J. Plasma Fusion Res. SERIES, Vol. 6 (2004) 433–436

Effect of Plasma Flow on the Gas Conductance in a Simulated Closed-Divertor

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(Received: 9 December 2003 / Accepted: 23 February 2004)

Abstract

The reduction of a baffle-conductance due to the plasma flow has been experimentally investigated. For various ion densities of the plasma flow through the aperture of the baffle, the conductance for the flow reversal of neutral gas was derived from the neutral pressure difference between both sides of the baffle. It has been observed that the value of conductance is reduced continuously with increasing the ion density, indicating clearly the effect called "plasma plugging". An effective formula expressing the reduction of the conductance is presented in consideration of the friction between the plasma and neutral flows.

Keywords:

linear machine, closed divertor, plasma plugging, conductance, plasma flow, neutral gas, friction

1. Introduction

Divertor baffles in the magnetic confinement devices remind us of the concept of gas conductance. In vacuum, the flow rate of neutral gas flowing through the aperture or duct, Q [Pa m^3·s^{-1}], is given by

$$Q = C\Delta P, \tag{1}$$

where C [m^3·s^{-1}] is the conductance and ΔP [Pa] is the pressure difference between neutral pressures at the inlet and outlet. If substantial dense Scrape Off Layer (SOL) plasma passes through the opening of the baffle, the impurity flow toward the core plasma can collide with the SOL plasma flow at the opening of the baffle, which will induce the enhancement of the friction between the plasma and neutral reverse flows. The friction leads to the reduction in the conductance of the neutral reverse flow [1]. This effect is called "plasma plugging", improving an impurity screening [2]. The plasma plugging has been clearly found in linear machines [2-5]. The value of conductance for the impurity was found to be reduced by a factor of 8 compared to the value of vacuum.

In this article, an useful formula that fairly expresses the relationship between conductance and the plasma flow will be presented based on the experimental results obtained by using the linear machine TPD-II (Test Plasma produced by a Dc discharge) with a baffle [5]. It has been observed that the value of C is reduced continuously with increasing the ion density of the plasma flow. The formula for the reduction of C will be given from the force balance between the friction and the neutral pressure gradient in one-dimensional fluid equations for the neutrals.

2. Experimental setup

The experiment was carried out in the linear machine TPD-II at the National Institute for Fusion Science (see Fig. 1) [5]. Helium plasma is continuously generated by a dc discharge between the anode and the LaB_6 cathode. As can be seen from Fig. 1, the plasma goes into the simulated edge plasma region (E region) and then into the divertor region (D region). An orifice (20 mm in length and 15 mm in diameter somewhat larger than the plasma diameter) is located 1.4 m from the anode. This orifice serves as the opening of baffle

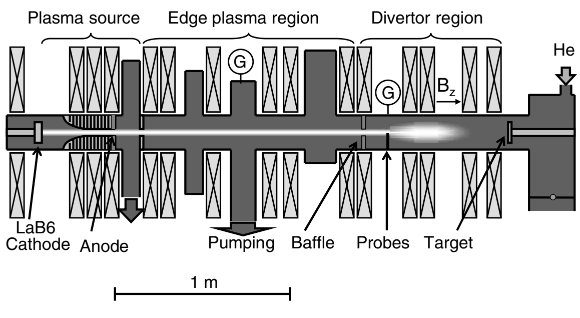

Fig. 1 Schematic of TPD-II with the baffle.

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plates in magnetic confinement devices. The electron plasma density n_e ($\approx n_i$) is 10^{18}~10^{19} m^{-3} under the axial magnetic field of 0.2 T. The control in n_e is achieved by varying the discharge current I_d; n_e increases as I_d is increased. The value of n_e was obtained by the single cylindrical Langmuir probe located at 1.5 m away from the anode. The probe measurement was carried out in a low neutral pressure condition ($P_E \approx P_D \approx 0.1$ Pa). Note that the electron temperature T_e is 5 eV that is almost independent of I_d. The ion flow velocity toward the target u_i ($= 5 \times 10^3$ m/s) was measured from Doppler-shift of the emission line of He II 468.57 nm, and was comparable to the ion thermal velocity v_{thi} for $T_i \approx 1$ eV. No change in u_i with I_d has been observed.

The neutral helium gas is injected into the D region, flows against the plasma flow through the orifice, and is evacuated at the E region (the pumping speed is 0.3 $m^3 \cdot s^{-1}$). The neutral gas pressures at the D and E regions, P_D and P_E, were measured by using baratron gauges located in the corresponding regions. As the flow rate of the gas injection into the D region, Q_D, is increased, the value of P_D increases, and when P_D becomes greater than ~1 Pa, the plasma detachment clearly appears in the D region. Then, the position of the ionization front, z_f, moves toward the E region. Note that in this article we deal with the case that z_f remains in the D region.

3. Experimental results and discussion

As Q_D is increased slowly keeping the steady state, P_D and P_E monotonically increase, which are shown in Figs. 2(a) and 2(b). The variation of the pressure difference between P_D and P_E, ΔP, is shown in Fig. 2(c). One can see that the functional relationship between ΔP and Q_D is offset-linear as

$$\Delta P = \frac{Q_D}{C} + \Delta P_0 \ , \tag{2}$$

where, $1/C$ is the slope and ΔP_0 is the intercept (at $Q_D = 0$ Pa $m^3 \cdot s^{-1}$) of each line. The symbol C means the effective conductance influenced by the plasma flow through the orifice.

The values C and ΔP_0 drawn from each line are shown as a function of the mean area density of ion, $\langle n_i \rangle$, in Figs. 3(a) and 3(b), respectively. The gas conductance for vacuum (C at $I_d = 0$ A), C_0, is 0.027 $m^3 \cdot s^{-1}$, which is comparable to the value of 0.028 $m^3 \cdot s^{-1}$ estimated as the conductance of the short duct in vacuum [6]. It can be seen from Fig. 3(a) that the value of C decreases with increasing $\langle n_i \rangle$, indicating that the plasma flow suppresses the conductance. On the other hand, the value of ΔP_0 increases with increasing $\langle n_i \rangle$.

The appearance of ΔP_0 suggests an additional gas injection into the D region. This injection can arise from the plasma flow. Ions in the plasma flow come into the D region, recombine, and become neutrals. The flow rate of the gas injection by the plasma flow, Q_p, is proportional to $\langle n_i \rangle$. The total gas injection into the D region, Q, is summation of Q_D and Q_p : $Q = Q_D + Q_p$. Equation (1) is rewritten as

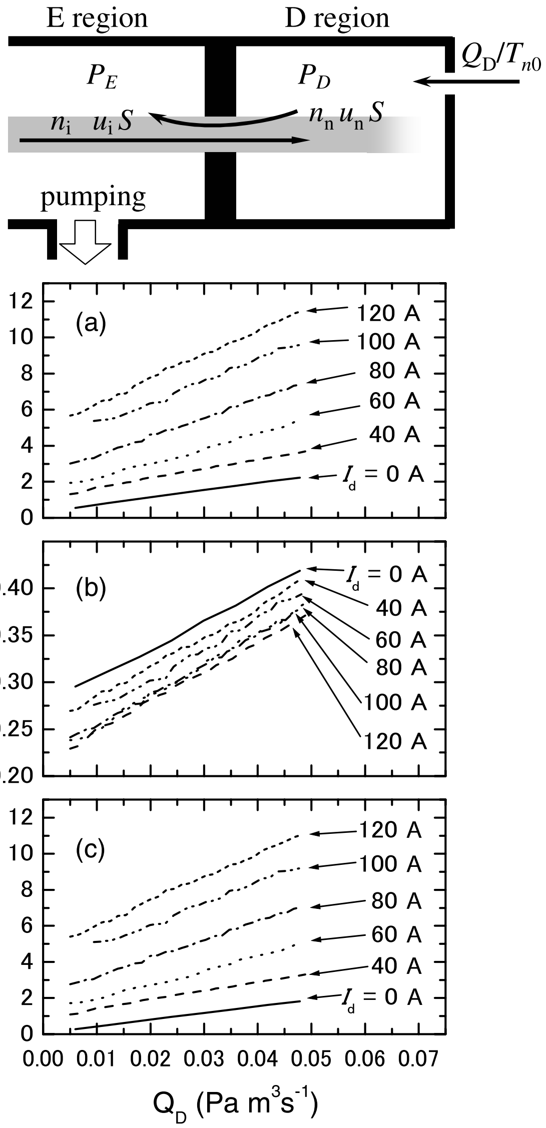

Fig. 2 Variations of P_D, P_E, and ΔP as a function of Q_D for various values of discharge current I_d.

$$\Delta P = \frac{Q_D}{C} + \frac{Q_p}{C} \ . \tag{3}$$

By defining Q_p / C as ΔP_0, eq. (3) becomes equal to eq. (2). The experimentally obtained offset-linear scaling of eq. (2), thus, can be interpreted.

We now attempt to find a formula that expresses the change in both C and ΔP_0 as shown above. The effective conductance C can be considered as the combined-conductance for the series-connection of C_0 and the conductance due to the plasma flow, C_p:

$$C = \left(\frac{1}{C_0} + \frac{1}{C_p} \right)^{-1} . \tag{4}$$

Equation 3 is rewritten as

$$\Delta P = \frac{Q_D + Q_p}{C_0} + \frac{Q_D + Q_p}{C_p} \ . \tag{5}$$

The second term in right hand side means the pressure

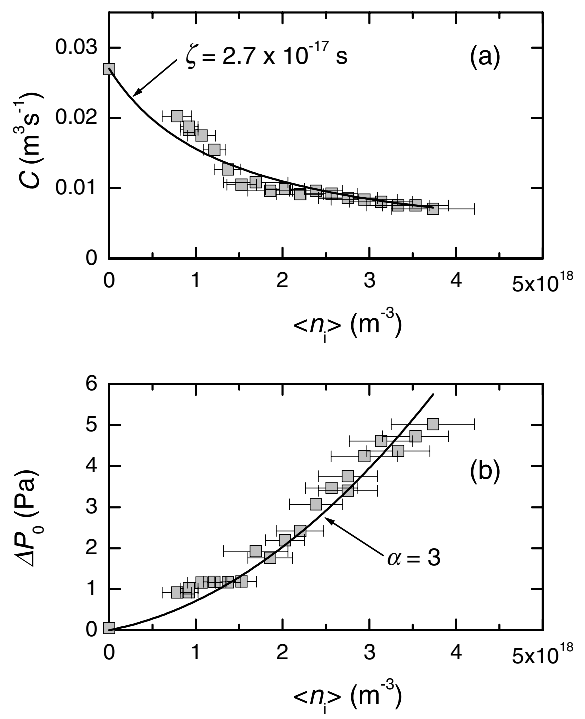

Fig. 3 Variations of C and ΔP_0 as a function of the mean area density $\langle n_i \rangle$.

difference caused by the plasma flow, and is defined as $\Delta P'$:

$$\Delta P' = \frac{Q_D + Q_p}{C_p} . \tag{6}$$

The substance of C_p can be assumed to be almost friction between the neutral and plasma flows. For the present experimental condition, the influence of viscosity is supposed to be much smaller than that of the friction, because the mean free path of neutrals becomes not much smaller than the aperture diameter of the baffle. The one-dimensional (along z axis toward the target) equation of force balance for the neutral particle at the orifice can be written as follows:

$$- m n_n \nu_n (-u_n - u_i) - \frac{\mathrm{d}P'}{\mathrm{d}z} = 0 , \tag{7}$$

where, n_n and u_n are the neutral density and the neutral gas flow velocity at the orifice, respectively, ν_n is collision frequency, and dP' is corresponding to the pressure difference $\Delta P'$ in eq. (6). The signs of u_n and u_i themselves are positive; the direction of $(-u_n)$ in eq. (7) is opposite to that of the plasma flow. The conservation of the neutral particle for the D region prescribes n_n under the steady state [see also upper schematic of Fig. 2]:

$$n_n = \frac{u_i}{u_n} \alpha \langle n_i \rangle + \frac{Q_D}{u_n S T_{n0}} , \tag{8}$$

where, S is the orifice cross-sectional area, T_{n0} is room temperature (300 K), and α is a factor of $\langle n_i \rangle$ for fitting the experimental data with the theoretical curve as shown below. Substitution of eq. (8) into eq. (7) yields

$$\Delta P' = \frac{m \nu_n \Delta z}{S T_{n0}} \left(1 + \frac{u_i}{u_n} \right) Q_D + \alpha \frac{m \nu_n \Delta z}{S T_{n0}} \left(1 + \frac{u_i}{u_n} \right) \langle n_i \rangle u_i S T_{n0} , \tag{9}$$

where, we assume that there are no significant changes in $\langle n_i \rangle$, u_p, and u_n along with scale length Δz. Equation (9) shows Q_D- and plasma flow $(\langle n_i \rangle u_i S T_{n0})$- dependencies on $\Delta P'$, which is similar to eq. (6). Then we define C_p as

$$C_P \equiv \left(\zeta \langle n_i \rangle \right)^{-1} , \tag{10}$$

where, ζ is

$$\zeta = \alpha \frac{m(\sigma_{in} + \sigma_{cx}) \Delta z \, v_{thi}}{2 S T_{n0}} \left(1 + \frac{u_i}{u_n} \right) . \tag{11}$$

In derivation of eq. (11), $\nu_n = 0.5\alpha \langle n_i \rangle (\sigma_{in} + \sigma_{cx}) v_{thi}$ is adopted into ν_n in eq. (9), where σ_{in} ($\approx 3.3 \times 10^{-19}$ m^2) and σ_{cx} ($\approx 2.0 \times 10^{-19}$ m^2) are the cross sections for neutral–ion and charge exchange collisions, respectively [7]. From eqs. (4) and (10), we obtain a formula for the effective conductance C as

$$C = \frac{C_0}{1 + \zeta \langle n_i \rangle C_0} . \tag{12}$$

Since ΔP_0 is given as Q_p / C [see eq. (3)], ΔP_0 is

$$\Delta P_0 = \alpha S T_{n0} u_i \left(\frac{1 + \zeta C_0 \langle n_i \rangle}{C_0} \right) \langle n_i \rangle . \tag{13}$$

The curves given from eqs. (12) and (13) as a function of $\langle n_i \rangle$ are shown as solid curves in Figs. 3(a) and 3(b), respectively. From the curve fitting to the experimental data, the parameters of ζ and α providing the best fit are $\zeta = 2.7 \times 10^{-17}$ s and $\alpha = 3$.

The factor of α (> 1) implies necessity of a further gas injection proportional to $\langle n_i \rangle$. This may arise from neutrals accompanying the plasma flow, since there exists the friction in the upstream (the E region). The mean free path for charge exchange collision in the E region is a few times smaller than the distance between the anode and the probe for present experimental condition. This allows us to consider that the neutral flow can grow along the distance from the anode to compensate for the ion-flux loss. Note that there is no growth of ion density due to ionization, since the mean free path for the ionization is much larger than that for the momentum-loss collision.

For estimating ζ of eq. (11), first we deduce u_n from the experimental results, as follows. The neutral density at the orifice n_n can be regarded as a mean value: $n_n = (P_D + P_E)/(2T_n)$, where, T_n is the neutral gas temperature at the orifice ($\neq T_{n0}$). Then, eq. (8) will be rewritten as

$$u_n = \left(\alpha \langle n_i \rangle u_i + \frac{Q_D}{S T_{n0}} \right) \frac{2 T_n}{P_D + P_E} . \tag{14}$$

The value of T_n, unfortunately, has not been observed, so that we presuppose that T_n is approximately equal to the wall temperature surrounding the plasma. Then, the I_d-dependence of the wall temperature is adopted in eq. (14). In fact the wall temperature increases from room temperature (~300 K) up to

~500 K for I_d = 0–120 A. The evaluated values of u_n lie at (1.4 ± 0.2) × 10^2 m/s and is fairly independent of the discharge current I_d. Employing this value of u_n and $\Delta z \sim L$ = 20 mm (where L is the orifice thickness), thus, the value of ζ, is estimated as 3 × 10^{-17} s which is comparable to the experimentally obtained value of 2.7 × 10^{-17} s. This indicates, therefore, that the reduction of the effective conductance in this experiment can be explained by means of the friction between the neutral and plasma flows.

4. Conclusion

The effect of the plasma flow on baffle conductance for neutral reverse flow was investigated by using the linear machine with simulated divertor. It has been observed that the value of conductance is reduced continuously with increasing the ion density of the plasma flow, indicating clearly the effect called "plasma plugging". By considering the friction between the plasma and neutral flows, we presented the formula that expresses successfully the reduction of the conductance in this experiment.

Acknowledgment

This research was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research (B), 15360496, 2003.

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