Parameters Study of Plasma Jet Behavior with a Numerical Simulator

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ABSTRACT

Some numerical simulations have been done to examine influence of constricted nozzle shape and torch-working conditions in subsonic condition of plasma jet. The calculation within nozzle was performed with the wall low to determine the boundary condition. Out of nozzle, free boundary condition was employed. All difference equations deduced from governing formulae tobe solve were made with the control volume method. Adaptability of the simulated results was examined with measured ones of total pressure distribution for an actual plasma jet. The values were measured with a water-cooled pitot tube that is moving in constant speed. As a result, the influence of constricted nozzle shape and torch-working conditions on temperature and velocity distributions of plasma flow within and out of nozzle was clarified with the calculated results. Moreover, the influence of swirl component of plasma flow was investigated, too.

1. INTRODUCTION

Temperature distribution and velocity one of plasma jet have been aggressively observed by many researchers until now to characterize the plasma jet behavior and to clarify the governing factors and/or a procedure to decide the suitable working condition. Both of the temperature and flow speed, however, are very high (more than 8000 - 10000K and 1000 - 3000 m/s at center part), so that the measurement is not easy. Therefore, it seems to be almost impossible and not economical to measure perfect temperature distributions and velocity ones in many actual working conditions by using experiments only.

On the country, in the computer industry, down-sizing of the machine and reducing price of the system are remarkably advancing now. Such circumstance indicates that using of computer simulation technique is effective and helpful to characterize the plasma jet behavior and to clarify the governing factors. So, a new simulation program of high speed version was developed to run in personal computer, which is based on the GENMIX program [1] made by D.B. Spalding and his group coded for calculation of a cold gas flow. Then, influence of the constricted nozzle shape and working condition of plasma jet touch was examined with the new simulation program.

2. SIMULATION MODEL

The target flow was assumed to be steady-state, axisymmetric, subsonic and turbulent flow with swirl component. Then, the plasma stream was treated as a continuum of compressible flow, even though ionization or dissociation phenomena were occurred in the flow. Difference equations used in the present study were made from the Reynolds' equation which was obtained by averaging treatment for the Navier-Stokes equation to calculate some times of turbulent flow. In the calculating procedure, nozzle inlet pressure and magnetic Lorenz force were used for the forces acting to unit volume, which is in Eqs.(2).

Current distribution in the plasma stream was calculated with electric conductivity distribution. It was assumed that no current flows below 5000K. The length of Joule

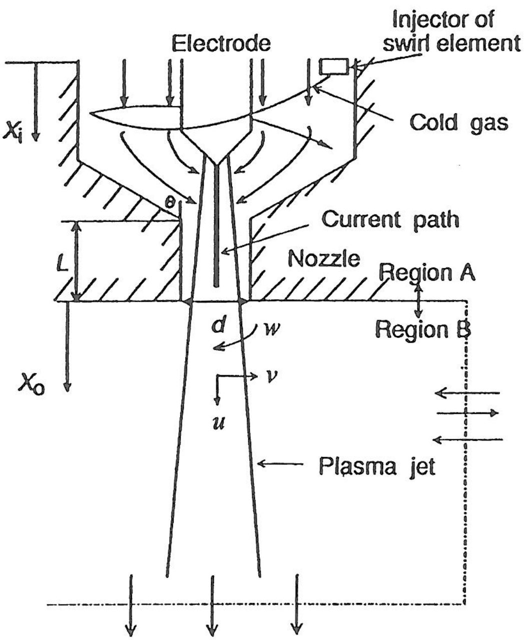

Fig. 1 Nozzle shape and definition of each size

heat area in a constricted nozzle indicated in Fig.1 was decided with that the voltage drop value from nozzle inlet part to each end position of current path in the nozzle becomes larger than the sheath voltage value just at the inlet part of the constricted nozzle.

All physical properties and transport properties used in the present simulation were supposed to vary with temperature. Energy of dissociation and ionization was treated with the enthalpy method. Equation (1) indicates the effect of turbulence treated with an equivalent viscosity coefficient μ_{eff} and equivalent thermal conductivity Γ_{eff}, that are calculated from sum of property values for laminar condition (μ_l)and for estimated turbulent one (μ_t). The viscosity value for turbulent flow was calculated with the mixing length model. Turbulent thermal conductivity coefficient was decided from the estimated turbulent viscosity value with Prandtl number Pr.

$$\mu_l = \rho\, l^2 \left| \frac{\partial u}{\partial r} \right| , \quad l = 0.075b , \quad \mu_{eff} = \mu_l + \mu_t , \quad \Gamma_{eff} = \mu_{eff} / \mathrm{Pr} \qquad \text{---- (1)}$$

Where, l is mixing length, b is half width of stream and ρ is density.

The calculations were achieved divided into two regions shown in Fig.1. In the region A, curvilinear coordinates were used, which was determined by the stream

$$\frac{\partial u}{\partial x} = \frac{\partial}{\partial \psi}\left(r^2 \rho u \mu_{eff} \frac{\partial u}{\partial \psi} \right) + \frac{1}{\rho u}\left(F_x - \frac{\partial P}{\partial x} \right) \qquad \text{---- (2a)}$$

$$\frac{\partial r w}{\partial x} = \frac{\partial}{\partial \psi}\left(r^2 \rho u \mu_{eff} \frac{\partial r w}{\partial \psi} \right) \qquad \text{---- (2b)}$$

function calculated from nozzle inner shape, and boundary condition was given by the wall low. Raynolds equations used in the Region A are shown in Eq.(2).

Energy conservation equation used in the Region A is shown in Eq.(3).

$$\frac{\partial h}{\partial x} = \frac{\partial}{\partial \psi}\left(r^2 \rho u \Gamma_{eff} \frac{\partial h}{\partial \psi} \right) + \frac{\partial}{\partial \psi}\left\{ (\mu_{eff} - \Gamma_{eff}) r^2 \rho u \frac{\partial \left(u^2/2 \right)}{\partial \psi} \right\} + \frac{\mathbf{J}\cdot\mathbf{J}}{\rho u \kappa} - \frac{\nabla\cdot\mathbf{q}_r}{\rho u}$$

where, ---- (3)

$$dh = C_p dT , \quad d\psi = \rho u r\, dr , \quad \mathbf{F} = \mathbf{J}\times\mathbf{B}$$

h is enthalpy, Cp is specific heat at constant pressure, κ is electric conductivity, **J** is current density, **B** is magnetic flux density, **F** is Lorenz force and $\mathbf{q}_r$ is radiative loss.

The solution was decided when the calculated pressure values just at nozzle exit (Boundary line between Region A and B in Fig.1) equal to the atmosphere pressure. So, the calculation was achieved in various inlet pressure conditions.

The other hand, difference equations to calculate in Region B (out of nozzle) were deduced from following equations with cylindrical coordinates. Equation (4) indicates a mass conservation relation.

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{1}{r}\cdot\frac{\partial r \rho v}{\partial r} = 0 \qquad \text{-------------- (4)}$$

Equation (5) is momentum conservation relation, and Eq.(6) is energy one.

$$\rho\frac{\mathrm{D}u}{\mathrm{D}t}=\rho F_x-\frac{\partial P}{\partial x}+\left(2\mu_{eff}\frac{\partial u}{\partial x}\right)+\frac{1}{r}\cdot\frac{\partial}{\partial r}\left\{\mu_{eff}\,r\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial r}\right)\right\}$$

$$\rho\left(\frac{\mathrm{D}v}{\mathrm{D}t}-\frac{w^2}{r}\right)=\rho F_x-\frac{\partial P}{\partial r}+\frac{\partial}{\partial r}\left(2\mu_{eff}\frac{\partial v}{\partial r}\right)+\frac{\partial}{\partial x}\left\{\mu_{eff}\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial r}\right)\right\}+\frac{2\mu_{eff}}{r}\left(\frac{\partial v}{\partial r}-\frac{v}{r}\right)$$

$$\rho\left(\frac{\mathrm{D}w}{\mathrm{D}t}+\frac{vw}{r}\right)=\frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial w}{\partial x}\right)+\frac{\partial}{\partial r}\left\{\mu_{eff}\left(\frac{\partial w}{\partial r}-\frac{w}{r}\right)\right\}+\frac{2\mu}{r}\left(\frac{\partial w}{\partial r}-\frac{w}{r}\right)$$

------------ (5)

$$\frac{\mathrm{D}(\rho h)}{\mathrm{D}t}=\frac{\mathrm{D}P}{\mathrm{D}t}+\frac{\partial}{\partial x}\left(\Gamma_{eff}\frac{\partial T}{\partial x}\right)+\frac{1}{r}\cdot\frac{\partial}{\partial r}\left(r\Gamma_{eff}\frac{\partial T}{\partial r}\right)+\frac{\mathbf{J}\cdot\mathbf{J}}{\kappa}-\nabla\cdot\mathbf{q}_r \qquad \text{------- (6)}$$

Where, $\mathrm{D}/\mathrm{D}t$ is substantive derivative.

In the region B, the calculation was achieved with a time-dependent approach for steady-state problem. The boundary condition at the nozzle exit was given by the distribution obtained from Region A's results.

3. ADAPTABILITY OF THE PROCEDURE

Adaptability of the simulated results was examine by some data measured with a special-made pitot tube of water-cooled type with sharp cone edge. The adaptability was checked with measured and calculated total pressure distributions. In the measurement of total pressure, moving sequence in constant speed of about 2m/min was employed to keep pitot edge shape during measuring.

Typical result is shown in Fig.2. Solid line in the figure indicates the simulated

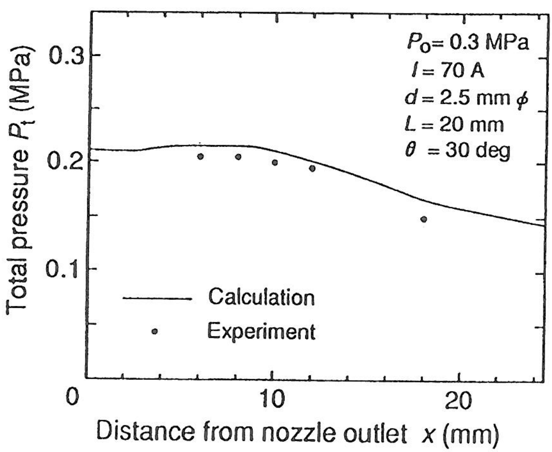

Fig. 2 Comparison between measured result and simulated one

result, and dot marks are measured ones. Both values have a good agreement with each other. So, it was concluded that the new simulation system can be applicable for parameters study of plasma jet behavior.

4. SIMULATED RESULTS

The simulation was done for Argon plasma jet in Ar-shielded atmosphere, since the plasma spraying usually used with a argon plasma jet torch. Arc current, plasma gas flow rate and nozzle throat length etc. were examined for nozzle shape parameter and torch-working parameter. Moreover, influence of swirl component of plasma stream was investigated with the computed results.

Temperature distributions and velocity ones on and along the torch center line are shown in Fig. 4. These computed results suggest that the temperature change on the

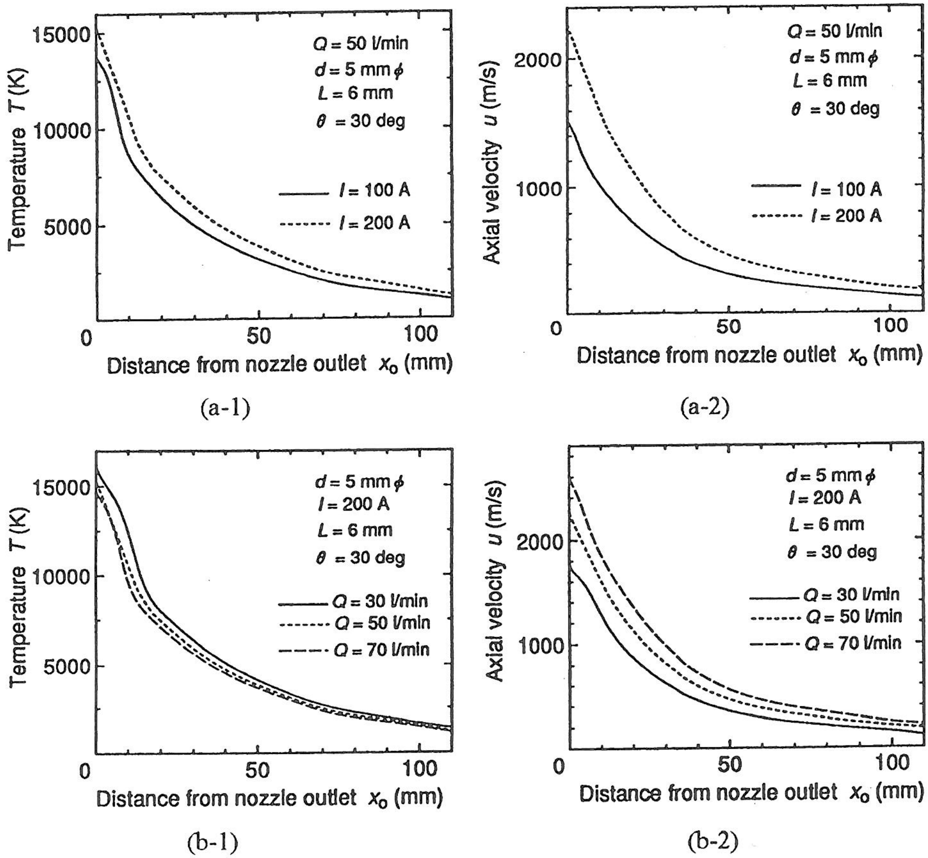

Fig. 3 Influence of arc current value and plasma gas flow rate on the simulated results

$$S \equiv \int \rho r^2 u w \mathrm{d}r \Big/ \int \left(P + \rho u^2\right) r \,\mathrm{d}r \Big/ d \qquad \text{---- (7)}$$

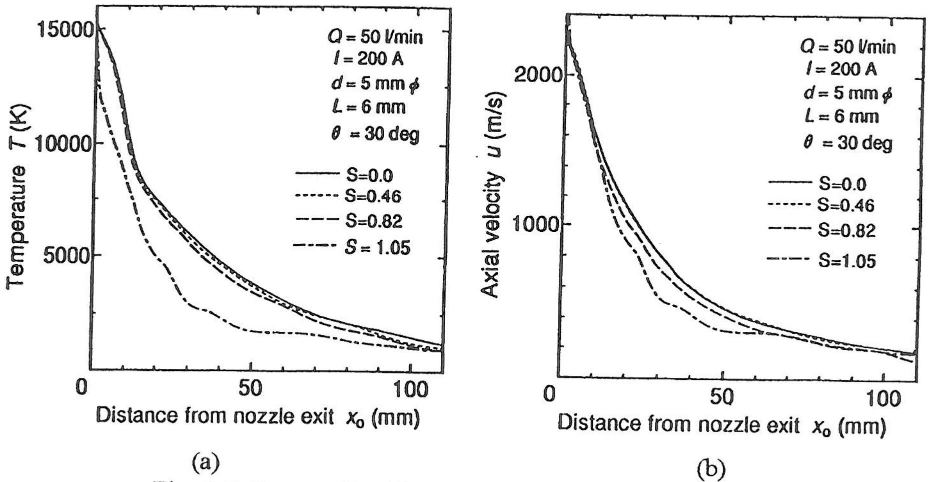

Fig. 4 Influence of swirl component on the simulated results

center axis is not so large, but the change of velocity relatively large.

Influence of swirl component on the plasma jet behavior is shown in Fig. 4. Degree of swirl component was assessed with Eq. 7. The flow pattern scarcely changed in plasma jet stream even though the swirl number S was varied in such a remarkably wide range. This phenomenon is quit different from that in cold gas stream.

The influence of nozzle constricted length of nozzle appeared relatively strong in velocity distribution, too.

5. SUMMARY

A numerical simulator was developed in the present study. As a result, the computed results shown the influence constricted nozzle bore shape and torch-working conditions on the temperature distribution and velocity one of plasma jet stream within and out of nozzle. Moreover, it was clarified that the swirl component in plasma stream scarcely influence on the jet stream with the numerical simulation.

REFERENCES

[1] Spalding D.B., "GENMIX : A General Computer Program for Two-dimentional Parabolic Phenomena", Pergamon Press, (1977)