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Neutral atom and molecular transport in a gaseous divertor

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Abstract

The Monte Carlo code DEGAS with the addition of ion–neutral elastic collisions was used to evaluate the ability of a dynamic gaseous divertor to remove power to the side walls through charge exchange and ion–neutral elastic collisions. The geometry simulated was a louvered ITER divertor. The plasma parameters for each of the four toroidal slices simulated was taken from PLANET, a 2D plasma fluid code. Results show that only in the initial hottest region of the plasma extending into the divertor throat do neutrals carry away significant energy. Even in this region at most 0.1 MW/m^2 is removed to the side walls by neutral atoms for a pressure behind the louvers of 10 mTorr. Given the proposed area of the side walls and 30 cm of hot region extending into the divertor channel, less than 10 MW of the 200–300 MW of input power are removed. This occurs because an individual atom undergoes many charge exchange and ion elastic collisions before returning to the wall. The chance for ionization during the multiple charge exchange and elastic collisions is higher in general than the chance of exiting the plasma region.

1. Introduction

A 1500 MW fusion power for ITER requires the divertor to handle up to 300 MW of power from the particles flowing along the field lines. Though perhaps 50% of this power could be lost via radiation to the first wall a significant power and particle flux remains. One concept to handle this power is a gaseous divertor with a detached plasma. Detached means that the electron temperature is less than ≈ 3 eV at the point where the field lines strike the divertor target plate. This may be accomplished through a long, closed divertor which will extinguish the plasma in a "flame-front" or "ionization-front" due to the action of the neutral atoms and molecules.

There are two possible mechanisms to create such a detached plasma. The first is to rely on a very high neutral gas pressure which balances the plasma pressure along the field lines. Such a solution has been shown to exist using the two-dimensional fluid model PLANET [1]. Petravic recently reported [2] a PLANET plasma solution where 220 MW enter the outer divertor scrape-off layer and a midplane separatrix density of 1.5×10^{20} m^{-3} is assumed. He found a neutral atom pressure of around 10 Torr in front of the divertor target plate. Our group investigated the same simulation space as PLANET using DEGAS [3] with the addition of neutral-ion collisions [4] (hereafter referred to as DEGAS +) finding only a 100 mTorr molecular density downstream of the flame front [5]. This lower density may result from the inclusion of molecules and more realistic boundary conditions absent in the PLANET work.

The other mechanism to create a detached plasma has been termed a Dynamic Gas Target [6–7]. In it the neutral atoms and molecules created through recombination and wall collisions at or near the flame front are free to travel through open louvers and emerge into higher temperature regions of the divertor upstream of the flame-front region. This concept relies on momentum and energy transfer by charge exchange and ion-neutral elastic collisions from the plasma to the divertor walls to maintain the pressure balance along the field lines. A pressure of 1–10 mTorr is envisioned behind the louvers.

The goal of this paper is to examine the transport issues of a Dynamic Gas Target in detail to determine if such a solution is indeed possible. This work also

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utilizes DEGAS + and therefore simulates both the charge exchange and ion–neutral elastic collisions in a realistic geometry.

2. Model

Fig. 1 shows the conceptual ITER divertor with vertical louvers along the sides of the plasma channel. Overlaid on this figure is the PLANET simulation space [2,5]. This work models toroidal slices along the lines marked A, B, C and D which include three of the louvers in cross section. Fig. 2 shows the DEGAS + simulation space used for this work. By including the region behind the louvers and the openings between louvers the effect of the molecules coming from deeper in the divertor channel and the power distribution around the louvers can be investigated.

The plasma from the PLANET solution was used as an input to DEGAS + . Though this plasma is not self-consistent with the neutral flows shown here it does have the important characteristics shared by any plasma extinguishing in a flame front – the density increases in the ionization region and the temperature is lowered as the depth into the divertor is increased. Fig. 3 shows profile of the electron temperature and density across the divertor for the four toroidal slices marked A, B, C, and D. The data in Fig. 3 is plotted along the diagonal line shown in Fig. 2 which intersects two of the divertor louvers. Region A is representative of a hot plasma region; B is at the very start of the ionization front where the edge temperature first begins to drop and the ion flux is at a maximum; C spans the ionization front region; and D just captures the very front of the ionization front. The ion temperature is close to that of the electrons and is not shown. The ion density is equal to the electron density. These temperatures and densities along the edge of the plasma in slice A and B are higher than those predicted by 1D models for the current ITER design [8].

The ion current to the side walls is only one source of neutral atoms and molecules. The more important source by at least one order of magnitude is the recirculated molecular gas from recombination beyond the ionization front and/or gas puffing. To simulate its effect the magnitude of input neutral current for each of the toroidal slices was scaled so that the resultant molecular density behind the louvers in the gas box for each of the toroidal slices was the same. The density was then scaled to be 1.93×10^{20} m^{-3} which corresponds to 10 mTorr at 500 K. This pressure was used to maximize the likelihood of energy and momentum transfer but still remain in the Dynamic Gas Target regime. In this open divertor design where the neutral gas is not confined to a cushion region between the ionization front and a plate, the neutrals produced by recombination would be free to equilibrate the pressure in the gas box. Given the current gas box design, a pressure of 1–10 mTorr is also consistent with the expected neutral particle production rate.

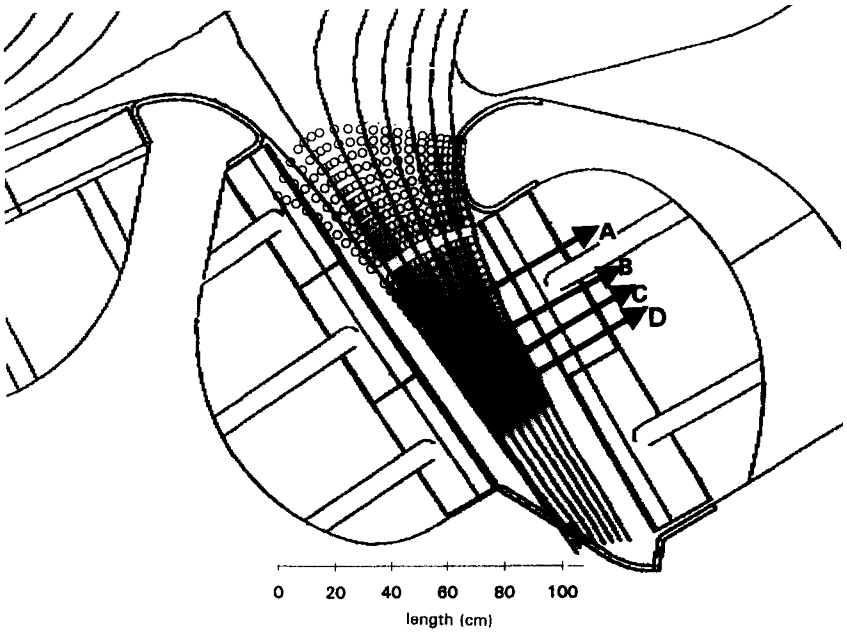

Fig. 1. A side view of the ITER divertor overlaid with the Petravic PLANET simulation space and the four toroidal slices A, B, C and D, investigated in this work.

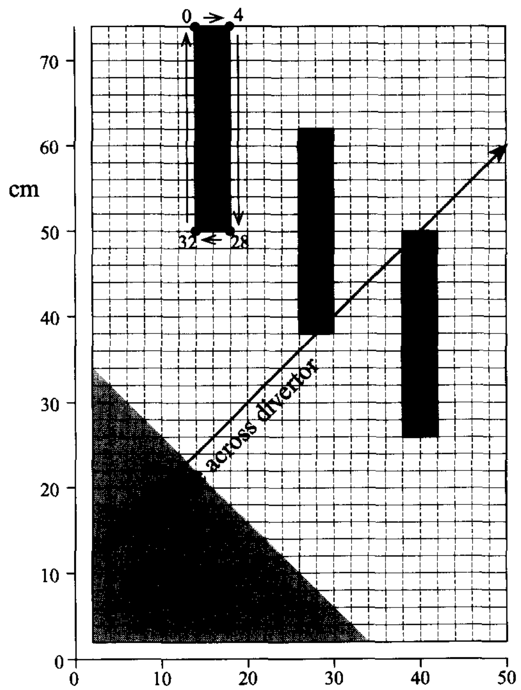

Fig. 2. DEGAS simulation space for this work. The diagonal slice from the separatrix through the louvers refers to the temperature and density distributions in Figs. 3–5. The dimensions around one louver refer to the flux energy and power distributions shown in Fig. 6. Ions from the plasma strike each louver from the point at 28 cm to the point at 50 cm along the circumference.

3. Results

Fig. 4 shows the molecular density for each of the four toroidal slices. The molecular density does not drop much between the louvers and only falls rapidly once the edge of the plasma channel is reached. The atomic density (Fig. 5a) shows the opposite effect. As expected atoms are most prevalent in the space between the plasma channel and the louvers, and then drop significantly between the louvers and on the other side of the louvers. In the colder plasma at the ionization front (slices C and D) the atomic density reaches the magnitude of the molecular density in the edge plasma. Fig. 5b shows the average temperature of the atoms. Only in slice A do the neutral atoms have a significant energy. Charge exchange with relatively cold ions predominates in the other regions leaving the neutral atoms at less than 1 eV. These density contours also show the relative unimportance of neutral–neutral collisions. Behind and between the louvers the neutral–neutral mean free path is about 1 cm. Though this implies many collisions, the net effect is still the same neutral molecular flow back to the plasma. In the region where there is a significant plasma, the neutral–ion collision rate is much greater than the neutral–neutral collision rate since the neutral density has dropped precipitously.

Fig. 6 shows the atomic flux, average atomic energy and atomic power flux around the louver surface. The vertical lines at 0, 4, 28 and 32 cm correspond to the four corners of the louver cross section shown in Fig. 2. The surface from 28–50 cm intercepts ion flux coming perpendicular to the separatrix. The flux and energy in toroidal slice A are an order of magnitude higher than those slices deeper in the divertor. Accordingly the power flux due to energetic neutral atoms in slice A is two orders of magnitude higher than those slices near and beyond the ionization front.

Though both neutral molecules and reflected atoms from ion collisions travel into the plasma from the side wall, Figs. 4 and 5 show that the predominant flux is the neutral molecules. These molecules become dissociated and the resultant atom or atoms gain the

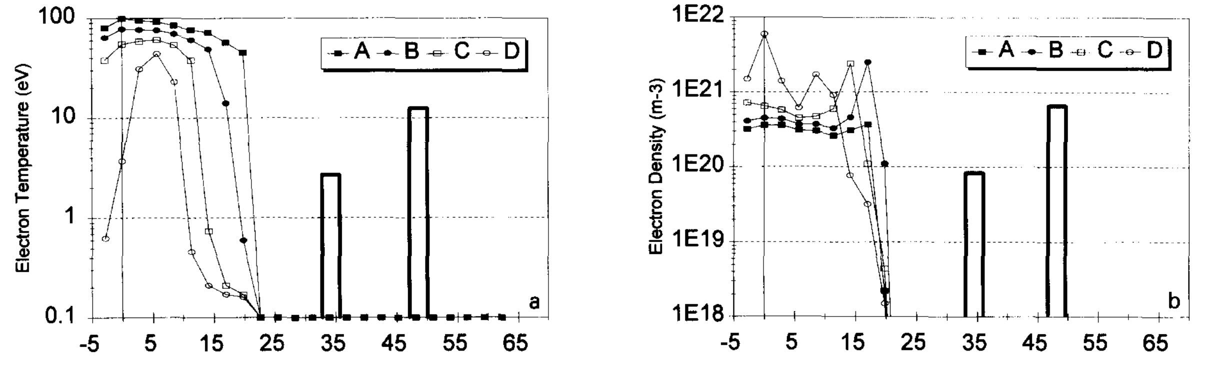

Fig. 3. Input plasma values across the divertor at each of the four toroidal slices shown in Fig. 1 along the diagonal line shown in Fig. 2. The position of the louvers are shown by the rectangular boxes: (a) electron temperature, (b) electron density.

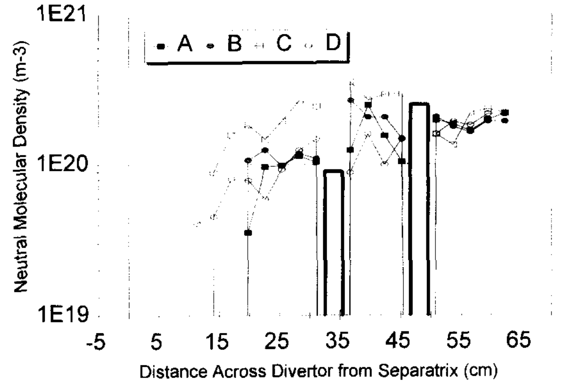

Fig. 4. Molecular density for each of the four toroidal slices. The pressure behind the louvers is 10 mTorr. The position of the louvers are shown by the rectangular boxes.

Table 1

Neutral power balance. The neutral atoms gain energy through dissociation and charge exchange. They lose energy through being ionized and contact with the walls. All powers are listed in kW/cm of divertor depth. The toroidal slices refer to the locations shown in Fig. 1

Toroidal slice	Gain from dissociation (kW/cm)	Gain from charge exchange (kW/cm)	Loss to ionization (kW/cm)	Loss to wall (kW/cm)
A	63.5	138.0	142.0	60.0
B	33.7	33.5	62.0	0.5
C	66.5	77.5	130.0	0.02
D	29.4	0	34.0	0.15

Frank–Condon dissociation energy. Atoms can also gain energy from charge exchange with the ions. Any energy gained is eventually lost. Energy can be lost back to the ion population via ionization, or the energetic atom can travel to a wall and deposit its energy there. Table 1 shows these four power balance factors for each of the four regions considered. Only the hot region A succeeds in transferring significant momentum and energy to the walls.

Unfortunately the magnitude of this power loss is small. The peak power flux from neutral atoms is 0.1 MW/m^2. If this value were constant over the region from 28–56 cm, and for the first 30 cm of divertor depth, the area exposed to this neutral flux along one louver would be 0.084 m^2. Each louver intercepts about 17 cm of ITER's 5000 cm circumference, so the total exposed area on the outboard side of the outer divertor leg is only 25 m^2. Therefore a maximum of 10 MW is removed by neutrals counting all four possible divertor side walls. This number is corroborated by the figures in Table 1. A loss of 60 kW/cm of divertor depth times 30 cm of depth and 4 walls gives 7.2 MW. If the hot region extends for a longer distance into the divertor slot the power removed will increase proportionally.

Momentum loss is also small and is primarily in the direction perpendicular to the field lines since the neutrals from the louvers enter the plasma in that direction. The momentum loss occurs in a 1–2 cm thick band surrounding the flame front and has a magnitude of 1.0×10^{11}–15.0×10^{11} ergs/cm^3 reaching the maximum in slice B. These numbers correspond to a pressure drop of 0.12–1.8 mTorr.

4. Discussion

Table 2 and plots of individual flights show the reason why so little power and momentum is transported by the neutral atoms to the walls. It is quite

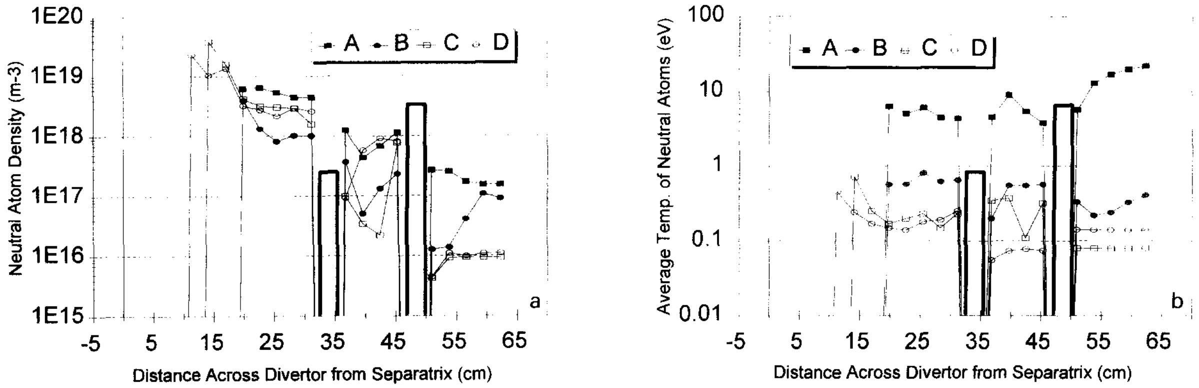

Fig. 5. Atomic values for each of the four toroidal slices: (a) atomic density, (b) average temperature.

Table 2
Collision Statistics. Number of events per flight of a molecule leaving the louver region. A flight stops when it is ionized. The *N* effective is a measure of the ability of neutral atoms to remove energy and momentum from the plasma. The toroidal slices refer to the locations shown in Fig. 1

Toroidal slice	Charge exchange	Ion–neutral elastic	Wall collisions	*N* effective
A	9.0	1.0	13.5	1.5
B	27.0	9.0	6.25	0.22
C	24.0	7.4	6.43	0.27
D	371.0	106.0	11.8	0.03

unlikely for an atom to strike the wall after only one charge exchange or elastic collision with the ions. It is much more likely to make several collisions in rapid succession once it has reached the plasma region. Only in region A does the number of wall collisions per flight exceed the number of ion collisions. As seen in Table 1 or Fig. 6c this is also the only region that removes significant power to the walls.

The ratio of the number of wall collisions to (charge exchange + elastic collisions) can be defined as a measure of the ability for the atom to transfer the energy gained from the plasma to the side walls. This is similar to the *N* effective defined by Stangeby in Ref. [7] where he states that it is difficult to refine its value between 1 and 10 without using a multidimensional hydrogen neutral Monte Carlo code. In region A this *N* effective is larger than 1, however in regions B and C the chance for a given molecule to return to a wall as an atom (and therefore energetic to some degree) is less than 1. In region D, at the tip of the flame front, the chance is much less than 1.

From this work the realism of significant energy and momentum transfer by energetic atoms across the field lines to the side walls at a gas box pressure of 10 mTorr is questionable. There are two factors which may mitigate these results: (1) the plasma parameters used in this simulation are not self-consistent and (2)

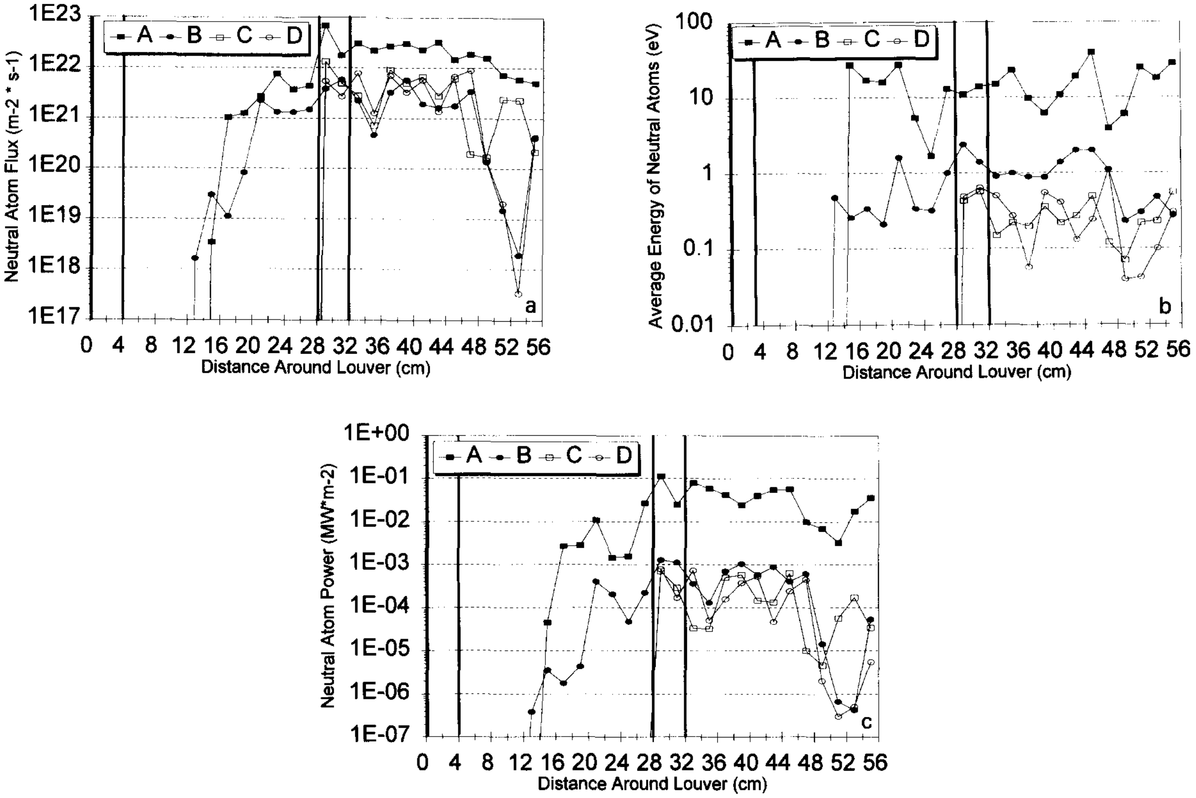

Fig. 6. Neutral atom values on the louver surface as a function of position around the louver for each of the four toroidal slices. The section from 28–50 cm face the plasma (see Fig. 2): (a) neutral atom flux, (b) average energy of impacting neutral atoms, (c) deposited power from neutral atoms.

the full three-dimensional geometry was not simulated. However, additional work has been completed using a less dense and less energetic plasma in the divertor slot which shows a similar lack of energy transfer. If the midplane and divertor density are reduced, the momentum loss may be greater due to a greater neutral atom transparency; momentum loss along the field lines will be due to neutrals recycling from the divertor plate.

Acknowledgements

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