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Effect of core-edge coupling on operation regimes of ITER-like reactor

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Abstract

A model has been developed which is capable to describe in a self-consistent way plasma dynamics in the center and edge region of fusion reactor. The core plasma is treated in the frame of 1D radial transport model whereas in the edge the 2D multifluid code EPIT has been used. The EPIT code solves in the slab geometry the MHD equations for densities and velocities for all ions species as well as for electron and ion temperatures. In the paper the iteration scheme leading to steady state solution of coupled core and SOL system has been analyzed and tested numerically. The model has been used to investigate operation regimes of the ITER-FEAT tokamak.

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1. Introduction

In the high power and long pulse operation regimes for magnetic confinement fusion devices the power load to the target plates is determined by strong interactions between the core and edge regions. In order to reduce the heat load to divertor plates additional losses are required to spread the heat over a wider area. It can be achieved by efficient impurity radiation in the SOL and the core region. The intrinsic impurities released from the first wall and divertor plate can penetrate into the main plasma column and reduce the heat flux to the SOL. The heat flux to the divertor in turn determines the impurity production. Thus it seems necessary to treat core plasma and boundary layer self-consistently.

In the recent years the necessity of the global modelling of the plasma dynamics in the core and the SOL region has been widely recognized. Various efforts have been made in the development of global transport codes [1–3]. In the previous papers [3,4] the authors analyzed the steady states of fusion reactors in the frame of the simple 1D radial transport model for the bulk plasma coupled to 1D analytical model for the boundary layer. The analyses presented were not fully satisfactory due to oversimplified model of the SOL, because the proper treatment of the edge requires 2D modelling of the boundary layer.

In the present paper the code COREDIV is presented which has been developed to analyze self-consistently the core and the edge plasma of tokamak-reactor. The model consists of the 1D radial transport in the core plasma which has been coupled to the 2D multifluid code EPIT describing plasma transport in the edge. The EPIT code is based upon the MHD equations for densities and velocities for all ions species and equations for the electron and ion temperatures. In the SOL model for the sake of simplicity the drifts and currents have not been included and equations of the model are solved in the slab geometry. The model presented in the paper can be considered as the intermediate step between complicated numerically and computer time consuming codes and the simple approach previously used by the authors. Due to the complexity of the problem and different time

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scales for the core and SOL plasmas special care should be taken to develop an efficient iteration procedure. In the paper the iteration scheme leading to steady state solutions of the coupled core and SOL system has been analyzed and tested numerically. Calculations have been performed to investigate the operating regimes of the ITER-FEAT tokamak. The influence of the core-SOL coupling due to the production of the sputtered impurities has been analyzed for low Z (carbon) and middle Z (nickel) plasma facing components.

2. Physical model

The model is based on the 1D radial transport of the plasma energy, main plasma and impurity ions in the core and on the 2D multifluid model for the scrape of layer and the divertor region. Sputtering and self-sputtering processes as well as radiation losses caused by the intrinsic impurity ions are included self-consistently in the model. The model used for describing the core plasma was presented in Refs. [3,4] and only main points of the model are pointed out here. The plasma temperatures in the core (T_e, T_i) are determined by a solution of the heat conduction equations. The energy sources are due to the Ohmic heating, the alpha heating power and the additional heating whereas the losses are caused by Bremsstrahlung and line radiation. The electron and ion energy fluxes are defined as

$$q_{e,i} = -n_{e,i} C_{e,i} \frac{a^2}{\tau_E} \left(5.5 - \frac{r}{a}\right)^{-1} \frac{\partial T_{e,i}}{\partial r}, \tag{1}$$

where τ_E is the energy confinement time defined by the ELMy H-mode scaling law [5], $n_{e,i}$ is the electron (ion) density, a is the plasma radius and $C_e = 2C_i$ is an adjustable coefficient. The value of $C_e = 1.8$ was chosen in order to get an agreement between the value of the energy confinement time calculated from the bulk plasma solution and given by the scaling law. In the scaling law the impurity radiation in the power losses are not included. In the future works we intend to replace the simple transport model by more realistic, e.g. predictive transport model presented in [6]. Multifluid radial transport of sputtered impurity ions is considered in the model [3]. The fluxes of impurity ions for each ionization state are the sum of neoclassical [7] and anomalous fluxes. It is assumed that all impurity ions have the same temperature as the bulk ions. For simplicity, the seeded impurities have been assumed to be distributed according to the corona equilibrium and to the prescribed space profile given by $n_z^{inj} = (n_e/n_{es})^{\alpha_z} n_{zs}^{inj}$. The peaking factor $\alpha_z = 0.5$ was assumed in order to achieve a flat Z_{eff} radial profile [8] and n_{es} (n_{zs}^{inj}) is the plasma (injected impurity) density at the LCMS. The profile of the main plasma ions has been modelled by the solution of the radial diffusion equation with the diffusion coefficient of the form $D_i = D_{i0}/(1 + 2(r/a)^2)$ and the source $S_i = S_{i0}[1 - \exp(-(r/a)^{16})]$ yielding flat density profiles [5]. The electron density is defined by the neutrality condition and the value of S_{i0} is determined by the condition that the averaged electron density is prescribed.

In the SOL we use the 2D boundary layer code EPIT which is primarily based on the Braginski [9] transport equations. The model has been described elsewhere [10,11] and only main points of the model are discussed in the paper. The transport along field lines is assumed to be classical whereas the radial transport is anomalous with prescribed transport coefficients of the order of Bohm diffusion. The transport equations are written in a rectangular geometry corresponding to radial and poloidal directions. It is assumed that all ion species have the same temperature. The equations for different fluids are coupled by electrostatic, friction and thermal forces as well as by atomic processes such as collisional ionization, recombination, excitation and chargie exchange. The dynamics of fuel atoms and impuritiy neutrals is described by an analytical model taking into account sputtering and self-sputtering processes at divertor plates. In the case of carbon plate, for simplicity, the chemical sputtering has been neglected. The hydrogen recycling is taken into account self-consistently in the model and the recycling coefficient R is an external parameter. For the sake of simplicity we have omitted the contribution of the injected impurity to the SOL radiation. The proper treatment of the seeded impurities requires solving for them the 2D transport equations and it is left for the future considerations. The standard sheath boundary conditions are imposed at the plate whereas at the wall, the boundary condition are defined by imposing the decay lengths [10,11].

3. Iteration procedure

In order to solve the coupled system of equations for the core and boundary plasma a special numerical procedure had to be developed. The method takes into account the fact that both regions are coupled only by requirements of continuity of the plasma parameters and fluxes on the separatrix. In particular the iteration scheme used in the code COREDIV can be described by the following steps:

Stage 1: This step is used to initiate the plasma parameters in the boundary layer. A steady state solution is found in the SOL using the boundary layer code EPIT for a given values of the main ions particle flux and the plasma energy fluxes at the separatrix. For impurity ions, the total particle flux through the separatrix equals to zero, which means that impurity ions density follow the corona equilibrium at the core boundary [10].

Stage 2: Now the calculations of the plasma parameters in the core are performed. The boundary values of the ion and electron temperatures and plasma and impurity densities (for all ionization stages) at the separatrix are taken from the SOL part of the code. The prescribed number of the iteration steps in the core N^{c}_{step} is performed for the partially decoupled and linearized equations. The only coupling is due to atomic processes which connect the different ionization levels of impurity ions.

Stage 3: In this step of calculations the plasma parameters in the boundary layer are adjusted. The values of energy and particle fluxes at the separatrix obtained from the core module of the code are used as the new boundary condition for the boundary layer calculations. The prescribed number of time steps in the SOL ($N^{\text{SOL}}_{\text{step}}$) is performed leading to new boundary condition for the core part of the code.

The stages 2 and 3 are consecutively repeated until convergency is reached. The freedom in the choice of the number of the iteration steps N^{c}_{step}, $N^{\text{SOL}}_{\text{step}}$ can be used to improve the convergency. The above described procedure turn out to be robust and efficient in finding the steady state solution of the problem.

The convergence of the iteration procedure is presented in Fig. 1 where the variations of energy and particle fluxes on the separatrix with respect to the number of iteration steps are shown. It appears that in order to obtain the stationary solution within the reasonable computational time the number of time steps

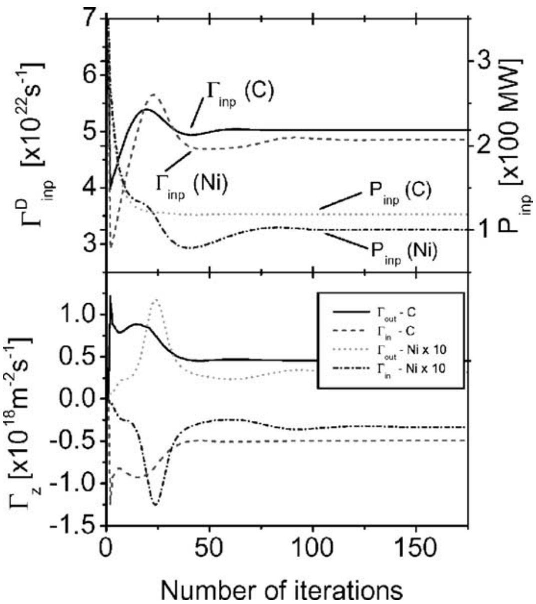

Fig. 1. Changes of the boundary conditions at the separatrix during iterations. The impurity fluxes Γ_{in} and Γ_{out} correspond to the sums over various ionization levels of the positive and negative fluxes (with respect to core), respectively. P_{inp} is the total energy flux to the SOL and Γ^{D}_{inp} is the main ions flux to the SOL.

(iterations) for the SOL calculations $N^{\text{SOL}}_{\text{step}}$ should be much larger (factor 5 or more) than the number of iterations in the core N^{c}_{step}.

The results are presented with the starting point corresponding to zero density of impurities in the core leading to high initial temperatures in the plasma center and high energy fluxes to the SOL. In consequence, the large production of impurity and rapid fall off of the temperatures in the core can be observed. It should be noted that sometimes in this phase the temperature inside the core becomes so small that the burning of the plasma is stopped and the iteration process does not lead to the final solution.

4. Results of numerical simulations

We have simulated stationary discharges of ITER-FEAT tokamak for two characteristic wall materials (C, Ni) and argon has been chosen as injected impurity. It should be noted that we have neglect the effect of the chemical sputtering for the carbon plate and that only physical sputtering at the divertor plates has been considered. An ITER-FEAT [5] reference case ($R_{\text{T}} = 6.20$ m, $a = 2.0$ m, $I_{\text{p}} = 15$ MA, $\langle n_{\text{e}} \rangle = 1.01 \times 10^{20}$ m^{-3}, 3.2% He) has been assumed. Prescription of the averaged electron density $\langle n_{\text{e}} \rangle$ and recycling coefficient R ($= 0.99$ in our calculations), together with the injected impurity concentration determines the self-consistent solution of the problem.

In order to analyze the operating regimes of ITER-FEAT tokamak we have changed the particle transport properties in the core by taking different values of the background ions diffusion coefficient $0.25 \leqslant D_{\text{i0}} \leqslant 2.7$ m^2/s. The energy flux to the SOL (P_{inp}), the alpha power (P_{α}), the heat load to the plates (P_{plate}), the total energy losses relative to the total input power (P_{loss}), the line radiation losses in the core ($P^{\text{core}}_{\text{lin}}$) and in the edge ($P^{\text{edge}}_{\text{lin}}$), the averaged effective charge (Z_{eff}) and the total sputtered impurity density at the separatrix (n_{zs}) are presented as functions of the edge plasma density n_{es} in Fig. 2. In all calculations the additional heating $P_{\text{add}} =$ 30 MW was assumed.

First we would like to point out differences and similarities with the old (1D-analytical) model for the SOL described in Ref. [3]. In order to compare the results of the present model with the old one the same quantities for Ni plate calculated by 1D core-edge model are also shown in Fig. 2. The comparison between 1D and 2D results clearly demonstrates the necessity of using 2D description in the edge. The essential difference between the old and new model comes from the fact that impurity retention in the SOL is different in both models. The 1D model is too simplified to describe correctly the impurity transport in the edge and consequently the radiation losses in the SOL were underestimated in our

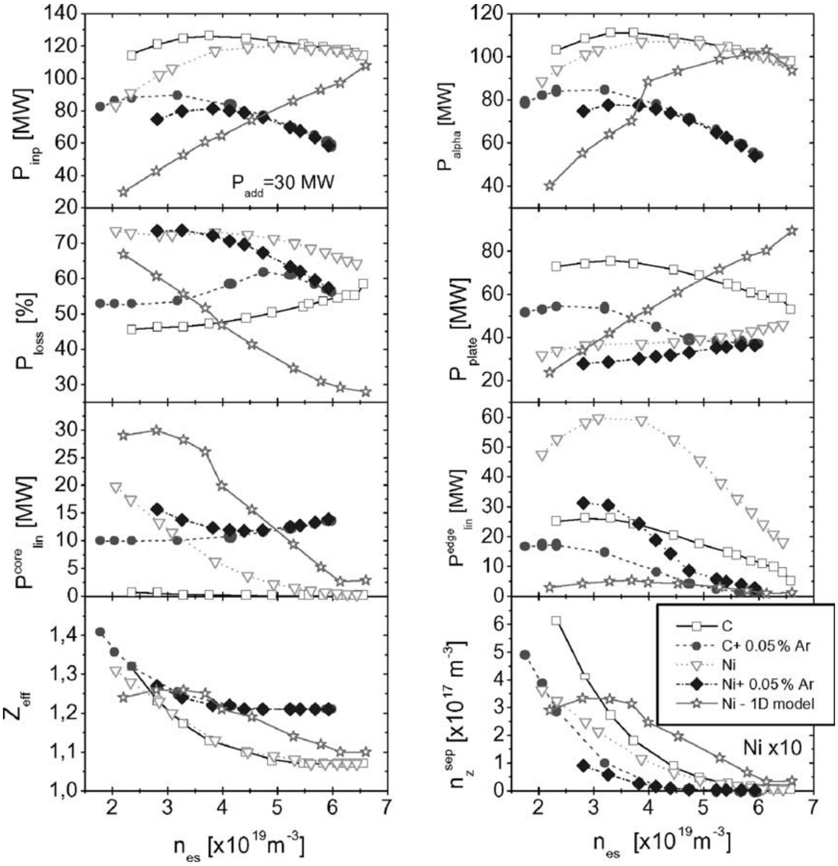

Fig. 2. P_{inp}, P_{α}, P_{loss}, P_{plate}, P_{lin}^{core}, P_{lin}^{edge}, Z_{eff} and n_{zs} versus edge plasma density n_{es} for carbon and nickel plates.

previous calculations [3,4]. The lower impurity radiation in the edge for 1D model modifies the energy balance in the whole tokamak plasma and induces reduction of the alpha power for small edge densities which is required in order to obtain the self-consistent solution for the coupled core-edge system. Another very important difference with the old model is connected with the distribution of impurity ions at the separatrix. In our old model ions were distributed at the LCMS according to the corona equilibrium (for given total impurity density n_{zs} calculated in the SOL). Usually, similar assumption is used in the 2D edge codes [10]. It comes out from the self-consistent solution that such assumption is wrong, particularly in the case of nickel ions. For the typical edge temperatures ($T_{es} \approx 140$ eV) almost all ionization stages of Ni ions are present and are equally important at the separatrix.

However there are also strong similarities between both models. For both edge descriptions the influence of the sputtered impurities on the overall energy balance is strong due to the coupling between the core and SOL region. In the case of Ni plates the coupling with the SOL manifests itself by the strong line radiation of the sputtered Ni ions. For the C plate the sputtered carbon ions increase the dilution of the core plasma and simultaneously the line radiation is small. The edge-core coupling is present for all considered edge plasma densities but its effect is weaker, of course, for higher densities when the sputtering is reduced and impurity retention improved. Also the effect of additional (injected) impurity (0.05% Ar) is the same as in the old model. The presence of the additional radiator in the core leads to the changes in the core energy balance and reduction of the alpha power and consequently the heat load to the plate is reduced. Additionally, with injected impurities the solution with burning plasma exists only for edge density n_{es} in the interval bounded by two limits (similarly as in Refs. [3,4]): the low density limit being connected to the screening efficiency of the SOL and the upper density limit imposed by the SOL radiation. Thus the operation region of ITER, defined by admissible values of the edge plasma density might be strongly reduced.

The 2D results demonstrate that nickel as the plate material is much better as far as the reduction of the power load to the plate is concerned. For both materials

Ni and C the alpha power, the power flowing to the SOL and power loads to the plates depend weakly on the edge plasma density. For Ni facing components energy losses are high (up to 70%) and the power load to the plates is at the acceptable level (~30) MW. In the case of Ni plate introduction of argon impurity does not modify the power load to the plate significantly but the plate erosion is reduced and, as the consequence, the line radiation of Ni ions is smaller. The effect of the additional impurity is equivalent to the shifting of the part of the edge radiation to the core and simultaneous reduction of the alpha power and the plate erosion. Therefore the additional radiator might be used in order to control the ignition conditions as well as the wall erosion. For the C plate the reduction of the power load to the plate below the required value of 30 MW can be achieved only in the presence of seeded impurity and for high values of the edge plasma density when the edge-core coupling is weak and the hydrogen radiation in the divertor volume is significant. Interestingly, at this conditions there are almost no differences between low Z (C) and middle Z (Ni) facing components.

5. Conclusion

An efficient iteration procedure has been developed which allows to solve self-consistently the 1D radial transport in the core together with the 2D transport in the plasma edge. The numerical code COREDIV seems to be very efficient and consuming relatively small amount of the computer time. Main part of the computation effort is devoted to the time iterations in the SOL modules of the code. Thus the proper choice of $N_{\mathrm{step}}^{\mathrm{SOL}}$ is important for the optimization of the computation time. The numerical calculations show that usually the value of $N_{\mathrm{step}}^{\mathrm{SOL}}$ smaller then 20 can be taken. Despite of using the 2D model for the SOL the COREDIV code is still suitable for fast scans of the parameter space of the tokamak type reactor.

With the code COREDIV numerical calculations have bee performed for ITER-FEAT tokamak. Results of calculations show that stationary solutions with burning plasma can be achieved in ITER-FEAT for both low Z (C) and middle Z (Ni) plate materials. However with the carbon plate the power load to the divertor is too high and can be reduced only by introducing additional impurity. For nickel the heat load to the target is acceptable and the plate erosion can be reduced by the injection of argon. It should be stressed that with the additional impurity the operation range of the edge plasma density might be strongly reduced.

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