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RADIATIVE DIVERTOR MODELING STUDIES

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INTRODUCTION

A two-dimensional fluid code called UEDGE is used to simulate the edge plasma in tokamak divertors and to evaluate methods for reducing the heat load on divertor plates by radiating some of the power before it reaches the plates. UEDGE is a fully-implicit code being developed jointly by us, D. A. Knoll and R. B. Campbell. For these studies, UEDGE uses a banded matrix solver [1-2] and a fixed-fraction impurity model. Work is presently underway with Knoll and Campbell to include a memory-efficient iterative solver [3] and a model of impurity transport [4]. Simulations of the proposed TPX device [5] show that a few percent nitrogen concentration in the scrape-off layer can radiate up to 80% of the divertor power, thus reducing the peak heat flux and electron temperature at the divertor plate to acceptable values. A comparison of the neutral gas distribution from UEDGE with results from the DEGAS Monte Carlo neutrals code [6] confirms the validity of our fluid neutrals model.

MODEL DESCRIPTION

The UEDGE model includes classical collisional transport [7] along the magnetic field, classical cross-field plasma flow and anomalous cross-field transport. Neutral hydrogen that evolves from the divertor plate as a consequence of recycling or gas puffing is modeled as a two-species fluid; one species represents Franck-Condon neutrals generated by molecular breakup, and another species represents energetic neutrals due to charge-exchange processes in the plasma. Rate parameters for ionization, recombination and charge-exchange processes are obtained from an atomic physics package [8] that includes density-dependent multi-step ionization processes for hydrogen [9].

The fluid model equations are implemented numerically as described in References [1,10,11]. Orthogonal mesh surfaces in our model are based on MHD equilibria from the TFQ code [12]. Figure 1 is a schematic representation of the double-null geometry for TPX that illustrates the configuration for results presented here. We assume up/down symmetry, but allow particles and energy to flow between the inboard and outboard halves of the core and private flux regions.

Fixed density and temperature boundary conditions are used at the innermost core plasma flux surface in our model. The boundary conditions at the outermost open flux surface are zero radial particle flux for ions and fixed temperature for both ions and electrons. For neutrals, the wall albedo (reflection coefficient) is fixed, typically at a value of 0.95 to simulate pumping of neutrals. Boundary conditions at the innermost flux surface in the private flux region under the x-point are the same as above except that fixed temperatures are replaced by zero energy flux conditions.

We use sheath boundary conditions at the divertor plates with energy transmission factors $\delta_i = 2.5$ and $\delta_e = 2.0 + \kappa$ where κ is the sheath potential drop in units of the electron temperature. We allow the ion parallel flow velocity at the plate to be supersonic if it approaches at a supersonic rate. Separate recycling coefficients for the Franck-Condon and charge-exchange neutral components specify the neutral sources at the divertor plates as a fraction of the incident ion flux.

Non-equilibrium radiative losses due to impurities are included in the electron energy balance equa-

tion; the energy loss rate is of the form $n_e \cdot n_Z \cdot L_Z(T_e, n_o/n_e, n_e\tau_{res})$, where n_Z is the impurity density and the radiative loss rate L_Z depends on electron temperature T_e, impurity charge exchange on neutral hydrogen of density n_o, and the residence time τ_{res} of the impurity atoms in the plasma. We use a table look-up for the radiative loss rate in UEDGE. The table data are obtained from a series of runs with the MIST code [8] which solves for the impurity charge state distribution, including the effect of charge exchange on neutral hydrogen and finite residence time in the plasma. The radiation rates for nitrogen are shown in Figure 2. One sees that the loss rate is enhanced over the coronal equilibrium rate (lowest curve) for electron temperatures greater than 10 eV. For the simulations presented here we assume a fixed spatially uniform impurity concentration, n_Z/n_e, and we set $\tau_{res} = 1$ sec, so non-equilibrium radiation effects are mainly due to charge exchange.

RESULTS

We present TPX simulation results on the effect of various levels of impurity radiation. We neglect drifts and net electrical current flow between divertor plates because these effects destroy the assumed up/down symmetry of the TPX plasma, requiring simulation of the full double-null geometry. The core plasma boundary values were fixed at $n_{core} = 1.69 \times 10^{19}$ m^{-3} and $T^e_{core} = T^i_{core} = 300$ eV. Anomalous perpendicular transport coefficients are the standard ITER-like values, $\chi^e_\perp = 3\chi^i_\perp = 3D_\perp = 2.0$ m^{2}sec^{-1}. These values yield 6.4 MW of power crossing the lower half of the separatrix from the core into the scrape-off layer; 5.3 MW via electrons and 1.1 MW via ions. We assume 100% recycling at the divertor plates and 95% recycling of neutrals at the radial boundaries. Results are given for various values of the impurity (nitrogen) fraction.

Figure 3 shows results from a scan of the impurity fraction. The total heat flux entering the sheath at the divertor plates decreases by about 80% as the impurity fraction is increased to 6% of the plasma density. Correspondingly, the radiated power due to the nitrogen impurity increases to 4 MW. The Hydrogen radiation decreased from 1.2 MW to 0.8 MW, and the radial ion heat loss was 0.2 MW. The peak heat flux and temperature at the outboard plate are both strongly reduced by the impurity radiation as shown by the radial profiles in Figures 4 and 5.

Plasma profiles along a flux surface just outside the separatrix in the outboard leg of the divertor are shown in Figures 6 and 7. The left edge of each figure (at ≈ 2.7 m) is the x-point position and the right edge (at ≈ 3.3 m) is the divertor plate. The solid lines show the results with no impurities and the dashed lines results with 6% nitrogen. As shown here, at high impurity fraction, the peak of the radiation zone moves upstream away from the divertor plate to where the electron temperature is above 10 eV. This is due to the strong dependence of the radiation rate on electron temperature shown in Figure 2. We also find that the peak of the hydrogen ionization source moves upstream, and the ion flow becomes supersonic near the plate for this case.

We tested the validity of our fluid neutrals model by comparing the neutral density distribution with results from the DEGAS Monte Carlo code. The DEGAS code used the geometry and plasma distribution from UEDGE. The comparisons shown in Figure 8 used the same TPX input parameters as described above, but on a radially extended mesh with no impurities present. We see that the 2-species fluid model, with flux limits imposed, tracks the DEGAS neutral density along the entire length of the divertor leg and even up to the outboard midplane. Without flux limits on the neutrals, the 2-fluid model yields a higher neutral density near the x-point and the 1-fluid model underestimates the neutral density there.

ACKNOWLEDGMENTS

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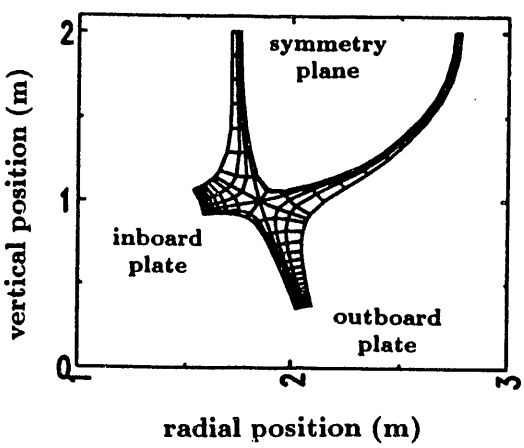

Fig. 1: TPX mesh configuration

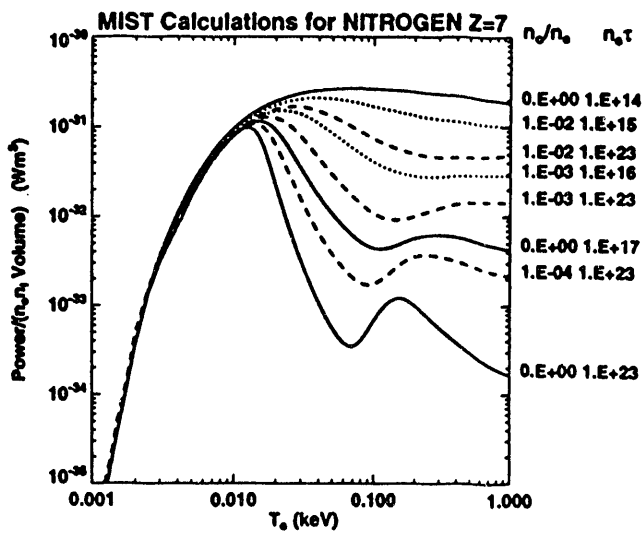

Fig. 2: Nitrogen radiative rates

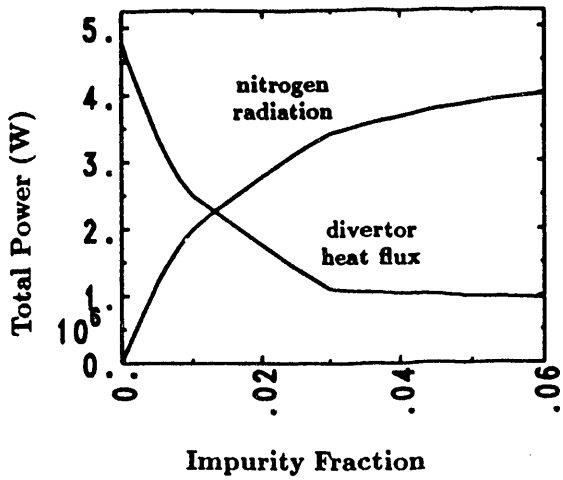

Fig. 3: Effect of nitrogen impurity

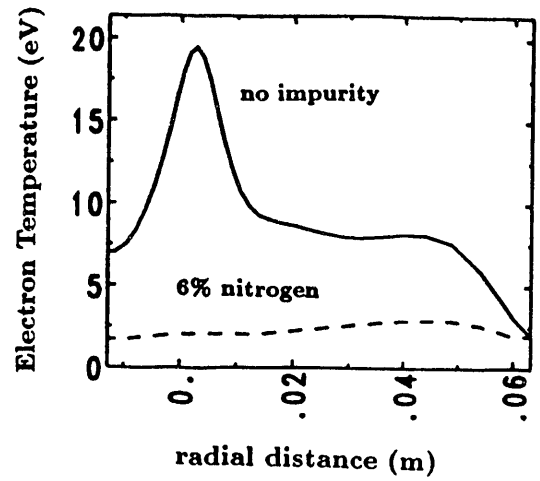

Fig. 4: Outboard divertor plate T_e

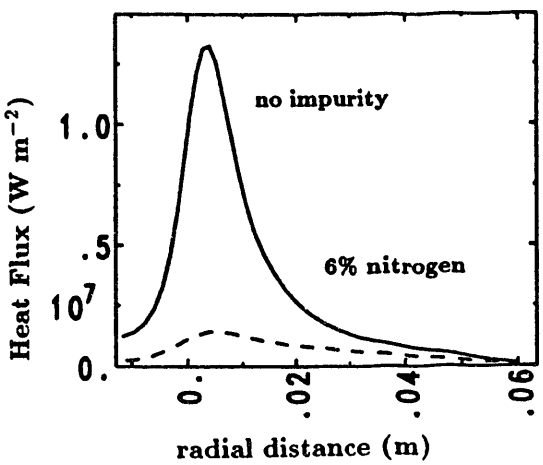

Fig. 5: Outboard divertor plate heat flux

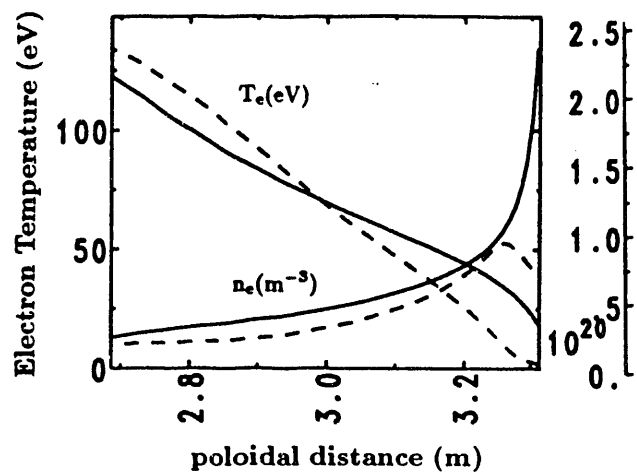

Fig. 6: Outboard divertor separatrix profiles

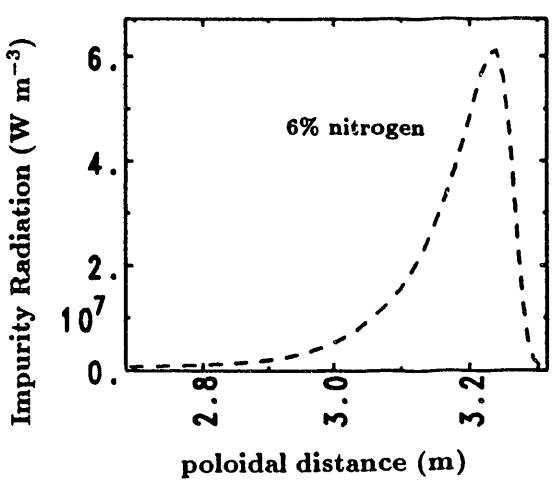

Fig. 7: Outboard divertor separatrix radiation

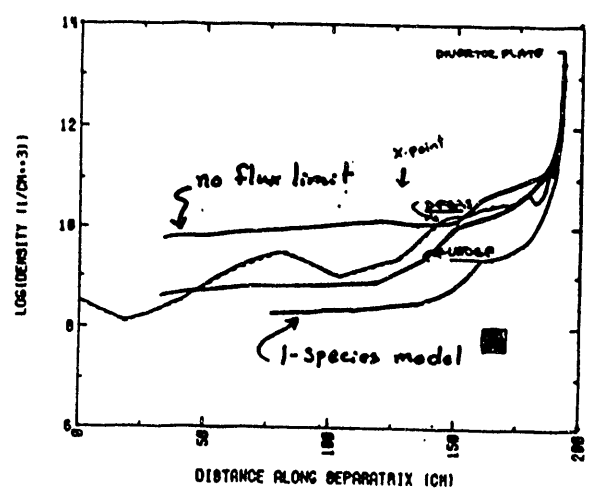

Fig 8: Neutrals model comparison

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