EFFECT OF RECYCLING FOR PHYSICAL PARAMETERS OF REACTOR-STELLARATOR

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The results of calculations of self-sustaining fusion reaction in a stellarator-reactor operating under partial recycling conditions are presented. The calculations were performed on the assumption of the implementation of neoclassical transport processes in a reactor with small ripples of a helical magnetic field.

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INTRODUCTION

The solutions of the space-time problem of plasma heating and confinement in a stellarator, carried out by the author in papers [1-5], demonstrated the possibility of achieving of self-sustaining thermonuclear reaction in a relatively compact stellarator reactor. In these works, it was assumed that all the plasma lost as a result of neoclassical diffusion goes into the divertor, and its replacement is carried out by the injection of fuel pellets. Such an ideal work of a divertor, apparently, cannot be realized, especially in the stellarator due to the complex helical structure of the magnetic field. A part of the plasma that went beyond the last closed magnetic surface will remain in the vacuum chamber without entering the divertor. Another part of the particles will leave the confinement volume as a result of recharging. Particles thus lost will return to the plasma, partially compensating for its deficiency. In the publication [6], the effect of recycling on the plasma parameters in the U-2M and LHD stellarators was studied under conditions when the plasma density was maintained in the installation only by returning the particles lost as a result of diffusion into the plasma. In the present work, an attempt has been made to evaluate the effect of recycling on the physical parameters of the reactor for different ratios between the flows of particles leaving the divertor and remaining in the reactor chamber.

As a basis for calculations, a reactor-stellarator was used, in which the ripples of the helical magnetic field, as in [5], turn out to be less than the inhomogeneities of the toroidal magnetic field ($\varepsilon_h < \varepsilon_t$). The work was carried out using the numerical code previously developed and described by the author in publications [5, 6], which was adapted to allow for recycling in reactor conditions.

1. THE ESSENCE OF THE PROBLEM AND FEATURES OF NUMERICAL CODE

A system of four spatially one-dimensional equations was solved: the thermal conductivities of electrons and ions, plasma diffusion, and diffusion of neutral atoms. The equation for the thermal conductivity of electrons in the right-hand side, except for the term with thermal conductivity, took into account the heating of electrons arising from the braking of α-particles produced in the fusion; heating from external energy sources, losses by bremsstrahlung and cyclotron radiation, heat exchange with ions due to Coulomb collisions and ambipolar electric field.The heat equation for ions takes into account heat exchange with electrons due to Coulomb collisions and as a result of interaction with an electric field, and also contains a source of external plasma heating.

The diffusion equations for plasma and neutral atoms of deuterium and tritium, in addition to diffusion terms, contain a member as a source and sink, taking into account the ionization of atoms. An equal content of deuterium and tritium in the reactor was assumed. Maintaining the density at a constant level was provided by the injection of fuel pellets and due to the ionization of neutral atoms entering the plasma by recycling. The contribution of other elementary processes was neglected because of its smallness. The magnitude of the radial electric field was found from the equality of the ion and electron neoclassical diffusion fluxes at each node of the spatial grid along the small radius of the plasma.

In the calculations, different models of plasma heating by external sources were used: individually heating electrons, ions, or simultaneously heating two components. It was also assumed that the specific heating power is proportional to the plasma density. The maximum of neoclassical losses in the stellarator is in the region where the effective collision frequency $\nu_{eff} = \nu_j / \varepsilon_{eff}$ is near the doubled frequency of plasma rotation in the radial electric field ω_E [7]. Here ν_j is the frequency of Coulomb collisions of ions or electrons of the plasma, ε_{eff} is the effective amplitude of the corrugations of the helical magnetic field. According to [7], if ε_{eff} turns out to be greater than the amplitude of the inhomogeneity of the toroidal magnetic field ε_t, then the diffusion coefficient to the left of the maximum is proportional to the square root of ν_j, and in the case of the inverse inequality ($\varepsilon_{eff} < \varepsilon_t$), the diffusion linearly increases with the collision frequency – $D \propto \nu_j^1$.

The possibility of creating a mode of self-sustaining synthesis reaction in the reactor for the case ($\varepsilon_{eff} > \varepsilon_t$) was considered in [2-4]. Publication [5] is devoted to a variant of the reactor with $\varepsilon_{eff} < \varepsilon_t$. In the present work, as well as in [5], the calculations were performed for the case of a reactor with small ripples of a helical magnetic field, when the inequality $e_{ff} < \varepsilon_t$ holds.

In most cases, a dome-shaped model of ablation of fuel pellets was used: $\delta n = n_\delta(1+x^4/\Delta^4-2x^2/\Delta^2)$, where Δ is the half-width of the evaporation region, which in different calculations was 0.5, 0.75, and 1. Size of the pellet varied in the range of 1–2 percent of the total number of particles in the reactor plasma. With a

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decrease in the number of particles in the plasma below 0.99, another pellet was thrown into the plasma. In this case, the energy expenses for heating the injected particles were taken into account, and the energy losses for the evaporation of the pellet and the ionization of atoms were neglected due to their smallness.

As initial parameters for numerical calculations, a reactor with a large radius R = 8 m, a small plasma radius r_p = 2 m, and a magnetic field B_0 = 5 T was taken. The radius of the first wall of the vacuum chamber is r_w = 2.3 m. As in [5], the reactor was calculated with amplitudes of the ripples of the helical magnetic field ε_{eff} = 0.008. Note that in the traditional stellarator, the value of the screw corrugation is approximately an order of magnitude greater.

A decrease in ε_{eff} leads to an increase in ν_{eff}. In [2-4], the condition ν_{eff} was almost always fulfilled for ions $\nu_{eff.} < 2\omega_E$. With the same plasma parameters in the stellarator with small ε_{eff}, the inequality can be reversed. The task was complicated by the fact that different dependences of the transfer coefficients on the collision frequency and the electric field could be realized at different plasma radii. At the same time, in some points of the radius, different dependences of the transfer coefficients on the plasma parameters can be used simultaneously, which leads to unsolvable contradictions in the numerical code. Therefore, sufficiently high plasma densities ($\langle n \rangle$ = 1.9, 2, and $2.1 \cdot 10^{20}\,m^{-3}$) were chosen for the calculations, at which the diffusion coefficients of electrons and ions almost always corresponded to the $D \propto \nu_j^{-1}$ dependence.

Additional complexity created a significant difference in the time scales of the calculated processes. Ionization of atoms occurs many orders of magnitude faster than diffusion processes, the calculation of which must be carried out simultaneously. This difficulty was removed using different time steps in the numerical model. Initially, the problem was solved with a small time step and, after establishing an approximately constant distribution of neutral atoms, the time step was increased so that diffusion processes in the plasma could be considered as reasonable time.

Neutral particles in the reactor space surrounding the plasma will have a wide energy spectrum — from a few to tens of electron volts [8]. The numerical code cannot take into account the energy distribution of the particles involved in recycling. Therefore, the calculations were carried out separately with the energies of neutral atoms 1, 7, and 50 eV. These energies are chosen so that the velocities of the atoms from one energy to another increase by the same number of times. The fraction of particles involved in recycling was determined by the coefficient k_n, which in most calculations was equal to 0.25 and 0.5.

2. CALCULATION RESULTS

In the calculations different initial and boundary conditions were used for the plasma density and temperature. Common for these conditions was the requirement that the spatial derivatives at the center of the plasma be zero and the values close to zero at its boundary. For heating the plasma to thermonuclear temperatures powers from 50 to 100 MW were used. Most calculations are performed with a heating power of 70 MW. Also in most calculations, the plasma heating source was turned off when the fusion power of the reactor reached 950 MW. After that, the plasma parameters evolved to a stationary self-sustaining reaction. In addition to the stationary power of the reactor, stable spatial distributions of plasma density, neutral atoms, ambipolar electric field, ion and electron temperatures were established, which were independent of the heating power and the shape of the initial distributions of plasma parameters.

Fig. 1 shows the time dependences of the fusion power of a reactor at different plasma heating powers. Regardless of the heating power, which in this case was invested in the electronic component of the plasma, after turning off its sources at P_t = 950 MW, the reactor in all cases reaches a power of about 850 MW. The average temperatures of electrons and ions are, respectively, 11 and 7 keV. The calculations were performed for plasma density $\langle n \rangle = 1.9 \cdot 10^{20} m^{-3}$, energy of neutral atoms E_n = 50 eV, evaporation half-width of tablets $\Delta = 0.75$ and with a fraction of recycling k_n = 0.5.

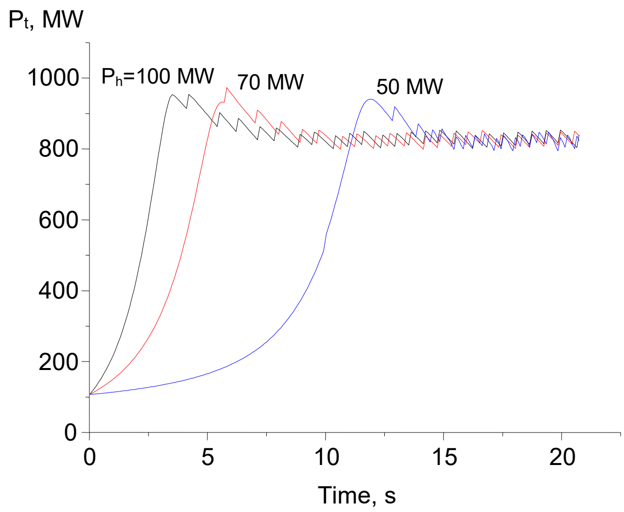

Fig. 1. Temporal dependences of fusion power at different heating power. P_{he} = 50, 70, 100 MW; $\langle n \rangle = 1.9 \cdot 10^{20} m^{-3}$, $k_n = 0.5$, E_n = 50 eV, Δ = 0.75

Fig. 2 illustrates the time dependences of the reactor power at different plasma densities. The power of the reactor increases with increasing plasma density.

Fig. 3 shows the dependence of reactor power on the fraction of particles involved in recycling. The growth of this share causes a decrease in reactor power. In the absence of recycling (k_n = 0), with the same plasma density, the reactor power was several dozen MW higher [5] than when k_n = 0.25.

As in previous studies, the power of the reactor and the spatial distribution of plasma parameters depended significantly on the width of the ablation region of the fuel pellets.

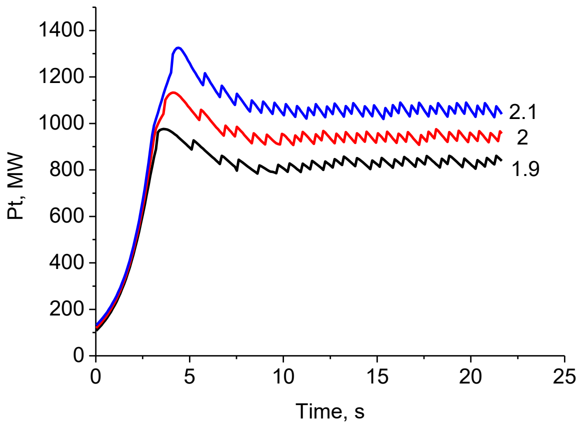

Fig. 2. Temporal dependences of fusion power at different plasma density. P_{he} = 100 MW; <n>=1.9, 2, 2.1·$10^{20}$$m^{-3}$, k_n=0.25, E_n=50 eV, Δ=0.75

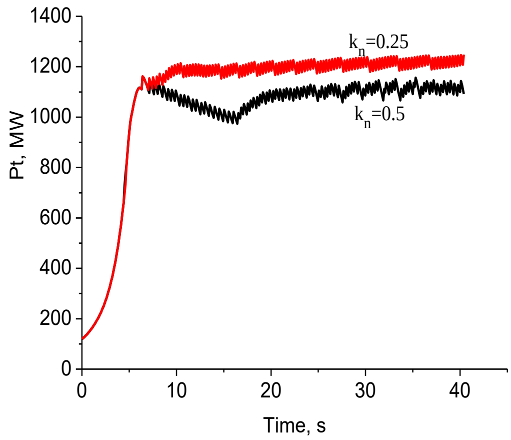

Fig. 3. Time dependences of the reactor fusion power at different values of particles, taking part in recycling k_n. P_{he} =70 MW; <n>= 2·$10^{20}$$m^{-3}$, k_n=0.25,·0.5; E_n= 50 eV, Δ=0.75

The next series of figures shows the radial profiles of the plasma density and the ambipolar electric field for Δ = 0.5, 0.75 and 1. The plasma density profiles are shown for two values of the energy of neutral particles - 7 (Fig. 4) and 50 (Fig. 5) electron-volt. The plasma density profiles at the energy of neutral atoms E_n = 50 eV have large gradients in the region of the plasma boundary. Similar plasma density profiles occurred when recycling was not taken into account [5]. The plasma density profiles in the case of a neutral energy of 1 eV almost coincide with the plasma density profiles at an energy of E_n = 7 eV.

Noticeable differences from the shape of the profiles E_r (r) with widths Δ = 0.75 and 1 are observed for the profile E_r (r) when Δ = 0.5. In this case, the maximum negative values of the electric field reach 70 kV/m and are located in the vicinity of the plasma radius r = 0.2. In the other two cases, the negative maxima of E_r (r) are located in the vicinity of the plasma boundary. Note also that directly at the plasma boundary the electric field acquires positive values.

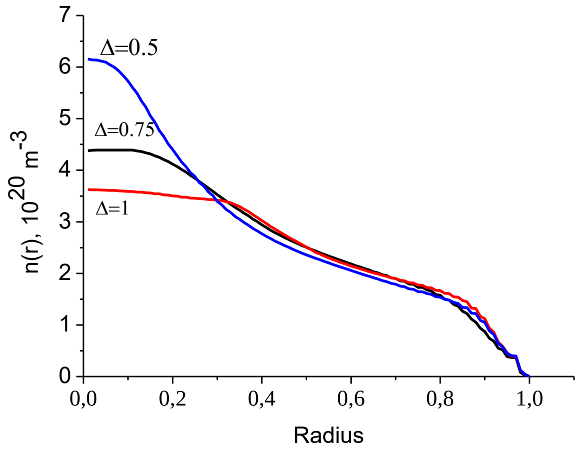

Fig. 4. Radial profiles of plasma densities Δ= 0.5, 0.75 and 1, <n>=1.9·$10^{20}$$m^{-3}$, k_n=0.5, E_n= 7 eV

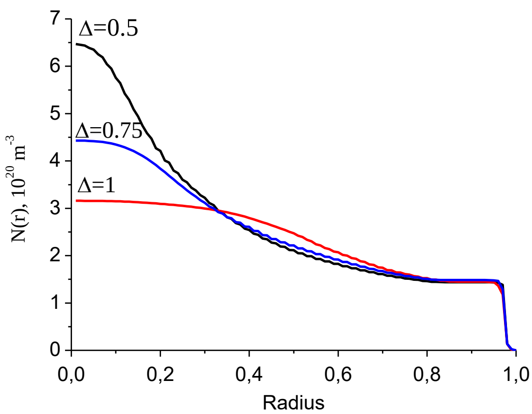

Fig. 5. Radial profiles of plasma densities for Δ= 0.5, 0.75 and 1; <n>=1.9·$10^{20}$$m^{-3}$, k_n=0.5, E_n= 50 eV

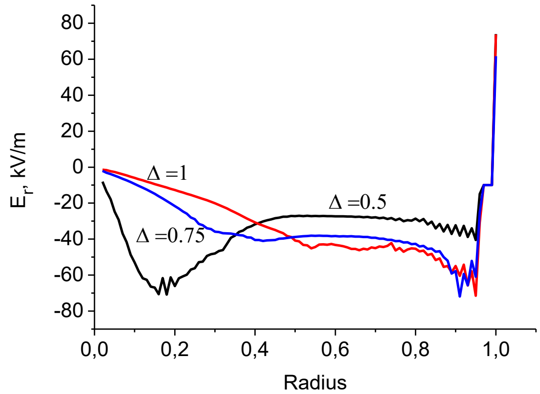

Fig. 6. Radial profiles of electric fields for Δ= 0.5, 0.75 and 1; <n>=1.9·$10^{20}$$m^{-3}$, k_n=0.5, E_n= 50 eV

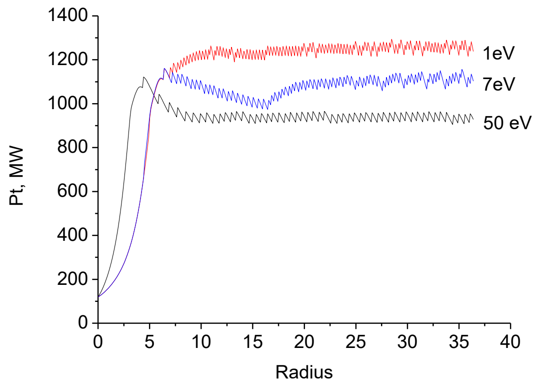

Fig. 7. Time dependences of the reactor fusion power at different particle energy taking part in recycling.
<n>= $2\cdot10^{20}$m^{-3}, k_n= 0.5;
E_n= 1,7 and 50 eV, Δ=0.75

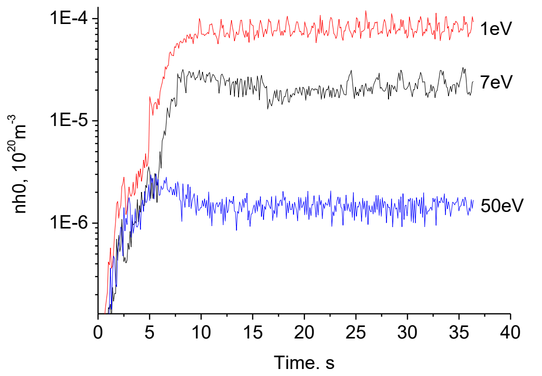

Fig. 8. Time dependences of neutral particle density outside of plasma at different particles energy

CONCLUSIONS

A divertor in a fusion reactor is needed to avoid the active interaction of the plasma leaving the containment volume with the chamber walls, as a result of which the material of the first wall can be destroyed and undesirable impurities enter the containment volume. In this paper, these effects are not considered. The subject of the research was only the role of atoms returned to the plasma that make up the reactor fuel.

The results of the calculations indicate that self-sustaining reaction in the stellarator reactor is also possible in the case of incomplete output to the divertor that leaves the plasma confinement volume. There is only a decrease in reactor power in proportion to the increase in the share of recycling in replenishing the plasma density.

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ВЛИЯНИЕ РЕЦИКЛИНГА НА ФИЗИЧЕСКИЕ ПАРАМЕТРЫ РЕАКТОРА-СТЕЛЛАРАТОРА

В.А. Рудаков

Представлены результаты расчетов режимов самоподдерживающейся термоядерной реакции в стеллараторе-реакторе, работающем в условиях частичного рециклинга. Расчеты выполнены в предположении реализации неоклассических транспортных процессов в реакторе с малыми гофрами винтового магнитного поля.

ВПЛИВ РЕЦИКЛІНГУ НА ФІЗИЧНІ ПАРАМЕТРИ РЕАКТОРА-СТЕЛАРАТОРА

В.А. Рудаков

Представлено результати розрахунків режимів самопідтримуючої термоядерної реакції в стелараторі-реакторі, що працює в умовах часткового рециклінгу. Розрахунки виконані в припущенні реалізації неокласичних транспортних процесів у реакторі з малими гофрами гвинтового магнітного поля.