UCLA/PPG--1053

DE87 010023

**An Analytic Model for Flow Reversal
in Divertor Plasmas**

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UCLA-PPG-1053

April, 1987

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ABSTRACT

An analytic model is developed and used to study the phenomenon of flow reversal which is observed in two-dimensional simulations of divertor plasmas. The effect is shown to be caused by the radial spread of neutral particles emitted from the divertor target which can lead to a strong peaking of the ionization source at certain radial locations. The results indicate that flow reversal over a portion of the width of the scrape-off layer is inevitable in high recycling conditions. Implications for impurity transport and particle removal in reactors are discussed.

1. INTRODUCTION

Over the last few years much effort has been invested in modelling of the edge plasma of tokamaks, and two-fluid computer codes have been developed that give a full treatment of the scrape-off layer in two-dimensions [1,2]. One of the most interesting results from applications of these codes has been the observation that in certain circumstances the plasma flow can reverse its direction and be directed away from the divertor target over a portion of the width of the scrape-off layer [3,4]. Recently, Neuhauser has predicted the same effect with a one-dimensional radial model of the scrape-off layer [5]. Such a flow reversal would have a strong impact on impurity transport in the boundary plasma and may seriously reduce the efficiency of the divertor in impurity control and ash removal. However, the complexity of these two-dimensional codes and their computational demands make a systematic investigation of the effect difficult and further the nature of the physics which is responsible for the flow reversal is unclear.

The purpose of this letter is to explain how flow reversal arises by identifying the essential physical mechanisms which are responsible for its occurrence, with the aid of a simple model which demonstrates the effect in a high-recycling divertor. Although many broad assumptions are made in the model, a comparison is made with the predictions of a two-dimensional code for NET [3] and qualitative agreement is obtained.

2. THE MODEL

We aim to determine the plasma flow velocity as a function of radial position in the scrape-off layer at an axial location just upstream of the recycling zone. Cross-field diffusion is ignored in the recycling region. Continuity along a field line requires

$$\frac{d\Gamma}{dz} = S = n_0 n \langle \sigma v \rangle \quad (1)$$

where the coordinate z is measured along the field line, Γ is the parallel particle flux and S is the ionization source per unit volume. n_0 is the neutral particle density, n is the plasma density and $\langle \sigma v \rangle$ is the rate coefficient for electron impact ionization. Integrating through the recycling zone, assuming sonic flow at the divertor target, yields

$$\left(\frac{2k}{m_i}\right)^{1/2} (n_T T_T^{1/2} - n_U M_U T_U^{1/2}) = \int_T^U n_0 n \langle \sigma v \rangle dz \quad (2)$$

where T is the plasma temperature (equal ion and electron temperatures are assumed) and the flow velocity is expressed in terms of the Mach number, M , for convenience. The subscripts T and U refer to the target and the upstream locations respectively. We now approximate the ionization source by using the target values of plasma density and $\langle \sigma v \rangle$ to remove these terms from the integral.

The magnitude of the recycling can be described by a global recycling coefficient, R , which is the fraction of the total number of particles striking the target which is re-ionized in the divertor plasma.

$$R \int \Gamma_T dr = \iint S dz dr \quad (3)$$

To evaluate the double integral in equation (3) we assume that the neutral density is constant across the radius and again approximate $n\langle\sigma v\rangle$ with the target values. The assumption of a radially constant neutral density is made on the grounds that charge-exchange reactions (for which the cross-section is greater than for electron impact ionization, especially at low electron temperatures) will cause the neutral particles to spread radially. Thus,

$$\left(\frac{2k}{m_1}\right)^{1/2} R \int n_T T_T^{1/2} dr = \int n_T \langle\sigma v\rangle_T dr \int_T^u n_0 dz \quad (4)$$

Equations (2) and (4) can be combined by eliminating the line-averaged neutral density to give a relationship for the upstream Mach number at each radius

$$M_u = \frac{n_T T_T^{1/2}}{n_u T_u^{1/2}} \left[1 - R \left(\frac{\langle\sigma v\rangle}{T^{1/2}} \right)_T \frac{\int n_T T_T^{1/2} dr}{\int n_T \langle\sigma v\rangle_T dr} \right] \quad (5)$$

From equation (5) it is clear that the Mach number will vary with radius as it depends on the local value of $\langle\sigma v\rangle/T^{1/2}$. This parameter is a measure of the "relative" strength of the ionization source for a given field line, i.e. the ratio of the source $S (=nn_0\langle\sigma v\rangle)$ to the loss $(\sim nT^{1/2})$ for the assumption of radially constant neutral density. The flow can reverse at a certain radius if the term in square brackets becomes negative, which is possible if the recycling is sufficiently great and if the local value of $\langle\sigma v\rangle/T^{1/2}$ greatly exceeds the average value across the radius. A curve of $\langle\sigma v\rangle/T^{1/2}$, compiled using the analytical approximation in [6], is given in Fig. 1. It shows a maximum at about 40 eV with a steep fall with decreasing temperature

below ~10 eV. This implies that the flow will be most strongly reversed (or most weakly forward) around the 40 eV contour given the assumptions made earlier, in particular, the radially constant neutral density.

Equation (5) can be reduced further by using the equation for momentum balance along the field line.

$$2n_T T_T = n_u T_u (1 + M_u^2) \quad (6)$$

Substituting in equation (5) to eliminate the axial density variation yields

$$\frac{2M_u}{1+M_u^2} = \left(\frac{T_u}{T_T} \right)^{1/2} \left[1 - R \left(\frac{\langle \sigma v \rangle}{T} \right)^{1/2} \frac{\int n_T T_T^{1/2} dr}{\int n_T \langle \sigma v \rangle_T dr} \right] \quad (7)$$

This quadratic equation for the upstream Mach number can be solved if radial profiles of temperature and density at the divertor target and the global recycling coefficient are given. For simplicity the axial temperature gradient can be ignored as it only appears as a square root term and will only affect the magnitude of the Mach number, not its sign.

3. RESULTS

A representative set of results is obtained assuming the radial profiles of density and temperature at the divertor target to be exponential.

$$T = T(0) e^{-r/\lambda_T} \quad (8)$$

$$n = n(0) e^{-r/\lambda_n}$$

Fig. 2 shows several sets of curves for the upstream Mach number as a function of radial position in the scrape-off layer. These results apply to a 5 cm thick scrape-off layer with e-folding lengths for the density and temperature of 4 cm and 1.5 cm respectively. Each set of curves is for a fixed separatrix temperature, and the global recycling coefficient is varied from 0.5 to 1.

In each case the flow reverses across a portion of the radius if the recycling is sufficiently intense. The part of the scrape-off layer where reversal occurs depends on the temperature profile; for low temperatures, $T(0) \leq 50$ eV, the flow reverses around the separatrix, but for $T(0) = 150$ eV, the reversal occurs in the center of the scrape-off layer. For higher temperatures still, the flow would reverse in the outer regions of the scrape-off layer. This pattern reflects the observation made earlier that the flow can be expected to reverse around the 40 eV temperature contour.

The case with $T = 20$ eV shows that the Mach number reaches -1 near the separatrix for $R = 1$. This arises because a large part of the scrape-off layer is at very low temperatures where the relative ionization source $\langle \sigma v \rangle / T^{1/2}$ is very low. The source near the separatrix is thus greatly in excess of the average, causing extreme reversal. Some of the simplifications introduced into the model are no longer valid in this regime. Firstly, at such low temperatures, the neutral particle mean free path will be long, and the neutrals may penetrate far upstream to regions of higher temperature, weighting the source in favor of the outer parts of the scrape-off layer. The approximation whereby the source is evaluated using the target values of density and $\langle \sigma v \rangle$ is therefore poor. Secondly, if the source is highly localized around one part of the radius, the assumption that cross-field diffusion and radial momentum transport are insignificant is incorrect as the

radial gradients will become steep. Both of these factors will tend to smooth out the radial profile of the Mach number and reduce the magnitude of the reversal.

An attempt to include the first of these effects was made by axially averaging the source for each field line. The $n\langle\sigma v\rangle$ term is now approximated as $1/2 (n_u\langle\sigma v\rangle_u + n_T\langle\sigma v\rangle_T)$. Equation (7) becomes

$$\frac{2M_u}{1+M_u^2} = \left(\frac{T_u}{T_T}\right)^{1/2} \left[1 - R \left(\frac{\langle\sigma v\rangle_T + \frac{2T_T}{T_u(1+M_u^2)} \langle\sigma v\rangle_u}{T_T^{1/2}} \right) \frac{\int n_T T_T^{1/2} dr}{\int n_T \left(\langle\sigma v\rangle_T + \frac{2T_T}{T_u(1+M_u^2)} \langle\sigma v\rangle_u \right) dr} \right] \quad (9)$$

This expression is more complicated than equation (7) and must be solved iteratively as the Mach number appears within the integral on the right hand side of the equation.

As a test of the applicability of the model equation (9) has been solved using profiles for the outer divertor target from a two-dimensional simulation of NET [3]. Although this approach relies on using the target values, which are the results of the calculations of reference [3], a comparison at the flow profiles should serve to indicate the validity of the assumptions made in the model. The upstream temperatures were obtained from an approximate solution to the electron conduction and convection equations over the recycling zone. Figure 3 shows the upstream Mach number across the scrape-off layer for the NET global recycling coefficient of 0.998. These results agree qualitatively with the NET results given in reference [3], showing reversal occurring in the vicinity of the separatrix. The radial extent of the region over which the flow is reversed agrees very closely with the two-dimensional results, although the magnitude of the flow evaluated here is somewhat greater than found in [3], where the Mach number at the point of strongest reversal

was ~ -0.2 . In the outer regions of the scrape-off layer, the Mach number is very close to 1, because at the low temperatures found here ($\sim 1-2\text{eV}$) $\langle u/v \rangle$ for ionization is very low. Inclusion of cross-field transport effects and matching the flow just upstream of the recycling zone to the flow far upstream would smooth the results presented here leading to closer agreement with reference [3].

4. DISCUSSION AND CONCLUSIONS

The simple model presented in this paper indicates that flow reversal will occur over a fraction of the scrape-off layer for a wide range of target profiles if the recycling is sufficiently great. The underlying cause of this effect is that the neutral particles generated at the plate are not simply reflected back along the same field line but are distributed radially. As the global recycling coefficient approaches unity, it is clear that unless the ionization source profile exactly matches the flux profile then flow reversal must occur locally. The fact that the neutrals move across the field lines ensures that such an exact match will not occur. Another way of looking at this is to say that the local recycling coefficient, R_L , may exceed unity, although the flux-averaged value of R_L across the target remains below 1.

Although many simplifying assumptions were made in the model, the conclusion that flow reversal is inevitable in high recycling conditions is clear. The precise location of the reversed flow depends on the approximations made, in particular, the assumption of a radially constant neutral density. Also, the neglect of radial diffusion and the prescribed plasma density and temperature profiles (which were not self-consistently determined) affect the quantitative results, but the qualitative result of the reversal of flow at certain radial locations remains.

The results given in this paper apply only to the flow immediately upstream of the recycling region. Further upstream in the scrape-off layer

cross-field effects may cause the radial variation of the flow to smooth out and possibly eliminate the reversal region. However, the results from reference [3] suggest that the flow remains reversed all the way to the "watershed" point between divertors.

The implications of flow reversal for reactors are profound. A very high value of the global recycling coefficient is necessary for reactor divertors in order to reduce the plasma temperature at the target and thus to minimize the sputtering damage. The resultant flow reversal will have a strong effect on the efficiency of the divertor for impurity control and particle removal. Impurity transport in the scrape-off layer is dominated by a frictional force which tends to drag the impurity ion along with the flow of the background plasma, and a thermal force which points in the direction of increasing temperature [7]. In the region where the flow is reversed both these forces act so as to drive the impurity out of the divertor towards the main plasma. Thus, impurities which are generated by sputtering at the divertor target may not be retained within the divertor and contamination of the core plasma may result.

Peak target temperatures below ~ 50 eV imply that the flow will be reversed at the separatrix and forward at the wall. While this may help to remove impurities produced at the first wall, it is likely to have a detrimental effect on the particle removal rate. Coupling of core and edge plasma codes [8] has shown that the stagnated flow in the upstream scrape-off layer caused by the high recycling conditions in the divertor leads to a flattening of the radial density profile near the edge of the core plasma. Flow reversal at the separatrix is expected to increase this tendency which has the effect of increasing the particle confinement time in the core plasma. Removal of the fusion generated alpha particles may thus pose

a problem leading to a higher fraction of helium in the core plasma than is desirable and a reduction of the fuel density and fusion power if the plasma is operating at its β limit.

ACKNOWLEDGMENTS

The authors wish to thank Prof. Robert Conn for continued support and encouragement. This work was supported in part by the U.S. Department of Energy.

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Figure Captions

- Fig. 1 Variation of $\frac{\langle \sigma v \rangle}{T^{1/2}}$ with electron temperature T .
- Fig. 2 Variation of the Mach number with radius at an axial location immediately upstream of the recycling zone for a range of values of the global recycling coefficient and for various values of the peak target plasma temperature; (a) 150 eV, (b) 50 eV and (c) 20 eV.
- Fig. 3 Variation of the Mach number with radius at an axial location immediately upstream of the recycling zone for NET, using target profiles of density and temperature from [3].

Figure 1

Figure 2(a)

Figure 2(b)

Figure 2(c)

Figure 3