SIMULATION OF THE DYNAMICS OF TWO-PHASE PLASMA JET IN THE ATMOSPHERE


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Introduction

The plasma spraying is the injection of metal or ceramic powder (10-50 microns) into a hot gas plasma (10,000-20,000 K) which melts and projects the molten droplets at high velocity onto a substrate to form a coating. Gases such as argon or hydrogen are passed through an electric arc inside a torch. The gas molecules dissociate and recombine, producing an extremely hot, high velocity plasma stream. Powdered coating material is automatically injected into the hottest zone of the plasma, which melts and atomizes the particles. The droplets are then propelled towards the substrate and bond to it.

In spite of impressive developments, some of the underlying fundamentals of the spray process are still poorly understood. Because of space limitations, this paper will be restricted to the numerical study of the Ar plasma flow in air, i.e. it will not include the interaction of powder particles with the plasma and coating formation. The physics and numerical models for prediction of the transition of the transonic plasma jet into the steady-state mode are discussed. It is shown that the initial stage of the development of the jet in air is highly complex flow and the transition time into the steady-state mode is about 20 ms.

Mathematical and Numerical Models

The motion of the plasma jet is governed by the conservation laws of mass, momentum, and energy and is described by Eulerian approach. The mathematical model developed is based on the following assumptions: 1) the plasma jet is time-dependent; 2) the gas in the plasma jet is compressible; 3) the flow is laminar; 4) the plasma is continuous and in the state of local thermodynamic equilibrium; 5) the plasma jet has azimuthal symmetry and the governing equations are two-dimensional in the axisymmetric coordinate system.

The governing equations are solved using the very-high-resolution Total Variation Diminishing (TVD) scheme /1/. It utilizes a Roe-type linear Riemann solver /2/. The TVD scheme ensures that the numerical total variation of the discretized conservative variables does not increase with time, thus no spurious
numerical oscillations are generated. This TVD property is achieved by applying the slope limiters /3/ on the jumps allowed in each of the characteristic wave fields. It allows to achieve the TVD property close to sharp gradients (the accuracy degenerates to first order near such extrema), while second order spatial accuracy is maintained where the solution is smooth.

The powder particles are modeled as discrete Lagrangian entities that exchange mass, momentum, and energy with the plasma. A group of similar particles with close characteristics is represented as a single particle-representative. The state of a representative is determined using the following parameters: spatial coordinates, components of velocity and mass. Trajectories of representatives are simulated stochastically using the Monte-Carlo method. For this purpose, the displacement of a representative in space during a small time step is set as a random function of the local gas-dynamic characteristics. Particle histories including melting and turbulent dispersion are calculated simultaneously with the motion of the gas in a self-consistent manner.

**Numerical Results and Discussion**

It is assumed that the argon transonic jet exits the nozzle with diameter of 8 mm into a cold atmosphere at normal conditions. A rectangular mesh was used, subdivided in a uniform 60x50 grid. The length of the calculation domain was 80 mm and its radius 30 mm. At the nozzle exit, the following profiles were used for the temperature and the axial component of the velocity /4/:  

\[
T = T_a + (T_m - T_a) \left(1 - \left(\frac{r}{R}\right)^{4.5}\right) \quad \text{and} \quad v = v_m \left(1 - \left(\frac{r}{R}\right)^2\right),
\]

where \(T_m\) and \(v_m\) are the velocity and temperature on the jet centerline at the nozzle exit, \(T_a\) is the temperature of the anode wall, set to 700 K, \(R\) is the nozzle radius. In accordance with measurements /5/ the \(T_m\) and \(v_m\) values were taken as 13000 K and 1800 m/s, respectively. At the inlet the profiles (1) are used for the temperature and the axial component of the velocity. The initial pressure at the inlet is set equal to 8 atm. At the nozzle exit the conditions of the continuity of density and the axial and radial components of the velocity are applied. The remaining part of the nozzle exit plane as well as the substrate is considered as a wall. The other boundaries are assumed free.

As the high velocity plasma jet exits the nozzle into a stagnant atmosphere its internal energy is transformed into the kinetic energy of the entrained air. Part of the initial kinetic energy of the jet is also transferred to the surrounding medium. It leads to the development of highly complex flow in ambient air. Fig. 1 shows the two-dimensional velocity and temperature distributions at 130.03 µs. It is seen that the plasma flow develops a shear layer at the outer
edge of the jet. This shear layer is rolling up into a ring vortex which is pulled downstream by the plasma flow. During the roll-up process, the entrainment of the surrounding air into the potential core of the jet takes place. This effect will be more pronounced with account of the turbulence in our model. Figs. 2 and 3 show the axial profiles of temperature and velocity for several times. The flow at the inlet is subsonic. Due to transformation of the internal jet energy into the kinetic one, the velocity rapidly increases from the nominal velocity at the inlet to a peak value near the nozzle exit. There is a minimum of temperature in this region of the jet. Temperature decreases up to 5000 K. Close to the nozzle exit the plasma flow becomes supersonic and the shocked jet is generated. It is known that subsonic and supersonic jet flows are qualitatively different. Front, hanging, and terminal shocks (Mach disk) are formed near the nozzle exit. After this region, the axial velocity and temperature increase with time along the centerline. At 200 \( \mu \)s the front of the plasma flow reaches the substrate. After this moment, the velocity and temperature decrease gradually near the substrate. Transition time of the jet into the steady-state mode is about 20 ms. This time is very large compared to duration (~200 \( \mu \)s) of the earliest stage of the flow development. Fig. 3 demonstrates that the final axial velocity remains constant near the nozzle exit in agreement with the experimental measurements using a single-velocity component laser Doppler anemometer system /6/. The potential core of the jet extends for about 7 mm. Then, the temperature and velocity decrease rapidly due to the mixing with air which reaches the centerline. In general the predictions of the model concerning the length of the potential core at the start of the jet, final temperature and velocity profiles and the shape of the plasma plume compared to time-resolved photographs /6/ are in acceptable agreement with theoretical and experimental data available in the literature.

Fig. 1. Two-dimensional fields of velocity and temperature at 130.03 \( \mu \)s.
Fig. 2. Axial profiles of temperature for several times.

Fig. 3. Axial profiles of velocity for several times.

References