ELSEVIER

Journal of Nuclear Materials 313–316 (2003) 1331–1334

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Two-dimensional particle simulation of the flow control in SOL and divertor plasmas

T. Takizuka [a,*], M. Hosokawa [b], K. Shimizu [a]

[a] Japan Atomic Energy Research Institute, Naka Fusion Research Establishment, 801-1 Mukoyama Naka-machi, Naka-gun, Ibaraki 311-0193, Japan

[b] Research Organization for Information Science and Technology, Tokai, Ibaraki 319-1106, Japan

Abstract

Two-dimensional (2D) particle simulations are performed by using PARASOL code to study the flow control in SOL and divertor plasmas in a double-null magnetic configuration with the separatrix. The divertor asymmetry is induced by the drift effect. The $E \times B$ drift ($V_{E\times B}$) and the diamagnetic drift ($V_{\rm dia}$) work to induce the asymmetric flow in different ways with each other. The condition of 2D sheath formation is developed. Different influences of $V_{E\times B}$ and $V_{\rm dia}$ on the asymmetric flow generation are clearly explained. Effects of divertor biasing and gas puffing on the flow are investigated with PARASOL simulations. The divertor asymmetry can be controlled by both the biasing and the gas puffing. It is found that the control of the drifts is essential to control the flow and the asymmetry.

PACS: 52.25
Keywords: Divertor plasma; SOL plasma; Flow; Biasing; Gas injection; Simulation

1. Introduction

In course of tokamak fusion research, particle and heat control is one of the most crucial issues. Divertor configuration is expected to play a role of the control. Helium ash exhaust and impurity retention in the divertor region are owed to the plasma flow towards divertor plate. The localization of heat load on the divertor plate depends on the flow pattern. Accordingly, particle and heat control can be achieved by the proper control of the flow in scrape-off layer (SOL) and divertor plasmas. Experiments of the flow control by the divertor biasing [1,2] and by the combination of puff and pump [3] have been performed, and affirmative results have been obtained. Although the important role of the drift on SOL/divertor plasma characteristics was clearly observed experimentally [4,5], the physical mechanism of the flow generation and the aspect of the flow pattern have not fully been understood. Numerical studies on these subjects are being carried out by using fluid simulation codes. In the fluid model, however, various physics models are introduced, i.e., boundary conditions at the plasma–wall boundary, effects of drift and so on. On the other hand, particle simulations can demonstrate directly the physical features of the flow without using such physics models. The divertor asymmetry induced by the $E_{\rm r} \times B$ drift ($E_{\rm r}$: radial electric field) was shown with one-dimensional (1D) particle simulations by using PARASOL (particle advanced simulation for SOL and divertor plasmas) code [6]. The asymmetry due to the $E_{\rm r} \times B$ drift and diamagnetic drift was shown with PARASOL simulations in a two-dimensional (2D) slab configuration [7]. It was found that the $E_{\rm r} \times B$ drift and the diamagnetic drift work to induce the asymmetry (or to modify the flow pattern) in different ways with each other.

In this paper, we investigate the flow control in SOL and divertor plasmas with PARASOL simulations in a 2D magnetic configuration with the separatrix like a

* Corresponding author. Tel.: +81-29 270 7518; fax: +81-29 270 7419.
E-mail address: takizukt@fusion.naka.jaeri.go.jp (T. Takizuka).

0022-3115/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
PII: S0022-3115(02)01513-1

divertor tokamak. Effects of divertor biasing and gas puffing on the flow are studied.

2. Simulation model

The PARASOL code is an advanced particle simulation code employing a PIC method and a binary collision model. Details of the model were described in [8,9]. In the present study, 2D plasmas in a rectangular box with sizes $L_x \times L_y$ are simulated by PARASOL code.

A double-null magnetic configuration with the separatrix is given as shown in Fig. 1. Vector potentials induced by a core plasma current distributed in an elliptic region and two divertor coil currents are compounded. The longitudinal magnetic field B_z is uniform, and the pitch of magnetic field at $x = 0$ on a separatrix, $\Theta \equiv |B_x/B_z|$ is small like a tokamak configuration.

Electron motions are approximated as their guiding-center motions (2D-2V), while ion motions are fully traced (2D-3V). The $E \times B$ drift, diamagnetic drift and polarization drift of an ion are intrinsically simulated. The electrostatic field in the rectangular conducting wall is calculated with a PIC method. The bias voltage between the wall ($\phi = 0$) and the bias plate ($\phi = \phi_{\text{bias}}$) can be applied (see Fig. 1).

Effects of Coulomb collisions are essential in the SOL and divertor plasmas, and are simulated by a binary collision model. Collisions with neutral particles are not taken into account in this paper for simplicity.

The anomalous cross-field diffusion is added with the use of a Monte-Carlo method.

Hot particle source is put in the core plasma, and recycling cold particle sources are put near divertor plates. The recycling particle flux, $\Gamma_{\text{rec},j} = R\Gamma_{\text{d,j}}$, is determined in each divertor region ($j = 1$: upper-left in Fig. 1, $j = 2$: upper-right, $j = 3$: lower-right, and $j = 4$: lower-left), where R is the recycling rate and $\Gamma_{\text{d,j}}$ is the particle flux to the divertor plate in the jth region. Cold particles are also supplied by gas puff in SOL plasmas. The gas-puff flux in each SOL region is given by $\Gamma_{\text{GP},k} = (R_{\text{GP}}/2)\Sigma_j\Gamma_{\text{d},j}$ ($k = 1,2$), where R_{GP} is the gas-puff rate. Generated particles flow into divertor plates finally and vanish there. The ion particle balance holds during a simulation discharge; $\Gamma_{\text{hot}} + \Sigma_j\Gamma_{\text{rec},j} + \Sigma_k\Gamma_{\text{GP},k} = \Sigma_j\Gamma_{\text{d},j}$, where Γ_{hot} denotes the hot particle flux in the core.

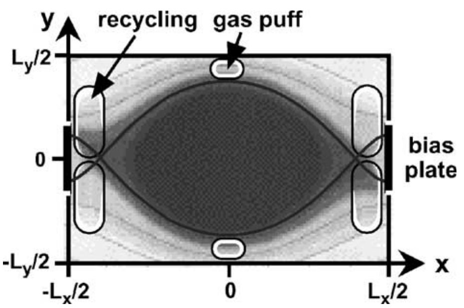

Fig. 1. 2D divertor system in a rectangular conducting wall. Magnetic separatrix with double-null points is drawn. Divertor plates can be biased. 2D distribution of density is shown, which is asymmetric in SOL and divertor plasmas. Hot particle source is in the core, and recycling particle sources are near the plates. Cold particles are also supplied by gas puff in SOL plasmas.

Simulation parameters are as follows. The number of superparticle ions N_i is 10^6 and the number of spatial grids $M_x \times M_y$ are 400×256. As for the physical parameters, the charge number of ions is unity, the mass ratio m_i/m_e is chosen as 400 to save the computation time but to keep the major physics of SOL and divertor plasmas, the pitch of magnetic field Θ is 0.2 at $x = 0$ on the separatrix, the temperature ratio of hot source T_{i0}/T_{e0} is 1/2, the normalized mean free path $l_{\text{mfp}}/(L_x/\Theta)$ is about 1/2, the normalized ion Larmor radius ρ_i/L_x is about 0.005, and the normalized diffusion coefficient $D_\perp/L_xC_s$ is about 10^{-5} (C_s is sound speed). Note that these values of $l_{\text{mfp}}/(L_x/\Theta)$, ρ_i/L_x and $D_\perp/L_xC_s$ are similar to some present tokamak divertor plasma parameters, but the ratio of Debye length to system size λ_D/L_x is much larger than that of a realistic tokamak divertor plasma. Even though the λ_D/L_x value is not so small, the quasi-neutrality condition holds in SOL and divertor plasmas and the major characteristics of the plasmas can be simulated accurately [8].

A simulation run continues to the time steps $K_t = 5 \times 10^4$, when the plasma becomes almost stationary. A parallel computer SGI Origin 3800 (MIPS R-14000/500MHz) is used for PARASOL simulations. A domain decomposition method is applied in the x-direction, while Poisson's equation is solved by an appointed processor. The computation time of a run is about 5 h with 64 processors.

3. Condition of 2D sheath formation

In this section we present analytically a condition of the sheath formation in a 2D system (ξ the normal direction to the divertor plate, ψ the radial direction, $B_\xi/B_z = \Theta$, and $B_\psi/B_z = 0$).

The equation of continuity for ions, and the equation of ion momentum parallel to B are used to obtain the linear response of the ion density perturbation δn_i against the potential perturbation $\delta\phi$. In these equations, the $E \times B$ drift, diamagnetic drift and polarization drift are taken into account as well as the flow parallel to B. In tokamak divertor plasmas with $\Theta \ll 1$ and $\Theta\lambda_{\text{SOL}}/\rho_i \sim 1$ (λ_{SOL} is the characteristic decay length of SOL), roles of drifts in the poloidal flow are important. Unperturbed drift velocities in the x-direction at the sheath entrance are $V_{E\times B} = E_\psi/B$, $V_{\text{dia}} = -P'_{i\perp}/n_eeB$, and

$V_{\text{polar}} = 0$. Unperturbed parallel velocity is $V_{\parallel}$. The electron Boltzmann's relation, $\delta n_e/n_e = e\delta\phi/T_{e\parallel}$ $(\equiv \delta\Phi)$, and the ion adiabatic response, $\delta P_i/P_i = \gamma\delta n_i/n_e$, are applied. Here the subscripts $\parallel$ and $\perp$ represent 'parallel' and 'perpendicular' to B, the superscript $'$ denotes the radial gradient $\mathrm{d}/\mathrm{d}\psi$, and γ is the adiabatic index approximately equal to 3 [6]. Through a straightforward calculation by assuming $\partial\delta\Phi/\partial\psi = 0$, we derive a linearized Poisson's equation:

$$\rho_{\text{eff}^2}\,\mathrm{d}^2\delta\Phi/\mathrm{d}\xi^2 = K\,\delta\Phi,$$
$$K \equiv (V_{\xi^*}/V_{\xi 0}) - \Theta^2\{T_{\text{eff}_\parallel} + (V'_\parallel/\Theta\Omega)T_{\text{eff}_\perp}\}/m_i V_{\xi 0}^2,$$

where $\rho_{\text{eff}} = (T_{\text{eff}\perp}/eB\Omega)^{1/2}$ is an effective ion Larmor radius, $T_{\text{eff}\parallel} = T_{e\parallel} + \gamma T_{i\parallel}, T_{\text{eff}\perp} = T_{e\parallel} + \gamma T_{i\perp}$, $V_{\xi 0} = \Theta V_\parallel + V_{E\times B} + V_{\text{dia}}$, $V_{\xi^*} = \Theta V_\parallel + V_{E\times B} - V_{\text{dia}^*}$, and $V_{\text{dia}^*} = -n'_e T_{e\parallel}/n_e eB$ is an effective diamagnetic drift.

For the 1D case, the expression of K is reduced to $K \equiv 1 - \Theta^2(T_{e\parallel} + \gamma T_{i\parallel})/m_i(\Theta V_\parallel + V_{E\times B})^2$ [6], which is like Bohm–Chodura condition [5,10].

The condition for the sheath formation is $K \geqslant 0$, because $\delta\Phi$ can grow exponentially without oscillation. Note that this sheath is a magnetic presheath with a scale length of ρ_i. Detailed derivation of the above condition and the comparison with particle simulation results will be shown elsewhere.

As mentioned in the introduction, the $E\times B$ drift and the diamagnetic drift work to induce the asymmetry (or to modify the flow pattern) in different ways with each other. Major cause of this difference is found from the above condition. The total flow $V_{\xi 0}$ and the 'imaginary' flow V_{ξ^*} are the same positively linear functions of $V_{E\times B}$. On the other hand with respect to V_{dia}, the $V_{\xi 0}$ is positively linear one as well, but the V_{ξ^*} is negatively linear one oppositely. By taking account of the pressure balance against the change in $V_{E\times B}$ and V_{dia} (V_{dia^*}), we find that the density at the sheath boundary increases with the increase of $V_{E\times B}$ but decreases with V_{dia}. This tendency completely agrees with the previous simulation results [6,7] and the present result shown in Section 4.

4. PARASOL simulation of flow control

We perform PARASOL simulations of the flow control for low recycling (low-R) case, $R = 0$, and high recycling (high-R) case, $R = 0.9$. At first the effect of divertor biasing is studied in the range of the bias voltage, $-2 \leqslant \Phi_{\text{bias}}(\equiv \phi_{\text{bias}}/T_{e0}) \leqslant 2$. Second the effect of gas puffing is investigated in the range of the gas-puff rate, $0 \leqslant R_{\text{GP}}/(1-R) \leqslant 1/2$. Fig. 2 shows the flow pattern for $R = 0$ without biasing and gas puffing. In this SOL plasma with $V_{\text{dia}} > V_{E\times B}$ (see Fig. 5(b)), the $V_\parallel$ flows towards drift direction (Fig. 2(a) and (b)) and the n_e at V_{dia}-flowing-inside becomes lower (Fig. 2(c)) as predicted in Section 3.

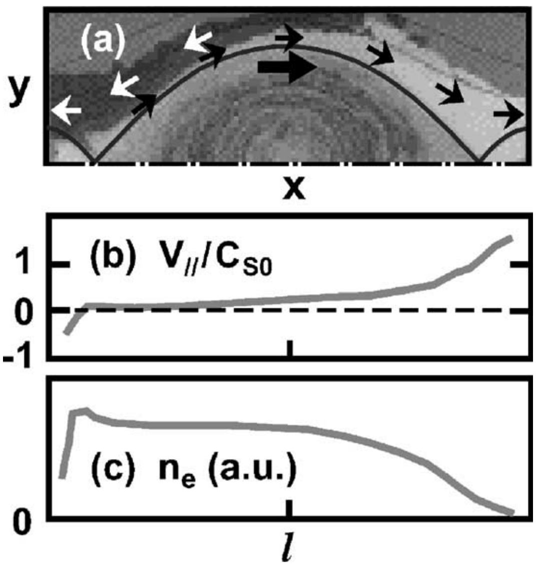

Fig. 2. 2D distribution of $V_\parallel$ for low-R case (a). Arrow indicates direction of $V_\parallel$. A big arrow represents direction of drift velocity. Profiles of (b) $V_\parallel$ and (c) n_e along poloidal length on a field line outside the separatrix are shown. Remarkable asymmetry is seen.

In order to evaluate quantitatively the divertor asymmetry, we introduce the 'particle-flux asymmetry index' $\alpha_P = (\Gamma_{d,1} - \Gamma_{d,2})/(\Gamma_{d,1} + \Gamma_{d,2})$ and the 'heat-flux asymmetry index' $\alpha_H = (Q_{d,1} - Q_{d,2})/(Q_{d,1} + Q_{d,2})$, where $Q_{d,j}$ is the energy flux to the divertor plate in the jth region ($j = 1$: upper-left, and $j = 2$: upper-right). In the present plasmas obtained by PARASOL simulations, these values are rather large without biasing and gas puffing; $\alpha_P = 0.39$ and $\alpha_H = 0.24$ for low-R case, and $\alpha_P = 0.37$ and $\alpha_H = 0.15$ for high-R case.

These asymmetries can be controlled successfully by the divertor biasing. The dependence of asymmetry indexes on Φ_{bias} is shown in Fig. 3. The positive bias enhances $V_{E\times B}$ from the natural one as seen in Fig. 4(b), and reduces the asymmetry. As Φ_{bias} increases further, the opposite asymmetry is induced for high-R case. On the contrary, the negative bias reduces $V_{E\times B}$ (Fig. 4(c)), and enhances the asymmetry. Because of the modification of the plasma profile and the resultant increase of $V_{E\times B}$, the enhancement of asymmetry stops (or the reduction arises) for the strongly negative biasing. The biasing is more effective in high-R case. One of the reasons is that the bias normalized by divertor plasma temperature is higher for high-R case by about twice than that for low-R case. Even though this normalization is taken into account, the biasing in high-R case seems more effective. This problem is to be solved in future.

Mitigation of the asymmetry is brought by the gas puffing effectively in low-R plasmas. Asymmetry indexes

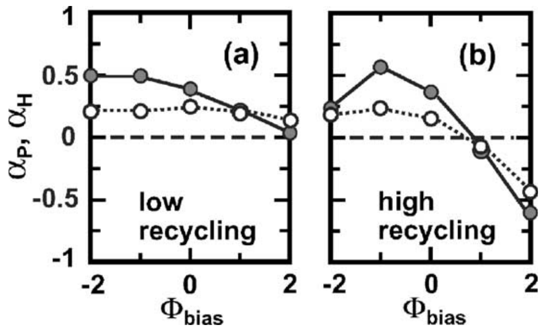

Fig. 3. Particle-flux asymmetry index α_P (solid line) and heat-flux asymmetry index α_H (dotted line) vs. normalized bias voltage Φ_{bias} for (a) low-R and (b) high-R cases.

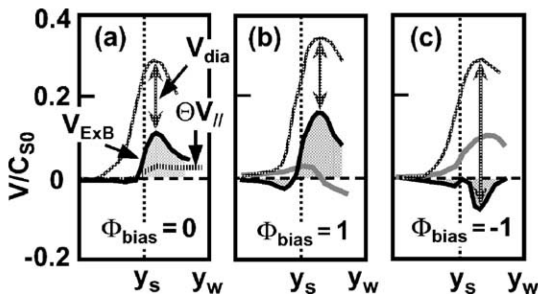

Fig. 4. Radial distribution of flow velocities, $\Theta V_{\parallel}$, $V_{E\times B}$, and V_{dia} at the middle of SOL ($x = 0$) in high-R plasmas for various bias, $\Phi_{bias} = 0$, 1, and -1. Positions of separatrix and wall are plotted by y_s and y_w, respectively. C_{s0} is a sound speed defined as $C_{s0}^2 = T_{e0}/m_i$.

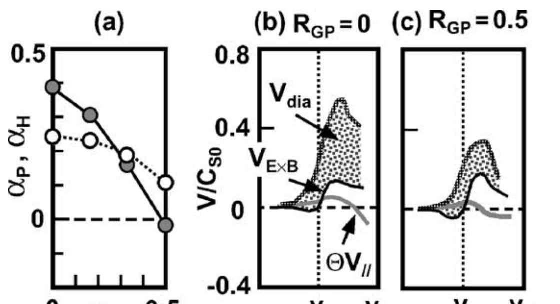

Fig. 5. Asymmetry indexes α_P (solid line) and α_P (dotted line) vs. gas-puff rate R_{GP} for low-R case (a). Radial distribution of flow velocities, $\Theta V_{\parallel}$, $V_{E\times B}$, and V_{dia} at the middle of SOL ($x = 0$) is shown for (b) $R_{GP} = 0$ and (c) $R_{GP} = 0.5$.

decreases to $\alpha_P = -0.01$ and $\alpha_H = 0.11$ for $R_{GP} = 0.5$ as shown in Fig. 5(a). Sometimes it has been considered that the gas-puff particle source directly induces $V_{\parallel}$ flow. Present simulation results show, however, that the gas puff modifies the n_e profile in SOL region and make the V_{dia} small as shown in Fig. 5(b) and (c). This reduction of V_{dia} is the direct cause of the mitigation of the asymmetry. The flow control by gas puffing becomes difficult in high-R plasmas, because the gas-puff rate is restricted as $R_{GP} < 1 - R$.

For both biasing and gas puffing, the control of the drifts is essential to control the flow and the asymmetry, which are strongly influenced by the condition of 2D sheath formation at the divertor plates.

5. Summary

2D particle simulations are performed by using PARASOL code to study the flow control in SOL and divertor plasmas in a double-null magnetic configuration with the separatrix. The divertor asymmetry is induced by the drift effect. The $E \times B$ drift ($V_{E\times B}$) and the diamagnetic drift (V_{dia}) work to induce the asymmetric flow in different ways with each other. The condition of 2D sheath formation is developed. Different influences of $V_{E\times B}$ and V_{dia} on the asymmetric flow generation is clearly explained. Effects of divertor biasing and gas puffing on the flow are investigated with PARASOL simulations. The divertor asymmetry can be controlled by both the biasing and the gas puffing. It is found that the control of the drifts is essential to control the flow and the asymmetry.

Acknowledgements

This work was performed under the Numerical Experiment of Tokamak (NEXT) project in JAERI. The authors thank Drs T. Ozeki and Y. Kishimoto for their encouragement.

References

[1] H. Ogawa et al., J. Nucl. Mater. 266–269 (1999) 623.
[2] C. Boucher et al., J. Nucl. Mater. 128&129 (1999) 788.
[3] M.R. Wade et al., J. Nucl. Mater. 266–269 (1999) 44.
[4] N. Asakura et al., in: Proceedings of the 15th Conference, vol. 1, IAEA, Vienna, Seville, 1995, p. 515.
[5] A.V. Chankin, J. Nucl. Mater. 241–243 (1997) 199.
[6] T. Takizuka, M. Hosokawa, Contribution Plasma Phys. 40 (2000) 471.
[7] T. Takizuka, M. Hosokawa, K. Shimizu, N. Hayashi, in: Proceedings of the 18th Conference, CD-ROM, IAEA, Vienna, Sorrento, 2001, file THP1/22.
[8] T. Takizuka, M. Hosokawa, K. Shimizu, Trans. Fusion Technol. 39 (2001) 111.
[9] T. Takizuka, M. Hosokawa, K. Shimizu, J. Nucl. Mater. 290–293 (2001) 753.
[10] R. Chodura, Phys. Fluids 25 (1982) 1628.