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MODELING OF ULTRA-HIGH RECYCLING DIVERTORS
WITH THE PLANET CODE

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PPPL

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Modeling of Ultra-High Recycling Divertors with the PLANET Code

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The handling of power carried by the charged particles into the scrape-off layer of a tokamak reactor remains a major obstacle for its continuous and reliable operation. Ways of reducing this power through radiation have been studied numerically using fluid models for both the plasma and neutral gas. A new model for the combined plasma and neutral gas 2-D transport capable of simultaneously representing regions of fully-ionized plasma, partially ionized plasma, and pure neutral gas has been assembled and implemented in the PLANET code. Divertor plasma temperatures of just below 1 eV have been achieved in a pure hydrogen plasma, resulting in an ionization-free region together with ionization and recombination fronts detached from the material walls. In this regime energy reaches the walls almost exclusively in the form of radiation which, in principle, solves the divertor heat load problems.

Introduction

The charged particle power handling remains the critical issue for ITER [1] and all the future burning plasma experiments and fusion power generation facilities. Reduction of the heat flux before it reaches the divertor plates appears imperative.

The plasma energy is first conducted and then convected to the divertor plates along a (magnetic) flux tube whose width at a tokamak midplane is less than 5 cm. The energy can be, in principle, taken out of this flux tube and deposited on the large side-wall area by charge exchange, hydrogen radiation, and impurity radiation.

The high recycling divertors have been looked upon principally as a means of reducing the plasma temperature at the divertor plate to minimize sputtering. This is achieved by ionizing (recycling) the neutral gas from the plate which lowers the plasma temperature by two mechanisms. Ionization converts some of the heat energy into the potential energy of recombination. This amounts to 13.6 eV per ionization, which reappears within the plate as plasma recombines. Ionization also creates a large number of electron-ion pairs which carry energy convectively to the plate, the temperature being inversely proportional to the number of carriers. Thus, within the (high) recycling region $T \cong Q_{||}/5\Gamma_{||}$, where $Q_{||}$ and $\Gamma_{||}$ are the parallel heat and particle fluxes, respectively, and $T = (T_e + T_i)/2$ is the average temperature.

The particle flux $\Gamma_{||}$ is given by the integral of the ionization and recombination rate along the flux tube

$$\Gamma_{||}(s) = \Gamma_{s1} + \int_{s1}^s (\langle \bar{\sigma}_{ion} v \rangle n_e(s) n_o(s) - \langle \bar{\sigma}_{rec} v \rangle n_e^2(s)) ds. \quad (1)$$

The combined heat and (much smaller) kinetic energy flux can be written in the form

$$Q_{||}(s) = Q_{||}(s1) - \int_{s1}^s [(E_{rad} + 13.6eV)(\Gamma(s) - \Gamma(s1))] ds. \quad (2)$$

The energy reaching the plate must include the 13.6 eV recombination energy so the relevant quantity is the total energy flux

$$Q_{||}^t(s) = Q_{||}(s) + (13.6eV)\Gamma_{||}(s). \quad (3)$$

The ratio $Q_{||}^t/Q_{||}$ increases as the temperature is lowered. At $T = 2$ eV, $Q_{||}^t \cong Q_{||}$. Equations (2) and (3) show clearly that ionization alone does not lower $Q_{||}^t(s)$. However, if $Q_{||}(s)$ is first reduced by making $\Gamma_{||}(s)$ large, and subsequently $\Gamma_{||}(s)$ is lowered by recombination, the total energy flux $Q_{||}^t(s)$ can itself be reduced and, in principle, made to vanish completely.

The Mathematical Model

In order to study the recombination regime which should occur under ultra-high recycling conditions, the mathematical model should adequately describe the fully and partially ionized

plasma, and the neutral gas which may occupy different portions of the divertor volume. The set of equations used for this purpose agrees with the Braginskij equations [2] in the fully ionized limit and with the standard fluid equations in the neutral gas limit. For the partially ionized plasma, the equations coincide with those of Hazeltine et al. [3], derived for highly ionized plasmas. Though the neutral heat conduction and viscosity may be questionable for the partly ionized plasma regimes, they play a minor role. The important neutral particle transport and the associated convection of energy and momentum follow directly from the (fluid) equations for the neutral gas, and should be valid in all the regimes. In the proposed model, the neutral energy and parallel momentum transport equations have been added to the corresponding ion equations assuming equal neutral and ion temperatures and equal parallel velocities. The equal velocity assumption is not valid normal to the magnetic field, resulting in a (neutral) pressure driven diffusion. Equations (4) through (10) represent, respectively, the conservation of the electron and ion plus neutral energies, electron (or ion) mass (particles), ion plus neutral parallel momentum, neutral mass (particles), and the neutral momentum normal to the field within the flux surfaces (ζ direction) and in the radial direction ($\perp$). The precise definition of the coordinate system (Fig. 1) and the notation used in the equations can be found in Ref. [4].

$$\begin{aligned} \frac{\partial}{\partial t} \left(\frac{3}{2} n_e T_e \right) + \nabla_{\parallel} \left(\frac{5}{2} T_e n_e v_{\parallel} \right) - \nabla_{\parallel} (k_{\parallel}^e \nabla_{\parallel} T_e) - \nabla_{\perp} (k_{\perp}^e \nabla_{\perp} T_e) \\ - \nabla_{\perp} \left(\frac{5}{2} T_e D \nabla_{\perp} n_e \right) = S E_e + v_{\parallel} \nabla_{\parallel} (n_e T_e) - C_{ei}, \end{aligned} \quad (4)$$

$$\begin{aligned} \frac{\partial}{\partial t} \left[\left(\frac{3}{2} T_i + \frac{1}{2} m v_{\parallel}^2 \right) (n_e + n_o) \right] + \nabla_{\parallel} \left[\left(\frac{5}{2} T_i + \frac{m}{2} v_{\parallel}^2 \right) (n_e + n_o) v_{\parallel} \right] \\ - \nabla_{\parallel} (k_{\parallel}^i \nabla_{\parallel} T_i) + \nabla_{\parallel} \left[\left(\frac{5}{2} T_i + \frac{m}{2} v_{\parallel}^2 \right) \left(\frac{B_{\phi}}{B_{\theta}} \right) n_o v_{o\zeta} \right] - \nabla_{\perp} [(k_{\perp}^i + k^o) \nabla_{\perp} T_i] \\ - \nabla_{\parallel} \left[\left(\frac{B_{\phi}}{B_{\theta}} \right)^2 k^o \nabla_{\parallel} T_i \right] - \nabla_{\perp} \left[\left(\frac{5}{2} T_i + \frac{m}{2} v_{\parallel}^2 \right) (D \nabla_{\perp} n_e - n_o v_{o\perp}) \right] \\ - \frac{4}{3} \eta_{\parallel} (\nabla_{\parallel} v_{\parallel})^2 - \eta_o \left(\frac{B_{\phi}}{B_{\theta}} \nabla_{\parallel} v_{\parallel} \right)^2 = -v_{\parallel} \nabla_{\parallel} (n T_e) + C_{ei}, \end{aligned} \quad (5)$$

$$\frac{\partial n_e}{\partial t} + \nabla_{\parallel} (n_e v_{\parallel}) - \nabla_{\perp} (D \nabla_{\perp} n_e) = S N. \quad (6)$$

$$\begin{aligned} \frac{\partial}{\partial t} [m(n_e + n_o) v_{\parallel}] + \nabla_{\parallel} [m v_{\parallel} (n_e + n_o) v_{\parallel}] + \nabla_{\parallel} \left(\frac{B_{\phi}}{B_{\theta}} v_{\parallel} m n_o v_{o\zeta} \right) - \frac{4}{3} \nabla_{\parallel} (\eta_{\parallel} \nabla_{\parallel} v_{\parallel}) \\ - \frac{B_{\phi}}{B_{\theta}} \nabla_{\parallel} \left(\eta_o \nabla_{\parallel} \frac{B_{\phi}}{B_{\theta}} v_{\parallel} \right) - \nabla_{\perp} (\eta_o \nabla_{\perp} v_{\parallel}) + \nabla_{\parallel} [n_e T_e + (n_e + n_o) T_i] \\ - \nabla_{\perp} (m n_{\parallel} D \nabla_{\perp} n_e) + \nabla_{\perp} (m v_{\parallel} n_o v_{o\perp}) = 0. \end{aligned} \quad (7)$$

$$\frac{\partial n_o}{\partial t} + \nabla_{\parallel} (n_o v_{\parallel}) + \nabla_{\parallel} \left(\frac{B_{\phi}}{B_{\theta}} n_o v_{o\zeta} \right) + \nabla_{\perp} (n_o v_{o\perp}) = -S N. \quad (8)$$

$$\frac{\partial}{\partial t}(mn_o v_{o\perp}) + \nabla_{\perp}(mv_{o\perp}n_o v_{o\perp}) + \nabla_{\perp}(n_o T_o) = mn_o \nu_{cx}(v_{\perp} - v_{o\perp}), \quad (9)$$

$$\begin{aligned} \frac{\partial}{\partial t}(mn_o v_{o\zeta}) + \nabla_{\parallel}\left(\frac{B_{\phi}}{B_{\theta}}mv_{o\zeta}n_o v_{o\zeta}\right) \\ + \frac{B_{\phi}}{B_{\theta}}\nabla_{\parallel}(n_o T_o) = mn_o \nu_{cx}(v_{\zeta} - v_{o\zeta}). \end{aligned} \quad (10)$$

The off-diagonal terms of the momentum flow tensor have been neglected in Eqs. (9) and (10). Retaining these terms, if necessary, presents no problems.

It is easily seen that in the limit of the large charge-exchange collision frequency ν_{cx} , Eq. (9) becomes

$$n_o v_{o\perp} = -\frac{1}{n_e m \langle \overline{\sigma v} \rangle_{cx}} \nabla_{\perp}(n_o T_o), \quad (11)$$

which is in agreement with the neutral particle flux derived in Ref. 3. Here $v_{\perp} = 0$ has been assumed for the plasma radial velocity. The same applies to Eq. (10), which balances the parallel plasma flow.

Here n_e is the electron (or hydrogen ion) density, n_o is the neutral (atom) density. T_e and T_i are the electron and ion temperatures, respectively, T_o is the neutral temperature. m is the ion mass, and $v_{\parallel}$ the parallel ion velocity. While the neutral atom temperature and the parallel velocity are assumed to be the same as for the ions, the radial neutral velocity, $v_{o\perp}$, and the normal velocity, $v_{o\zeta}$, are not. The corresponding plasma velocities $v_{\perp}$ and v_{ζ} are set to zero. The usual symbols are used for the transport coefficients. D is the plasma (particle) diffusion coefficient, $k_{\parallel}$, $k_{\perp}$, and k^o are the plasma and neutral heat conductivities, respectively, and $\eta_{\parallel}$ and η_o are the corresponding viscosities. C_{ei} is the electron to ion collisional energy transfer, and $\nu_{cx} = n_e \langle \overline{\sigma v} \rangle_{cx}$ is the charge-exchange frequency. $SN = n_o n_e \langle \overline{\sigma v} \rangle_{iz} - n_e^2 \langle \overline{\sigma v} \rangle_{rc}$ is the electron (ion) source due to ionization and recombination, and SE_e is the electron energy source. B_{θ} and B_{ϕ} are the poloidal and toroidal components of the magnetic field, respectively. The data for the atomic reaction rates are from Janev et al. [5].

Boundary Conditions

The following boundary conditions have been used close to the plate

$$Q_{\parallel e} = \left(\frac{5}{2}\right) T_e n_e v_{\parallel}, \quad (12)$$

$$Q_{\parallel i} = \left(\frac{5}{2}\right) T_i n_e v_{\parallel}. \quad (13)$$

and

$$[n_e(T_e + T_i)] = 0 \quad (14)$$

at the sheath. Equations (12) and (13) are considered valid about one charge-exchange mean-free path away from the plate. This distance is short enough so that the sources between the computational boundary and the plate proper can be neglected. The condition in Eq. (14) results in a close to sonic flow speed at the sheath when the flow is generally subsonic, but does not artificially slow down an already supersonic flow. The neutrals from the plate have a zero temperature and momentum. For the upstream boundary, it is assumed that the stagnation point is at the top of the scrapeoff. Zero velocity is specified there together with a zero gradient for all the scalar variables.

Method of Solution

The finite difference equivalent of Eqs. (4) through (10) is solved using the Alternate Direction Implicit (ADI) method implemented in the PLANET code [6].

The Problem and the Procedure

The plasma-neutral model has been used to study the problem of peak heat flux reduction for the ITER divertor. The computational mesh used for the divertor region is shown in Fig. 2. The divertor is bounded by solid side-walls and a plate at the bottom. The inner-wall coincides with the separatrix and the outer one with the outermost flux surface. The walls and the plate have a recycling coefficient $\mathcal{R} = 1$. Hydrogen gas has been injected into the divertor at the plate, over a period of time, forming a gaseous divertor. The effect on the plasma and the energy flux to the plate has been studied.

Results

Solutions of the model equations have been obtained for the outer scrape-off of ITER and the shortened divertor shown in Fig. 2. A power flux of 220 MW is injected into the outer scrape-off corresponding to approximately 330MW for the inner and outer scrape-off combined. The divertor chamber has been filled with various amounts of hydrogen gas. Only one typical solution is presented here. All the solutions are characterized by a low temperature, ionization-free region in front of the plate, and differ only in the size of this region, which is proportional to the amount of gas injected.

The neutral gas is therefore ionized within a narrow band, several centimeters away from the plate at the point where the plasma temperatures exceeds $\simeq 1$ eV. This is illustrated in Fig. 3 which shows the ionization rate and the electron temperature as a function of the distance from the plate along the separatrix. Ionization alone, as has been pointed out, lowers the temperature but not the total energy flux. The reduction of the total energy flux, $Q_{\parallel}^t$ defined by Eq. (3), can be achieved by the hydrogen line-radiation, in particular, by the radiation associated with recombination, which removes the term $13.6 \text{ eV } \Gamma_{\parallel}(s)$ in Eq. (3). The crucial feature of the result presented here is that the recombination-radiation

region has been moved away from the plate, which is essential in order for spreading the energy evenly over the plate and the side walls. This recombination-radiation region, to a large extent, overlaps the ionization region as seen in Fig. 4, which also shows the effect on the total energy flux $Q_{||}^t$. The result is that the energy reaches the plate only in the form of radiation.

The ionization and recombination-radiation fronts are shown in 2-D in Figs. 5 and 6. The location of these fronts can be easily regulated. The ionization-free region contains mostly neutral gas and a low temperature plasma of low enough density to keep the recombination rate at a very low level. The neutral and plasma densities are shown in Fig. 7 together with the ion temperature.

The mid-plane plasma density is $1.4 \times 10^{14} \text{ cm}^{-3}$, which is an overestimate since the kinetic effect in the electron heat conduction have been neglected. This value and the qualitative features of the solution are in agreement with the analytic estimates of Krasheninnikov and Pigarov [7] who also discuss the effect of opacity of the neutral gas on the radiation losses.

The mid-plane density is found to be only a weak function of the input power because the radiation losses (in the model) increase very rapidly (approximately as n_e^3) with plasma density.

So far no truly steady-state solutions have been obtained with Eqs. (4) - (11). This appears to be the result of the incomplete overlap of the ionization and recycling regions, combined with the fact that the plasma can not flow through the neutral gas due to the assumption of equal parallel velocities for the ions and the neutral atoms. (Neutrals diffuse into the plasma but not vice versa.) Adding to the model, anomalous plasma transport in the normal (ζ) direction may recover the steady-state solutions. The fact that the equations have been solved (as a function of time) assuming zero particle flux from the main plasma, no pumping and a fixed amount of neutral gas may also be partly responsible for the lack of a true steady state. However, the fluctuations of the solution around an average value are small, i.e., the excursions of the ionization front (in the poloidal plane) are of the order of 1 cm.

Conclusion

The gaseous divertor appears to offer an almost ideal solution to the divertor power load problem. For it to work in practice, the radiation front has to be tens of cm, 30 cm to 60 cm in the case of ITER, away from the plate. This is easily achievable (theoretically) by adding more gas. It seems likely that the side walls can also be moved away from the radiation region without affecting the recombination process. In practice this could be done by leaving the side-walls of this simulation intact but removing the plate and replacing it with a chamber of approximately 120 cm diameter. This would bring the total length of the divertor to $\cong 170$ cm, which is within the design limits.

The problems with the gaseous divertor can be expected near the separatrix in the "private flux" region, where it may be difficult to maintain a sufficiently high plasma pressure

to prevent the neutral gas from escaping. However, the gaseous divertor in this case is not filled with a pure neutral gas, as commonly perceived, but rather with a weakly ionized plasma which moves freely along the magnetic field lines and diffuses only slowly across them. Simulations in a more realistic geometry are planned to answer this question. The model does not allow for microinstabilities which, however, may even be beneficial.

The more serious deficiency is that the opacity of the neutral gas to the hydrogen radiation has not been taken into account. For the radiation transport to be computed, the ionization, recombination, and the radiation loss rates will have to be re-evaluated, taking into account the photon density. This should not change the results reported here in an essential way but may have important quantitative consequences.

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Fig. 1. The (ϕ, θ) and (ξ, ζ) coordinate systems. ϕ is the toroidal angle and θ is the poloidal angle. The ξ is synonymous with the parallel coordinate. All the vectors lie within a poloidal flux surface.

Fig. 2. The mesh used to model the ITER divertor. The divertor has been shortened by a factor of 2 from the standard divertor design. Only the region between the separatrix and an arbitrary outer wall has been considered.

Ionization Rate and Te Flux Surface at the Separatrix r20a24

Fig. 3. The ionization rate $n_e < \bar{\sigma} v >_{iz}$ and the electron temperature along the separatrix as a function of distance from the plate.

Ionization and Recombination Rates and Energy Flux Along Separatrix r20a24

Fig. 4. The ionization rate, recombination rate $n_e^2 < \bar{\sigma} \bar{v} > r_c$ and the total (parallel) energy flux $Q_{||}^t$ along the separatrix. The plate is at the left.

Fig. 5. A gray-scale plot of the ionization rate within the divertor volume. The separatrix is on the left and the plate at the bottom.

Fig. 6. A gray-scale plot of the recombination-radiation rate for the same volume as in Fig. 5. The region is well separated from the plate.

Temperature and Densities Along the Separatrix r20a24

Fig. 7. The neutral (atom) density, n_o , plasma density, n_e , and the ion temperature, T_i , along the separatrix. The distance is measured from the plate.

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