Spatial Diffusion Model and Simulation Analysis of the Heterogeneous Un-magnetized Jet Plasma

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Abstract： In this paper, the spatial distribution characteristics of electron density are calculated based on the plasma jet diffusion model. The computed results are compared with the results of numerical calculation, validation test results. Researches of the paper are demonstrated that the plasma electron density is attenuated as the approximate exponential with increasing distance from the nozzle exit, the closer distance from the nozzle exit, the greater the attenuation slope, on the far away from the nozzle exit, the electron density attenuation with distance is the flat state. This method is simple and efficient, and it is a good tool to solve engineering calculation problems.

Keywords: Jet Plasma, Spatial diffusion, Simulation and Analysis Model

I Introduction

Plasma technology in electron magnetic, dynamics, polymer physics, biology, environment and other multidisciplinary and interdisciplinary field has very broad application prospects [1-3], and has important military application prospect at the same time. Since the beginning of the 21st century, plasma stealth, plasma antenna, plasma communication, plasma resistance reduction and other technologies have attracted wide attention and high attention from relevant research institutes at home and abroad [4-9]. From the opening literature, the work about the plasma generated and diffusion that principle is rarely developed, and the research work for non-uniform, supersonic un-magnetized plasma in free space diffusion regularity of has not been reported at present. In the paper the jet plasma is studied, and it has the characteristics of inhomogeneous, non-magnetized and supersonic flow etc. The simulation model is applicable to the calculation of supersonic jet diffusion in rarefied gas environment, such as engine jet flame diffusion.

II The space diffusion model of the non-uniform, non-magnetized, jet plasma

The expansion process of point source jet under rarefied gas environment is shown in figure 1.

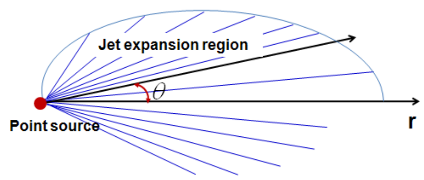

Figure 1 Point source jet expansion in rarefied gas environment

In Figure 1, the mass density of jet plasma is inversely proportional to the square of the distance r, and it depends on the angle of the streamline and axis, and the expression can be represented as:

$$\rho(r,\theta) = C\frac{1}{r^2} f(\theta) \qquad (1)$$

Currently, the widely used formula to solve C and $f(\theta)$ is the expression offered by Simons that is suitable for central isentropic flow [10] and boundary layer flow [11], and it is called Simons model.

The spatial distribution of the total particle density of jet plasma is given as follows:

$$n(r,\theta) = A_p n^* \cdot (\frac{r^*}{r})^2 \cdot f(\theta) \qquad (2)$$

Where, r^* is the radius of nozzle throat, and the value is known when the size of supersonic nozzle is given. n^* is the total particle number density of nozzle throat, it is determined by the working medium flow G, throat velocity of particles U^* and throat radius r^*. If the ionization degree is given, the spatial distribution of electron density can be found out:

$$n_e(r,\theta) = I_\alpha A_p n^* \cdot (\frac{r^*}{r})^2 \cdot f(\theta) \qquad (3)$$

In equation (3), the calculation expression of A_p is:

$$A_p = \frac{U^*/U_L}{\int_0^{\theta_{\lim}} f(\theta)\sin\theta d\theta} \qquad (4)$$

Where, U^* is the velocity of plume flow in nozzle throat, and U_L is the ultimate speed.

In equation (3), the calculation expression of $f(\theta)$ is:

$$f(\theta) = \begin{cases} [\cos(\frac{\pi\theta}{2\theta_{\lim}})]^{\frac{2}{\gamma-1}} & \theta \le \theta_0 \\ f(\theta_0)e^{-\beta(\theta-\theta_0)} & \theta_0 < \theta < \theta_{\lim} \end{cases} \qquad (5)$$

Where, θ_0 is the critical angle of two different distribution modes of jet flow, $\theta_{\lim}$ is the limiting expansion angle, and β is the exponential distribution coefficient.

Thus, the total particle number density and electron density can be resolved by using the expressions of (2)～（5）.

III The simulation results and analysis

3.1The simulation input parameters

The values of simulation parameters are shown in table 1 below.

Table 1 The simulation parameters

Compo-nents	Discharge temperature（K）	Ionizatio-n I_a	Pressure P（Pa） and flux G（g/s）
Li	3000	0.1	P=1300,G=0.1
	3000	0.3	P=1950,G=0.15
	3000	0.6	P=2600,G=0.2
	3000	0.9	P=3220,G=0.25
Cs	3000	0.1	P=300,G=0.1
	3000	0.3	P=440, G=0.15
	3000	0.6	P=600,G=0.2
	3000	0.9	P=740, G=0.25

3.2 simulation model

Simulation model is shown in Figure 2, L_1 = 4 mm, L_2 = 28 mm, r^* = 8 mm, r_e = 13 mm, M_{ae} = 2.8.

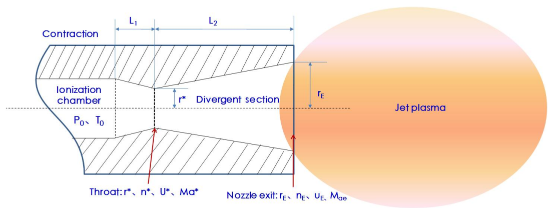

Figure 2 Schematic diagram of simulation model

3.3 results and analysis

The results are shown from figure 3 to figure 6, the abscissa is the horizontal distance from the axis of the nozzle exit, the ordinate is demonstrated the plasma electron density.

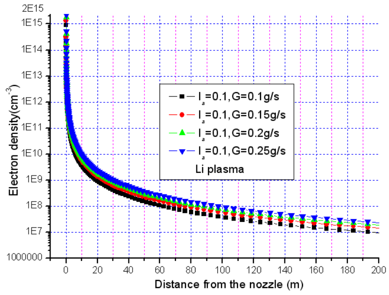

Figure 3 The electron density of lithium plasma for different fluxes

The results are shown that for the lithium plasma the bigger the flow rate, the greater the electron density of exit section (when G=0.1g/s then ne=9.5×10^{14}cm^{-3}, when G=0.25g/s then ne=2×10^{15}cm^{-3}). When the boundary electron density is set as 10^{8}cm^{-3}, the greater the flux, the larger the effective scale of plasma (when G=0.1g/s then L=62.5m, when G=0.25g/s then L=97.5m).

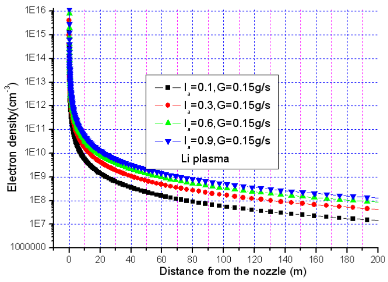

Figure 4 The electron density of lithium plasma for different ionization degrees

The results in Figure 4 are shown that for the lithium plasma, the bigger the ionization degree, the greater the electron density of exit section (when Ia=0.1 then ne=1.3×10^{15}cm^{-3}, when Ia=0.9 then ne=1.2×10^{16}cm^{-3}). When the boundary electron density is set as 10^{8}cm^{-3}, the greater the ionization degree, the larger the effective scale of plasma (when Ia=0.1 then L=77.5m, when Ia=0.9 then L=220m).

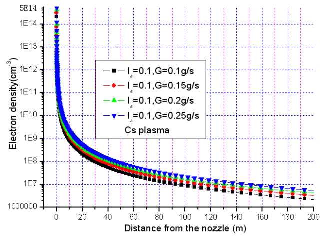

Figure 5 The electron density of cesium plasma for different fluxes

The results in Figure 5 are shown that for the cesium plasma the bigger the flow rate, the greater the electron density of exit section (when G=0.1g/s then ne=2×10^{14}cm^{-3}, when G=0.25g/s then ne=5×10^{14}cm^{-3}). When the boundary electron density is set as 10^{8}cm^{-3}, the greater the flux, the larger the effective scale of plasma (when G=0.1g/s then L=30m, when G=0.25g/s then L=47.5m).

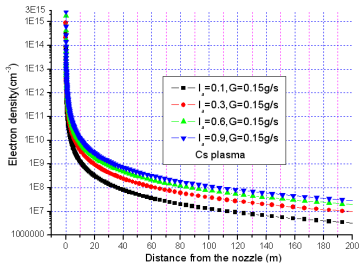

Figure6 The electron density of cesium plasma for different ionization degrees

The results in Figure 6 are shown that for the cesium plasma, the bigger the ionization degree, the greater the electron density of exit section (when Ia=0.1 then ne=3×10^{14}cm^{-3}, when Ia=0.9 then ne=3×10^{15}cm^{-3}). When the boundary electron density is set as 10^{8}cm^{-3}, the greater the ionization degree, the larger the effective scale of plasma (when Ia=0.1 then L=37.5m, when Ia=0.9 then L=110m).

IV conclusions

The heterogeneous, non-magnetized, jet plasma diffusion model is presented in this article, and it is a good engineering model used to compute the electron density distribution conveniently. The calculation model can also be applied for all the rarefied gas environment of hypersonic plasma diffusion, the method is simple, high the computational efficiency is fast, it is one of the best tools to solve the problem of engineering calculation.

In the immediate future, the authors would study further for changing the supersonic nozzle structure features and the parameters of the ionization chamber and so on.

References

【1】ZHANG Zhihao, DENG Yongfeng, HAN Xianwei, TAN Chang. Development of an Electron Density Distribution Model of Electron-beam-generated Air plasma[J]. High Voltage Engineering，2013, 39（7）: 1745-1749.

【2】ZHENG Chao, XU Yuzhen, HUANG Yifan, LIU Zhen, YAN Keping. State-of-the-art non-thermal plasma disinfection and medicine[J]. Chemical Industry and Engineering Progress，2013, 32（9）: 2185-2191.

【3】WANG Meiting, ZHOU Chunliang, GUO Jia, WANG Meiyu. Hybrid surface plasmon photonic crystal waveguide[J].Chinese Journal of Quantum Electronics，2017, 34（4）: 507-512.

【4】Huang FangYi, Shi JiaMing, Yuan ZhongCai Wang JiaChun. Theoretical and experimental study of plasma directional antenna array[J]. Acta Physica Sinica，2013, 62（15）: 155201-1-7.

【5】MO Jinjun, LIU Shaobin, YUAN Naichang. Study on Basic Theory for Plasma Stealth[J]. Modern Radar,2002, 24(3): 9-12.

【6】LI Qian, XU Sheng, LIU Shaochong, WANG Gao. Discussion on Terahertz Against Plasma Stealth Technology[J]. Electro-Optic Technology Application, 2011, 26(2): 9-11.

【7】Wei Pinglan, He Liping. Development of Plasma Technology for stealth[J]. Missiles and Space Vehicles. 2009, 303(5): 22-25.

【8】YUAN Zhongcai, SHI Jiaming, HUANG Yong, xu Bo. Faraday Angle of Linearly Polarized Waves Along Magnetic Field in Magnetized Collisional plasmas[J]. Plasma Science and Technology, 2010, 12(5):519-521.

【9】Zhao Qing, Li Hongfu, Ren Tong, Yan Yang. Study on Plasma Stealth Technology[J]. Journal of University of Electronic Science and Technology of China, 2004, 33（2）: 142-145.

【10】WU Shourong. Analysis of steadytransonic isentropic flow in two-dimensions[J]. Acta Aerodynamica sinica, 2012, 30（6）: 699-703.

【11】 CHE Xueke, NIE Wansheng, TU Hengzhang. Numerical simulation of plasma boundary layer flow control[J]. Acta Aerodynamica sinica, 2010, 28（3）: 279-283.