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Two-dimensional modelling for HT-7U tokamak divertor

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Abstract

The different recycling operations in the HT-7U divertor plasma are studied in the present B2.5 modelling. The modelling results show that in the HT-7U high density operation regime, with a boundary density at the core–SOL interface of $N_{\mathrm{edge}} \geqslant 2 \times 10^{19}$ m^{-3}, high recycling operation in the divertor plasma can be obtained and plasma with high density and low temperature can be formed in front of the target plate and the plasma heat flux arriving at the target plate is greatly reduced because of the ionization loss in the high recycling processes. For the HT-7U low density operation regime, with $N_{\mathrm{edge}} < 2 \times 10^{19}$ m^{-3}, the high recycling operation cannot be formed and the plasma with low density and higher temperature is formed in front of the target plate, and the plasma heat flux towards the target plate become larger than in the high recycling operation.

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Keywords: HT-7U tokamak; Divertor plasma; Modelling

1. Introduction

SOL and divertor plasma may have different operational regimes which can impact on the properties of the edge plasma in a tokamak, one of the most important operation regimes is the recycling of particles near the target plate of a divertor. The choice of reasonable recycling operations has become an important issue for divertor research and design in a fusion experimental device or a fusion reactor. Usually, the recycling can be divided into two types, high recycling and low recycling. These produce different behavior of ions and neutrals in the divertor plasma, as determined by the plasma temperature, density and the plasma heat flux towards the target plate. In general, in a fusion experimental device with low heating power, a high recycling operation can be chosen in the divertor plasma in order to reduce the heat flux towards the target plate and simplify the engineering design of the divertor. The high recycling near the target plate can consume a large fraction of the incoming power by atomic and molecular processes in the neutral recycling, for example, by ionization, radiation and charge-exchange processes, which causes the temperature of the plasma near the target plate and the heat flux towards the target plate to be reduced, at the same time, good impurity control can be realized in a high recycling divertor. It can be estimated that the conventional high recycling divertor approach should work well for the present generation tokamaks and the heat load keeps well below 5 MW/m^2 with good impurity control [1]. By injecting the radiative impurity or cold gas, the high recycling plasma can be transformed into strongly radiative SOL plasma with a semi-detached or fully detached plasma and the specified lower level of power arriving at the target plate of the divertor can be approached. The high recycling divertor forms a basis on which the radiative divertor and the dynamic gas target divertor can be formed. So, the research for a high recycling plasma has become an important step for further comprehensive research of the divertor plasma. In this paper, the high recycling and low recycling divertor plasma in the HT-7U tokamak are studied by using two-dimensional modelling.

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2. Modelling results

The B2.5 code [2] is used for the present modelling. The parameters of the HT-7U tokamak for the modelling mainly include, major radius $R = 1.94$ m, minor radius $a = 0.518$ m, elongation $\kappa = 1.614$, triangularity $\delta = 0.737$, toroidal field $B = 3.5$ T, heating power $P_{\text{in}} = 8$ MW. The heating power P_{in} is controlled by the edge density and edge temperature which are set as boundary conditions at the core–SOL interface in the modelling and P_{in} will not be directly set as input data in the modelling. Multi-fluid plasma in the present B2.5 modelling includes hydrogen atoms H^0, hydrogen ions H^{+1} and electrons e^- for HT-7U hydrogen discharge. Simple anomalous cross-field transport is characterized by a particle diffusivity of $D = 0.5$ m^2/s and heat diffusivities $\chi_e = 1.0$ m^2/s, $\chi_i = 1.0$ m^2/s. The computational region for the modelling is based on a double-null [3], the computation mesh is divided into 64 × 32 units. Fig. 1 shows the 64 × 32 units of mesh in the computational region, the extra thin meshes which are located at the boundaries of the computational region for exerting the boundary conditions are not shown in Fig. 1. The x- and y-direction in the two-dimensional modelling represent the direction along flux surfaces and the direction across the flux surfaces respectively. Some boundary conditions are used [3]. On the core–SOL interface which is located between the core region and the computational region, the two temperatures, electron temperature and ion temperature, are prescribed at a common value T_{edge} which is set as temperature boundary condition and the two densities, neutral hydrogen H^0 density and hydrogen ion H^{+1} density, are prescribed with each being fixed at a given value, the neutral hydrogen density is set as 0 and hydrogen ion density N_{edge} is set as the density boundary condition. The midplane is assumed as a symmetry boundary. On the outer wall, the inner boundary of the private flux region and the target plate of the divertor, the particle recycling coefficient and the energy recycling coefficient are set as 1.0 and 0.3 respectively and no pumping is set on these boundaries for the present modelling. The power entering the computational region Q can be obtained from the modelling results for specified boundary conditions and the heating power P_{in} on the device can be deduced from the relations between Q and P_{in} [3].

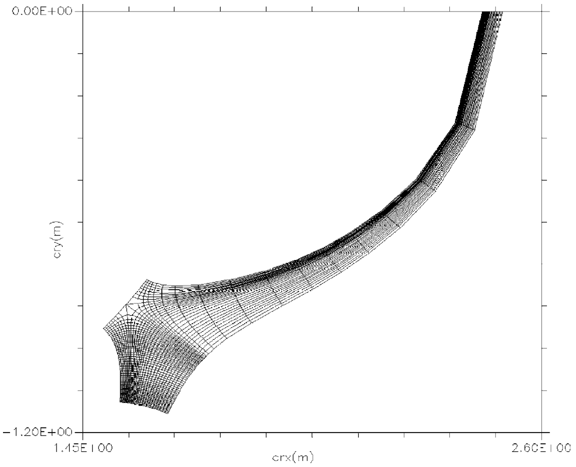

Fig. 1. Computation mesh in the computational region of the HT-7U SOL.

The modelling results show, for the boundary density at the core–SOL interface $N_{\text{edge}} \geqslant 2 \times 10^{19}$ m^{-3}, a high recycling operation can be obtained in the HT-7U divertor plasma. Figs. 2–4 show respectively the distributions of electron density, electron temperature and electron heat flux towards the x-direction for a core–SOL boundary density $N_{\text{edge}} = 2 \times 10^{19}$ m^{-3} and a core–SOL boundary temperature $T_{\text{edge}} = 300$ eV. Two coordinates, the x- and y-coordinate, in Figs. 2–4 and in the following Figs. 5–7, represent the cell number along the x- and y-directions, i.e. ix, iy, respectively which include the extra boundary cells. The X-point is located at the cell i$x = 16$, i$y = 8$ and separatrix is located at the cells i$y = 8$.

From Figs. 2 and 3 it can be found that a plasma with high density and low temperature near the target plate can be formed, the peak value of electron density at the target plate $N_{\text{emax}} = 3.38 \times 10^{19}$ m^{-3} which is also the maximum value of the electron density in the computational region, and the peak value of electron temperature $T_{\text{emax}} = 6.26$ eV exists at the target plate. The great gradient along the x-direction of the electron density and temperature near the target plate can be found in the figures. The present modelling results also show the high plasma density can cause high hydrogen atom density near the target plate in the high recycling, therefore, the high recycling can enhance the gas exhaust through the divertor channel. In fact, there are some impurities in the computational region which are produced because of the interaction between the plasma and the target plate and the impurities are not taken into account in the present modelling. It can be estimated that the impurities have difficulty entering into the core plasma through the high density plasma near the target plate, the plasma with low temperature near the target plate can reduce the sputtering yield of the target plate material and the damage of the material, so, the impurities produced by the sputtering also can be reduced.

Fig. 4 shows the distribution of the electron heat flux towards the x-direction in the computational region. Although the modelling results show the electron particle flux at the target plate reach its maximum, it can be seen from Fig. 4 that the electron heat flux at the target plate does not reach its maximum, the peak value of electron heat flux at the target plate is 3.92 MW/m^2, less

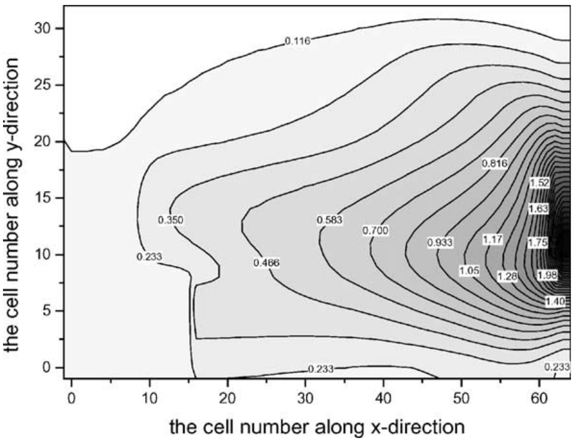

Fig. 2. Distribution of electron density in the computational region for high recycling operation regime (10^{20} m^{-3}).

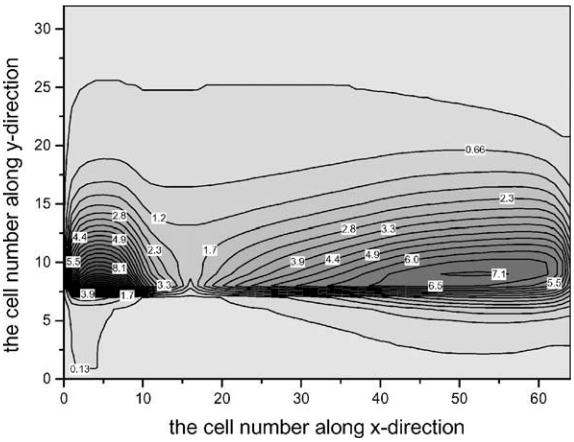

Fig. 4. Distribution of electron heat flux in the computational region for high recycling operation regime (MW/m^2).

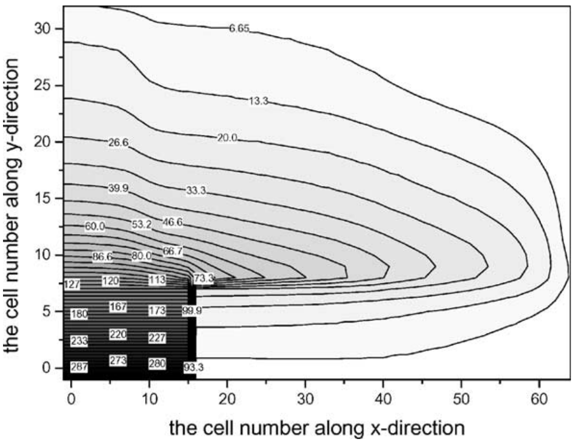

Fig. 3. Distribution of electron temperature in the computational region for high recycling operation regime (eV).

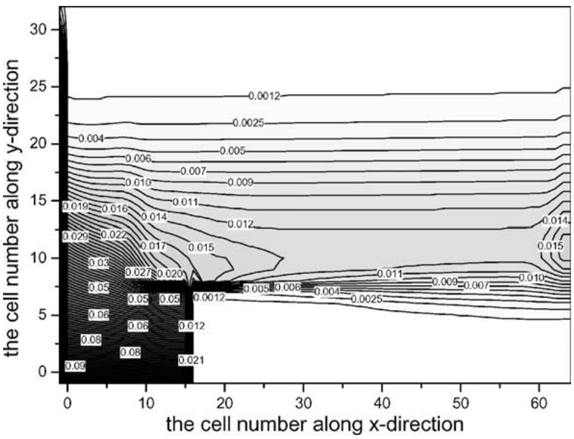

Fig. 5. Distribution of electron density in the computational region for low recycling operation regime (10^{20} m^{-3}).

than the maximum of electron heat flux in the whole computational region 12.8 MW/m^2 which appears at the separatrix near the midplane. Although simple magnetic flux expansion can produce some influence on the distribution of the electron heat flux along x-direction, the ionization and other energy loss in high recycling processes near the target plate play an important role for the distribution of the electron heat flux. The modelling results show the total electron heat flux along the x-direction is $P_e = 1.15$ MW and only $P_e = 0.605$ MW of that arrives at the target plate, so, some energy is lost by ionization and other radiation loss before arriving at the target plate, the total radiation loss in the computational region P_{rad} is about 0.545 MW. The total heat flux entering the computational region $Q = 1.684$ MW can be gotten from the present modelling results and the heating power on the device $P_{in} \approx 8$ MW can be deduced from the relation between Q and P_{in} [3].

The modelling results also show, for the boundary density at the core–SOL interface $N_{edge} < 2 \times 10^{19}$ m^{-3}, a high recycling operation cannot be obtained in the HT-7U divertor, only the low recycling happens and the plasma with low density and higher temperature forms in front of the target plate. Figs. 5–7 show the distributions of electron density, electron temperature and electron heat flux towards the x-direction in the computational region respectively for a boundary density $N_{edge} = 1 \times 10^{19}$ m^{-3} and a boundary temperature $T_{edge} = 400$ eV, from the modelling results of the total heat flux entering the computational region Q, the heating power P_{in} on the device can be deduced to be $P_{in} = 5.5$ MW according to the relations between Q and P_{in}. It

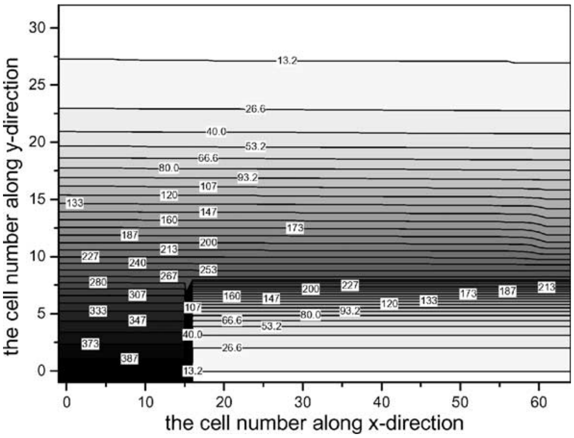

Fig. 6. Distribution of electron temperature in the computational region for low recycling operation regime (eV).

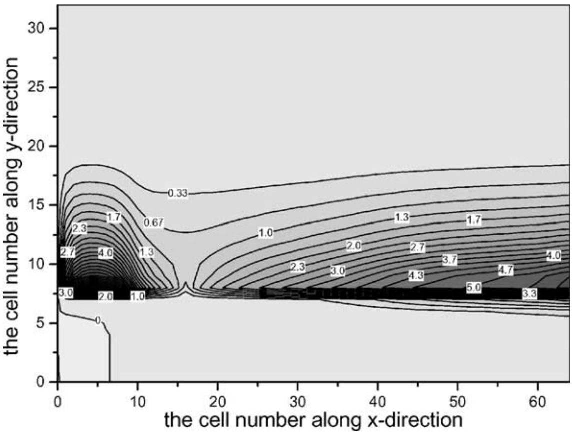

Fig. 7. Distribution of electron heat flux in the computational region for low recycling operation regime (MW/m^2).

is clear that for a heating power $P_{\rm in} = 8$ MW and boundary density $N_{\rm edge} = 1 \times 10^{19}$ m^{-3}, the boundary temperature at the core–SOL interface must be $T_{\rm edge} > 400$ eV which may be unacceptable for actual HT-7U operation, so, the modelling results for heating power $P_{\rm in} = 8$ MW at a boundary density $N_{\rm edge} = 1 \times 10^{19}$ m^{-3} shall not be included in the present modelling. From Fig. 5, it can be found that the maximum value of the electron density 1×10^{19} m^{-3} exists at the core–SOL interface which is set as a boundary condition for the modelling, the density is reduced gradually along the separatrix and increased gradually again towards the target plate, the maximum value of the electron density at the target plate is $N_{\rm emax} = 1.695 \times 10^{18}$ m^{-3}, only 16.95% of the boundary density. The gradient of the density along the separatrix and the density at the target plate keep a very low value, which illustrates the low recycling in the divertor plasma. The low plasma density causes low hydrogen atom density near the target plate in the low recycling, which will be unfavourable to prevent the impurities from entering into the core plasma and to pump the gas through the divertor channel.

Fig. 6 shows that electron temperature is reduced along the direction across the flux surfaces (y-direction) and at the flux surfaces outside the separatrix, the electron temperature has nearly the same value at the same flux surface, the electron temperature near the separatrix striking point reaches 272 eV which is close to the value of 400 eV at the core–SOL boundary. So, the electron temperature near the separatrix striking points is more than 272 eV for heating power $P_{\rm in} > 5.5$ MW. Due to higher plasma temperature at the target plate, the sputtering yield of the target plate material will be increased, causing the target plate material to be seriously damaged. Both the density and the temperature are lower at the plate than at the midplane in a low recycling solutions state, which implies the pressure drop in the plasma will be greater than 1.

It can be found that for low recycling operation, a strong electron heat flux from plasma near the X-point can directly arrive at the target plate without reduction, as showed in Fig. 7, the peak value of electron heat flux at the target plate is 5.8 MW/m^2 and the peak value of electron heat flux in the computational region is 8.9 MW/m^2 which appears at the separatrix near the midplane.

3. Conclusions

The modelling results obtained in the present B2.5 modelling show that the HT-7U divertor plasma can form different recycling operations for different density operation regions and recycling operations can be controlled by controlling the boundary plasma density $N_{\rm edge}$ at the core–SOL interface. In the HT-7U high density operation region, $N_{\rm edge} \geqslant 2 \times 10^{19}$ m^{-3}, high recycling operation in the divertor plasma can be obtained and plasma with high density and low temperature can be formed near the target plate, a lot of energy is lost because of frequent ionization events with high recycling. The plasma temperature at the target plate and the plasma heat flux arriving at the target plate are greatly reduced, which is very favourable to reduce the damage of the target plate material and to simplify the design of the HT-7U tokamak divertor. A very high density plasma with very high density hydrogen atoms exists near the target plate in high recycling operation, so, the impurities produced near the target plate have difficulty to entering the core plasma and the pumping of gases through the divertor channel becomes very easy.

In the HT-7U low density operation region, $N_{\mathrm{edge}} < 2 \times 10^{19}\ \mathrm{m}^{-3}$, high recycling operation cannot be formed and plasma with low density and higher temperature is formed near the target plate. The electron heat flux coming from the X-point directly strikes the target plate without reduction and the plasma temperature at the target plate approaches the boundary plasma temperature at the core–SOL interface, which causes the plasma temperature and the heat flux at the target plate to be much higher than that with the high recycling operation for the same heating power. So, high recycling operation plays an important role in the HT-7U divertor design.

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