Numerical Analysis of the Influence of Atmospheric Plasma Gun Structure on Plasma Flow

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Abstract. To investigate the gun structure influence on gas flow characteristics during plasma spraying process, a simplified 3-D computing model was developed to calculate the multi-physical properties of the gun. The geometric model included cathode and anode, and electrodes boundary layers. Besides the temperature of ions and electrons was treated separately. In other words, the model used a two-temperature plasma model, which took into account ionization and recombination reactions of ions and electrons, the plasma flow inside the spray gun was studied. From the calculation results, decreasing of gun throat diameter caused the increase of velocity and decreasing of temperature. The change of velocity behaved a linear relationship with diameters, while temperature decreasing slowed down when the diameters reached a certain value. The research will provide theoretical guidance for the optimal design of spray gun.

1. Introduction
Plasma is a dense cloud of electrons, ions, atoms and molecules, defined as the fourth state of matters. There is no clear-cut boundary between the plasma and the gas. Atmospheric Plasma Spraying (APS) uses the high intensity of DC arc plasma which operates at current levels (I >500A) and pressures (p >10kPa) to heat and accelerate injected particles [1]. With a high temperature in the core of the plasma flame, APS can melt most of engineer materials including refractory materials. It has been used as a method of fabricating a thermal or corrosion barrier in many engineering applications like aviation, automation etc.

Plasma spraying has been used to produce high performance coatings. Since the plasma spraying process needs high precision and multiple parameter control. The lack of research on the basic theory and the influence between various process parameters hinders the development of plasma spraying technology [2]. In recent years, some researches focused on improving batch stability of high performance thermal barrier coatings have been conducted by Huang [3-4] and Mauer [5]. The first thing to understand is the thermodynamic and kinetic behavior of the gas inside and outside the plasma gun [6].

In the earlier days, two-dimensional (2D) computing model was used to study the muti-physics field by Han and Chen [7]. Later, Cheng used two-dimensional model to research the airflow characteristics outside the plasma gun [8]. The development of computer technology promotes the improvement of numerical simulation methods, Bhuyan and Goswami, Selvan and Ramachandran
analysed plasma flow characteristics by 3-D model [9-10]. Subsequently, Huang treated plasma flow as a chemical equalizing fluid [3]. However, there are few researches on the influence of plasma nozzle structure on plasma flow performance.

In this paper, a simplified 3-D computing model was developed to calculate the multi-physical properties of the gun. The geometric model included cathode and anode, and electrodes boundary layers. Besides the temperature of ions and electrons was treated separately. The model used a two-temperature plasma model, which took into account ionization and recombination reactions of ions and electrons. Further, different spray gun structures were defined to investigate how the flow properties changed.

2. Model Methodology

2.1 Background

According to realistic spray gun, a relative fan-shaped simulation model of plasma spray gun and ambient atmosphere was set up. Dimensions of the model are scripted as follows. As showed in the Fig.1, The plasma gun contains cathode, anode and outer powder injector.

Figure 1. Atmospheric plasma spray gun and its drawing

Some basic assumptions in the computation:
1) Argon is filled in the ambient gas of the spraying jet;
2) The plasma is optical thin;
3) The spraying process has been in the steady mode;
4) The rotational velocity component in fluid flow is ignored, so that the $k-e$ turbulence model can be used to analyse this problem.

Because the plasma flow temperature varies from room temperature to more than 10000 K, it is necessary to consider the variation of the density of the fluid medium. But the ideal gas law is still valid in the plasma flow with little deviation.

2.2 Computational Model and Plasma Reactions

In hot plasma, when the electron number density is very high (higher than $10^{23} \text{m}^{-3}$), the electron and the heavy particle may collide sufficiently, thus reaching the thermal equilibrium state. This state often occurs at the center of the plasma jet. But at the edge of the plasma jet, the electron density is much higher than the density of heavy particles, and the thermodynamic temperature of electrons $T_e$ is higher than that of heavy particles $T_h$. It is necessary to analyse the problem of non-thermal equilibrium by using the two-temperature plasma model. This model, provided all reactions and coefficients are known, gives realistic species compositions. However the reactions of the ionization and recombination are complex, so only some dominating reactions and species were considered in a numerical model. The Arhenius theory was used to compute the reaction rates between the productions and reactants. Arrhenius form is described as follows:

$$k_f = AT^n \left( \frac{P}{P_{\text{amin}}} \right)^m e^{-E_a/RT} \tag{1}$$

where $A$ is pre-exponential constant, $n$ is temperature exponent, $E_a/R$ is activation temperature, $m$ is pressure exponent.
When the reaction, either ionization or recombination, involves electrons, cross section theory can be another alternative method to describe it. The electron induced reaction rate can be calculated according to:

\[ k_f = \int f(u) \sigma(u) \, du \]  

(2)

where \( f \) is the electron energy distribution function (EEDF), \( \sigma \) is the collision section and varies according to electron energy \( u \).

In this paper, when the working gas is only argon, the gas reactions to be considered are as follows:

- Activation of argon: \( \text{Ar} + e \rightarrow \text{Ar}^* + e \)
- Ionization of argon: \( \text{Ar} + e \rightarrow \text{Ar}^+ + 2e \)
- Recombination of argon: \( \text{Ar}^+ + 2e \rightarrow \text{Ar} + e \)

When the working gas is a mixture of argon and 20% hydrogen, additional chemical reactions need to be considered as follows:

- Dissociation of \( \text{H}_2 \): \( 2\text{H}_2 \rightarrow 2\text{H}, 3\text{H} \rightarrow \text{H} + \text{H}_2, \text{e} + \text{H}_2 \rightarrow 2\text{H} + e, 2\text{H} + \text{Ar} \rightarrow \text{H}_2 + \text{Ar} \);
- Ionizations: \( \text{e} + \text{H} \rightarrow \text{H}^+ + 2e, \text{e} + \text{H}_2 \rightarrow \text{H}_2^+ + 2e; \)
- Recombination: \( \text{e} + \text{H}_2^+ \rightarrow 2\text{H}, \text{e} + \text{ArH}^+ \rightarrow \text{ArH} + \text{H} \)
- Charge transfer: \( \text{H}^+ + \text{H}_2 \rightarrow \text{H} + \text{H}_2^+, \text{Ar}^+ + \text{H}_2 \rightarrow \text{Ar} + \text{H}_2^+, \text{Ar}^+ + \text{H}_2 \rightarrow \text{ArH}^+ + \text{H} \)

Other higher ionization, like \( \text{Ar}^{2+} \), of different species were eliminated due to their negligible fraction compared to the above species.

2.3 Model Settings

The calculation model conditions extracted from the actual process of plasma spraying are shown in Table1.

| Parameters                          | Value       |
|-------------------------------------|-------------|
| Gun inside diameter                 | 7 [mm]      |
| Gun Length                          | 32.5 [mm]   |
| Density calculation method          | Ideal Gas Law|
| Diameter of the ambient domain      | 35.5 [mm]   |
| Length of the ambient domain        | 160 [mm]    |
| External pressure of the region     | 1 [atm] (0.1 [MPa]) |
| Turbulence model                    | RNG k-\( \varepsilon \) |
| Inlet velocity                      | 35 [m/s]    |
| Cathode inlet current density       | \(5.35 \times 10^6\) [A/m²] |

3. The Relationship Between Gun Structure and Plasma Jet

Since the arc was restricted within the gun chamber, it's size and shape couldn’t change according to current density, which lead to different current density within the arc. When the arc got smaller, the current density climbed. According to the Joule Law, higher current density leads to a higher temperature. Using the above model with Ar-H\(_2\) as working gas, different gun shapes were used to investigate gas temperature and velocity changing. The diameter of throat in the gun, which showed in Fig.2, was changed in serials.
When the diameter of throat in the gun changed, the gas flow would change coherently. If the flow was assumed to one dimensional isentropic steady flow in round tube, the velocity and cross section are correlated according to the following equation.

\[(M_a^2 - 1) \frac{dV}{V} = \frac{dA}{A}\]  \hspace{1cm} (3)

where \(M_a\) is the Mach number, \(V\) is the velocity, \(A\) is the cross-sectional area.

When Mach number is less than 1, larger cross section will lead to smaller velocity. In contrast, when Mach number is greater than 1, which means the flow have reached a supersonic status; larger cross section will lead to higher velocity.

The decreasing law of throat diameter was that: the next diameter was 0.9 times of the former one. When the diameter decreased from \(R_3=3.5\) mm, different velocity, Mach number and temperature are shown in Fig.3.

According to Fig. 3, although the inner diameter changed, the high temperature and velocity zones still appeared inside of the gun chamber. To investigate the difference of those serial diameters in detail, the velocity, Mach number and temperature distribution along the axis were extracted as shown in Fig.4.
According to Fig. 4, the velocity and Mach number increased with the decreasing of the throat diameter. When \( R_3 \) reached to 0.801 mm, that is \( 0.801 = 3.5 \times 0.9^{14} \), the Mach number exceeded 1. And the largest velocity appears not at the tip of the cathode, but somewhere in front of it. At that temperature, the sound velocity was nearly 3300 m/s. The intervals between neighboring distribution lines were equal. On one hand, the reason for velocity change can be explained that flow is constant...
(Q=v*S, where v is velocity and S is surface) and a reduction of the surface (S=πr², where r is the anode radius) induce an increase of the velocity. On the other hand, higher current density means more heat in the gun chamber leading to accelerating of flow.

Compared to the distribution of velocity, the temperature along axis decreased with the decreasing of throat diameter. The reason for the decreasing of temperature was the increasing of plasma velocity, since in higher velocity flow, the gas was cooled down faster than that in a lower one. But the intervals between neighboring distribution lines were different. At the beginning, when the diameter started to decrease, the temperature difference was larger than that at the end of the diameter changing. As discussed above, the current density in the arc would increase with smaller arc size. So when the diameter of gun chamber decreased, the arc current would increase as well, thus the working gas can be heated more efficiently.

4. Conclusions
According to analyse the flow properties under different spray gun structures, the relationship between kinetic properties of plasma jet and structure parameters have obtained. The velocity and Mach number increased with the decreasing of the throat diameter, while the temperature along axis decreased with the decreasing of throat diameter. This was because when the diameter of gun chamber decreased, the arc current would increase as well, thus the working gas can be heated more efficiently.

Acknowledgments
This work was supported by Fuyang Municipal Government-Fuyang Normal University Horizontal Cooperation Scientific Research Project(XDHX2016023), Fuyang Normal University Natural Science Research Project(2016FSKJ01), Fuyang Normal University Teaching Research Project (2016JYXM54).

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