Numerical analysis of high Mach flow and flow reversal in the experimental advanced superconducting tokamak divertor*

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The B2-Eirene (SOLPS 4.0) code package is used to investigate the plasma parallel flow, i.e., the scrape-off layer (SOL) flow, in the experimental advanced superconducting tokamak (EAST) divertor. Simulation results show that the SOL flow in the divertor region can exhibit complex behaviour, such as a high Mach flow and flow reversal in different plasma regimes. When the divertor plasma is in the detachment state, the high Mach flow with approaching or exceeding sonic speed is observed away from the target plate in our simulation. When the divertor plasma is in the high recycling state, the flow reversal with a small Mach number ($|M| < 0.2$) is observed near the X-point along the separatrix region. The driving mechanisms for the high Mach flow and the reversed flow are analysed theoretically through momentum and continuity equations, respectively. The profile of the ionization sources is shown to be a possible formation condition causing the complex behaviour of the SOL flow. In addition, the effects of the high Mach flow and the flow reversal on the impurity transport are also discussed in this paper.

Keywords: high Mach flow, flow reversal, ionization source, divertor plasma

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1. Introduction

The plasma parallel flow, i.e., the scrape-off layer (SOL) flow, is generally considered to flow from the SOL and the divertor regions to the divertor target, which is a strong plasma sink.[1] The complex behaviour of the SOL flow, such as the flow reversal (the direction of the SOL flow is away from target plate) and the high Mach flow (the SOL flow velocity approaches or exceeds the sonic speed), associated with different plasma regimes have been observed in several tokamak experiments.[2,3] Recently, analytic models and numerical simulations have been used to reproduce some experimental results,[4,5] and the physical mechanisms driving the SOL flow, including ionization imbalances, toroidal rotation, poloidal transport asymmetries, Pfirch–Schlüter flows and classical drift, are suggested.[5,6] However, the driving mechanism and the formation condition for such a complex SOL flow are not yet clear enough. In addition, the SOL flow has an influence on impurity retention in the divertor, impurity transport in the SOL region and the balance of the impurity erosion and re-deposition between the inner and the outer target plate surfaces, all of which may affect the experimental advanced superconducting tokamak (EAST) experiments. The EAST is a fully superconducting tokamak in China. The engineering design of the EAST requires that the maximum power flux to the target plates during the first operation phase is below 1 MW/m^2 to ensure a long pulse (> 100 s) operation, which dictates that the EAST must be operated close to the plasma detachment condition.[7] In the present paper, numerical analyses of the SOL flow in the EAST divertor region in the detachment and the high recycling regimes are performed by using the SOLPS4.0 code package. To investigate the driving mechanisms and the formation condition for the SOL flow, we focus on the profiles of the ionization sources. One of the possible driving mechanisms for the SOL flow is analysed theoretically by using the continuity and the momentum equations. In addition, the effect of the SOL flow on the impurity

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transport is discussed.

2. Numerical model

The SOLPS4.0 code package is one of the most reliable and powerful tools to study the SOL and the divertor plasma.[8,9] It couples the multi-fluid plasma code B2[8] with the Monte–Carlo neutral code Eirene.[11] The B2 code was developed first by Bramms[8] and later by the IPP-Garching in Germany.[9] The Eirene code was developed by Reiter *et al.*[11] The SOLPS4.0 code has been allowed by the IPP-Garching to be used in the Institute of Plasma Physics, China, and has been applied to the simulation of the EAST plasma.[7,10] In the present analysis of the EAST, the single null divertor configuration is considered and the schematic diagram of the SOL and the divertor plasma is shown in Fig. 1. The major parameters of the EAST used in the modeling are listed in Table 1.

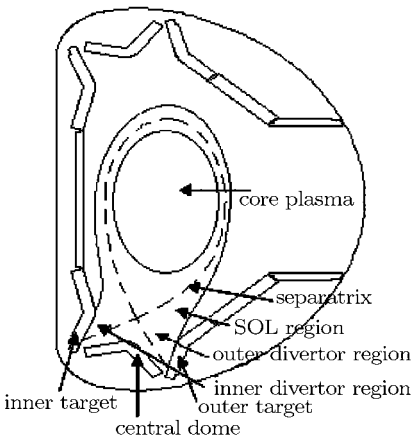


Fig. 1. Schematic diagram of the SOL and divertor plasma in the EAST with a single null divertor.

Table 1. Major parameters of the EAST with a single null divertor configuration.

Parameters	Value
Major radius R/m	1.94
Minor radius a/m	0.46
Elongation at separatrix $\kappa_{\rm x}$	1.69
Upper triangularity at separatrix $\delta_{\rm xu}$	0.32
Lower triangularity at separatrix $\delta_{\rm xl}$	0.54
Plasma volume $V_{\rm p}/{\rm m}^{-3}$	11.9

Figure 2 shows the numerical mesh used in the SOLPS covering the whole SOL and the divertors. The plasma includes deuterium and carbon ions, which are generated self-consistently by sputtering. Sputtering coefficient $Y_{\rm ch}$= 2.0% is used at all material surfaces, which is a typical value for the divertor plasma conditions in the present machine.[7] The anomalous diffusion coefficients are set as D = 0.3 $\rm m^2 \cdot s^{-1}$ and $\chi_{\rm i}$= $\chi_{\rm e}$= 1.0 $\rm m^2 \cdot s^{-1}$. The recycling coefficient for deuterium is set to unity at the target plates and the vacuum vessel walls for the envisaged long pulse operation in the EAST. The core-edge density is fixed, $n_{\rm D}^{\rm core} = 2.0 \times 10^{19}$ $\rm m^{-3}$. The total power escaping from the core is 4.0 MW and is equally distributed between the electron and the ion channels. For these input parameters, the divertor plasma is in a detachment state in the inner divertor region while in a high recycling state in the outer divertor region. The classical drifts are not considered here, since the profiles of the ionization sources are focused on the analysis of the driving mechanism of the SOL flow in the present paper.

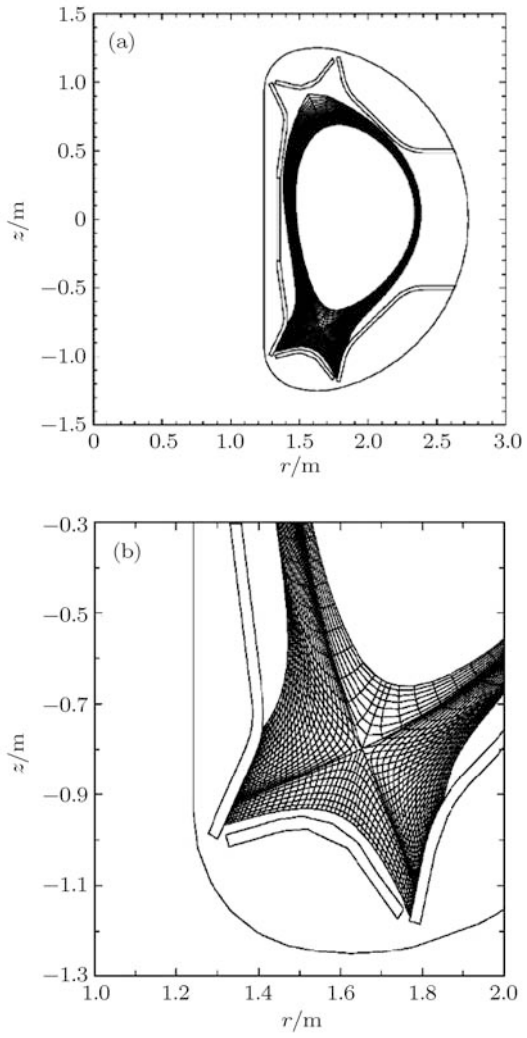


Fig. 2. The EAST geometrical configuration: (a) numerical grids for the analysis and the vacuum and (b) zoom-in view of the divertor region.

3. Simulation result and discussion

3.1. Basic characteristic

In the EAST, an international thermonuclear experimental reactor (ITER) like vertical target configuration is adopted with tightly fitted side baffles and a central dome in the private region to separate physically the inner divertor from the outer divertor and minimize the leakage of neutrals from the divertor region into the core plasma region. As a result, most of the particle flux incident on the target plates is prevented from escaping back into the SOL and reemitting towards the separatrix below the X-point.[7] Since the SOL flow shows different behaviour, such as the flow reversal and the high Mach flow associated with plasma regimes in the edge tokamaks, we first discuss the divertor operation regime before proceeding to the detailed analysis of the SOL flow. We can see from Fig. 3(a) that near the separatrix region from the target plate to the X-point, the electron density is high due to the preferential reflection of the neutrals towards the separatrix by the vertical targets. A comparison between the electron densities in the inner and the outer divertor regions shows that the electron density in the inner divertor region is higher than that in the outer divertor region. Figure 3(b) shows the two-dimensional (2D) spatial profile of the electron temperature (T_e). Along the field lines, the electron temperature decreases towards the target plates. In the inner divertor, the electron temperature decreases rapidly and, near the target plate, $T_e < 4.0$ eV. While in the outer divertor, the electron temperature decreases slowly and, near the target plate, $T_e > 10.0$ eV in most of the region. The divertor detachment regime is characterized by a high density and a temperature below 5.0 eV near the target plate in experiment. As seen from the characteristics of the profiles of density and temperature in our simulation results, we can consider the inner divertor region to be in the detachment regime and the outer divertor region to be in the high recycling regime.

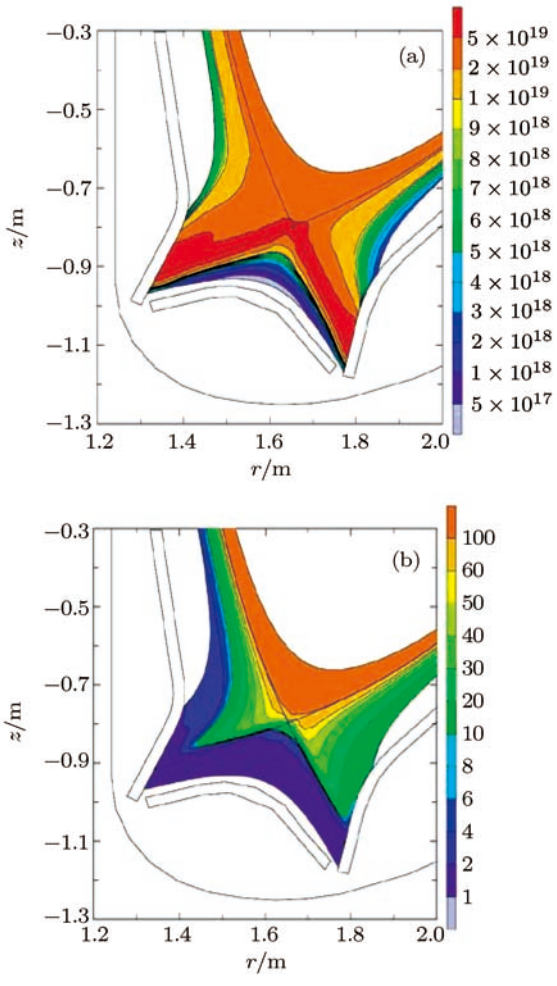


Fig. 3. Two-dimensional spatial profiles of (a) electron density $n_e(m^{-3})$ and (b) electron temperature T_e (eV) in the divertor region.

Figure 4(a) shows the 2D spatial profile of the parallel flow velocity for D^+. The flow velocity is shown as local Mach number M, i.e., the parallel flow velocity is normalized by the local isothermal sound speed defined by $C_s = \sqrt{k(T_i + T_e)/m_i}$, where k is the Boltzmann constant and m_i is the ion mass. The negative sign means that the flow is directed towards the inner target plate, while the positive sign means that it is directed towards the outer target plate. As expected, in our simulation, the high Mach flow in the detachment regime and the flow reversal in the high recycling regime can be observed. From Fig. 4(a), we can see that in the inner divertor region, the plasma is in the detachment state. From the X-point region to the target region, the Mach number increases along the field line and has a maximum, with the maximum value $M \sim 1$ or $M > 1$, i.e., the SOL flow approaches or exceeds the local sound velocity. It decreases along the field line towards the divertor plates after reached its maximum, then increases again and reaches the sound velocity at the target plates. In the outer divertor region, the plasma is in the high recycling state. The Mach number increases monotonically along the field line towards the target plates and reaches the local sound velocity at the target plates. Near the X-point region, the flow reversal (the direction of the flow is away from the outer target plate) has been observed

and the Mach number of the flow reversal is small ($|M| < 0.2$). The region of the flow reversal is narrow and is located near the separatrix. Away from the separatrix, the reversed flow disappears. It is indicated by the direction of the flow that a stagnant flow region exists. The flow shows different behaviour in different regimes due to the effect of the plasma regimes on the driving mechanism of the SOL flow. The profiles of the ionization sources depend on the plasma regime, which is a possible formation condition causing the complex behaviour of the SOL flow.

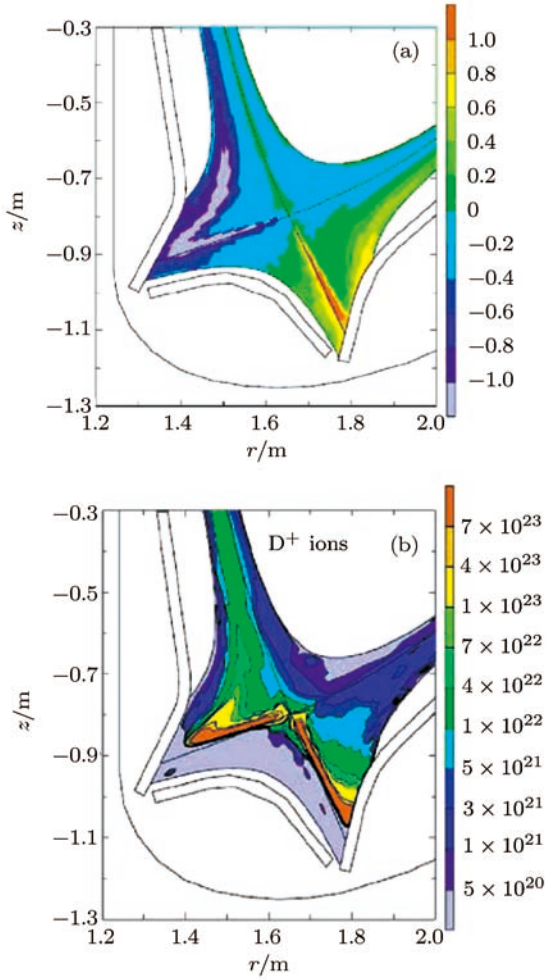


Fig. 4. Two-dimensional spatial profiles of (a) local Mach number and (b) ionization source $S_{\rm i}$ ($\rm m^{-3}{\cdot}s^{-1}$) in the divertor region. In panel (a), the positive direction of the velocity is defined as the direction from the inner plate to the outer plate along the field lines in the plasma edge region.

3.2. Analysis of driving mechanism

The high Mach flow in the detachment regime has been predicted in a simple one-dimensional (1D) analytic mode[4] and in more complete 2D considerations.[12] It is expected to occur near the ionization front, where the plasma static pressure rapidly drops down and the dynamic pressure rises without a large momentum loss. Due to the rapid decrease of the electron temperature in the inner divertor region (Fig. 3(b)), especially in the electron temperature below 10.0 eV region, the rate of the ionization atomic process depending on the electron temperature decreases along the field line, and becomes very small near the target. On the other hand, the density increases along the field line towards the divertor plates. As a result, the profile of the maximum of the ionization source density is away from the target (Fig. 4(b)). The momentum loss region is near the target plate, where both the plasma and the neutral densities are large and the rate coefficient of the charge exchange atomic process does not strongly depend on the electron temperature even in the low electron temperature regime. As such, in the detachment state, the ionization and the momentum loss regions in front of the target plate are almost separated.[4,12] In the ionization region along the field line, the static pressure $P_{\rm static}$ caused mainly by the rapid decrease in temperature drops down, the dynamic pressure $P_{\rm dynamic}$ rises to keep the total pressure $P_{\rm total}$ (static and dynamic pressure) constant. That is to say, away from the target plate in the ionization region, the momentum is conserved

$$P_{\rm static}(nT_{\rm i} + nT_{\rm e}) + P_{\rm dynamic}(m_{\rm i} n V_{\parallel}^2) \sim P_{\rm total}, \quad (1)$$

where n is the plasma density, $T_{\rm i}$ is the ion temperature, $m_{\rm i}$ is the ion mass and $V_{\parallel}$ is the velocity along the field line. Mach number M can be given by

$$M^2 = \frac{V_{\parallel}^2}{(T_{\rm i} + T_{\rm e})/m_{\rm i}} = \frac{P_{\rm dynamic}}{P_{\rm static}} \approx \frac{P_{\rm total} - P_{\rm static}}{P_{\rm tatic}}. \quad (2)$$

From Eq. (2), we can see that without the large momentum loss and with the decreasing static pressure and the increasing dynamic pressure, the pressure redistribution is a possible driving mechanism for the high Mach flow observed in the simulation.

The flow reversal has been predicted analytically in pure deuterium plasma, and the analysis shows that the flow reversal appears associated with large ionization sources.[1,12] To analyse the flow reversal, we consider the continuity equation. By denoting the coordinate along the field line as l and along the coordinate radial direction as r, the continuity equation can be written as

$$\frac{\partial}{\partial l}\Gamma_{\parallel}(l,r) + \frac{\partial}{\partial r}\Gamma_{r}(l,r) = S_n(l,r), \quad (3)$$

where $\Gamma_\parallel$, Γ_r and S_n denote the particle flux in the parallel direction, the particle flux in the radial direction and the particle source, respectively. The flow along the field line can be expressed with the local Mach number, $\Gamma_\parallel(l,r) = MnC_\mathrm{s}$, such that

$$MnC_s = n_\mathrm{d}C_{s,\mathrm{d}} - \int_\mathrm{d}^l S_n(l',r)\mathrm{d}l' - \frac{\partial}{\partial r}\int_\mathrm{d}^l \Gamma_r(l',r)\mathrm{d}l', \quad (4)$$

where subscript d refers to the divertor target, the last term on the right-hand side in the above equation is generally diffusive and so of less importance.[1] Thus $\Gamma_\parallel(l,r)$ changes sign when the net integrated source along a magnetic tube of force exceeds the flux that is being recycled at its target end. From Fig. 4(b), we can find a strong ionization source density near the target plates in the outer divertor region, since the plasma is in the high recycling state. As a result, near the X-point along the separatrix region, the flow reversal is observed in our simulation.

3.3. Influence on impurity transport

The flow pattern is determined by the parallel force balance. Different contributions determine the impurity flow. For the parallel momentum balance of species α ($1 \le \alpha \le N$), self pressure, electric field, electron thermal and frictional forces are included.[13,14] The dominant forces acting on the impurity (carbon) along the field line are the friction force F_fric due to the plasma flow and the electron thermal force $F_\mathrm{i\text{-}therm}$ associated with the longitudinal plasma temperature gradient. The friction and the ion thermal forces of bulk ions on the impurity are estimated from[15]

$$F_\mathrm{fric} = (V_\mathrm{imp} - V_\mathrm{i})\tau_\mathrm{imp}^{-1} \sim 1.6\times10^3 Z^2 n_\mathrm{i} M T_\mathrm{i}^{-1} \quad (5)$$

and

$$F_\mathrm{i\text{-}therm} = \beta\boldsymbol{\nabla}_\parallel T_\mathrm{i} \sim 2.2Z^2\boldsymbol{\nabla}_\parallel T_\mathrm{i}, \quad (6)$$

where τ_imp is the impurity collision time with the background ions, V_imp is the impurity velocity, V_i is the plasma ion velocity, Z is the charge of the impurity ion, n_i is the plasma ion density, β is the ion thermal gradient coefficient. The thermal force drives the impurities into the high temperature region, i.e., away from the plate, since the temperature decreases towards the target plate. The direction of the friction force entraining the impurities is determined by the direction of the plasma flow (local Mach number). Usually, the direction of the friction force is towards the target plate. However, in the high recycling regime, in some place near the separatrix, the direction of the friction is away from the target due to the flow reversal, which is the same as the direction of the ion thermal force. In the detachment regime away from the target, the friction force becomes large and high Mach flow occurs.

The effects of the high Mach flow and the flow reversal on the carbon flux are shown in Fig. 5(b). We can see that the high Mach flow and the flow reversal strongly influence the carbon transport. In the inner divertor region away from the target, where the high Mach flow occurs, the carbon flux becomes very large due to the increased friction. In the outer divertor region near the separatrix, with the flow reversal, the larger carbon flux is away from the target and flows to the SOL, as the direction of the friction force is the same as that of the thermal forces (away from the target).

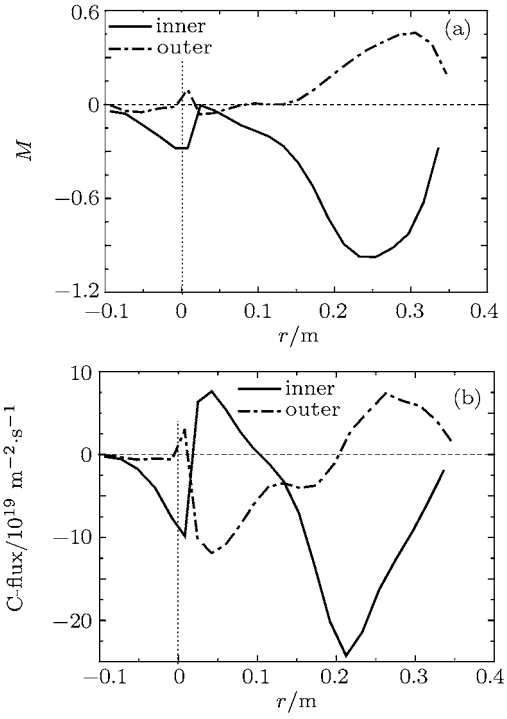


Fig. 5. Profiles of (a) Mach number and (b) corresponding carbon flux along the radial direction near the X-point region.

4. Conclusion

The high Mach flow and the flow reversal in the EAST divertor are studied using the SOLPS 4.0 code

package. With an input power of 4 MW and an edge core density of $n_{\rm D}^{\rm core} = 2.0 \times 10^{19}$ m^{-3}, the divertor plasma is in the detachment state in the inner divertor region and in the high recycling state in the outer divertor region. The simulation result shows that the SOL flow in the divertor region can exhibit complex behaviour, such as the high Mach flow and the flow reversal in different regimes. In the detachment regime away from the target plate, the Mach number of the SOL flow has a maximum, and the velocity approaches or exceeds the sonic speed. In the high recycling regime near the X-point along the separatrix region, the direction of the SOL flow is away from the target, and the velocity of the SOL flow is small ($|M| < 0.2$). To discuss the driving mechanisms and the formation condition of the high Mach flow and the reversed flow, we focus on the profile of the ionization source and make theoretical analysis using the momentum and the continuity equations, respectively. In the detachment regime, as the ionization and the momentum loss regions are almost separated, the temperature decreases rapidly along the field line in the ionization region, while the momentum has no big loss. According to the momentum equation, to maintain the total pressure conservation, the decrease in the static pressure results in the increase in the dynamic pressure. The redistribution from the static pressure to the dynamic pressure is a possible mechanism causing the high Mach flow in our simulation. One of the mechanisms causing the flow reversal is the strong ionization located near the target plate. From the continuity equation, we can deduce that the flow reversal occurs in places where the flux caused by the ionization is larger than that towards the target. In addition, the effect of the SOL flow on the carbon flux is also discussed. It is found that the high Mach flow and the flow reversal have influence on the carbon transport. When the high Mach flow occurs, the carbon flux becomes larger towards the target plate due to the increased friction force towards the target. In the flow reversal region, the direction of the friction force that is the same as that of the electron thermal force is away from the target, which leads to more carbon flux away from the target plate. It must be pointed out that the classical drifts are not included in our simulation and discussion. In some conditions, the classical drifts may influence the SOL flow strongly,[1] the detailed analysis will be carried out in the future study.

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