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托卡马克边界等离子体数值模拟

NUMERICAL SIMULATION OF EDGE PLASMA IN TOKAMAK

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托卡马克边界等离子体数值模拟

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摘　要

用合适的模拟程序，通过数值求解二维多流体等离子体输运方程来模拟托卡马克边界等离子体输运过程和输运特性。模拟结果能显示边界层区域等离子体参数的分布特性，尤其能显示第一壁和偏滤器靶板附近等离子体参量的分布特性。模拟计算的结果对托卡马克偏滤器和第一壁的设计有重要意义。

NUMERICAL SIMULATION OF EDGE PLASMA IN TOKAMAK

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ABSTRACT

The transport process and transport property of plasma in edge layer of Tokamak are simulated by solving numerically two-dimensional and multi-fluid plasma transport equations using suitable simulation code. The simulation results can show plasma parameter distribution characteristics in the area of edge layer, especially the characteristics near the first wall and divertor target plate. The simulation results play an important role in the design of divertor and first wall of Tokamak.

So far, fusion research has come into the phase of reactor design, the edge plasma research has become popular in the aspect of international fusion research. Theory and numerical simulation research of edge plasma are taken seriously at the same time of experimental research for the design of fusion reactor or fusion-fission hybrid reactor. Some large-scale simulation codes, for example, B2, PLANET, EDGE2D/U, UEDA and so on [1], have been developed, these simulation codes have simulated transport property of plasma in edge layer of fusion reactor or hybrid reactor with some success and have important meaning for guiding design of Tokamak first wall or divertor in reactor.

Taking fusion-fission hybrid reactor as an example, this paper simulates transport property of edge plasma in Tokamak and shows plasma parameter distribution near first wall and divertor plate in Tokamak by solving two-dimensional and multi-fluid plasma transport equations using suitable simulation code [2] in order to guide analysis and design of first wall and divertor in Tokamak.

In this paper, basic hypothesis about edge plasma of Tokamak include [2]:

(1) Plasma is electrically neutral and current-free;

(2) Plasma contains several ion species and electrons, each ion fluid is governed by a Navier-stokes system of equations;

(3) Coupling between the plasma species occurs through ionization and recombination processes, interspecies friction, electric and thermal forces, and temperature equilibration.

Systems of equations of edge plasma in Tokamak are:

continuity equation:

$$\frac{\partial n_a}{\partial t} + \frac{1}{\sqrt{g}}\frac{\partial}{\partial x}\left[\frac{\sqrt{g}}{h_x}n_a u_a\right] + \frac{1}{\sqrt{g}}\frac{\partial}{\partial y}\left[\frac{\sqrt{g}}{h_y}n_a v_a\right] = S_n^a$$

momentum balance equation:

$$\frac{\partial}{\partial t}(m_a n_a u_{\mathrm{I}a}) + \frac{1}{\sqrt{g}}\frac{\partial}{\partial x}\left[\frac{\sqrt{g}}{h_x}m_a n_a u_a u_{\mathrm{I}a} - \frac{\sqrt{g}}{h_x^2}\eta_x^a\frac{\partial u_{\mathrm{I}a}}{\partial x}\right]$$

$$+ \frac{1}{\sqrt{g}}\frac{\partial}{\partial y}\left[\frac{\sqrt{g}}{h_y}m_a n_a v_a u_{\mathrm{I}a} - \frac{\sqrt{g}}{h_y^2}\eta_y^a\frac{\partial u_{\mathrm{I}a}}{\partial y}\right]$$

$$= \frac{B_\theta}{B}\frac{1}{h_x}\left[-\frac{\partial p_a}{\partial x} - \frac{Z_a n_a}{n_e}\frac{\partial p_e}{\partial x} + c_e\left[\frac{Z_a}{Z_{\mathrm{eff}}} - 1\right]Z_a n_a\frac{\partial T_e}{\partial x}\right.$$

$$\left. + c_i\left[\frac{Z_a}{Z_{\mathrm{eff}}} - 1\right]Z_a n_a\frac{\partial T_i}{\partial x}\right] + \sum_{b=1}^{N}F_{ab} + S_{mu\mathrm{I}}^a$$

diffusion equation:

$$v_a = -\frac{D_n^a}{h_y}\frac{\partial}{\partial y}(\ln n_a) - \frac{D_p^a}{h_y}\frac{\partial}{\partial y}(\ln p_a)$$

electron energy balance equation:

$$\frac{\partial}{\partial t}\left[\frac{3}{2}n_e T_e\right] + \frac{1}{\sqrt{g}}\frac{\partial}{\partial x}\left[\frac{\sqrt{g}}{h_x}\frac{5}{2}n_e u_e T_e - \frac{\sqrt{g}}{h_x^2}k_x^e\frac{\partial T_e}{\partial x}\right]$$
$$+ \frac{1}{\sqrt{g}}\frac{\partial}{\partial y}\left[\frac{\sqrt{g}}{h_y}\frac{5}{2}n_e v_e T_e - \frac{\sqrt{g}}{h_y^2}k_y^e\frac{\partial T_e}{\partial y}\right]$$
$$= \frac{u_e}{h_x}\frac{\partial p_e}{\partial x} + \frac{v_e}{h_y}\frac{\partial p_e}{\partial y} - k(T_e - T_i) + S_E^e$$

ion energy balance equation:

$$\frac{\partial}{\partial t}\left[\frac{3}{2}n_i T_i + \sum_a \frac{1}{2}\rho_a u_{Ia}^2\right]$$
$$+ \frac{1}{\sqrt{g}}\frac{\partial}{\partial x}\left[\frac{\sqrt{g}}{h_x}\left[\sum_a \frac{5}{2}n_a u_a T_i + \sum_a \frac{1}{2}m_a n_a u_a u_{Ia}^2\right]\right.$$
$$\left. - \frac{\sqrt{g}}{h_x^2}\left[k_x^i\frac{\partial T_i}{\partial x} + \sum_a \frac{1}{2}\eta_x^a\frac{\partial u_{Ia}^2}{\partial x}\right]\right]$$
$$+ \frac{1}{\sqrt{g}}\frac{\partial}{\partial y}\left[\frac{\sqrt{g}}{h_y}\left[\sum_a \frac{5}{2}n_a v_a T_i + \sum_a \frac{1}{2}m_a n_a v_a u_{Ia}^2\right]\right.$$
$$\left. - \frac{\sqrt{g}}{h_y^2}\left[k_y^i\frac{\partial T_i}{\partial y} + \sum_a \frac{1}{2}\eta_y^a\frac{\partial u_{Ia}^2}{\partial y}\right]\right]$$
$$= -\frac{u_e}{h_x}\frac{\partial p_e}{\partial x} - \frac{v_e}{h_y}\frac{\partial p_e}{\partial y} + k(T_e - T_i) + S_E^i$$

In above equations, a indicates ion of species a, if N species exist, $1 \leqslant a \leqslant N$. x, y indicate poloidal and radial coordinate respectively, $\sqrt{g}, h_x, h_y$ are metric coefficients, B_θ, B are poloidal and total magnetic field, Z_a, m_a are charge number and mass of an ion of species a, η_x^a, η_y^a are poloidal and radial viscosity coefficients for species a, F_{ab} is friction force on ion species a due to b, c_e, c_i are coefficients in the thermal force for electrons and ions, D_n^a, D_p^a are diffusion coefficients for species a, $k_x^{e,i}, k_y^{e,i}$ are heat conduction coefficients, k is energy equipartition coefficient, $S_n^a, S_{mu\,I}^a$ are volume sources of ions and momentum for species a, S_E^e, S_E^i are volume sources of electron and ion energy. If N ion species exist, *they may have different speed, but, their temperature are the* same, auxiliary quantities used in above equations are:

$$n_i = \sum_a n_a, n_e = \sum_a Z_a n_a, \rho_a = m_a n_a, P_a = n_a T_i, P_e = n_e T_e, u_a = \left[\frac{B_\theta}{B}\right]u_{Ia}$$

$$u_e = \left[\sum_a Z_a n_a u_a\right]/n_e, v_e = \left[\sum_a Z_a n_a v_a\right]/n_e, Z_{eff} = \left[\sum_a Z_a^2 n_a\right]/\left[\sum_a Z_a n_a\right]$$

Simulated edge layer area is shown as Fig. 1 for double null configuration of Tokamak. A part of edge condition is given in Fig. 1. The simulated edge layer area in Fig. 1 must be expended for single null configuration of Tokamak.

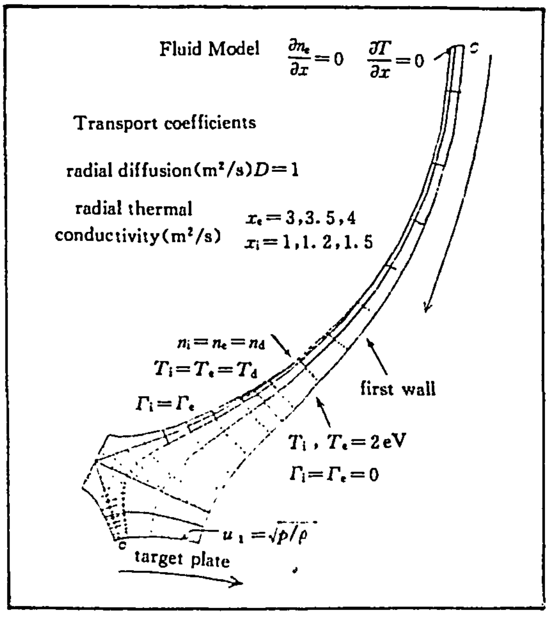

Fig. 1 The area of simulated edge layer

Taking fusion-fission hybrid reactor (configuraton of single null, main parameters and parameters of edge plasma are shown in Table 1.) as an example, plasma parameter distribution property near first wall and divertor plate of Tokamak in hybrid reactor is shown in Fig. 2 by numerically solving above equations using suitable simulation code [2].

Table 1 Plasma parameters of hybrid reactor

average density	average temperature	edge density	edge temperature	main radius	minor radius	elongation
n_i/m^{-3}	T_i/keV	n_d/m^{-3}	T_d/eV	R/m	a/m	k
1.0×10^{20}	10.0	5.0×10^{19}	400.0	4.0	1.0	1.8

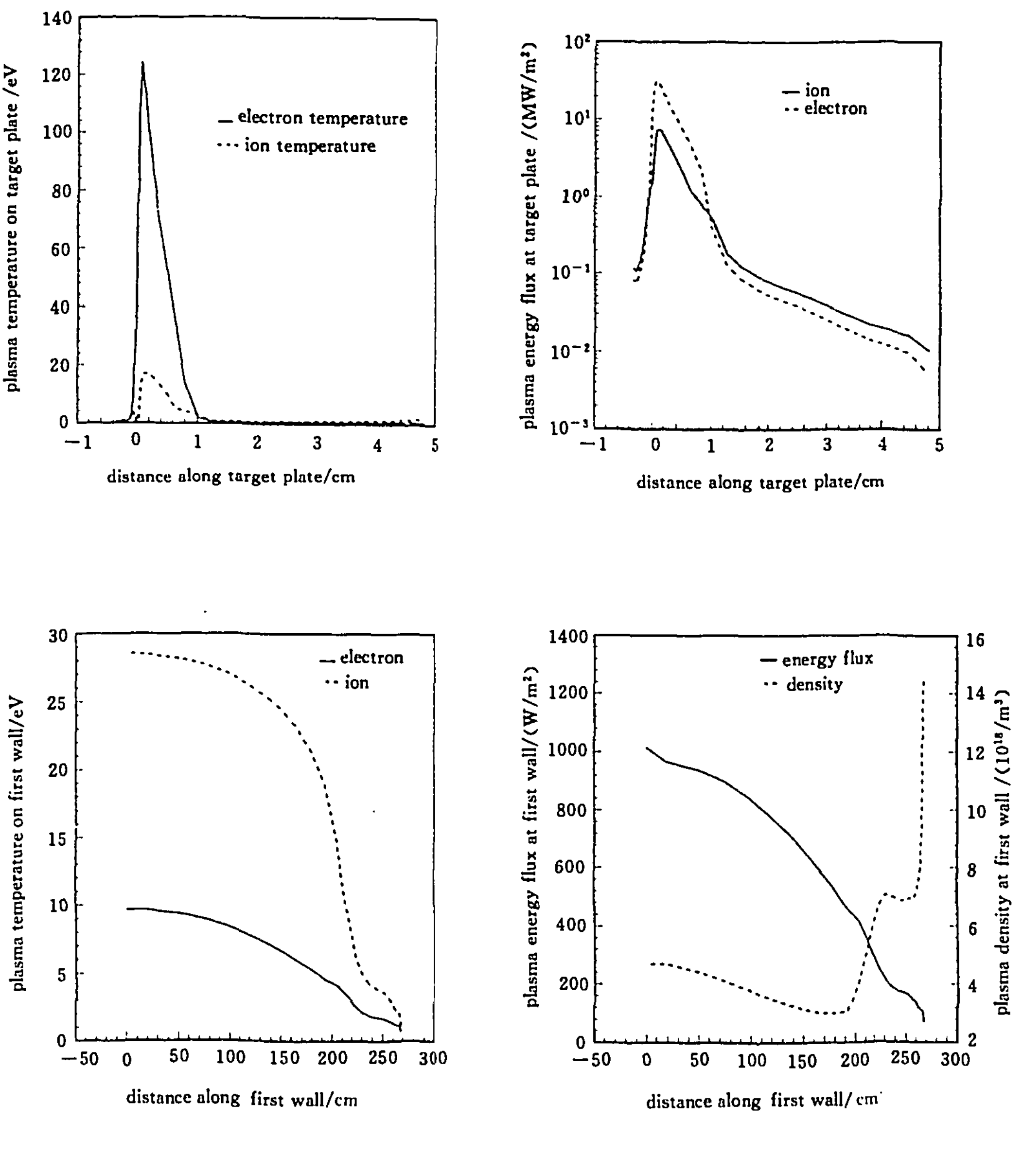

Fig. 2 Plasma parameter distribution near divertor plate and first wall of hybrid reactor

It can be shown from Fig. 2 that plasma high temperature and large energy flux peak value exist near divertor target plate. It may be a method to puff neutral and cold gas in the room of divertor in order to reduce energy flux on divertor plate. Recycle process (mainly charge exchange, ionization, radiation, re-combination) in divertor room is increased due to puffing gas, so, losed energy is increased in divertor room, energy flux is decreased at divertor plate. Further, research about gas puffing divertor by numerical simulation method may be carried out in our next step research.

Thank Mr. XIAO Binjia for his help during calculation.

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