FLUID FLOW AND TEMPERATURE FIELDS OF PLASMA JET
IN LOW PRESSURE SPRAY PROCESS

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ABSTRACT

Computational analyses were made to predict the fluid flow and temperature fields of the plasma jet in low pressure spraying. Calculations proceeded by specifying the boundary conditions at the plasma torch exit, then the governing equations were solved numerically.
Flow fields obtained make it clear quantitatively that the low pressure operation results in the elongation of the heating zone of the plasma jet.

1. INTRODUCTION

Plasma spraying has been used for over two decades in applying metals and ceramics for protection against wear, corrosion and erosion, and thermal barriers. In typical atmospheric plasma spraying (APPS), a structure of the coating is somewhat porous and a bond strength is often unsatisfactory. Moreover, reactive materials can not be sprayed. These problems restrict the application of this procedure to coating highly-stressed or key structural components.

To overcome these drawbacks, a new technique of low pressure plasma spraying (LPPS) has been developed by E.Muehliberger in Electro-Plasma Incorporation. The advantages of the LPPS have been demonstrated to be 1) higher density, 2) better adhesion and 3) less contamination with oxygen and nitrogen. Because of the excellent quality of the deposit, this advanced spraying is opening up promising fields of new application.

With the extension to critical coating, it becomes more important to comprehend details of the spraying process not only qualitatively but also quantitatively. The analysis of the thermal history of the particles requires the exact knowledge of the flow fields in the plasma jet. As for APPS, many studies were made experimentally1,2 and analytically,3,4 Recently an excellent work was carried out on the characterization of the plasma jet and the associated particles by N.Kaddah and his co-workers.5

It is known that the plasma flame elongates drastically with decrease of the ambient pressure. In spite of large difference between APPS and LPPS, the quantitative studies on the low pressure plasma jet are few.6

The purpose of this work is to investigate the fluid flow and temperature fields of the LPPS jet. As it is difficult to measure a high range of temperature and velocity experimentally, authors use computational techniques to predict the flow fields of the plasma jet.
2. MODEL FORMULATION

2.1 MODEL

A model of the system is shown schematically in Fig. 1. The problem of practical importance is to calculate the flow fields in the plasma gas downstream of the torch exit. A set of boundary conditions at the exit was specified by the well-known equations for the adiabatic flow through the nozzle.

Following assumptions were used for the flow upstream of the exit:

1) The anode of the torch is designed in the form of a Laval nozzle. The nozzle throat to exit area ratio is matched to the upstream to downstream pressure ratio.

2) Working gas, Argon, is perfect and continuous.

3) The flow is steady and isentropic. The heat loss which occurs in a real case is treated as the decrease of the input power.

4) For the free jet downstream of the exit, assumptions used were as:

5) The flow is steady and axi-symmetrical.

6) Ionized natures of the plasma gas is neglected, but compressible and viscous effects are taken into account.

7) Radial profiles of temperature and velocity are 'top-hat' distribution at the exit.

Two cases of APPS and LPPS were solved and both results were compared.

2.2 BOUNDARY CONDITIONS AT THE TORCH EXIT

In general, the flow velocity and temperature at the exit are not known. They should be specified by using the known quantities. Temperature (T₀), pressure (P₀) and density (ρ₀) of the plasma gas at a stagnation point are related to the given value of mass flowrate (Qₘ) and enthalpy flux (Qₜ) in the following form as:

\[ Qₜ = c₀ T₀ Qₘ \]  \hspace{1cm} (1)

\[ Qₘ = \pi rₜ^{2} ((2\gamma / R / (\gamma + 1))(\gamma+1) / (\gamma-1) / T₀)^{\gamma / 2} P₀ \]  \hspace{1cm} (2)

\[ ρ₀ = R T₀ / P₀ \]  \hspace{1cm} (3)

where c₀, γ and R represent specific heat at constant pressure, the ratio of specific heats and gas constant, respectively. The radius of the nozzle throat is denoted by rₜ.

Combined with the following isentropic equations:

\[ T₁ = T₀ (P₁ / P₀)^{(\gamma-1) / \gamma} \]  \hspace{1cm} (4)

\[ v₁ = (\gamma R T₀)^{\gamma / 2} M₁ \]  \hspace{1cm} (5)

and

\[ M₁^{2} = 2 / (\gamma-1) \left( P₀ / P₁ \right)^{(\gamma-1) / \gamma} - 1 \]  \hspace{1cm} (6)

temperature (T₁), velocity (v₁) and Mach number (M₁) at the exit can be expressed in terms of the given quantities of Qₘ, Qₜ, rₜ and the static pressure at the exit (P₁).

Calculations were carried out under the following conditions:
1) \( P_t = 1.01 \times 10^5 \text{ N/m}^2 \) in the case of APPS, and \( 3.55 \times 10^3 \text{ N/m}^2 \) in the case of LPPS. Values of \( Q_m \), \( Q_h \) and \( r_t \) were common in both cases.

2) \( Q_m = 0.375 \text{ kg/sec} \). The corresponding volumetric flowrate was 0.12 NL/min.

3) \( Q_h = 30 \text{ kW/sec} \). In order to give such amount of the heat flux to the flow, more than 60 kW should be supplied to the torch since in most cases the heat loss exceeds to 50% of the input power within the torch.

4) The throat radius, \( r_t = 5 \text{ mm} \).

The boundary conditions specified at the torch exit are shown in Table.1.

### 2.3 MATHEMATICAL FORMULATION AND NUMERICAL PROCEDURE

The governing equations to calculate the velocity and temperature fields downstream of the torch are as follows:

**Equation of Mass Conservation:**

\[
\text{div} ( \rho \mathbf{v} ) = 0
\]  

(7)

**Equation of Momentum Conservation:**

\[
\text{div} ( \rho \mathbf{v} \mathbf{v} ) = \text{div} ( \mathbf{v}_{\text{eff}} \text{ grad } \mathbf{v} ) - \text{ grad } P
\]  

(8)

**Equation of Energy Conservation:**

\[
\text{div} ( \rho h \mathbf{v} ) = \text{div} ( \mathbf{v}_{\text{eff}} / \nu h \text{ grad } h ) - S_R
\]  

(9)

Where \( h \) is the enthalpy defined as

\[
h = c_p T + \frac{1}{2} \nu^2.
\]  

(10)

Since no adiabatic assumption is used here, the enthalpy is not conservative. The effective viscosity, \( \mathbf{v}_{\text{eff}} \) is expressed as,

\[
\mathbf{v}_{\text{eff}} = \mu_t + \mu_1.
\]  

(11)

A laminar viscosity, \( \mu_1 \) is assumed to be proportional to the square root of the absolute temperature. The turbulent viscosity \( \mu_t \) is represented in terms of the \( k-\epsilon \) model:

\[
\mu_t = C_\mu \frac{k^2}{\epsilon}.
\]  

(12)

Where \( k \) and \( \epsilon \) are the turbulent kinetic energy and the rate of dissipation of \( k \) respectively. And a dissipation constant, \( C_\mu \), and effective Prandtl number for enthalpy, \( \sigma_h \), are taken as 0.09 and 0.9 respectively.

The radiative heat loss per unit mass is assumed in the following form:

\[
S_R = \alpha / T \exp (-\beta / T ).
\]  

(13)

From the experimental data reported by Evans and Tankin, the \( \alpha \) and \( \beta \) are deduced to be \( 8.3 \times 10^{16} \text{ J/K/kg/sec} \) and \( 5.9 \times 10^4 \text{ K} \), respectively.

The governing equations were solved numerically by using a computer-code system for simulating phenomena of fluid mechanics, which was developed by Spalding. A grid of 15 x 18 cells were employed as shown in Fig.2.
3. RESULTS AND DISCUSSIONS

Calculated results are shown in Figs. 3 to 7. Figs 3-a and 3-b show the contour maps of the velocity fields in APPS and LPPS respectively, where equi-velocity lines are drawn at intervals of 100 m/sec and the velocity of the outermost line is 100 m/sec. The profiles of the enthalpy fields are illustrated at intervals of 0.8 x 10^6 J/kg in Figs. 4-a and 4-b. The distributions of velocity, enthalpy and temperature on the center line of the free jet are shown in Figs. 5, 6 and 7, respectively.

The LPPS jet is characterized by a higher velocity and a lower temperature, compared with the APPS jet. It should be noticed that the heating of the sprayed particle in the LPPS jet is owing to not only thermal but also kinetic energy of the flow. The temperature increase of the gas at the stagnation point behind the particle, ΔT, is known to be represented as:

\[ \Delta T = \frac{(v - v_p)^2}{2c_p}, \]

(14)

where \( v_p \) is the particle velocity. Thus, enthalpy which includes thermal and kinetic energy is a key quantity in the estimation of the heat transfer in the LPPS process. From this point of view, gradual decrease of the enthalpy as is shown in Fig. 6 is one of advantages in LPPS process.

The predicted fluid flow and temperature fields in the APPS jet are consistent with experimental and analytical results reported already\(^1\)\(^5\). Because of a coarse grid in the present calculations, shock waves are smeared. The predicted supersonic region extends to 20 cm downstream of the torch exit in the LPPS jet. The observation of 'shock diamonds' in the real LPPS flow confirms this prediction.

Characteristic features of the LPPS jet and possible explanations are summarized as follows:
1) A higher velocity and a lower temperature: Expansion of the gas due to the low pressure results in the conversion of a considerable part of the input power to the kinetic energy within the Laval nozzle. Therefore, a bright hot-core could not be seen, but a series of oblique shock waves could be observed in the LPPS plasma.
2) A longer heating zone: Radiation loss increases rapidly with the gas temperature. A low temperature of the LPPS jet attributes to the reduction of the heat loss, and a conversion of the kinetic energy to the thermal one enhances the elongation of the plasma flame.
3) A longer accelerating zone: Depression of temperature induces the compression of the gas, which is followed by the deceleration of the flow velocity. The gradual velocity decrease in the LPPS jet is owing to the low temperature of the plasma gas also.

The results obtained above suggest that the plasma/particles interaction in LPPS is rather different from that in APPS. Based on the present work, the thermal history of the sprayed particle will be calculated.

REFERENCES

(2) J.A.Lewis and W.H.Gauvin, A.I. Ch. E. J., 19, 982 (1975)
(3) D.B.Lattacharyya and W.H.Gauvin, A.I. Ch. E. J., 21, 879 (1975)
(8) D.L.Evans and R.S.Tankin, Phys. Fluids, 10, 1137 (1967)
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<th>APPS</th>
<th>LPPS</th>
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<tr>
<td>PRESSURE, $P_1$ (N/m²)</td>
<td>$1.01 \times 10^5$</td>
<td>$3.55 \times 10^3$</td>
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<tr>
<td>TEMPERATURE, $T_1$ (K)</td>
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<tr>
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<tr>
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<td>3.0</td>
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<tr>
<td>EXIT RADIUS, $r_1$ (cm)</td>
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<td>0.87</td>
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Table 1 Boundary conditions at the torch exit.

Fig. 1 Schematic drawing of the model.

Fig. 2 Geometry and grid nodes.

Fig. 3 Predicted velocity profiles. Contour lines are drawn at intervals of 100m/sec.
(a) APPS

Fig. 4 Predicted enthalpy profiles. Contour lines are drawn at intervals of 0.8 x 10^6 J/kg.

(b) LPPS

Fig. 5 Velocity distribution on the center line.

Fig. 6 Enthalpy distribution on the center line.

Fig. 7 Temperature distribution on the center line.