20PB-099

Relation of an asymmetric plasma with an ambient gas flow

非対称プラズマと背景気体の流れの関係

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A plasma system exchanges its momentum with an ambient gas and the rate of the momentum exchange is expressed as force. So, the spatial profile of the force acting to the ambient gas and the resulting integrated force is evaluated using a one-dimensional stationary fluid model with the spatial profile of ion production.

1 Introduction

Asymmetry of a plasma is induced when momentum is introduced into the plasma and, simultaneously, an asymmetric plasma transfers its momentum to surroundings. Examples of such the applications are plasma actuators [1] and electric propulsions. [2]

As for a plasma actuator, plasma momentum is transferred to its ambient gas, which surround the plasma actuator, and flow of the ambient gas is generated. The rate of momentum transfer is referred to as force and its spatial profile might be important from the viewpoint of the efficiency to cause gas flow. In fact, the spatial profile of force has been experimentally evaluated by measuring ambient gas flow velocity. [3] However, the spatial profile of force has not been related with a plasma discharge so far.

The purpose of this work is, then, to relate the spatial profile of force with the plasma discharge, more specifically, the spatial profile of plasma production; and this work corresponds to the extension of the previous work, where the total force acting between a one dimensional plasma with its surroundings has been discussed.[4]

2 model

The basic equations for a one-dimensional stationary plasma bounded at $x = \pm a$ are given by

$$\frac{\mathrm{d}}{\mathrm{d}x}(nv) = \alpha n \,, \tag{1}$$

$$nmv\frac{\mathrm{d}v}{\mathrm{d}x} = -ne\frac{\mathrm{d}\phi}{\mathrm{d}x} - (\alpha+\beta)nmv \,, \tag{2}$$

and

$$n = n_0 \exp\left(e\phi/k_B T_e\right) \,, \tag{3}$$

where n, m, v are the ion density, mass, velocity, respectively, e is the elementary charge, ϕ is the electrostatic potential, k_B is the Boltzmann constant, α is the ionization rate, and β is the rate of momentum transfer due to ion-neutral collision.

The above equations can be reduced to the following differential equations:

$$\frac{\mathrm{d}\tilde{v}}{\mathrm{d}\tilde{x}} = \tilde{\alpha}_0\frac{r_\alpha + (r_\alpha + r_\beta)\tilde{v}^2}{1-\tilde{v}^2} \tag{4}$$

$$\frac{1}{\tilde{n}}\frac{\mathrm{d}\tilde{n}}{\mathrm{d}\tilde{x}} = -\tilde{\alpha}_0\frac{(2r_\alpha + r_\beta)\tilde{v}}{1-\tilde{v}^2} \tag{5}$$

where normalized values such that $\tilde{x} = x/a$, $\tilde{v} = v/c_s$, $\tilde{n} = n/n_0$, $r_\alpha = \alpha/\alpha_0$, $r_\beta = \beta/\alpha_0$, and $\tilde{\alpha}_0 = a\alpha_0/c_s$, are used with $c_s = (k_B T_e/m)^{1/2}$. Here, we set the value of α as α_0 when the ionization rate is uniform ($\alpha = \alpha_0$ for $-a < x < a$ or $r_\alpha = 1$ for $-1 < \tilde{x} < 1$), because we would like to compare different spatial profiles of α or r_α under the condition of

$$\int_{-1}^{1} r_\alpha \tilde{n}\mathrm{d}\tilde{x} = \frac{2}{\tilde{\alpha}_0}(2+r_\beta)^{-(2+r_\beta)/(2+2r_\beta)} \,. \tag{6}$$

This equality can be analytically derived for the uniform ion production case ($r_\alpha = 1$ for $-1 < \tilde{x} < 1$). In addition, it might be worth to note that Eqs (4) and (5) are singular and $\tilde{v}^2 = 1$ at the boundaries $\tilde{x} = \pm 1$. This boundary condition agrees with the Bohm criterion. [4, 5]

After solving Eqs (4) and (5), we have the spatial profile of force acting to the ambient gas using the normalized form

$$\tilde{f} = \tilde{\alpha}_0 r_\beta \tilde{n}\tilde{v} \,. \tag{7}$$

The total amount of force is also obtained by integrating the above equation, that is,

$$\tilde{F}_1 = \tilde{\alpha}_0 \int_{-1}^{1} r_\beta \tilde{n}\tilde{v} \mathrm{d}\tilde{x} \tag{8}$$

and its modified form

$$\tilde{F}_2 = \tilde{\alpha}_0 \int_{-1}^{1} r_\beta \tilde{n}|\tilde{v}| \mathrm{d}\tilde{x} \tag{9}$$

might be useful, because (symmetric) gas flow is generated for $\tilde{F}_2 \neq 0$ even if $\tilde{F}_1 = 0$.

3 Results

To investigate how the spatial profile of $\tilde{f}$ is influenced by that of ion production, let us consider the cases of $r_\alpha \neq 0$ for $\tilde{x}_0 - \Delta\tilde{x}/2 < \tilde{x} < \tilde{x}_0 + \Delta\tilde{x}/2$ and $r_\alpha = 0$ for $-1 < \tilde{x} \leq \tilde{x}_0 - \Delta\tilde{x}/2$ or $\tilde{x}_0 + \Delta\tilde{x}/2 \leq \tilde{x} < 1$. The magnitude of r_α ($\neq 0$) is obtained from Eq. (6), which indicates the condition that the whole ion production rate in the system ($-1 < \tilde{x} < 1$) is kept a constant. Thus, the spatial profile of ion production is expressed through the two parameters: $\tilde{x}_0$ and $\Delta\tilde{x}$.

The spatial profiles of $\tilde{n}$ for $\Delta\tilde{x} = 0.4$ with $\tilde{x}_0 = -0.7$, -0.4, and -0.1 and for the uniform ion production case can be obtained in the case of $r_\beta = 1.0$, corresponing to a low electron temperature, $T_e \approx 3$ eV, and are represented in Fig. 1.

The maximum of $\tilde{n}$ is always located in the region with the ion production ($r_\alpha \neq 0$) and agrees with the location of $\tilde{v} = 0$. Therefore, $\tilde{v} > 0$ in the right-side-region from the maximun of $\tilde{n}$ and $\tilde{v} < 0$ in the left-side-region from the maximun of $\tilde{n}$. The sign of $\tilde{v}$ gives the direction of force, $\tilde{f}$, acting to the ambient gas, as shown in Fig. 2, where the relations between $\tilde{f}/\tilde{\alpha}_0$ and $\tilde{x}$ in the case of $r_\beta = 1.0$ are represented by a bold curve for $\tilde{x}_0 = -0.7$ and $\Delta\tilde{x} = 0.4$; a solid curve for $\tilde{x}_0 = -0.4$ and $\Delta\tilde{x} = 0.4$; a broken curve for $\tilde{x}_0 = -0.1$ and $\Delta\tilde{x} = 0.4$; and a dotted curve for the uniform ion production case. For any non–uniform ion production case, $\tilde{f}/\tilde{\alpha}_0 =$ const. in the region of $r_\alpha = 0$, because of $\mathrm{d}(\tilde{n}\tilde{v})/\mathrm{d}\tilde{x} = 0$ from Eq. (1).

In summary, since $\tilde{f}$ in the ion production region does not contribute on $\tilde{F}_1$ so much, we find the integrated force

$$\tilde{F}_1 \approx -0.35\tilde{x}_0 \tag{10}$$

and

$$\tilde{F}_2 \approx 0.45 - 0.106\Delta\tilde{x} - 0.084\tilde{x}_0{}^2 \,. \tag{11}$$

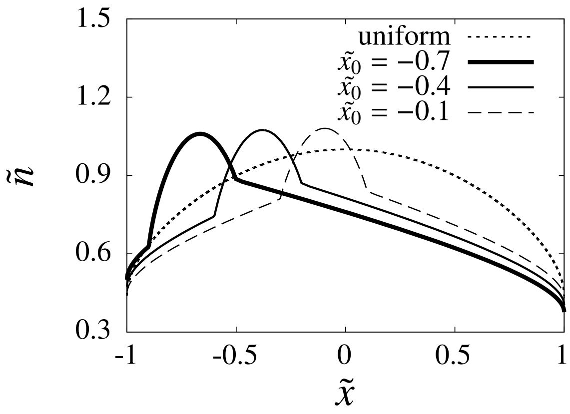

Fig 1: Spatial profiles of $\tilde{n}$ in the case of $r_\beta = 1.0$ are represented by a bold curve for $\tilde{x}_0 = -0.7$ and $\Delta\tilde{x} = 0.4$; a solid curve for $\tilde{x}_0 = -0.4$ and $\Delta\tilde{x} = 0.4$ a broken curve for $\tilde{x}_0 = -0.1$ and $\Delta\tilde{x} = 0.4$; and, as a reference, that of $\tilde{n}$ for the uniform ion production case is represented by a dotted curve.

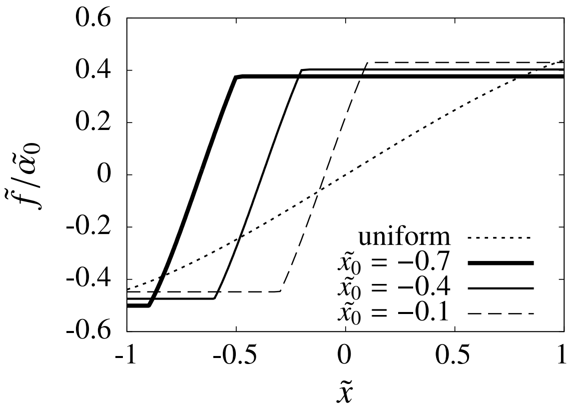

Fig 2: Spatial profiles of $\tilde{f}/\tilde{\alpha}_0$ in the case of $r_\beta = 1.0$ are represented by a bold curve for $\tilde{x}_0 = -0.7$ and $\Delta\tilde{x} = 0.4$; a solid curve for $\tilde{x}_0 = -0.4$ and $\Delta\tilde{x} = 0.4$ a broken curve for $\tilde{x}_0 = -0.1$ and $\Delta\tilde{x} = 0.4$; and, as a reference, that of $\tilde{f}/\tilde{\alpha}_0$ for the uniform ion production case is represented by a dotted curve.

References

[1] T. C. Corke, C. L. Lon, and S. P. Wilkinson: Ann. Rev. Fluid Mech. **4**2 (2010) 505.

[2] E. Stuhlinger, *Physics of Electric Propulsion* (McGraw-Hill, New York, 1968).

[3] I. Maden, R. Maduta, J. Kriegseis, S. Jakirlić, C. Schwarz, S. Grundmann, C. Tropea: Inter. J. Heat Fluid Flow **4**1 (2013) 80.

[4] A.Tsushima: JPS Conf. Proc. **1** (2014) 015048.

[5] G. S. Kino annd E. K.Shaw: Phys. Fluids. **9** (1966) 587.