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Temperature's optical tomography diagnosis of arc plasma jet flowing into air

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ABSTRACT

An argon arc jet plasma flowing into air is chosen as a practical example to study the multiple species jet plasma's optical computerized tomography (OCT) diagnosis. The refractive index models of the pure argon and the multiple species arc plasmas are supplied. On the basis of which, the temperature reconstruction model of the multiple species arc plasma is further derived. By theoretical calculation, the effect of mixed air on the refractive index is given. For the sake of better proving the effect of directly omitting the mixed air on flow field's temperature reconstruction from the refractive index, a simulated experiment is supplied. Finally, the condition, which can be adopted to estimate that whether the pure argon arc plasma refractive index model still can be used as the temperature reconstruction model of the argon arc plasma jet flowing into air, is proposed.

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1. Introduction

With the rapid development of science and technology, high-temperature complex flow fields have great existence and application in various domains. There are typical examples in industry, such as the cutting and welding plasmas. In essence, plasmas have been widely applied in industry, including etching [1], coating [2], surface modification [3], spraying [4], heating [5], handling hazardous materials [6], and so on. Therefore, it is obvious that the structure visualization and the parameter diagnosis have important guiding role on better and more effectively taking advantage of them.

Optical computerized tomography (OCT) with the characteristics of real-time, stable, non-contact and can supply 3-D distribution, has been widely adopted in visualizing and diagnosing various flow fields whose temperature is not so high [7–11]. Therefore, in contrast, it has unique advantages in visualizing structure and measuring key parameters for high-temperature complex flow fields. Up to now, OCT methods have been seldom adopted in multiple species flow fields. Most of the measuring objects are single composition [12], or the ratio of species composition is known, or the ratio of species composition is easy to be determined [13]. Yet, when the jet plasma flowing into air to cut or weld, it will be mixed by air certainly [14]. And, the ratio and distribution of mixed air can not be definitely known, which can be attributed to it has a close relation with the jet plasma's flow velocity, pressure, and so on. Consequently, the multiple species make the optical methods which are based on the measurement of the refractive index are badly restricted in this kind of multiple species jet plasmas. Since, species composition is one of the most important factors which can affect the refractive index of flow fields [15], the effect of mixed air should be studied.

In principle, directly omitting the contribution of the mixed air should have influence on reconstructing the temperature and electron number density distributions of the jet plasma flowing into air from the experimentally measured refractive index. However, the irrationality of directly omitting the effect of mixed air has not been definitely concluded. In this paper, an argon arc jet plasma flowing into air is chosen as a practical example to study the effect of mixed air on temperature reconstruction by OCT. A condition, which can be adopted to estimate that whether the pure argon arc plasma refractive index model still can be used as the temperature reconstruction model for the multiple species mixed plasma, will be proposed.

2. Models and analysis

2.1. Refractive index models

The refractive index of a pure argon arc plasma is usually described as [16]:

$$n_{\mathrm{Ar}} - 1 = \frac{1}{L}\left(A_{\mathrm{Ar}} + \frac{B_{\mathrm{Ar}}}{\lambda^2}\right)(N_n + 0.67N_i) - 4.46 \times 10^{-14}\lambda^2 N_e, \quad (1)$$

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where L is the Loschmidt number ($2.687 \times 10^{19}\,\mathrm{cm}^{-3}$), A and B are the constants relevant to specific composition [17], λ is the probe wavelength, while N_n, N_i and N_e are the number densities of neutral particles, ions and electrons respectively.

When an argon arc jet plasma flowing into air, if the contribution of the mixed air is considered, the total refractive index n_t of the multiple species mixed flow field should be denoted as:

$$n_t - 1 = \mu(n_{\mathrm{Ar}} - 1) + (1-\mu)(n_{\mathrm{air}} - 1), \tag{2}$$

where $\mu(\leq 1)$ is the ratio of argon in the mixed flow field, and n_{air} is the refractive index of air.

In view of the air is basically composed by nitrogen and oxygen with the ratio of 78% and 22% respectively, the total refractive index n_t of the multiple species mixed flow field can be rewritten as:

$$n_t - 1 = \mu(n_{\mathrm{Ar}} - 1) + (1-\mu)\left[0.78\left(n_{\mathrm{N_2}} - 1\right) + 0.22\left(n_{\mathrm{O_2}} - 1\right)\right]. \tag{3}$$

According to Ref. [8], the mixed air will be ionized, which means the refractive index of nitrogen and oxygen in Eq. (3) should be respectively expressed as:

$$n_{\mathrm{N_2}} - 1 = \frac{1}{L}\left(A_{\mathrm{N_2}} + \frac{B_{\mathrm{N_2}}}{\lambda^2}\right)N_{\mathrm{N_2}} - 4.46 \times 10^{-14}\lambda^2 N'_e \tag{4}$$

$$n_{\mathrm{O_2}} - 1 = \frac{1}{L}\left(A_{\mathrm{O_2}} + \frac{B_{\mathrm{O_2}}}{\lambda^2}\right)N_{\mathrm{O_2}} - 4.46 \times 10^{-14}\lambda^2 N''_e. \tag{5}$$

Distinctly, the above models cannot distinctly describe the relation between the refractive index with the temperature and pressure of the plasma. That is to say, the models do not facilitate to directly reconstruct the temperature of the plasma. Hereby, the temperature reconstruction model of them should be deduced in further, and the first ionization will be mainly considered in this study.

2.2. Temperature reconstruction models

As known, by introducing the first ionization degree α_1, the refractive index of the pure argon arc plasma can be described as [18]:

$$n_{\mathrm{Ar}} - 1 = \left[\frac{1}{L}\left(A_{\mathrm{Ar}} + \frac{B_{\mathrm{Ar}}}{\lambda^2}\right)(1 - 0.33\alpha_1) - 4.46 \times 10^{-14}\lambda^2\alpha_1\right]\frac{P}{(1+\alpha_1)\kappa T} \tag{6}$$

where P and T represent the pressure and temperature of the argon arc plasma respectively, κ is the Boltzmann constant.

According to Ref. [19], the refractive index of nitrogen and oxygen arc plasmas should be respectively written like:

$$n_{\mathrm{N_2}} - 1 = \left[\frac{1}{L}\left(A_{\mathrm{N_2}} + \frac{B_{\mathrm{N_2}}}{\lambda^2}\right)\left(1 - \beta_{\mathrm{N_2}}\right) - 8.92 \times 10^{-14}\lambda^2\alpha'_1\beta_{\mathrm{N_2}}\right]\frac{P}{\kappa T\left(1 + \beta_{\mathrm{N_2}} + 2\alpha'_1\beta_{\mathrm{N_2}}\right)}, \tag{7}$$

$$n_{\mathrm{O_2}} - 1 = \left[\frac{1}{L}\left(A_{\mathrm{O_2}} + \frac{B_{\mathrm{O_2}}}{\lambda^2}\right)\left(1 - \beta_{\mathrm{O_2}}\right) - 8.92 \times 10^{-14}\lambda^2\alpha''_1\beta_{\mathrm{O_2}}\right]\frac{P}{\kappa T\left(1 + \beta_{\mathrm{O_2}} + 2\alpha''_1\beta_{\mathrm{O_2}}\right)}, \tag{8}$$

where β whose definition can be found in Ref. [20] is the dissociation degree of molecule, while $\alpha_1{}'$ and $\alpha_1{}''$ are the first ionization degrees of nitrogen and oxygen atom respectively.

Consequently, the refractive index of the multiple species mixed plasma should be finally obtained like:

$$n_t - 1 = \frac{P}{\kappa T}\left\{\begin{array}{l} \mu\left[\dfrac{1}{1+\alpha_1}\left(\dfrac{1}{L}\left(A_{Ar} + \dfrac{B_{Ar}}{\lambda^2}\right)(1 - 0.33\alpha_1) - 4.46 \times 10^{-14}\lambda^2\alpha_1\right)\right] \\ +(1-\mu)\left[\begin{array}{l} \dfrac{0.78}{1 + \beta_{\mathrm{N_2}} + 2\alpha'_1\beta_{\mathrm{N_2}}}\left(\dfrac{1}{L}\left(A_{\mathrm{N_2}} + \dfrac{B_{\mathrm{N_2}}}{\lambda^2}\right)\left(1 - \beta_{\mathrm{N_2}}\right) - 8.92 \times 10^{-14}\lambda^2\alpha'_{11}\ \beta_{\mathrm{N_2}}\right) \\ + \dfrac{0.22}{1 + \beta_{\mathrm{O_2}} + 2\alpha''_1\beta_{\mathrm{O_2}}}\left(\dfrac{1}{L}\left(A_{\mathrm{O_2}} + \dfrac{B_{\mathrm{O_2}}}{\lambda^2}\right)\left(1 - \beta_{\mathrm{O_2}}\right) - 8.92 \times 10^{-14}\lambda^2\alpha''_1\ \beta_{\mathrm{O_2}}\right) \end{array}\right] \end{array}\right\}. \tag{9}$$

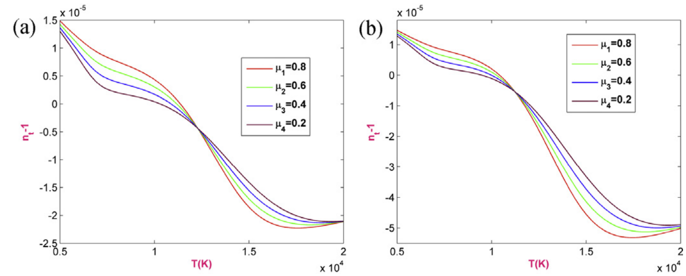

Fig. 1. The dependence of the refractive index on temperature (a) 532 nm (b) 808 nm.

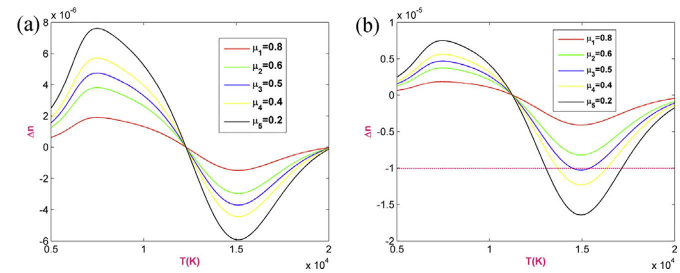

Fig. 2. The dependecne of the refractive index difference on temperature (a) 532 nm (b) 808 nm.

As a result of the ionization and dissociation degrees are both the functions of the temperature and pressure, Eq. (9) describes the refractive index of the multiple species mixed plasma by species composition, temperature, pressure and probe wavelength. Obviously, if the ratio of argon arc plasma is big enough ($\mu \to 1$), Eq. (9) can be regressed to Eq. (6). Meanwhile, if the ratio of argon arc plasma is so small ($\mu \to 0$), Eq. (9) can be regressed to the refractive index model of the air arc plasma. Hereby, the mixed plasma's refractive index model which is expressed by Eq. (9) is correct and rational.

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