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THE INVESTIGATION OF PLASMA RECYCLING AT SURFACES USING A SELF-CONSISTENT MODEL FOR THE WALL INTERACTION

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ABSTRACT

A computer model is proposed for the description of plasma-wall interactions in a Tokamak. The model is based on the classical transport equations used by Düchs and others. However new boundary conditions have been proposed which require fewer arbitrary assumptions and which allow the values of the plasma density, electron and ion temperatures at the plasma edge to vary.

The model has been used to compare the evolution of a plasma for a variety of wall conditions, including the cases of a total absorbing wall, and a reflecting wall with an adsorbed gas layer. The principal result of this model is that the particle containment time is significantly reduced by the plasma-wall interaction. This reduction is associated with only a small change in the plasma temperature which is confined to the boundary layer.

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1. INTRODUCTION

The importance of wall interactions, which result in the injection of neutral gas or other impurities into plasma containment devices is being increasingly recognised, and their importance will increase as containment devices increase in size towards reactor conditions. Thus it is important to have a model of the plasma wall interaction to understand how they will scale with the plasma confinement system, and to find out how the deleterious effects can be minimised.

Experiments on the ATC Tokamak[1] show that any model must include the interior of the plasma as well as the surface layers. The present model is a modification of the transport codes originally developed for the determination of the diffusion coefficient in tokamak plasmas from the experimental observations, a fuller description of the model will be published elsewhere[2].

The geometry of the model is shown in Figure 1, a cylindrical hydrogenous plasma of radius R defined by a diaphragm limiter is surrounded by cylindrical wall of slightly greater radius. The plasma carries a constant axial electric

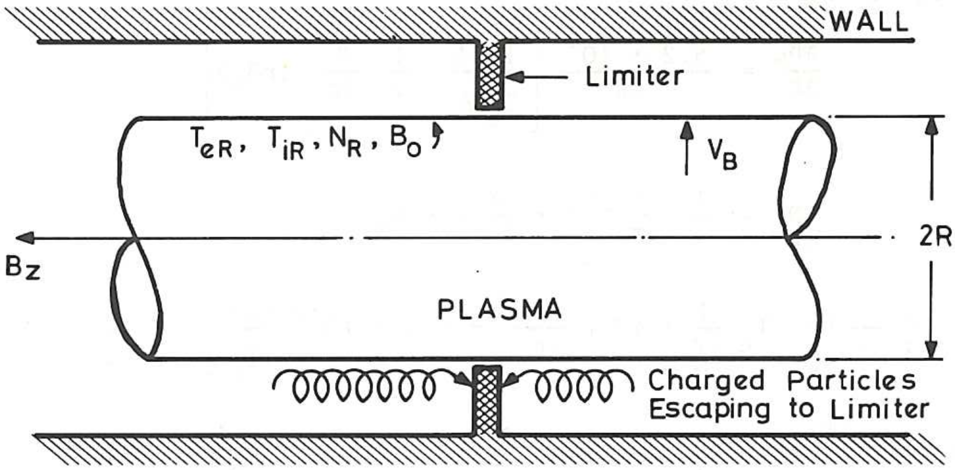

Figure 1 Illustrating the geometry of the model. The cylindrical plasma column is surrounded by a tubular wall. The plasma has a constant axial field B_Z imposed upon it.

current I_0(A), which generates an azimuthal magnetic field B_θ(gauss) at radius r, the current density J is given by:

$$J = \frac{2.5}{\pi} \frac{1}{r} \frac{\partial}{\partial r} (r B_\theta) \quad (A\ cm^{-2}) . \tag{1}$$

Once charged particles have escaped from the plasma they are assumed to reach the limiter without colliding with other particles.

Particle diffusion in the plasma is predominantly pseudo-classical with a diffusion coefficient D_P defined by:

$$D_P = G_1 \frac{8.37 \cdot 10^{-6} N(T_e+T_i) \ln \Lambda}{B_\theta^2 T_e^{3/2}} \quad cm^2 s^{-1} \tag{2}$$

where N is the electron density (cm^{-3}), T_e, T_i are the electron and ion temperatures (eV), and Λ has its usual meaning[3]. G_1 is an empirically determined constant which is taken as 600. Because B_θ is zero on the axis of the plasma the diffusion coefficient D is assumed to change smoothly from the Bohm value[4] on the axis to the pseudo-classical value at larger radii. In the examples given below Bohm diffusion is dominant over the inner 10% of the plasma volume.

The values of the plasma parameters at time t are related by four coupled diffusion equations:

$$\frac{\partial B_\theta}{\partial t} = \frac{5.2 \cdot 10^6}{4\pi} \left[\frac{\ln \Lambda}{T_e^{3/2}} \frac{1}{r} \frac{\partial}{\partial r} (rB_\theta) \right] \tag{3}$$

$$\frac{\partial N}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[D\, r \frac{\partial N}{\partial r} \right] + S_N \tag{4}$$

$$\frac{\partial}{\partial t} (NT_e) = \frac{1}{r} \frac{\partial}{\partial r} \left[rD\, T_e \frac{\partial N}{\partial r} + rD\, N \frac{\partial T_e}{\partial r} \right] - 1.6 \cdot 10^{-9} \frac{T_e - T_i}{T_e^{3/2}} N^2 \ln \Lambda +$$

$$\frac{1.3666 \cdot 10^{16} \ln \Lambda}{T_e^{3/2}} \left[\frac{1}{r} \frac{\partial}{\partial r} (rB_\theta) \right]^2 - 6.4 \cdot 10^{-14}\, T_e^{\frac{1}{2}} N^2 - S_E \tag{5}$$

$$\frac{\partial}{\partial t} (NT_i) = \frac{1}{r} \frac{\partial}{\partial r} \left(r\, D\, T_i \frac{\partial N}{\partial r} + C_1 r \frac{\partial T_i}{\partial r} \right) + 1.6 \cdot 10^{-9} \frac{T_e - T_i}{T_e^{3/2}} N^2 \ln \Lambda - S_I . \tag{6}$$

The symbols S_E, S_I ($4.15 \cdot 10^{-13}$ erg $cm^{-3} s^{-1}$) represent the power sinks on the electrons and ions due to the presence in the plasma of material injected from the wall, and S_N ($cm^{-3}s^{-1}$) is the rate of creation of plasma electrons due to the ionisation of the injected material. In the examples given, C_1 the ionic thermal conductivity is 200 times the classical value[5]. A subsidiary investigation has shown that the results are insensitive to the value of C_1, in agreement with the work of Hughes[6]. Similar transport equations have been used by other workers[6,7,8]. The present treatment differs from the earlier papers in the boundary conditions used in solving the equations.

2. THE BOUNDARY CONDITIONS

Symmetry requires that on the axis at r = 0:

$$B_\theta = 0, \quad \frac{\partial T_e}{\partial r} = 0, \quad \frac{\partial T_i}{\partial r} = 0, \quad \frac{\partial N}{\partial r} = 0 . \tag{7}$$

The assumption that the plasma carries a constant current I_0 causes B_θ to take the value B_R at the plasma boundary (r=R) given by:

$$B_R = I_0/5R . \tag{8}$$

The values T_{eR}, T_{iR}, N_R taken by the other variables at the boundary require more careful consideration. The electrical power supplied to a unit length of the plasma column equals the rate of increase of the stored magnetic energy plus the power used in ohmically heating the electrons. The ohmic power communicated to the electrons per unit volume is balanced by a set of power sinks W_1-W_5 where:

W_1 = the rate of increase of thermal energy of the electrons
W_2 = the power transferred to the ions by collisions with the electrons
W_3 = the power radiated as free-free radiation
W_4 = the power transferred to the injected impurities by collisions
W_5 = the power transferred by convective and conductive effects.

The electron power budget for a unit length of the plasma is written as:

$$\frac{1}{8\pi}\left[\frac{5.2 \ln\Lambda}{T_e^{3/2}} B_\theta \frac{\partial(rB_\theta)}{\partial r}\right]_{r=R} = \frac{1}{4}\frac{\partial}{\partial t}\int_0^R B_\theta^2 r\,dr + \int_0^R 2\pi\,(W_1+W_2+W_3+W_4)\,r\,dr + W_6 + W_7 \quad \left[10^{18} \text{ ergs s}^{-1}\right] \tag{9}$$

The right hand side of equation 9 is the integral of the Poynting Vector over the plasma surface, and W_6, W_7 are the power flows to the plasma boundary due to the convection and thermal conduction of the electrons. Typical experimental results[1] show that W_7 is less than W_6. In a well confined plasma the total power loss represented by the terms W_6, W_7 should be less than the sum of the other terms on the right hand side of equation 9. Because of this W_7 has been set equal to zero and equation 9 used to define T_{eR}, the neglect of W_7 introducing only a small error in T_{eR}. Formally this is equivalent to using $(\partial T_e/\partial r)_R = 0$ as a boundary condition, although as the transport equations are solved numerically the examples given below have a finite temperature gradient at the boundary corresponding to a small but finite value of W_7.

The values of T_{iR}, N_R are obtained by considering the power balance and conservation equations for the ions. If the protons escaping from the plasma approach the plasma boundary with a drift velocity V_B (cm s^{-1}), then the power carried to the plasma boundary per unit length in units of $1.51 \cdot 10^{-11}$ erg cm^{-1} s^{-1} is:

$$N_R \, V_B \, T_{iR} \, R = \int_0^R \left(1.6 \cdot 10^{-9} \, (T_e - T_i) \, T_e^{-1.5} \, N^2 \ln \Lambda - S_I - \frac{\partial}{\partial t} (NT_i)\right) r \, dr. \quad (10)$$

The right hand side of equation 10 equals the rate at which the protons gain energy from the electrons minus the rate of increase of thermal energy and the power loss to the injected impurities.

The corresponding particle conservation equation is:

$$2\pi R \, V_B \, N_R \doteq 2\pi \int_0^R \left[\frac{\partial N}{\partial t} - S_N\right] r \, dr. \quad (11)$$

Equations 10, 11 define T_{iR}, N_R in terms of V_B, a quantity which has not been measured directly, although its order of magnitude may be deduced. Values of N_R of about 2.0 10^{12} cm^{-3} have been reported[9,10] for plasmas with density per unit length in the region of 2.0 10^{16} cm^{-1}, radii in the range 12-25 cm, and particle confinement times of approximately 10 ms, giving an order of magnitude estimate for V_B of 10^4 cm s^{-1}. As the values of T_{iR} were unlikely to have been less than a few eV the values of V_B would have been at most 0.01 times the thermal velocity of the protons. In the absence of better information it has been assumed that:

$$V_B = G_7 \, T_{iR}^{\frac{1}{2}} \cdot 10^6 \ (\text{cm s}^{-1}) \quad (12)$$

where G_7 is a numerical factor probably less than 0.01. The results which have been obtained using this assumption are insensitive to the value of G_7.

3. RESULTS

(a) Absorbing wall

The temperature and density profiles have been calculated for parameters of the DITE Tokamak[11]:

$$R = 25 \text{ cm}, \; B_Z = 28000 \text{ gauss}, \; I_0 = 2.7 \cdot 10^5 \text{A}, \; G_7 = 0.001.$$

The initial temperature, density and current distributions were assumed parabolic. Figure 2 shows the profiles at zero time and at 6 msec for the case of an absorbing wall. The boundary values are defined by equations 9, 10, 11 and the parameters S_E, S_I and S_N are all set to be zero. It is seen that both T_e and T_i rapidly rise at the boundary while the density n_e falls as expected.

(b) The recycling boundary condition

Ions or neutral particles which escape from the plasma and strike either the limiter or the wall may be returned to the plasma. The two principal processes by which this can happen are, backscattering by lattice atoms, where the recycled particles have an appreciable fraction of the emitted energy[12,13] or by slowing down in the lattice to thermal energies and then diffusing out[14]. In the first case they will return to the plasma as relatively energetic atoms since the probability of neutralisation at surface is high for energies below 10 keV[15]. In the second case they will be emitted as neutral molecules with an energy characteristic of the surface. Hydrogen molecules emitted or reflected from the surface by any means will be rapidly dissociated to hydrogen atoms by electron bombardment, so that for the initial model the wall is assumed to emit neutral hydrogen atoms of temperature T_N.

In practical confinement systems there is a third mechanism which can lead to recycling. Since these systems operate with starting pressures $\sim 10^{-4}$ torr there will be a layer of adsorbed gas which can be desorbed by incident energetic ions or neutrals[16]. These desorbed atoms will have the same effect on the plasma as the recycled particles and are treated in the same way, except that the depletion of the adsorbed layer with time is taken into account.

A first attempt to model the recycling was to assume that all the incident particles arriving at the wall were reflected, as would be the case when the wall is saturated and has reached equilibrium with the incident flux. The hydrogen atoms re-injected into the plasma traverse it as a stream which is attenuated by ionisation by electrons and by charge exchange collisions with the protons.

The collision rates are calculated assuming the classical ionisation cross section [17], and Riviere's empirical expression for the charge exchange cross section [18]. Some of the collisions with the electrons result in excitation of the neutrals and not in ionisation, and in calculating S_E in equation 5, it is assumed that the power drain on the electrons due to excitation equals that required for ionisation [19]. As a first approximation it has been assumed that the hot neutrals escape from the plasma; the transport of such particles has been intensively investigated [6,8, 20] and the results of these investigations will be incorporated in the model later.

The results for the case where one neutral atom of 10 eV energy is injected into the plasma for every proton which diffuses out are shown in Figure 2. It is seen that the boundary values of the temperatures and density are changed and that the particle confinement time is lowered by a factor of 2 at 6 msec.

A better model is to assume that the protons leaving the plasma hit the limiter and that the hot neutrals hit the wall surrounding the plasma, both types of escaping particles having an energy T_{iR}. The limiter and wall reflect these particles as neutral atoms with reflectivities R_L, R_W respectively. Additionally it is assumed that the hot neutrals formed inside the plasma have a 0.5 chance of reaching the wall, and that the effective area of the limiter is 0.002 times that of the wall. Two cases are shown in Figure 3. In the first case C it is assumed that the particles re-emitted from the limiter come off with an energy of 30eV corresponding to the case where all ions are backscattered. The second case E is similar except that the particles re-emitted have the much lower energy of 2eV, corresponding to the case where the atoms diffuse out rather than being backscattered. A significant difference in the particle containment is found between these two cases as shown in Figure 3. The lower energy of the diffusively released ions cools the outer edge of the plasma and reduces the containment time by about 30%. The density profile is also changed, the edge density being higher in the case of the low energy re-injection.

(c) <u>The effects of adsorbed gas</u>

As discussed above, another contribution to "recycling" in practice is the desorption of gases from the walls of the system facing the plasma. The desorption rate R is approximately proportional to surface concentration [16] n_s so that:

$$R = \sigma J n_{so} \exp\left(-\sigma \int_0^t J\, dt\right)$$

where J is the current density and σ is the cross section for desorption. Values of the cross section increase with energy but are typically 10^{-17} to 10^{-15} cm. As no data is available for protons at low energies we have used the data for K^+ ions [21] for the energy dependence, using an empirically fitted curve:

$$\sigma = n_s \left[1.0 - \exp(- .0015\ T_{iR}) \right] 10^{-15}\ cm^2.$$

The result of the calculation for desorption only (the plasma ions being absorbed at the wall) is shown in Figure 3 case B. Then τ_p is seen to be reduced considerably at a time t = 1 msec as the gas is desorbed from the limiter. When the gas has been removed τ_p recovers. The rate of desorption from the walls is negligible as no plasma is re-emitted from the limiter and hence the production of charge exchange neutrals is small.

Cases D and F in Figure 3 illustrate the situation when both plasma re-emission and desorption take place. The limiter is assumed to be saturated and hence the reflection coefficient has been made 1.0. The wall coefficient has been made 0.5 as the flux calculations indicate that many shots are required before saturation is reached. In case D, with one monolayer initially adsorbed, it is seen that the limiter is cleaned up and τ_p is slowly recovering, though much less rapidly than in case B. In case F with 5 monolayers the value of τ_p is still decreasing at 6 msec.

(d) High z impurities

No attempt has been made to include the effects of high z impurity. However the calculation yields values of the plasma flux to the wall and the plasma temperature. Using extrapolated experimental data for sputtering yields [22] and integrating over the Maxwellian distribution, making due allowance for the threshold energy for sputtering [23], an approximate estimate of the flux of sputtered atoms into the plasma has been made. For the parameters listed above this gives an increase in density of $\sim 4 \times 10^7$ atoms cm^{-3} $msec^{-1}$. The sputtering yields are not known to better than a factor of 2 or 3. Moreover the effect of the flux of sputtered atoms on the plasma temperature has not been calculated. However it appears that the flux of impurities is lower than the flux estimated in typical experiments [24].

4. CONCLUSIONS

A model has been set up to describe the plasma wall interaction using a modification of existing transport codes. This allows the boundary values of temperature and density to assume values free of any arbitrary constraint. The model has been used to study the effect of plasma recycling on the plasma parameters. It has been shown that both ion backscattering, diffusive release and desorption of adsorbed gas cause the plasma temperature and the particle containment time to be reduced by factors of about 5 compared with an absorbing wall. The effect of backscattering is less than the other two because of the higher energy of particles returning to the plasma. When there is adsorbed gas on the wall this leads to an appreciable addition to the effective recycling. The gas is desorbed from the limiter in 1 to 2 msec but the concentration on the wall is changed only by ∿ 1% in 6 msec. These results are rather dependent on the choice of cross section for desorption which has been rather arbitrarily chosen. Further experimental data is required.

In the present analysis no account has been taken of the effect of high z impurities. It is intended to take sputtering into account in the model in its next stage of development.

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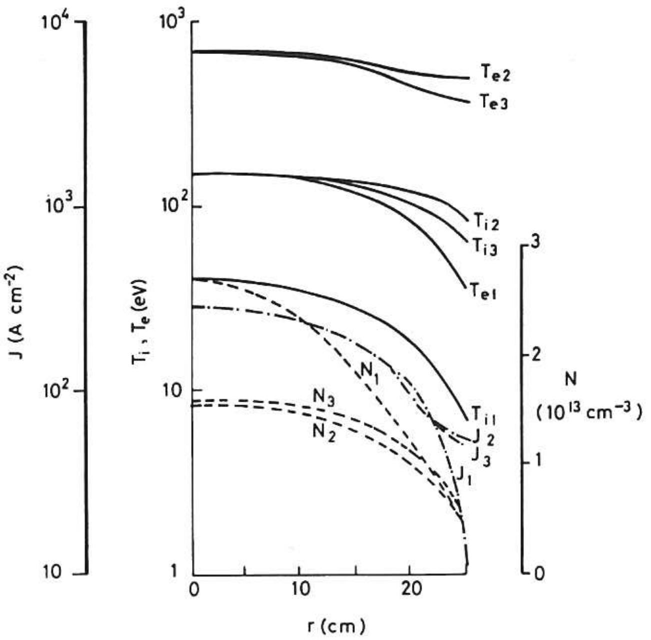

Figure 2 Profiles of electron temperature T_e, ion temperature T_i, electron density N, and current density J as a function of radius r. The suffixes 1,2,3 have the following meanings:

1	t = 0	
2	t = 6 ms	no injection of impurities from wall
3	t = 6 ms	neutrals injected from wall at 1.0 times the proton loss rate starting from t = 0. T_N = 10 eV, G_7 = 0.001

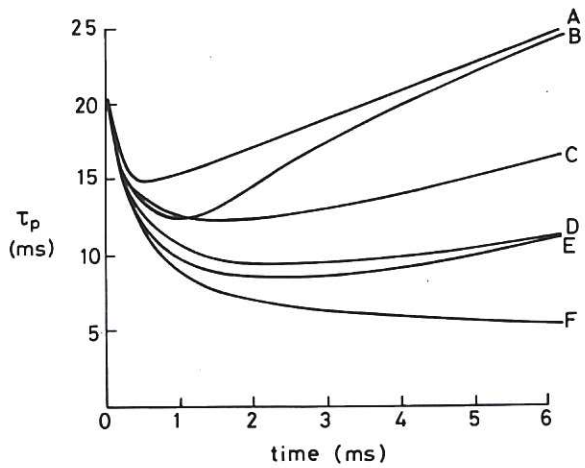

Figure 3 Variation of the mean particle containment time τ_p with time for different plasma wall interactions.
G_7 = 0.001

	R_L	R_W	x	T_N	x_L	x_W
A	0	0	0	-	-	-
B	0	0	5.0	2.0	0.4	4.997
C	1.0	0.0	0.0	30.0	-	-
D	1.0	0.5	1.0	10.0	0.03	0.99
E	1.0	0.0	0.0	2.0	-	-
F	1.0	0.5	5.0	10.0	0.1	4.93

x = monolayers of adsorbed gas on limiter and wall at t = 0.

x_L = monolayers of adsorbed gas on limiter at t = 2 ms.

x_W = monolayers of adsorbed gas on wall at t = 6 ms.