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Technical Note

Effects of natural convection on the characteristics of a long laminar argon plasma jet issuing horizontally into ambient air

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Abstract

Three-dimensional modeling results show that the appearance of the long laminar plasma jet is less influenced by natural convection even as it is issuing into ambient air horizontally. However, plasma parameter distributions may deviate from axi-symmetry in the jet downstream region, especially for the cases with lower jet flow rates, and affect the applicability of Abel inversion employed in plasma diagnostics.

1. Introduction

Stable long laminar plasma jets have been successfully generated recently by use of elaborately designed DC non-transferred arc plasma torches [1,2]. For the plasma torch with an anode-nozzle of 4 or 8 mm inner diameter, the visual length of the generated long laminar plasma jet can be as long as 500 mm or more. In comparison with the turbulent plasma jets usually employed in industries or labs, the marked advantages of the long laminar plasma jet are that it is highly stable; its high-temperature region length is much longer and can be adjusted by changing the arc current or the working-gas flow rate of the plasma torch [2]; the axial gradients of plasma temperature and axial velocity within the long laminar plasma jet are much smaller; the emitted noise-level is negligibly low; and the entrainment of ambient air into the plasma jet is significantly reduced. These merits of the long laminar plasma jet make it very attractive from the viewpoint of materials processing, since it provides new possibility to achieve low noise-level working surroundings, better process controllability and repeatability, and reduced oxidization degree of metallic materials exposed to the plasma jet even as the materials are processed in air surroundings.

So far our understanding on the characteristics of the long laminar plasma jet is still incomplete. Ref. [1] conducted a two-dimensional (2-D) modeling study in order to compare the characteristics of laminar and turbulent argon plasma jets issuing into argon surroundings. Xu et al. performed a three-dimensional (3-D) [3] modeling study on the long laminar argon plasma jet issuing into air surroundings for the cases without or with lateral injection of particulate matter and its carrier gas. In those previous modeling studies [1,3], the effect of natural convection on the long laminar plasma jet characteristics was completely ignored. However, since a temperature difference as large as 10^4 K and a jet

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length/diameter ratio as great as 70 or more may be involved in the long laminar plasma jet system, a question is often asked about whether natural convection may appreciably affect the plasma flow and heat/mass transfer characteristics of the long laminar plasma jet.

As is well known, the influence extent of the natural convection in a combined forced and natural convection system is determined by the buoyancy/inertial-force ratio, i.e. by Gr/Re^2, where Gr and Re are the Grashof number and Reynolds number, respectively. For the laminar plasma jet issuing into ambient air horizontally, usually the estimated values of Gr/Re^2 is small (e.g. $Gr/Re^2 \approx 10^{-5}$–10^{-6}), and thus the effect of natural convection on the appearance of the laminar plasma jet is expected to be small. However, it should be noted that the estimated value of Gr/Re^2 could not provide us too many details concerning the buoyancy effects, while sometimes those details are required in plasma diagnostics. For example, in the spectroscopic or probe measurements of plasma parameters (e.g. temperature, velocity, etc.), Abel inversion is often used to obtain the radial profile of the plasma parameter from its accumulative values measured from a lateral direction. Since jet axi-symmetry is the necessary prerequisite of the Abel inversion applicability, slight deviation from axi-symmetry of plasma parameter distributions may lead to non-negligible errors due to the employment of the Abel inversion. On the other hand, as mentioned later on in this paper, deviation from axi-symmetry for the plasma parameter (e.g. temperature) distributions can be detected at downstream cross sections of the laminar plasma jet even as the estimated Gr/Re^2 values at those sections are still small. Hence, a detailed study on the natural convection effects is performed in this note using a 3-D modeling approach. The modeling results will be compared with corresponding experimental observation.

2. Modeling approach

Main assumptions employed in this study are identical to those used in our previous studies [3], including steady and laminar flow, LTE (local thermodynamic equilibrium) and optically thin plasma. And the combined-diffusion-coefficient method as used in [3] is also employed to deal with the diffusion of surrounding air into the laminar argon plasma jet.

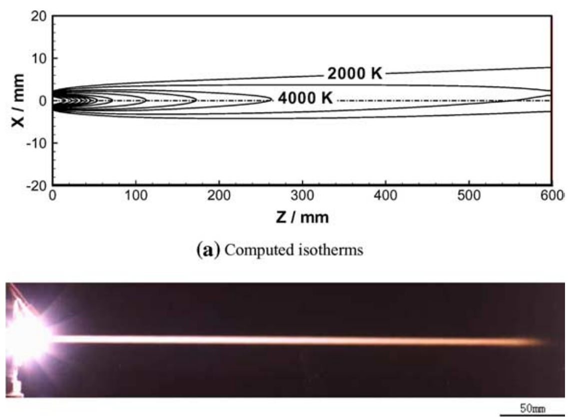
3-D governing equations in cylindrical coordinates (r, θ, z), including continuity, momentum, energy and argon species conservation equations, employed in the present study are almost the same as those used in Ref. [3] except that here the buoyancy term $(\rho_s - \rho)g\cos\theta$ has been added into the radial momentum equation and the term $-(\rho_s - \rho)g\sin\theta$ added into the tangential momentum equation in order to study the effect of natural convection on the flow and heat/mass transfer characteristics of the long laminar argon plasma jet issuing horizontally into ambient air.

The computational domain and the boundary conditions employed in this study are also almost the same as those used in Ref. [3] except that the computed plasma temperature and velocity profiles obtained from the 2-D modeling of the DC arc plasma torch for generating the long laminar argon plasma jet [4] are employed at the jet inlet (the maximum temperature and axial velocity at the jet inlet center are 14,690 K and 1320 m/s at the jet inlet center).

As in Ref. [3], temperature- and composition-dependent thermodynamic and transport properties of argon–air mixture with temperature range 300–20,000 K and interval 200 K are used, and the SIMPLE-like algorithm is employed to solve the governing equations associated with correspondent boundary conditions.

3. Results and discussion

For the typical case with torch exit (or jet inlet) diameter of 8 mm, argon flow rate of 100 sccs (100 standard cm^3 per second) and arc current 170 A, the modeling prediction is compared with correspondent experimental observation in Fig. 1. Fig. 1(a) shows the computed isotherms at the vertical longitudinal section (with $\theta = 0$ and π) of the laminar plasma jet, while Fig. 1(b) shows a photograph taken from lateral (horizontal) side of the jet and thus the effect of natural convection on the long laminar plasma jets can be observed. The temperature corresponding to the outer edge of visual region in the plasma jet photograph is estimated to be about



(a) Computed isotherms

(b) Photograph of the plasma jet

Fig. 1. Comparison of the modeling prediction with corresponding experimental observation. (a) Computed isotherms at the jet vertical longitudinal section (outer isotherm—2000 K, isotherm interval—1000 K) and (b) photograph for the long laminar argon plasma jets horizontally issuing into ambient air (170 A, 100 sccs).

3000 K. If one notices that the ordinate scale of Fig. 1(a) is larger than the abscissa scale, the agreement between the modeling prediction shown in Fig. 1(a) and the experimental observation shown in Fig. 1(b) is excellent concerning the jet appearance, and they all demonstrate that the effect of natural convection on the laminar plasma jet appearance is small. The computed axial velocity and argon mass fraction contours for this typical case also show that the effect of natural convection on the long plasma jet appearance is slight, but not shown here as separate figures due to the paper space limit.

Almost axi-symmetrical plasma parameter distributions are obtained at cross sections in upstream region, but the buoyancy effects manifest themselves in the downstream region of the plasma jet. Namely, parameter distributions deviate from axi-symmetry at downstream cross sections and the degree of non-axi-symmetry increases with increasing axial distance from the jet inlet. For the typical case, although the effect of the natural convection on the appearance of the long laminar plasma jet is small even in the downstream region far from the jet inlet, as mentioned above, deviation of plasma parameter distributions from axi-symmetry in downstream cross sections may affect the applicability of the Abel inversion in plasma diagnostics. It is expected that the errors caused by the Abel inversion will increase when the jet-inlet flow rate is reduced.

Additional computation is performed for the case in which the arc current of the plasma torch is still taken to be 170 A, but the argon flow rate is reduced to 20 sccs. The computed isotherms at the vertical longitudinal section of the laminar plasma jet are shown in Fig. 2. Comparison of the computed results shown in Fig. 2 with those shown in Fig. 1(a) demonstrates that the length of the high-temperature region (e.g. the axial distance represented by the isotherm 3000 K) of the laminar plasma jet decreases appreciably with decreasing argon flow rate (or decreasing axial velocity) at the jet inlet. The farthest axial distances of the computed isotherm of 3000 K decreases from 601 mm for the case with argon flow rate of 100 sccs to 103 mm for the case with flow rate of 20 sccs. It is also seen that the influence extent of the natural convection increases appreciably with the decrease of the working-gas flow rate at the jet inlet. Although the estimated values of the buoyancy/inertial-force ratios for the case with argon flow rate of 20 sccs are still small ($Gr/Re^2 = 3.0 \times 10^{-5}$ at jet inlet), the deviation from axi-symmetry of isotherms in jet downstream region cannot be ignored in the plasma diagnostics. The less the working-gas flow rate, the shorter the axial distance of the region will be in which the Abel inversion can be employed.

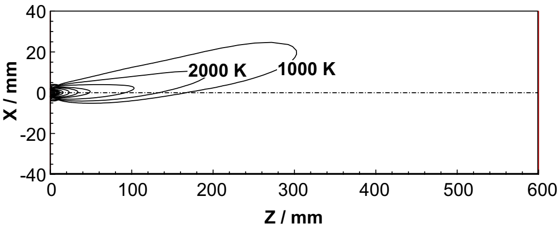


Fig. 2. Computed isotherms at the jet vertical longitudinal section for a lower argon flow rate (170 A, 20 sccs, outer isotherm—1000 K, isotherm interval—1000 K).

4. Conclusions

The present 3-D modeling study concerning the effect of natural convection on the long laminar argon plasma jet horizontally issuing into the ambient air shows that for the typical case with torch arc current of 170 A and argon flow rate of 100 sccs, the appearance of the long laminar plasma jet is less influenced by the natural convection, in consistence with the experimental observation. However, deviation of the computed plasma parameter distributions from axi-symmetry occurs in the jet downstream region and increases with decreasing gas flow rate, which may affect the applicability of Abel inversion.

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