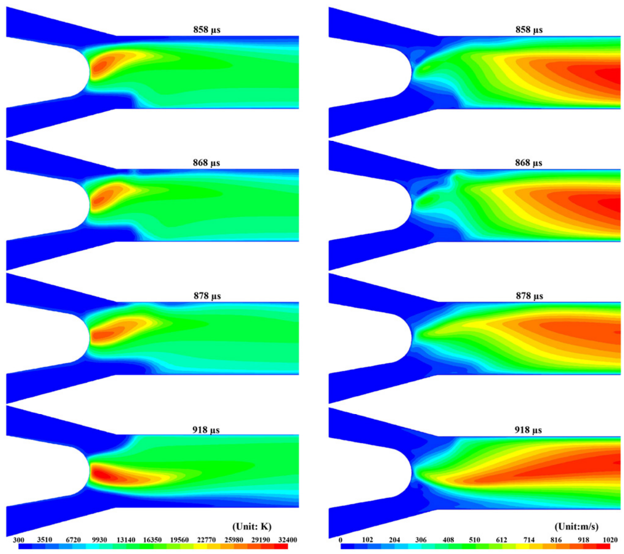


Fig. 4. Electric current distribution inside plasma torch at different time.



(a) (b)

Fig. 5. Plasma gas temperature (a) and velocity (b) distributions inside plasma torch at different time

Figure 6 shows the gas temperature and velocity at different cross sections inside plasma torch. It can be seen that the gas temperature and velocity distributions are asymmetric even though the geometry of plasma torch is axisymmetric due to the fluctuations of arc.

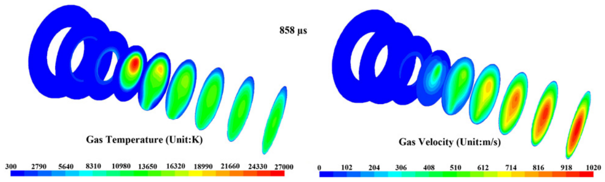
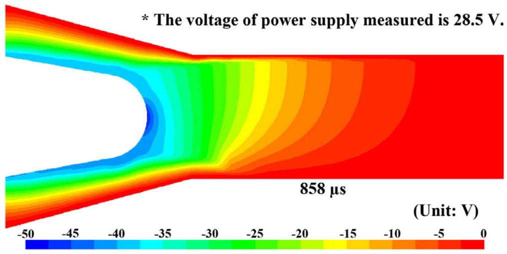
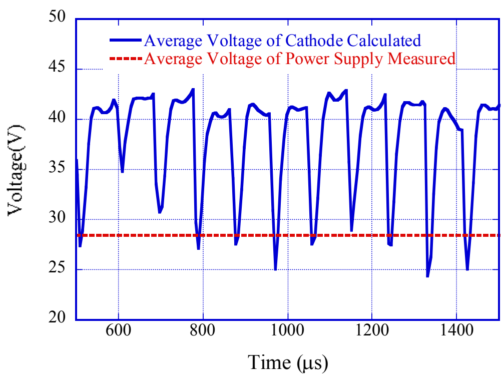


Fig. 6. Plasma gas temperature and velocity distribution at different cross sections inside plasma torch.

The electric potential distribution of plasma arc is showed in **Fig. 7** (a). The voltage drop of the arc column should be lower than the voltage of power supply theoretically because the voltage drop of sheath exists. However, the arbitrary higher electric conductivity nearby electrode and LET assumptions result to a lower accuracy for the electric potential distribution especially the vicinity of cathode. Therefore,the sheath voltage drop cannot be observed and the voltage drop of the arc column calculated is much higher than the voltage of power supply measured experimentally. Figure 7 (b) shows the time-evolution of average voltage on the cathode. It reveals the frequency of plasma arc fluctuation is about 11 kHz.



(a)

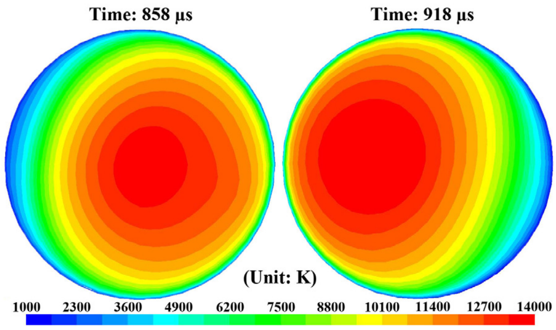


(b)

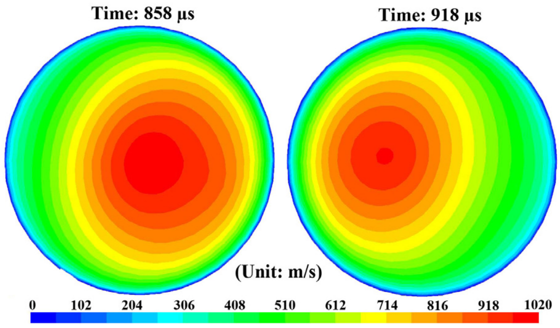
Fig. 7. The electric potential distribution inside plasma torch (a) and the time-evolution of cathode voltage.

3.2 Gas flow at the torch exit

The plasma jet are mainly determined by the gas flow at the torch exit. The parameters of plasma jet can be predicted by the distributions of gas temperature and velocity of torch outlet. Therefore, it is extremely important to mimic the outlet temperature and velocity of gas in order to understand the fluctuations of jet of plasma spray. The calculated distributions of gas temperature and velocity at the nozzle exit are shown in **Fig. 8**. The maximum temperature of about 14000 K and velocity of about 1000 m/s are obtained at the nozzle exit. It can be founded that the value calculated is well agree with the results measured experimentally according to the references [25-27].



(a)



(b)

Fig. 8. Plasma gas temperature (a) and velocity (b) distributions at the torch exit

The gas temperature and velocity at the nozzle exit fluctuate with the time elapsed too as shown in the Fig. 8. The fluctuations result to the vibration of the gas flow rate of torch outlet around 50 SLM, the inlet gas flow rate, as shown in the **Fig. 9**.

4 Conclusions

A LTE model has been developed and applied to the three-dimensional and time-dependent simulation of the flow inside a DC arc plasma torch. This mode well mimiced the arc fluctuation inside a plasma torch. The temperature and velocity distribution of arc gas inside the torch were calculated. The electric current mainly conducts through the arc-root to the anode. The concentration of electric current causes the warp of arc resulting to the rise of electric field strength at the contrary side of arc-root. When the arc is closed enough to the anode boundary and the elecrric field strength is strong enough, the old acr-root will transfer to a new one. The movement and transiation of arc-root result to the fluctuation of plasma arc inside plasma torch with the frequency of 11 kHz. A gas temperature of about 14000K and velocity of about 1000 m/s were obtained at the torch exit. A higher voltage drop of arc column was obtained compared to the one measured experimentally due to the LTE assumption underestimated the electric conductivity of plasma gas inside the torch, especially the regions around the arc-root.

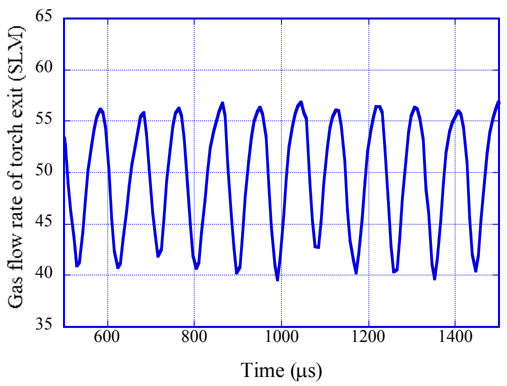


Fig. 9. The time-evolution of gas flow rate to the torch exit.

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