HL-2M Divertor Geometry Exploration with SOLPS5.0

CUI Xuewu (崔学武), PAN Yudong (潘宇东), CUI Zhengying (崔正英),
LI Jiaxian (李佳鲜), ZHANG Jinhua (张锦华), MAO Rui (毛瑞)
Southwestern Institute of Physics, Chengdu 610041, China

Abstract One of the critical issues to be solved for HL-2M is the power and particle exhaust. Divertor target plate geometry strongly influences the plasma profiles by controlling the neutral recycling pattern, which has in turn a strong effect on the symmetry and stability of the divertor plasma and finally on the whole edge region. The numerical simulation software SOLPS5.0 Package is used to design and explore the divertor target plates for HL-2M. We choose two divertor geometries, and assess the heat flux on the target plates and first wall, then further discuss the divertor plasma parameters, and how private flux baffling affects both neutral recirculation pattern and pumping efficiency.

Keywords: SOLPS5.0, numerical simulation, divertor geometry exploration

PACS: 28.41.Ak
DOI: 10.1088/1009-0630/15/12/04

1 Introduction

In a tokamak, the divertor is one of the key parts and its design is one of the most difficult tasks. To assess divertor design, a detailed analysis and modeling of the edge plasma is necessary. The numerical simulation software SOLPS5.0 [1,2] Package is a 2-D multi-fluid edge plasma code B2.5 combined with a Monte-Carlo neutral code EIRENE. It has become an important tool for edge plasma modeling and divertor design. For example, it has been used to model the edge plasma and design the divertor for ITER [3~5], AUG [6], EAST [7,8] and HL-2A [9,10].

The purpose of this work is to present an explorative strategy for the divertor of HL-2M through comparisons of performances between two divertor geometries, such as the heat flux at the target plates and first wall, the divertor plasma parameters and the pumping efficiency. Section 2 presents the simulation model and the divertor geometries. Simulation results are listed in section 3, and finally a summary is given in section 4.

2 Simulation model and divertor geometry

SOLPS5.0 [11] package code, which is a basic tool for most ITER calculations, consists of a 2-D multi-fluid edge plasma code B2.5 [11,12] for electrons and ions in various ionization states, combined with a Monte-Carlo code EIRENE [13,14] for neutrals.

In the first study, only D0, D+1 and electron E~ are included in the multi-fluid species of SOLPS5.0. All classical drifts, electric currents, and electric field can be handled by SOLPS5.0, but, in the present modeling drifts terms are switched off for the first step while electric currents and electric field are included in all cases. The magnetohydro-dynamic (MHD) equilibrium is generated by equilibrium code EFIT and TSC. The main plasma parameters are listed in Table 1. It is the basis of the numerical grid generation for the SOLPS5.0 code package. The computational region is different from the SOL. The SOL is commonly defined as the region of open field lines surrounding the region of confined plasma on closed field lines, but the computational region expands from a small segment of the region of closed field lines outwards across the separatrix well into the entire SOL and private flux regions (PFRs). The boundary conditions at the boundaries of the computational region include the boundary conditions at the core boundary, the wall, the inner and outer boundaries of PFRs and the divertor target plates. The particle recycling coefficient of ions to the neutrals is set to 1.0 at the material boundaries of the computational region. The computational region includes a small segment of the region of closed field lines, which means the computational region covers the ‘outer core’ region (the region of the core plasma adjacent to the separatrix). The boundary conditions for the present SOLPS5.0 modeling include:

| Table 1. Main plasma parameters of the HL-2M tokamak |
|-----------------|------------------|
| Plasma parameters | Value |
| Major radius $R$ (m) | 1.78 |
| Minor radius $a$ (m) | 0.65 |
| Elongation $\kappa$ | 1.875 |
| Triangularity $\delta$ | 0.45 |
| TF on axis $B_T$ (T) | 2.2 |
| Power flow into SOL $P_{\text{sep}}$ (MW) | 10 |
| Core plasma density $n$ (m$^{-3}$) | $(6\sim7) \times 10^{19}$ |
| Plasma current $I_p$ (MA) | 2 |

*supported by the National Magnetic Confinement Fusion Science Program of China (No. 2009GB104008) and National Natural Science Foundation of China (Nos. 10975048, 11175061)
a. At the core boundary which is closed at the normalized minor radius \( r/a = 0.95 \) in this work, the density of the deuterium ion \( \text{D}^+ \) is set as the edge density \( N_{\text{edge}} \).

The neutral deuterium \( \text{D}^0 \) density \( n_0 \) at the boundary is very low due to higher plasma temperature and stronger ionization at the boundary, the particle flux of neutral deuterium \( \text{D}^0 \) is set to zero. The edge density \( N_{\text{edge}} \) and the total edge power \( P \) on the machine are set as input parameters for the modeling. We fixed the total edge power as 10 MW, which flows into the SOL from the core according to the requirement during the first period of the plasma operation, equally distributed into the electron and ion channels. The normal current components are set to zero.

b. At the wall and the dome-side boundaries of PFRs, the same conditions on the normal current components are imposed as for the core boundary. The radial decay length for the electron density is set to 0.01 m. The neutrals are treated by the EIRENE code and the pumping rate of neutrals at the wall is set in the input data. In this study we set the rate as 100 m\(^3\)/s. The corresponding RECYCT values in the input data of EIRENE are set to 0.98.

c. At the target plates of the divertor, the neutrals are produced locally at a rate equal to that of the outlet of the charged species. The sheath boundary conditions are applied to the boundaries. The standard boundary condition is to require that the flow must be at least sonic at the sheath entrance, i.e.

\[
V_\parallel \geq c_s - \frac{b_z}{b_x} V_\perp,
\]

where \( V_\parallel \) is the parallel speed and \( V_\perp \) is the perpendicular speed. Magnetic fields are given by \( B_x \) and \( B_z \) in the poloidal \( x \) direction and in the toroidal \( z \) direction. Their unit components are \( b_x = B_x/B \) and \( b_z = B_z/B \) with \( B^2 = B_x^2 + B_z^2 \).

The electron and ion heat fluxes\(^{[15]}\) to the target plates are, respectively,

\[
q_{ex} = b_x \frac{1}{\sqrt{2\pi}} \frac{T_e}{m_e} \exp\left(-\frac{e\Phi}{T_e}\right)\left(1 - \gamma_e\right)\left(T_e \frac{1 + \gamma_i}{1 - \gamma_e} + e\Phi\right),
\]

\[
q_{ix} = \frac{5}{2} n T_e c_b b_x.
\]

The atomic processes, i.e., ionization, recombination and charge exchange, are taken into account by using atomic physics data. Due to the uncertainties associated with the cross-field anomalous transport, values of the particle diffusion coefficient \( D \), and the electron heat diffusivity \( \chi_e \) and ion heat diffusivity \( \chi_i \), some assumptions on \( D \), \( \chi_e \) and \( \chi_i \) are usually made according to reasonable judgement. In ITER divertor modeling, the cross-field transport coefficients are assumed to be constant with \( \chi_e = \chi_i = 1.0 \text{ m}^2/\text{s} \), \( D = 0.3 \text{ m}^2/\text{s} \)\(^{[16]}\). For the present modeling, a similar assumption has been made, and the radial particle and heat transport coefficients \( D \), \( \chi_e \) and \( \chi_i \) are set to \( D = 0.4 \text{ m}^2/\text{s} \) and \( \chi_e = \chi_i = 1.0 \text{ m}^2/\text{s} \).

At the first step, the simple flat plates which we called Divertor-I are used in HL-2M. The angle between the inner target plates and the separatrix surface is fixed as 60 degrees, and the angle between the outer target plates and the separatrix surface is also fixed as 60 degrees. Then, the optimized divertor structure, called Divertor-II, is formed with curved plates instead of flat plates and the angles both are 30 degrees, as shown in Fig. 1.

Fig. 1 The schematic of numerical grids, pump duct and target plate configuration (color online)

3 Simulation results

3.1 Heat flux comparison

The heat flux on the target plates is an important characteristic for assessing the divertor target plates' design. Figs. 2 and 3 depict the radial profiles comparison of the heat flux on outer and inner targets for the cases with outer mid-plane separatrix density of \( N_{\text{sep}} = 1.7 \times 10^{19} \text{ m}^{-3} \) and \( N_{\text{sep}} = 2.8 \times 10^{19} \text{ m}^{-3} \), respectively. When the outer mid-plane separatrix density is \( N_{\text{sep}} = 1.7 \times 10^{19} \text{ m}^{-3} \), Fig. 2 shows that the heat flux profiles on the target of Divertor-I are much higher and pointier than Divertor-II’s. The peak heat flux on the outer target of Divertor-I is up to 7.6 MW/m\(^2\), and on the inner target is up to 6.6 MW/m\(^2\); both values exceed the allowable level of the heat load on the target (less than 5 MW/m\(^2\)). However, the peak heat flux on the outer target of Divertor-II is only 3.2 MW/m\(^2\), and on the inner target is also 1.3 MW/m\(^2\) only; these
are less than the allowable level 5 MW/m$^2$. Additionally, when the outer mid-plane separatrix density is $N_{sep}=2.8\times10^{19} \text{ m}^{-3}$, the heat flux on the outer target of Divertor-I not only doesn’t decrease with an increase in the separatrix density, but it increases with the density. From Fig. 3, the heat flux on the outer target of Divertor-I is up to 8.8 MW/m$^2$. Nevertheless, the heat flux on the outer target of Divertor-II decreases from 3.2 MW/m$^2$ to 2.4 MW/m$^2$, and the heat flux on the inner target decreases to less than 1 MW/m$^2$.

Simultaneously, from the two figures we can get that the peaks of heat flux on two divertor target plates of Divertor-I are all located near the separatrix (the horizontal ordinate equal to zero). But the profiles of heat flux for Divertor-II are broadened. The peak of the radial profile of heat flux on the inner target of Divertor-II is far from the separatrix, the distance to the separatrix is 10 cm. It is partly due to the increase of the wetted area that why the peak heat flux is reduced and the profiles are broadened.

Fig. 4 shows the comparison of poloidal profiles of heat flux on the first wall for $N_{sep}=1.7\times10^{19} \text{ m}^{-3}$ (color online).

3.2 Plasma parameters comparison

Divertor plasma parameters are also important values. Fig. 5 gives the radial profiles across the SOL at the two outer divertor targets for $N_{sep}=2.8\times10^{19} \text{ m}^{-3}$. It is shown that the electron temperature peak of Divertor-I is located near the separatrix, but the peak of Divertor-II is far from the separatrix (located in the SOL region). This is closely related to the electron density near the divertor target plates. From Fig. 5 we can see that the electron density of Divertor-I has two peaks, the trough between the two peaks is located at the separatrix, and the two peaks are located at the SOL and PFR (private flux region), so the electron temperature peak of Divertor-I is located at the separatrix. However, the electron density peak of Divertor-II is located at the separatrix and PFR. This difference is clearly shown in the distribution of electron density.
CUI Xuewu et al.: HL-2M Divertor Geometry Exploration with SOLPS5.0

Densities near the outer and inner target of Divertor-II are located at the separatrix strike point and PFR, as shown in Figs. 8 and 9. This distinguished feature has obvious advantages for pumping.

3.3 Pumping flux comparison

By changing the private flux baffling, the neutral recirculation pattern — especially the neutral penetration to the X-point — is strongly affected and is even able to suppress flow reversal zones in the hydrogenic flow pattern. These occur usually for high recycling conditions due to strong local ionization sources, resulting in incompatible divertor versus mid-plane profiles and forcing backflow. This suppression of flow reversal may also lead to better impurity entrainment. Different private flux baffle configurations show little change in detachment properties, but much higher neutral divertor fluxes, and therefore, better pumping in the case of optimized fluxes. To obtain high pumping efficiency, the effect of the gaps between the private dome wing and the divertor targets, which are labeled $d_{in}$ and $d_{out}$ in Fig. 1(a), is investigated.

For the case of $d_{in} = d_{out}$, we found that there is a proper gap width in the divertor configuration for which the pumping flux is better. This can be easily understood, because by closing most of the private flux region with baffles the very effective plasma pumping is strongly reduced. The distance from the baffle to the target plate has to be long enough so that the deuterium neutrals are still able to escape into the private flux area. The detachment properties are not changed, because they are more determined by quasi-1D balances along the field-lines close to the plate, which are not affected strongly by these private flux baffles. For the realization of the final geometry, the proper width gap, which is 2.9 cm as shown in the figure, is adopted.

In order to characterize the particle controllability using divertor pumping in these two geometries, the final step is to choose the better divertor configuration, which has the more effective plasma pumping. Fig. 10 shows the deuterium atomic pumping flux versus separatrix density for the two divertor configurations for the private flux baffle gaps of 2.9 cm. The deuterium atomic pumping flux increases with the increase of separatrix density. The deuterium atomic pumping flux profile of Divertor-II increases more rapidly than that of Divertor-I. The deuterium atomic pumping flux of Divertor-II is about two times larger than Divertor-I’s. This is clearly shown in the electron contour map in the previous section, the target plate of Divertor-II is
curved, resulting in the recycling neutrals being reflected down to the separatrix and the private flux region. In this region, due to the strong ionization sources from recycling neutrals and recombination, the high plasma and neutrals density lead to high neutral pressure, which helps to improve the pumping flux.

For the analysis of the pumping flux, Divertor-II is better. Its pumping efficiency is very high, and this helps to improve the particle controllability.

4 Summary

One of the most challenging issues in the design of HL-2M is a divertor concept that provides simultaneously tolerable heat loads on the target plates and sufficient particle exhaust. In an explorative process, the first step is the target plate geometry, which strongly influences the plasma profiles by controlling the neutral recycling pattern, which has in turn a strong influence on the stability of the divertor plasma and finally on the whole edge region. The lowest heat flux on the target plates is found for Divertor-II, because it reflects the neutrals towards the high energy zone at the separatrix, and is strongly tilted which increases the wetted areas. The heat flux on the first wall is also lower for Divertor-II. Therefore, concerning operational safety, it offers the best configuration to start with.

The private flux baffling affects strongly the penetration of neutrals to the X-point and can suppress flow reversal zones in the hydrogenic flow pattern. Experimentally even more important is the much better pumping found in respect of baffle length. From the simulated results, the proper width of the gaps from the domes to the target plates is 2.9 cm. With the proper width of the gaps, a final comparison is made for the particle pumping flux efficiency. This characteristic is useful for the improvement of particle controllability. Due to the special target structure (its divertor target is curved, which reflects the recycling neutrals towards the separatrix and private flux region), Divertor-II has the higher efficiency for exhausting the impurity and improving the particle controllability.

References


(Manuscript received 16 October 2012)
(Manuscript accepted 28 April 2013)
E-mail address of CUI Xuewu: cuixw@swip.ac.cn