Numerical Simulation of Suspension Plasma Spraying with Axial Injection^{*1}

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Two-dimensional simulation is performed for an annular-shaped plasma torch using argon gas under different operating currents and torch-substrate distances. The mathematical model is based on the conservation equations of mass, momentum, and total energy for gasdynamics and the steady-state Maxwell's equations for electrodynamics. Suspension carrying zirconium particles are axially injected into plasma flow and their trajectories and heating histories are analyzed with the Lagrangian method. A simplified model is used to simulate the evaporation of suspension droplets and the emergence of solid particles. The numerical results show that current stream lines are sharply curved downstream of the torch. In-flight particles are strongly heated in the area where the current streams are curved. An increase in operating currents results in shortening the length of current stream lines and moving the curved area further upstream. The numerical results also indicate that the particle impacting positions on a substrate get closer to its center as the operating current gets larger and the torch-substrate distance becomes shorter. Furthermore, the numerical results suggest that setting an operating current to higher values, which leads to an increase in particle impacting velocity, is suitable for impacting particles with molten state on the substrate. [doi:10.2320/matertrans.T-M2018842]

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1. Introduction

Suspension plasma spraying (SPS), using a liquid carrier such as ethanol or water, has the ability to spray metallic or ceramic particles much smaller than those used in conventional plasma spraying. The resultant coatings have a micro-structure with superior properties, so that SPS technique is expected to be utilized for thermal barrier coatings of high-efficiency gas turbine blades, manufacturing electrodes and electrolyte of Solid Oxide Fuel Cells (SOFC), and so on.^{1,2)}

Compared with conventional plasma spraying, SPS produces the coatings through more complicated processes due to the interaction between suspensions and a plasma jet. To obtain a better understanding of SPS processes for controlling the coating structures, several researches have focused on the suspension break up processes and the in-flight suspension behavior in the plasma jet.³⁻⁵⁾ It is needed for more advanced SPS applications to elucidate the process mechanism and its effect on the final coatings. There are two methods to inject suspensions: the one is a radial injection method which injects suspensions perpendicular to the plasma jet and the other is an axial injection method which injects suspensions parallel to the plasma jet. While the radial injection system has been generally used in conventional plasma spraying, there has not been enough understanding or knowledge of the axial injection system.^{6,7)} The remarkable feature of the axial injection system is active momentum and heat transfer from plasma to suspensions because the axially injected suspensions inevitably pass through the hot plasma jet. To realize more efficient SPS technique, it is essential to

clarify the transport processes and the flying characteristics of the injected suspensions.

The objective of the present study is to analyze the suspension behavior with heating histories and the suitable operation conditions for controlling the coating structures for an axial injection suspension plasma spray with a cylindrical configuration. It is a challenging task to observe experimentally the flying suspension solvents and sprayed particles under 5 micro meters in dimension in a plasma jet. Hence, the computational program was developed for analyzing the suspension trajectories and the thermal plasma flow. In this paper, it is discussed that the influence of operating current and torch-substrate distance on the distribution of particle positions, velocities, and melting states which directly affect coating structures.

2. Mathematical Model

2.1 Governing equations of flow and electric field

Mass conservation equation, momentum conservation equations, and total energy conservation equation for compressible fluid are used as the governing equations of flow field.

- Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

- Momentum conservation equations:

$$\frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = \nabla \cdot \bar{\bar{\tau}} - \nabla p \quad (2)$$

- Total energy conservation equation:

$$\frac{\partial(\rho E_{flu})}{\partial t} + \nabla \cdot (\rho H_{flu} \mathbf{u})$$

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$$= \nabla \cdot (\kappa \nabla T) + (\bar{\tau} : \nabla \mathbf{u}) + \mathbf{J} \cdot \mathbf{E} - \dot{q}_{rad} \quad (3)$$

where t is the time, ρ the mass density, p the pressure, T the gas temperature, E_{flu} the total internal energy per unit mass, H_{flu} the total enthalpy per unit mass, $\dot{q}_{rad}$ the radiation heat loss, $\mathbf{u}$ the gas velocity vector, κ the thermal conductivity, $\bar{\tau}$ the viscous stress tensor, $\mathbf{J}$ the current density vector, $\mathbf{E}$ the electric field vector. The total internal energy E_{flu} and the total enthalpy H_{flu} are defined, respectively, as $E_{flu} = e + |\mathbf{u}|^2/2$ and $H_{flu} = E_{flu} + p/\rho$, in which the variable e is the internal energy per unit mass.

In this work, fluid flow is assumed to be laminar because Reynolds numbers of fluid flow estimated with setting the characteristic length to the torch nozzle diameter are less than 2000 in 95% of the computational domain. The gas injection area and the fringe of the arc, however, have high Reynolds numbers over 2000. In addition, the critical Reynolds number for laminar-turbulent transition is expected to be less than 2000 for the flow exiting the plasma torch. To capture a more detailed picture of flow dynamics in thermal spraying, a proper turbulent model should be developed and included in our future work. We also ignore the momentum and energy transport from suspensions to fluid flow and the influence of suspension solvent evaporation on transport properties of the fluid. The ignorance is valid because the volume fraction of particles in fluid flow is sufficiently small in the most of the computational domain except for suspension injection area.⁸⁾ When focusing on the interaction between suspensions and fluid flow in the suspension injecting area, a proper model to take this local interaction into account should be introduced.⁹⁾ The conservation eqs. (1)–(3) are discretized by conventional finite volume method. The numerical flux of convective terms and the one of diffusion terms are evaluated by the first order AUSM-DV scheme¹⁰⁾ and the central differential scheme, respectively. When considering turbulent effects, higher-order discretization is needed. The time integration of the conservation equations is performed with the LU-SGS implicit method.¹¹⁾

The governing equations for electric field are composed of steady Maxwell's equations and Ohm's law as follows.

- Maxwell equations:

$$\nabla \times \mathbf{E} = \mathbf{0} \quad (4)$$

$$\nabla \cdot \mathbf{J} = 0 \quad (5)$$

- Ohm's law:

$$\mathbf{J} = \sigma \mathbf{E} = \sigma (-\nabla \phi) \quad (6)$$

in which σ is the electrical conductivity and ϕ is the electric potential. Using eqs. (4)–(6), the elliptic type partial differential equations on the electric potential ϕ is derived, and then the equations are discretized by the Galerkin finite element method using the first order triangle elements.

2.2 Governing equations for suspensions and particles

The governing equations for suspensions and particles are based on the Refs. 7, 12. Here, it is assumed that one suspension droplet is composed of one sprayed particle (ZrO_2) and one suspension solvent ($\text{C}_2\text{H}_5\text{OH}$), as illustrated in Fig. 1. In addition, both the particle and the suspension solvent are assumed to have a spherical shape. Although

Fig. 1 Suspension droplet and particle model.

multiple particles are immersed in the atomized solvent in real suspension plasma spraying processes, one solvent is assumed to include one particle for the simplicity. Furthermore, the sprayed particle and suspension solvent are assumed to have a same temperature until the solvent evaporates completely. This temperature, which is called “suspension temperature T_d ,” is calculated by

$$\frac{dT_d}{dt} = \frac{\dot{Q}_{conv}}{m_d c_{p,d}} \quad (\text{if } T_d < T_{v,sl}) \quad (7)$$

$$T_d = T_{v,sl} \quad \left(\text{if } \int_0^t \dot{Q}_{conv} dt \leq m_d c_{p,d} (T_{v,sl} - T_{d,0}) + m_{sl} \alpha_{sl} L_{v,sl} \right) \quad (8)$$

where $\dot{Q}_{conv}$ is the convective heat transfer rate from fluid flow to suspensions. The radiative heat transfer from fluid flow to suspensions is assumed to be negligible because the convective heat transfer is dominant compared with the radiative heat transfer under the suspension diameter condition used in this work.¹³⁾ The mass of suspension droplet m_d is the sum of the particle mass m_p and the suspension solvent mass m_{sl} , namely, $m_d = m_p + m_{sl}$. The variables $T_{v,sl}$, $T_{d,0}$ and constant $L_{v,sl}$ are the evaporation temperature of the suspension solvent, the initial temperature of the suspension droplet, and the evaporation latent heat of the suspension solvent, respectively. The specific heat of the suspension droplet $c_{p,d}$ is calculated by

$$c_{p,d} = c_{p,p} (1 - \alpha_{sl}) + c_{p,sl} \alpha_{sl} \quad (9)$$

where $c_{p,p}$ is the specific heat of the particle and $c_{p,sl}$ is the specific heat of the suspension solvent. The character α_{sl} is the mass fraction and is calculated by $\alpha_{sl} = m_{sl} / (m_p + m_{sl})$. Viscous drag force is assumed to be dominant in external forces working on suspensions, so that the suspension trajectories are calculated using the following equation:

$$m_d \frac{d\mathbf{u}_d}{dt} = \mathbf{F}_d = \pi r_d^2 C_D \frac{\rho |\mathbf{u} - \mathbf{u}_d| (\mathbf{u} - \mathbf{u}_d)}{2} \quad (10)$$

in which $\mathbf{u}_d$, r_d , C_D are the suspension velocity, the suspension radius, the drag coefficient, respectively. The coefficient C_D is calculated by the following equation:

$$C_D = \left(\frac{24}{Re_p} + \frac{6}{1 + \sqrt{Re_p}} + 0.4 \right) f_{prop}^{-0.45} f_{Kn}^{0.45} \quad (11)$$

where Re_p is the Reynolds number and is calculated by the eq. (19) described later. The functions f_{prop} and f_{Kn} represent

the effects of variable plasma properties and non-continuum, respectively, and are found in Ref. 12.

After the evaporation of a suspension solvent, a sprayed particle is ejected having the same velocity and temperature at the time when the suspension solvent evaporation completes. The distribution of the temperature in the particle T_p is assumed to have a spherical symmetry distribution and is calculated by the following equation of heat conduction:

$$\rho_p c_{p,p} \frac{\partial T_p}{\partial t} = \frac{1}{r_c^2} \frac{\partial}{\partial r_c} \left(k_p r_c^2 \frac{\partial T_p}{\partial r_c} \right) \quad (12)$$

in which ρ_p is the particle mass density, r_c is the distance from the particle center, and k_p is the particle thermal conductivity. The boundary conditions of the equation of heat conduction are given by

$$\left. \frac{\partial T_p}{\partial r_c} \right|_{r_c=0} = 0 \quad (13)$$

$$4\pi r_p^2 \left(k_p \frac{\partial T_p}{\partial r_c} \right) \bigg|_{r_c=r_p} = \dot{Q}_{conv} - \dot{Q}_{vap} - \dot{Q}_{rad} \quad (14)$$

where r_p is the radius of the sprayed particles. The variables $\dot{Q}_{vap}$ and $\dot{Q}_{rad}$ are the vaporization heat transfer rate and the radiative heat transfer rate, respectively, and are calculated using the following equations:

$$\dot{Q}_{conv} = 4\pi r_p^2 h_f (T_f - T_s) \quad (15)$$

$$\dot{Q}_{vap} = \dot{m}_v L_{v,p} \quad (16)$$

$$\dot{Q}_{rad} = 4\pi r_p^2 \epsilon_p \sigma_s (T_s^4 - T_\infty^4) \quad (17)$$

where T_f is the film temperature between the particle surface and the surrounding gas and is estimated by the simple average $(T_f = (T_s + T_g)/2)$ of the particle surface temperature T_s and the gas temperature T_g . The evaporation rate $\dot{m}_v$ in eq. (16) is calculated by following Ref. 12. The reduction of particle radius is also calculated by the evaporation rate $\dot{m}_v$. The constant $L_{v,p}$ in eq. (16) is the evaporation latent heat of particles. The constants ϵ_p and σ_s in eq. (17) are the emission coefficient and the Stephan-Boltzmann constant, respectively. The variable T_∞ in eq. (17) is the gas temperature in area far away from the particle. Hereafter, the subscript f means the value calculated by the film temperature T_f . The heat transfer coefficient h_f in eq. (15) is calculated by following equation:

$$Nu = \frac{2h_f r_p}{\kappa_f} = (2.0 + 0.6 Re_p^{1/2} Pr^{1/3}) \left(\frac{c_{p,g}}{c_{p,s}} \right)^{0.38} (f_{prop})^{0.6} f_{Kn} f_v \quad (18)$$

where the dimensionless number Nu is the Nusselt number. The Reynolds number Re_p is estimated by

$$Re_p = \frac{2\rho_d |\mathbf{u} - \mathbf{u}_d|}{\mu_f} \quad (19)$$

in which μ_f is fluid viscosity and Pr is the Prandtl number which is calculated by $Pr = \mu_f c_{p,f} / \kappa_f$. The variables $c_{p,g}$, $c_{p,s}$, $c_{p,f}$ are the specific heat of fluid calculated by T_g , T_s , T_f , respectively. The factor f_v accounts for the effect of mass transfer due to particle evaporation and is calculated by

$$f_v = \frac{\dot{m}_v c_{p,f} / 2\pi r_p \kappa_f}{\exp\{\dot{m}_v c_{p,f} / 2\pi r_p \kappa_f\} - 1} \quad (20)$$

The variable r_m is the position of the melting interface from the particle center and is calculated by the following equation:

$$L_{m,p} \rho_p \frac{dr_m}{dt} = \left(k_p \frac{\partial T_p}{\partial r} \right) \bigg|_{r=r_m^-} - \left(k_p \frac{\partial T_p}{\partial r} \right) \bigg|_{r=r_m^+} \quad (21)$$

The variable $r_m^\pm$ is the distance from the particle center to the grid points next to the melting interface. The constant $L_{m,p}$ is the melting latent heat of particles. The discretization of the differential equation of eqs. (7), (10), (12), and (21) are performed by the Euler explicit method, the four-stage Runge-Kutta method, the full implicit method, and the Euler explicit method, respectively, considering the calculation accuracy and the computational cost.

2.3 Thermodynamic and transport properties

Argon is assumed to be used as plasma gas. The number density for each species and thermodynamic properties are calculated by the partition function with the method of minimizing the Gibbs free energy under local thermodynamic equilibrium (LTE) approximation.¹⁴⁾ The argon plasma is assumed to be composed of Ar, Ar⁺, Ar⁺⁺, e⁻. The transport properties are calculated by the approximation of the Chapman-Enskog theory.¹⁵⁾

2.4 Numerical domain and boundary conditions

Numerical domain is a twin cathode plasma torch with an axial injection system found in Ref. 16. Although the plasma torch has a three-dimensional structure, its two cathodes are set in symmetry and have highly symmetric structure as a whole. As for the suspension injection, the three-dimensional characteristics can be neglected because suspensions are injected axially near the center lines. Therefore, axisymmetric two-dimensional approximation is adopted for numerical modelling.

Figure 2(a) and 2(b) show the schematic of plasma spray and the dimension of the numerical domain, respectively. Table 1 also shows the operating conditions of the plasma torch. The operating gas is pure argon. The operating current and the flow rates of each gas, the anode working gas, the atomizing gas, and the cathode working gas, are determined by referring Ref. 17. The torch-substrate distance d is determined by referring Ref. 16. The flow rate of the cathode working gas is given by considering the axisymmetric assumption.

On the wall surface boundary, non-slip wall condition is applied. The temperature of the wall and substrate is fixed at a constant value by referring Ref. 18. For simplicity, the fixed value is given by 300 K. On the boundary sufficiently far from the plasma spray, the pressure is set to 1 atm. The temperature and the pressure are decided using non-gradient condition in the direction normal to boundary surface. The electrical potential at the cathode is set to 0 V, while the one on the anode is determined so as to satisfy an electric current between the anode and cathode.

The suspension trajectories and heating histories are analyzed for the steady flow field. Table 2, Table 3, and Table 4 show the particle material properties, the suspension solvent properties, and the suspension injection conditions, respectively.

Fig. 2 (a) Schematic of plasma spray and (b) dimensions.

Table 1 Operating conditions.

Gas type	Ar
Anode working gas (L/min)	17
Atomizing gas (L/min)	1.3
Cathode working gas (L/min)	29.5
Operating current (A)	100, 200, 300
Torch-substrate distance (mm)	10, 20, 30

Table 2 Particle material properties (ZrO₂).

Solid density (kg·m ⁻³)	5.89×10^3
Liquid density (kg·m ⁻³)	5.89×10^3
Thermal conductivity of solid (W·m ⁻¹ K ⁻¹)	2.0
Thermal conductivity of liquid (W·m ⁻¹ K ⁻¹)	3.0
Specific heat of solid (J·kg ⁻¹ K ⁻¹)	580
Specific heat of liquid (J·kg ⁻¹ K ⁻¹)	713
Melting point (K)	2950
Boiling point (K)	5000
Melting latent heat (J·kg ⁻¹)	8.00×10^5
Evaporation latent heat (J·kg ⁻¹)	6.00×10^6
Emissivity (-)	0.3

Table 3 Suspension solvent properties (C₂H₅OH).

Liquid density (kg·m ⁻³)	0.8×10^3
Specific heat of liquid (J·kg ⁻¹ K ⁻¹)	2400
Boiling point (K)	351
Evaporation latent heat (J·kg ⁻¹)	9.25×10^5

Table 4 Suspension injection conditions.

Initial diameter of suspension droplet (μm)	80
Initial diameter of particle (μm)	5
Initial temperature (K)	300
z-Component of initial velocity (m·s ⁻¹)	10
Injection suspension number (-)	1000
Injection position (z, r) (mm)	0.5, 0.1

Fig. 3 Gas temperature distributions and current stream lines under different current conditions: (a) 100 A, (b) 200 A, (c) 300 A.

2.5 Validation of numerical modelling

The numerical simulation of thermal plasma was performed for the operating condition found in Ref. 16. In comparing the voltage between electrodes in steady state, there was about 8% difference for the voltage: the 150 V for the experiment and the 139 V for our simulation result. These results show a good agreement and the difference is probably caused mainly by the axisymmetric assumption.

3. Results and Discussion

In order to discuss the influence of the operating current on flow field and suspension behavior, the numerical results for the case of torch-substrate distance $d = 20$ mm are presented. Figure 3 shows the gas temperature distributions and the current stream lines for different operating current conditions: 100 A, 200 A, and 300 A. The gas temperature rapidly increases in the downstream area of the anode. The maximum temperatures are about 12200 K for the operating current of 100 A, 13500 K for 200 A, and 14800 K for 300 A. The increase in operating current strengthens Joule heating, so that the gas temperature is raised by increasing operating current. It can be seen that the current stream lines, instead of taking the shortest route between the anode and cathode, are sharply curved downstream of the torch due to the gas

Fig. 4 Gas velocity distributions and mass flux vector stream lines under different current conditions: (a) 100 A, (b) 200 A, (c) 300 A.

flow with high electrical conductivity which is heated and accelerated by the anode jet. At higher operating current, the current route is shorter since the gas is heated more rapidly and has higher electrical conductivity upstream. Therefore, the area where the current stream lines are curved moves to more upstream in the torch. As will be shown later, the position of the curvature area, which has a strong Joule heating, significantly influences the gas temperature distribution. Because of the shortening of current route with increasing operating current, the voltages between the electrodes become lower; they are about 104 V for 100 A, 89 V for 200 A, and 82 V for 300 A.

Figure 4 shows the gas velocity distributions and the mass flux vector stream lines for the operating current conditions of 100, 200 and 300 A. The gas velocity increases rapidly near the anode. This is caused by the volume expansion attributed to the Joule heating. The maximum velocities are about 160 m/s for 100 A, 255 m/s for 200 A, and 360 m/s for 300 A. It can be seen from Fig. 4 that the gas heated by Joule heating flows aside the substrate. Since SPS processes use smaller particles than conventional plasma spraying, the particle behavior is strongly influenced by the reduction of gas velocity in front of the substrate. To impact particles to the substrate, it is necessary for particles to have enough momentum in z -direction across the flow on the substrate.

Fig. 5 Particle trajectory on r - z plane.

Fig. 6 Gas temperature history along particle trajectory.

The particle trajectories for different operating current conditions are shown in Fig. 5. The particles injected with suspension solvent are heated and accelerated by the gas flow. They are bent in the r -direction near $z = 10$ mm where the cross section of the torch channel expands. At the operating current of 100 A, the particle is strongly bent in front of the substrate because the particle momentum in z -direction is almost lost by rapid gas deceleration. For the operating current of 200 A and 300 A, the particle gains the enough momentum in z -direction and reaches the substrate near the center line. This result indicates that high operating current is needed to impact the particles to the substrate.

Figure 6 shows the gas temperature history along the trajectory of the particle shown in Fig. 5. The gas temperature increases rapidly by Joule heating in the downstream area of the anode and reaches a peak value before $z = 20$ mm regardless of the operating current. From $z = 20$ mm to $z = 25$ mm, the gas temperature decreases gradually due to the cooling effect by the inflow of cathode working gas. There is a strong relation between the gas temperature after $z = 25$ mm and the position of the current curvature area. At lower operating current, the area where the current stream lines are curved having large Joule heating moves to the downstream side. As a result, at $z = 45$ mm, the gas temperature of operating current 100 A is higher than the other operating current cases. As the gas flow approaches the substrate, the temperature decreases rapidly. Figure 7 depicts

Fig. 7 z-Component of gas velocity along particle trajectory.

Fig. 9 z-Component of particle velocity history.

Fig. 8 Particle temperature history.

Fig. 10 Particle position and temperature distributions under different operating current conditions.

the history of the gas velocity in z -direction along the particle trajectory shown in Fig. 5. The gas velocity increases with increasing operating current, and also it gradually approaches zero near the substrate.

Hereafter, particle behavior is discussed in detail. In this work, the temperature distribution inside a particle was calculated by solving the equation of heat conduction. The difference between the particle surface and center, however, was little due to the small diameter and low heat capacity of the particle. In the following discussion, therefore, the particle surface temperature is regarded as the particle temperature.

Figure 8 shows the particle temperature history for different operating current conditions. After the particle experiences the constant temperature from about $z = 10$ mm to $z = 20$ mm, its temperature increases rapidly. This is because the particle keeps the evaporation point of ethanol until the complete evaporation of suspension solvent and then the temperature of the ejected particle rises after that. With increasing the operating current, the solvent evaporates more rapidly by larger Joule heating. In the flight from about $z = 15$ mm to $z = 20$ mm, particle temperature takes a constant value by particle melting. After the particle temperature rises by heating of high temperature plasma jet, it gradually decreases as the particle approaches the substrate. For the operating current of 100 A, the particle temperature decreases more than the other operating current conditions since the

particle is cooled by the flow in the temperature boundary layer on the substrate for longer time.

Figure 9 shows z -component of particle velocity history. After the evaporation of the suspension solvent, the particle is accelerated strongly by plasma jet. For each operating current condition, the particle velocity reaches its peak near $z = 40$ mm. After the peak, the particle decelerates by the gas velocity reduction in front of the substrate. At the operating current of 100 A, the particle velocity in z -direction approaches almost zero and therefore increasing operating current is needed to impact particles on the substrate.

Then, the behavior of sprayed particles in the vicinity of the substrate is discussed. In this work, a thousand suspension droplets are injected from $r = 0.3$ mm and the normal distribution with a standard deviation of 0.3 mm is given for initial radial positions. Thus, most of the suspension droplets are injected around $r = 0.3$ mm. In the following discussion, the position of $z = 69.85$ mm (position 0.15 mm away from the substrate) is selected as a representative position meaning a vicinity of the substrate. Figure 10 shows particle position and temperature distributions under different operating current conditions. The particle temperature in the vicinity of the substrate gets higher by larger Joule heating at higher operating current. The temperature of the particle

Fig. 11 Particle position and temperature distributions under different torch-substrate distance conditions (200 A).

reaching more away from the center line becomes lower through the particle transport processes by the cool gas flow on the substrate. The particle velocity in the vicinity of the substrate, as shown in Fig. 9, gets larger as increasing operating current. At higher operating current, the particles reach near the center line with less influence of the gas flow on the substrate. At the operating current of 100 A, the particles are strongly affected by the gas flow due to their small inertia. The temperature of the particles arriving near the center line, however, reaches the melting point of zirconia under the operating current of 100 A, which is lower than that generally used in conventional plasma spraying. The axial injection system allows particles to be melted with low operating currents and it is favorable in terms of the energy efficiency and the electrode lifetime.

The influence of torch-substrate distance on the particle position and temperature distributions is discussed. Because similar tendencies were obtained under all operating current conditions, only the results at the operating current of 200 A are displayed. Figure 11 shows the particle position and temperature distributions in the vicinity of the substrate (position 0.15 mm away from the substrate) for different torch-substrate distance conditions. The influence of the torch-substrate distance on the voltage between the electrodes is little and the voltage is about 89 V for all cases. As the torch-substrate distance is shorter, higher temperature and higher velocity plasma jet carries the particles, impacting particles with higher temperature on the substrate near the center line. For torch-outlet distance $d = 30$ mm, the gas flow near the substrate carries some particles to the edge of the substrate ($r = 20$ mm).

The higher temperature of the particle at the edge of the substrate can be explained by the gas temperature distribution of that area. At the edge of the substrate, the isothermal lines expand in fan-like fashion and the particles carried by the gas flow on the substrate fly across the isothermal lines. Since the particles fly from the low temperature region to the high temperature region, the particle temperature rises.

4. Conclusion

We performed axisymmetric two-dimensional numerical

simulations of a suspension plasma spray with an axial injection system to examine the influence of the operating current and the torch-substrate distance on the suspension trajectories with heating histories under the operating conditions covered in this work. Main results obtained by this work are summarized as follows:

- (1) Current stream lines, instead of taking the shortest route between the anode and cathode, are sharply curved in the downstream area of the plasma torch. The area where the current stream lines are curved has a large amount of Joule heating and moves to more downstream as the operating current decreases.
- (2) Axially injected suspensions are heated and accelerated rapidly by passing through hot plasma jet. After the complete evaporation of the suspension solvent, ejected particles are heated efficiently.
- (3) As the operating current gets larger and the torch-substrate distance gets shorter, particles impact on the smaller area of the substrate with keeping higher temperature.

In the real axial injection suspension plasma spray processes, plasma and suspensions have strong interaction with each other. In our future works, the influence of plasma-suspension interaction should be considered such as the two-way momentum and energy transfer between suspension and plasma and the effect of suspension solvent evaporation on the plasma transport properties. Additionally, a turbulence model and a higher-order discretization manner should be implemented in our numerical model.

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