A Numerical Analysis of Laminar and Turbulent Jets

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Abstract

Modeling results are presented concerning the characteristics of laminar and turbulent thermal plasma jets. Noise levels of turbulent plasma jet are also predicted using the $k-\varepsilon$ two-equation turbulence model and the noise emission model suggested by Fortune and Gervais.

1. Introduction

A long laminar plasma jet can be generated at atmospheric pressure using an elaborately designed D. C. arc plasma torch [1,2]. The luminous zone (e.g. defined as the axial length of isothermal line of about 3000 K) of the laminar plasma jet can be as long as 450 mm when the internal diameter of the torch nozzle is 8 mm. An interesting fact is that for almost the same operation conditions with a comparatively low gas flow rate, the length of the plasma jet generated by conventional D. C. arc plasma torches is much shorter (e.g. only 25 mm). Numerical simulation was conducted in Ref. [1,3] to reveal some of the jet characteristics. It was shown that the initial turbulence level is a critical parameter, and a very small value of the turbulent kinetic energy at the plasma jet inlet section may result in much significant shortening of the jet length [1]. Since the laminar plasma jet has a few important advantages, such as that with more concentrated radial energy distribution, lower impact pressure and smaller axial temperature gradient in comparison the turbulent jet, the laminar plasma jet may be useful for some cases of materials surface processing. The characteristics of plasma jets with low flow rates will be re-examined here for the case where an argon plasma jet is issued into the ambient air. The species diffusion within the plasma jet will be handled by the so-called combined diffusion coefficient approach proposed by Murphy [4], and the plasma properties are treated as the function of both gas temperature and composition, as in [3].

Noise level of the plasma jet is important for the study of laminar-turbulent transition [5] and is often concerned by the researchers working in the field of plasma spraying. Although numerous studies have been reported concerning the aeronautical noise (e.g. see references in [6]), most works are devoted to cold jets. So far almost no noise predictions can be found under thermal plasma conditions. Recently Fortune and Gervais [6] suggest a noise model to predict the acoustic emission from a hot jet with temperatures around 800 K, and their predicted results are shown to be fairly consistent with corresponding experimental data. In this paper, their noise model is extended to predict the acoustic emission intensity from thermal plasma jets with much higher temperature level than that of the hot jet studied in [6].
2. Characteristics of Laminar and Turbulent Jets

For an axi-symmetrical argon plasma jet issuing into ambient air, the conservation equations for mass, momentum, energy, species, turbulent kinetic energy and its dissipation rate have been given in Ref. [3] and are not repeated here. The difference is only that no swirling velocity component is included, and the following plasma temperature and axial velocity profiles at the jet inlet section are employed in the present study:

\[ T = (T_0 - T_w) \left( 1 - \left( \frac{R}{R_w} \right)^2 \right) + T_w, \quad u = U_0 \left( 1 - \left( \frac{R}{R_w} \right)^2 \right) \]  

(1)

Where \( T_0 \) and \( U_0 \) are the maximum temperature and axial velocity at the jet center, whereas \( R \) and \( R_w \) are the torch exit radius and the wall temperature, respectively. \( T_0 = 13000 \) K, \( T_w = 500 \) K, \( U_0 = 300 \) m/s and \( R = 4 \) mm are taken here for both laminar and turbulent jets.

Fig. 1 shows the computational domain. The axial and radial sizes of the domain are 0.45 m and 0.05 m, and the diameter \((2R)\) of jet inlet section is 0.008 m. 85×40 grid points with non-uniform spacing are employed in the computation.

The SIMPLE algorithm is employed to solve the governing equations. Some typical modeling results are presented in Fig. 2-7 for laminar and turbulent plasma jets. Figs. 2--4 show the temperature, argon mass fraction and axial velocity distributions within the laminar plasma jet with \( T_0 = 13000 \) K and \( U_0 = 300 \) m/s. Corresponding results for the turbulent case.

![Graphical representation](image)

**Fig. 1** Computational domain for the plasma jet and its noise emission

**Fig. 2** Computed isotherms in the laminar plasma jet. 1000—12000 K with interval 1000 K

**Fig. 3** Computed argon mass fraction distribution in the laminar jet. 0.1—0.9 with interval 0.1
are shown in Figs. 5—7. It is seen that the laminar jet has much more length, less axial temperature, velocity and concentration gradients than the turbulent one. It is found that even small inlet turbulent kinetic energy (e.g. as $k > 10^{13}$) may result in significant shortening of high temperature region of the jet, and result in the results similar to those shown in Figs. 5-7.

4. Noise of the Plasma Jet

For a hot jet, the acoustic emission is not only caused by the velocity fluctuation. Temperature fluctuation and its combination with the velocity fluctuation may even make more contribution. Fortune and Gervais [5] proposed a noise model to consider all those noise sources, and calculated the acoustic emission characteristics of a hot jet with temperature about 800 K. They derived the following expression for the acoustic intensity spectrum:

$$I(x, \omega) = \frac{1}{16\pi x^2} \rho_0 c_0 \left[ \frac{\omega^4}{c_0^4} \right] \int \int \hat{A}(y') \hat{A}(y'') \Gamma(y', y'', \omega) dy' dy''$$

$$- j \frac{2\omega^3}{c_0^2} \int \int \hat{S}(y') \hat{S}(y'') \Gamma(y', y'', \omega) dy' dy''$$

$$- \omega^2 \int \int \hat{S}(y') \hat{S}(y'') \Gamma(y', y'', \omega) dy' dy''$$

in which $\Gamma$ is the spatiofrequentational coherence function describing the spatial and frequency distributions of the jet noise, and is expressed as
\[ \Gamma(y', \xi, \omega) = \exp \left( -\frac{\pi \xi^2}{L_x} \right) \exp \left( -\frac{\pi \xi^2}{L_r} \right) \frac{\pi}{\beta \omega \cosh \left( \frac{\pi C \omega}{2 \beta \omega} \right)}, \quad \beta = 0.4 \]  

(3)

Here \( y' \) and \( y'' \) are vectors for the points located inside the noise source zone. \( L_x \) and \( L_r \) are the longitudinal and transversal integral scales, whereas \( \xi_x \) and \( \xi_r \) are the axial and radial distances between the two source points, respectively. \( L_x = 3D \) and \( L_r = L_x / 3 = D \) are used in the computation. \( \rho_o \) and \( c_o \) are density and sound speed at ambient temperature. \( \omega \) and \( \omega_i \) are the acoustic angular frequency and the turbulence characteristic angular frequency. \( \omega_i \) is calculated using \( \omega_i = C_o \times 2\pi \epsilon / k \), in which \( C_o \) is a dimensionless coefficient to be adjusted by comparison of predicted results with experimental data (\( C_o = 1.5 \) is used in [6]).

\( \hat{A} \) and \( \hat{S} \) represent aerodynamic (velocity fluctuation) and entropic (temperature fluctuation) noise source terms, respectively, and they are calculated through the local turbulent kinetic energy, mean gas density and temperature, and the gradients of time-averaged velocity and temperature as follows.

\[ \hat{A} = \rho \left( \frac{2}{3} k \right) \]  

(4)

\[ \hat{S} = \rho \frac{1}{T} \frac{1}{r} \left( \frac{1}{3} k \left( \frac{\partial \overline{y}}{\partial r} / \frac{\partial \overline{r}}{\partial r} \right) \right) \]  

(5)

As in [6], another dimensionless constant \( \alpha = 10^{-1} \) is used to change the amplitude of spectrum intensity, i.e., \( L_{\text{adjusted}} = \alpha \times L_{\text{computed}} \).

In the present noise computation, computational domain is the same as in the former Section and the observer is assumed to be located 60 diameters from the jet exit and with a 30 degree angle from the jet axis (Fig. 1). The velocity and temperature profiles at the jet inlet section are assumed to be uniform. Two different velocity and temperature combinations are used, i.e., (A) 90 m/s and 10000 K corresponding to argon flow rate of 0.4 STPm³/hr, and (B) 300 m/s and 13000 K corresponding to 1.0 STP m³/hr.

Since turbulent energy \( k \) and its dissipation rate \( \epsilon \) distributions within the plasma jets determine noise generation, they are computed at first using the k-\( \epsilon \) two-equation model as in the study of turbulent plasma jet characteristics. Computed results are shown in Fig. 8. Substituting these results into Eqs. (4) and (5), the noise sources due to the velocity and temperature fluctuations can be calculated for each grid point. The calculated results have been plotted in Fig. 9 for the aerodynamic source distributions (due to velocity fluctuation) and Fig. 10 for the entropic source distributions (due to temperature fluctuation), respectively. Using Eq. (2), the noise intensity spectra can then be calculated and the calculated results are shown in Fig. 11 for the two cases. From Figs. 8 – 10, it can be seen that the maximum values of the turbulent kinetic energy and the noise sources within the turbulent plasma jets increase with increasing gas flow rate or inlet velocity. The entropic noise source is often much greater than the aerodynamic noise source. Fig. 11 shows that the noise intensity of a turbulent plasma jet is mainly determined by the temperature fluctuations. One even can completely ignore the contributions due to the other factors, i.e., due to velocity fluctuations and the mixed effect of temperature and velocity fluctuations. For the case with a gas flow rate of 0.4 STP m³/hr and
Fig. 8 Computed turbulent kinetic energy fields for the gas flow rates of 0.4 STP $m^3/hr$ (left) and 1.0 STP $m^3/hr$ (right)

Fig. 9 Acrodynamic source distributions in the plasma jet for the gas flow rates of 0.4 STP $m^3/hr$ (left) and 1.0 STP $m^3/hr$ (right)

Fig. 10 Entropic source distributions in the plasma jet for the gas flow rates of 0.4 STP $m^3/hr$ (left) and 1.0 STP $m^3/hr$ (right)

jet inlet temperature of 10000 K, the maximum noise intensity of the turbulent plasma jet is about 45 dB in audible spectra (20—20000 Hz). On the other hand, for the case with gas flow rate of 1.0 STP $m^3/hr$ and jet inlet temperature of 13000 K, the maximum noise intensity increases to about 75 dB in audible spectra. It is noted that the noise intensity may be rather high in the ultrasound frequency range, although people cannot hear the noise.
4. Conclusions

At low flow rates of the working gas, two different flow regimes may indeed occur and the initial turbulent parameters at the jet inlet section are critical to determine the flow regime. When the inlet turbulence parameters are zero, a long laminar plasma jet is obtained. On the other hand, even a small value of turbulence kinetic energy at the jet inlet will result in the formation of short jet, although the associated turbulence level is low. The axial gradients of plasma temperature, axial velocity and argon mass fraction within the laminar plasma jet are significantly less than their counterparts within the turbulent plasma jet. The noise sources associated with the velocity and temperature fluctuations can be calculated from the spatial distributions of turbulent kinetic energy, its dissipation rate and the time-averaged temperature and axial velocity fields within the plasma jet. It is shown that the noise of a turbulent plasma jet is mainly caused by temperature fluctuations, and the noise level is determined by the velocity at the jet inlet or the gas flow rate. The noise level for the case with gas flow rate of 1 STP m$^3$/hr is about 30-40 dB higher than that with gas flow rate of 0.4 STP m$^3$/hr.

Acknowledgement
This work was supported by the National Natural Science Foundation of China under grant No. 59836220.

References