DISTRIBUTION OF PLASMA PARAMETERS IN THE STELLARATOR AT NEOCLASSICAL TRANSPORT UNDER CONDITIONS OF RECYCLING

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The spatial distributions of plasma parameters in the stellarators LHD and U-2M, operating under recycling conditions with the assumption of neoclassical transport realization, are calculated using the one-dimensional space-time numerical code. The stable solutions of the system of equations for the spatial distributions of ion and electron temperatures, plasma and neutral neutron density and ambipolar electric field are obtained. The flat spots formation in the radial profiles of plasma parameters near the plasma boundary is shown.

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INTRODUCTION

In the most of modern experimental stellarator-type devices the stationary plasma parameters are maintained by the return into the plasma of particles releasing from the confinement volume as a result of diffusion or other loss mechanisms. This process is named as “recycling”. A recycling effect on the increased plasma losses was first observed in the investigations using the stellarator “C” [1]. A cold gas, penetrating into the plasma, undergoes the ionization in the plasma column region, and exerts influence on the formation of the plasma density and temperature profiles. As a result, their gradients are increased that leads to the plasma loss increasing.

The recycling influence on the plasma parameters was investigated in the LHD stellarator. The investigation results have shown the formation of flat spots on the density and temperature profiles near the plasma boundary [2]. Calculations on the parameters of a reactor-stellarator, where the plasma density constancy is maintained due to the fuel pellet injection, have shown that the injection of fuel into the plasma periphery region significantly decreases the reactor power level because of plasma loss increasing [3].

In the present paper the spatial distributions of plasma parameters in the stellarators LHD and U-2M, operating under recycling conditions with the assumption of neoclassical transport realization, are calculated using the one-dimensional space-time numerical code. As distinct from [2] here we have used the numerical solution of the system of transport equations with taking into account ambipolar plasma fluxes. By this method, in addition to the plasma density and temperature distributions, we have obtained the profiles of the radial electric field, density of neutral atoms outside the plasma and their distributions in the plasma column volume.

1. PHYSICAL MODEL AND THE SYSTEM OF EQUATIONS

In the thermonuclear facility the process of plasma-neutral interaction can occur by the following reactions:

$$H_2 + e \rightarrow 2H + e; \qquad (1)$$

$$H_2 + e \rightarrow H^+ + H + 2e; \qquad (2)$$

$$H + H^+ \rightarrow H^+ + H; \qquad (3)$$

$$H + e \rightarrow H^+ + 2e; \qquad (4)$$

$$H^+ + 2e \rightarrow H + e. \qquad (5)$$

Expression (1) refers to the hydrogen molecule dissociation, (2) represents the dissociation with simultaneous atomic ionization. The last three expressions determine the charge exchange of atoms, atomic ionization and recombination. The rates of reactions are given in ref. [4]. In the active phase of the plasma discharge the hydrogen ions, escaping from the confinement volume, are recombining during interaction with the vacuum chamber walls and return into the plasma for the most part in the form of neutral atoms which are ionized due to the interaction with electrons according to the expression [4]:

$$<\sigma\upsilon>_\mathrm{i}=3.0526\cdot10^{-7}(\mathit{ln}T_\mathrm{e}-2.9017)T_\mathrm{e}^{-1/2}\ [\mathrm{cm^3s^{-1}, eV}]. \qquad (6)$$

From the point of view of the plasma density maintaining by recycling, in the present study we consider this process as a main one. The molecule ionization with subsequent dissociation and other processes denoted by expression (3)-(5) are neglected because their contribution to the density increase is insignificant.

The calculation model is based on the system of equations, given in [5, 6] for description of the space-time behavior of the plasma in the reactor-stellarator, which is supplemented by the equation for neutral atoms. In these equations the terms relating to the synthesis are omitted and instead of the pellet injection model we use, as a plasma source, the source taking into account the charged particle influx due to the neutral atom ionization. At last, the system of equation takes a following form

$$\frac{3}{2}n\frac{\partial T_e}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}r\Pi_e + Q_{he} - Q_{ei} - Q_b - Q_c + Q_E - \mathrm{Q}_{\delta\mathrm{e}}; \qquad (7)$$

$$\frac{3}{2}n\frac{\partial T_i}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}r\Pi_i + Q_{ei} + \mathrm{Q}_{hi} - Q_E - \mathrm{Q}_{\delta\mathrm{i}}; \qquad (8)$$

$$\frac{\partial n}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}rS_\mathrm{e} + \mathrm{S}_\delta; \qquad (9)$$

$$\frac{\partial n_\mathrm{a}}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}rS_a - S_\delta. \qquad (10)$$

The first two equations describe temperature behavior of the electron Eq. (7) and the ion Eq. (8) in the space and time. The next two are a plasma particle and neutral diffusion equations. The first terms on the right side of

Equations (7), (8) for the electron and ion heat conductions determine the temperature variation caused by the heat flux corresponding to the neoclassical theory Kovrizhnykh [7]. The rest terms on the right sides of Eqs. (7), (8) Q_{hi} and Q_{he} are, respectively, the heating of ions and electrons emitted by the external sources; Q_{ei} – electron-ion heat exchange as a result of Coulomb collisions; Q_b – bremsstrahlung; Q_c – cyclotron radiation; Q_E – energy change of particles in the ambipolar electric field during their radial motion; $Q_{\delta e}$ and $Q_{\delta i}$ are thermal expenses for heating the ions and electrons that erased in result of ionization. The charged particle flow S_i and S_e also correspond to [7]. The neutral atom flux is $S_a = n_a\, \upsilon_{T0}/\pi$, where υ_{T0} is the their thermal velocity. And the charged particle source is determined by the expression: $S_\delta = n_a\, n <\sigma\upsilon>_\mathrm{i}$.

The ambipolar electric field value was calculated from the flux equality $S_e = S_i$ at each time-space array pitch. The system of equations (7)-(10) was supplemented by the initial and boundary conditions. The total number of charged and neutral particles in the plasma and in the chamber volume was maintained to be constant. In all calculations the neutral atom velocity is taken corresponds to the temperature of 1 eV.

The different models of plasma heating by the external sources were used: the electron heating only, the ion heating only or simultaneous heating of two components. It has been supposed that the specific heating power is proportional to the plasma density: $Q_\mathrm{h} = k_\mathrm{h} n$.

2. CALCULATION RESULTS

Calculations were performed by the example of two devices LHD and U-2M, the parameters of which are given in papers [8, 9]. For U-2M it has been assumed that the plasma radius is 17cm, the chamber radius is 34 cm, and in the case of LHD the radii are 60 and 80 cm respectively. The confinement field values are 2.5 T for LHD and 1 T for U-2M.

The dependences of helical field amplitude modulations ε_h on the plasma radius, taken for the flux definition, were characteristic for the devices under consideration. In particular, a maximum value of ε_h is 0.6 for LHD and 0.25 for U-2M.

Calculations were carried out assuming different plasma density values (conventionally with high and low densities) and different plasma heating values. For the initial plasma density and temperature distributions we have used the expression such as $N=N_0(1-x^j)$, where j is an integral number. Most of calculations have been performed under the assumptions that the initial distribution of neutral atom concentration is uniform throughout the vacuum chamber volume, the "burning" of which in the plasma occurs during the evolution of plasma parameters. The value of the neutral density outside the plasma was defined as a result of the balance between the opposite streams of plasma and atoms at the plasma column boundary.

2.1. LHD RESULTS

Fig. 1 shows the time dependences of average electron and ion temperature values in LHD in the course of electron heating using the 2 MW source. The initial values of the plasma density and neutral atom density were equal to $n_0=5\cdot10^{19}\,\mathrm{m}^{-3}$ and $n_{h0}=5\cdot10^{18}\,\mathrm{m}^{-3}$ respectively. In the process of transition to the stationary mode the neutral atom combusting up to $8\cdot10^{14}\,\mathrm{m}^{-3}$ in the volume outside the plasma boundary occur. The average plasma density value is increased to $5.85\cdot10^{19}\,\mathrm{m}^{-3}$ and the constant level is reached during 0.4 s after the process start.

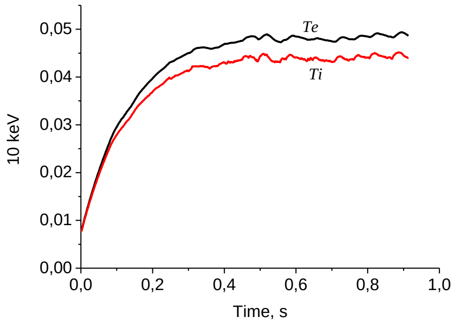

Fig. 1. LHD, Temperatures time dependences, P_{he} *=2 MW,* $<n>=5.85\cdot10^{19}\,\mathrm{m}^{-3}$, $n_{a0}=8\cdot10^{14}\,\mathrm{m}^{-3}$

The next Figs. 2-5 represent the radial profiles of ion and electron temperatures, plasma densities, ambipolar electric field and neutral atom density. All the profiles evidence on the large plasma parameter gradients at the plasma boundary.

Figs. 6 and 7 show the radial plasma density and plasma temperature profiles corresponding to the mode of a relatively low density $<n>\sim3.3\cdot10^{19}\,\mathrm{m}^{-3}$. In this case the plasma heating of electron and ions was done in equal parts $P_{he}=P_{hi}=2$ MW.

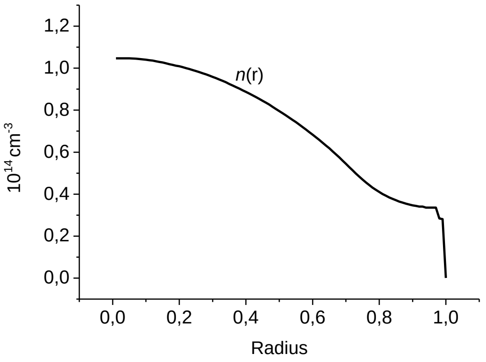

Fig. 2. Radial profile of the plasma density

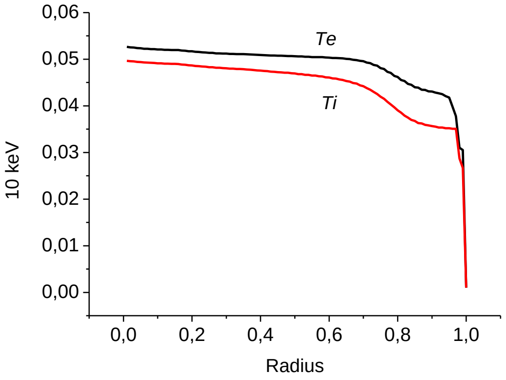

Fig. 3. Profiles of the electron and ion temperatures

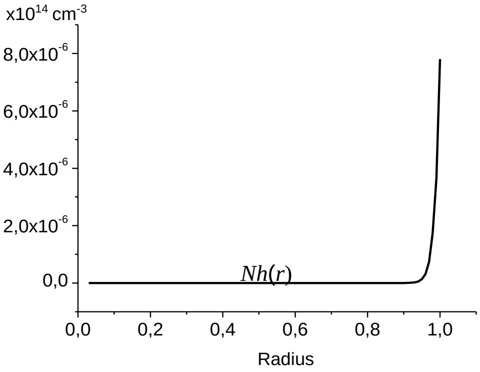

Fig. 4. Radial profile of the neutral density

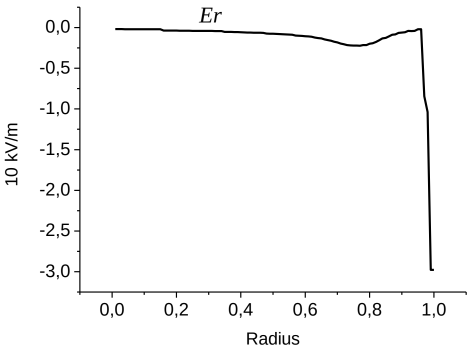

Fig. 5. Radial profile of the ambipolar electric filed

Here the power contribution, counting on a single charged particle, is larger approximately by a factor of 3.5 compared to the case of $<n>\sim 5.85\cdot 10^{19}$ m^{-3}. As a result, higher temperatures were obtained. Moreover, in the profiles of n(r), Te(r) and Ti(r) different features are observed. A dip in the density curve with a step near the plasma edge takes place. In the ion temperature curve a flat region is formed. The dependence of E_r on the radius, in main, is similar to the case with a high density, but there is a sharp dip to the negative values near the jump on the Ti profile. In this case the energy confinement time is 60 ms.

3. U-2M RESULTES

The stellarator U-2M has significantly less sizes and a lower magnetic field as compared with LHD. In U-2M helical magnetic field ripples are much larger. Moreover, for plasma heating in U-2M one uses lower powers P_h = 200 kW. As a result, the plasma density in this device does not exceed several units per 10^{18} m^{-3}. The mentioned features were taken into consideration when defining the parameters of calculations.

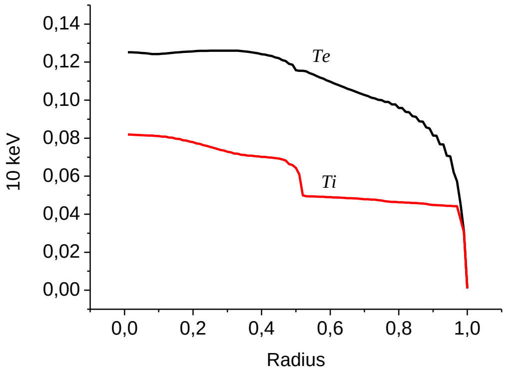

Fig. 7. Electron and ion temperature profiles, $<n>=3.3\cdot 10^{19}$ m^{-3}

Figs. 8-10 represents the profiles of temperature, plasma density and electric field for U-2M with the initial average plasma density value n=2.5·10^{18} m^{-3} and the neutral density in the chamber n_h=5·10^{17} m^{-3}. The plasma heating of electrons and ions was done in equal parts P_{he}=P_{hi}=0.1 MW. In that case the average electron and ion temperature values were set at a level of T_e~400, T_i~170 eV and the neutral atom concentration outside the plasma was n_{h0}~5·10^{16} m^{-3}. Within the confinement volume the concentration of neutral atoms quickly decreases with the distance from the plasma boundary. The profile of plasma density has a maximum in the vicinity of the boundary of the plasma column. This feature, apparently, is the result of the presence of an intense source S_δ in this area.

The calculations of plasma parameters with the initial plasma density value n=1·10^{18} m^{-3} and density neutrals in the chamber n_h=2·10^{17} m^{-3}, for the same heating variant as in the case with n=2.5·10^{18} m^{-3}, shows that the electric field and temperature distributions are of a similar form. However, the plasma density profile has a flat view along the main part of the plasma radius. There is observed a little decrease of n in the vicinity of the plasma center (Fig. 11). Note, that in the case of U-2M the energy confinement time was of 1…1.5 ms.

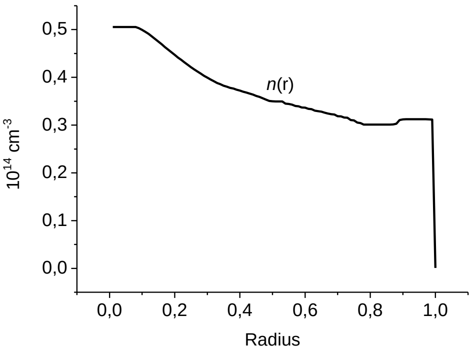

Fig. 6. Radial plasma density profile, LHD, case of low density, $<n>=3.3\cdot 10^{19}$m^{-3}

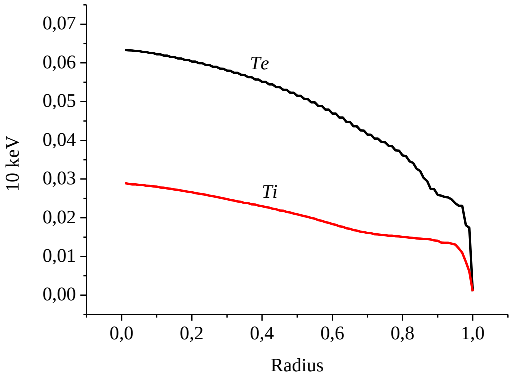

Fig. 8. U-2M, Temperature profiles

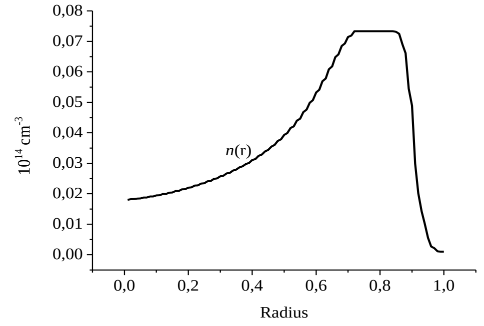

Fig. 9. U-2M, Density profile

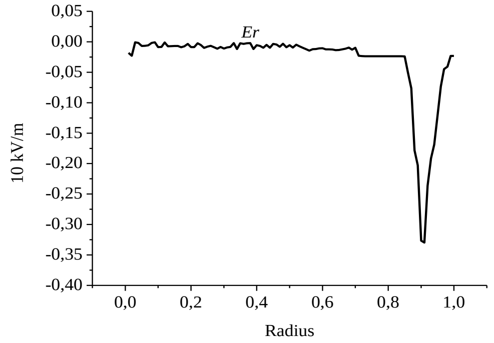

Fig. 10. U-2M, Electric field profile

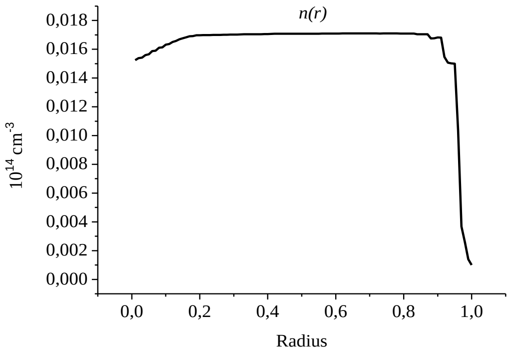

Fig. 11. U-2M, Density profile, $n_0=1\cdot 10^{18}$, $P_{he}=P_{hi}=0.1$ *MW*

CONCLUSIONS

Calculations of spatial plasma parameter distributions in the stellarators U-2M and LHD, operating under conditions of recycling and neoclassic transport realization, show the formation of high gradients for basic plasma and neutral atom parameters near the plasma boundary. In some cases the density profiles are formed with the density decreasing in the vicinity of the plasma center. There the flat spots formed before the gradient sharpening near the plasma boundary are observed.

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РАСПРЕДЕЛЕНИЯ ПАРАМЕТРОВ ПЛАЗМЫ В СТЕЛЛАРАТОРЕ В УСЛОВИЯХ РЕЦИКЛИНГА ПРИ НЕОКЛАССИЧЕСКОМ ПЕРЕНОСЕ

В.А. Рудаков

С использованием одномерного пространственно-временного численного кода рассчитаны пространственные распределения параметров плазмы в стеллараторах LHD и У-2М, работающих в условиях рециклинга в предположении реализации неоклассического переноса. Получены устойчивые решения системы уравнений для пространственных распределений температур ионов и электронов, плотности плазмы и нейтральных атомов, амбиполярного электрического поля. Показано образование плоских участков в радиальных профилях параметров плазмы вблизи границы плазмы.

РОЗПОДІЛИ ПАРАМЕТРІВ ПЛАЗМИ В СТЕЛАРАТОРІ В УМОВАХ РЕЦИКЛІНГУ ПРИ НЕОКЛАСИЧНОМУ ПЕРЕНЕСЕННІ

В.А. Рудаков

З використанням одновимірного просторово-часового числового коду розраховано просторові розподіли параметрів плазми в стелараторах LHD і У-2М, працюючих в умовах рециклінгу в припущенні реалізації неокласичного перенесення. Отримані стійкі рішення системи рівнянь для просторових розподілів температур іонів і електронів, щільності плазми та нейтральних атомів, амбіполярного електричного поля. Показано утворення плоских ділянок у радіальних профілях параметрів плазми поблизу межі плазми.