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COUPLED PLASMA-NEUTRAL TRANSPORT MODEL FOR THE SCRAPE-OFF REGION

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1. INTRODUCTION

There are three important considerations in the design of a divertor or pump-limiter for an ignited device: (1) handling the large heat fluxes, (2) coping with the severe material erosion problems, and (3) providing adequate neutral pumping to satisfy impurity exhaust requirements. A growing number of studies on the scrape-off (S.O.) plasma behavior have been undertaken that address these issues. Many of these studies¹⁻⁵ examine the cross-field transport to determine the radial plasma profiles in the S.O. This information is used to determine the shape of a neutralizing surface that can best handle the heat load. These methods rely on a simplified treatment of the plasma transport along the field lines. More sophisticated models⁶⁻¹⁰ have specifically addressed the plasma transport along the S.O. field lines, including the effects of neutral recycling, and have predicted the possibility of strong temperature and density gradients along the field lines. With the occurrence of these gradients, a regime of operation characterized by low temperatures and high densities at the neutralizing plate is identified, which has the beneficial effect of reducing the material erosion rates.

Less attention has been given to the issue of neutral pumping. This problem is becoming more critical with the trend toward smaller ignition devices because of the increasing difficulty of providing large-conductance pumping ducts. The majority of previous predictions of neutral pumping rates^{1-3,11,12} are derived from models that use simplified treatments of the S.O. plasma transport. However, the more sophisticated models show that when the neutral recycling effects near the neutralizer plate are accounted for, the plasma flow rates into the divertor (pump-limiter) can be drastically reduced (see refs. 6-9 and 13). This study provides a basis for determining neutral pumping rates while retaining the important coupled effects of the plasma and neutral transport. The method used here involves iteration between models that treat (1) plasma transport across S.O. field lines, (2) plasma transport along S.O. field lines, and (3) neutral transport in the vicinity of the neutralizer plate. The iteration technique and a discussion of the

individual components involved are presented in the next section, and results for the pump-limiter and divertor cases are described in Sect. 3.

2. METHOD

2.1 ITERATION PROCEDURE

A flow chart depicting the procedure used to find the pumping rates is shown in Fig. 1. The process begins by calculating the radial plasma profiles in the S.O. The model used for this purpose differs from previously used one-dimensional (1-D) radial transport S.O. models in the treatment of the terms that account for the losses of particles and energy along the field lines. Instead of using the usual assumption of particle flow rate at the sound speed everywhere and the associated convective heat loss for the axial loss terms, a two-point model^{13,14} is used here to evaluate these terms. This model is analytic in nature, accounts for the effects of neutral recycling on plasma flow rates along the field, and also includes heat conduction along the field lines. It is necessary to provide the two-point model with a guess for the neutral recycling that occurs at the neutralizer plate. Output from this model includes the S.O. width and the radially averaged density and temperatures. These values are used as input to the ZEPHYR⁸ code that models plasma transport along the field lines. An analytically based neutral transport model that accounts for the pumping effects¹¹ is used in conjunction with ZEPHYR. The neutral recycling found in this latter step is checked against that assumed in the two-point model, and the entire loop is redone if the recycling values do not coincide. Also, the simple neutral transport model used with ZEPHYR is benchmarked with the Monte Carlo neutral transport code DEGAS.¹⁵

Each of the components in this iteration loop is inadequate by itself to model the entire process of plasma transport in the S.O. along and across the field lines and the coupled effects from neutral transport. Each component relies on input and checks from other components. By separating the modeling process in this manner, it is possible to obtain solutions without excessive numerical effort while retaining the salient

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Fig. 1. Flow diagram for the procedure used to model the transport in the scrape-off region.

features of the individual models. Following is a detailed description of the components.

2.2 RADIAL PROFILE MODEL

The 1-D radial transport equations used for particles and energy are as follows (see ref. 1):

$$\frac{d}{dr} \left[D \frac{dn(r)}{dr} \right] = S_n \quad (1)$$

and

$$\chi \frac{d}{dr} \left[n(r) \frac{dT(r)}{dr} \right] + 3D \frac{d}{dr} \left[T(r) \frac{dn(r)}{dr} \right] = S_E, \quad (2)$$

where r is the direction perpendicular to the field lines, n is density, T is temperature, D (χ) is the cross-field particle (energy) transport coefficient, and S_n (S_E) is the term representing particle (energy) loss along the field lines. Here, it is assumed that D and χ are constant throughout the S.O., and the ion and electron temperatures are equal. As shown in ref. 1, if the particle loss term is represented by $n/\tau_{\parallel}$ and the energy loss term by $cnT/\tau_{\parallel}$, then the solutions for density and temperature are

$$n(r) = n_0 \exp(-r/\lambda_n), \quad (3a)$$

$$T(r) = T_0 \exp(-r/\lambda_T), \quad (3b)$$

where $c = \text{const}$, $\tau_{\parallel}$ = average ion confinement time (along the field line), and

$$\lambda_n = \sqrt{D\tau_{\parallel}}, \quad (4a)$$

$$\lambda_T = \frac{2\lambda_n b}{[(b+3)^2 + 4b(c-3)]^{1/2} - (b+3)}, \quad (4b)$$

and

$$b = \chi/D.$$

The usual additional assumptions used in the analytic solution are that $\tau_{||}$ is equal to the path length along the S.O. field line L , divided by an average sound speed, and $c = 2\gamma$, where γ is an energy transmission coefficient through the sheath at the neutralizer plate. More sophisticated treatments^{2,3} account for the dependence of the sound speed on temperature ($\propto \sqrt{T}$) across the S.O., but these methods must use numerical methods to solve Eqs. (1) and (2).

In situations characterized by high neutral recycling in the vicinity of the neutralizer plate, the particle flow rate along the field lines is often much less than the sound speed (i.e., Mach number $\ll 1$) except for a small region adjacent to the neutralizer plate, as seen in ref. 8. This situation is typical for plasma flow into "closed" volumes such as divertors or the bottom (shadow) of a limiter type envisioned for the Toroidal Fusion Core Experiment (TFCX).¹⁶ Another consequence of high neutral recycling is the possibility for substantial heat transfer via conduction due to the large temperature gradients that can exist along the field lines.¹³ The methods of refs. 3 and 4 use an additional source term in Eq. (1) to account for the ionization of neutrals formed at the neutralizer plate, but this procedure falls short of including the previously mentioned effects. In order to more properly include the effects of neutral recycling on reducing particle flow rates and introducing heat conduction, the following approach is taken.

At each radial location, the S.O. field lines are divided into two regions: (1) the length L_1 alongside the main plasma in which no neutral recycling is accounted for and (2) the length L_2 in the divertor region (or beneath the limiter) in which all the recycling of neutrals

formed on the neutralizer plate is assumed to occur. (Calculations presented later indicate that this is a good assumption.) This division of the S.O. region is depicted in Fig. 2. Throughout this work, $L_1 = 4/5\pi R_p q$ and $L_2 = \pi R_p q/5$ are used, where R_p is the plasma major radius and q is the safety factor. The common point of the flow regions is designated as the throat (t) entrance. In the first region, it is assumed that the temperature and density are constant along the field line. (Full 1-D calculations along the field^{6,8} show that important n and T gradients do appear in region 2.) The values of n and T in region 1 are used as input conditions at the throat for a two-point method^{13,14} that analyzes the transport along the field between the throat and the neutralizer plate (p). Boundary conditions at the sheath adjacent to the neutralizer plate used in the two-point model are as follows:

$$\text{Mach number} = 1.0 , \quad (5a)$$

$$\text{heat flux } Q_p = 2n\gamma T , \quad (5b)$$

and $\gamma = 4.0$ is used in all cases here. Also, the neutral recycling coefficient is defined as follows:

$$R = 1 - \frac{(nV)_t}{(nV)_p} , \quad (6)$$

where V is the plasma flow speed along the field lines and is specified for each position r . Output from the two-point model includes the heat flux and particle flow speed at the throat. Using these quantities, $\tau_{||}$ and the coefficient c used in calculating the sink terms from Eqs. (1) and (2) can be expressed as follows:

$$\tau_{||} = \frac{L_1}{V_t} \quad (7)$$

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Fig. 2. Division of the length along the field line in the scrape-off region for modeling purposes.

and

$$c = \left(\frac{Q}{nTV} \right)_t . \quad (8)$$

The two-point model used here uses T_t as input and solves for Q_t , as opposed to the procedure in Refs. 13 and 14 of inputting Q_t and solving for T_t .

With the framework previously outlined, the radial density and temperature profiles in the S.O. plasma can be solved for with a simple Euler's method as follows. First, the temperature $T(0)$ and density $n(0)$ at the main plasma-S.O. interface ($r = 0$) and a recycling profile $R(r)$ are chosen. Since $\tau_{||}$ and c are approximately constant over some small Δr , Eq. (3) can be used to estimate the temperature and density at $r + \Delta r$. This procedure is carried out over some specified radial extent. Typically, $\Delta r \leq 2$ mm was sufficient to reach converged solutions for cases in this work.

Tests of this radial profile model for the case $R = 0$ and $\tau_{||} = \text{const}$ agree with the analytic method of the solution [see Eqs. (3) and (4)]. Another comparison is made with the results of ref. 2, which assumes $R = 0$ but includes the temperature dependence of the flow speed. Figure 3 (taken from ref. 2) shows good agreement between the temperature and density profiles from ref. 2 (solid lines) and the corresponding values calculated with this model (dots for temperature and crosses for density). Both models show a departure from the exponential decay shape that is shown for comparison. Also shown in Fig. 3 are results from the radial profile model for the same case but with a finite R . In this case, R is taken to be 0.9 for the first 7.5 cm away from the main plasma and is decreased linearly to 0.0 over the next 3 cm. In this case, the density decays more slowly than the preceding example in the region of neutral recycling. This rate is slower because of the choking action of the neutral recycling on the flow rate along the field line. For $r < 7.5$ cm, the flow rate Mach number at the throat is ~ 0.05 . Despite the reduced particle loss rate along the field lines with recycling included, the

Fig. 3. Comparison of radial temperature and density profiles calculated with models from ref. 2 and the radial profile model presented here.

temperature falls off even faster than the $R = 0$ case. This effect is due to the inclusion of heat conduction losses.

2.3 TRANSPORT ALONG SCRAPE-OFF FIELD LINES

The primary tool used to investigate the plasma along S.O. field lines is the ZEPHYR code,⁸ developed at Culham. In order to include the effects of neutral recycling and the evaluation of neutral pumping rates, the neutral transport model described in ref. 11 has been coupled to the version of ZEPHYR used here. Detailed descriptions of ZEPHYR and the neutral transport model are provided in refs. 8 and 11, respectively, so only brief descriptions of them are provided here. The primary attention is directed towards the coupling procedure.

The ZEPHYR code finds the steady-state plasma parameters between the watershed (or symmetry) point (point A in Fig. 4) and the neutralizer plate. As depicted in Fig. 4, the present designs envisioned for TFCX incorporate neutral pumping on only one-half of the S.O. plasma (i.e., the inboard side for the pump-limiter and the outboard side for the divertor). In this study, only the half of the S.O. with pumping is investigated, and symmetry about point A is assumed. ZEPHYR requires input values for the density, the ion and electron temperatures at the watershed (taken from the radial profile model), the flow Mach number at the plate ($= 1.0$ throughout this work), the ion and electron heat transfer coefficients across the sheath at the plate ($= 4.0$), and the neutral density profile. All cases assume an exponentially decaying neutral density profile:

$$n_0(X) = n_0 \exp(-X/\lambda_0) , \quad (9)$$

where X is the distance along the field line from the neutralizer plate and λ_0 is an average neutral mean free path (MFP), which is approximated as:

$$\lambda_o = B_T/B_p \left[R_n \left(\frac{1}{\lambda_i} + \frac{1}{\lambda_{cx}} \right)^{-1} \right]_f + (1 - R_n) (\lambda_{cx})_s , \quad (10)$$

where B_T (B_p) is the toroidal (poloidal) magnetic field, R_n is the percent of neutrals reflected as fast (f) neutrals off the neutralizer plate (see ref. 11), $(1 - R_n)$ is the percentage reflected as slow (s) neutrals, and λ_i (λ_{cx}) is the ionization (charge-exchange) MFP. The ionization rate of neutrals in the divertor channel is simply

$$\Gamma_i = \int_p^t n \times n_o \langle \sigma v \rangle_{\text{ionization}} dx . \quad (11)$$

The coefficient n_o in Eq. (9) is determined through the iteration procedure described in the following paragraphs.

The neutral transport model from ref. 11 is analytic in nature, which allows for a fast iteration procedure with the ZEPHYR code. Calculations are based on neutral MFPs evaluated with average plasma density and temperatures. Output from this model includes the fraction of the neutral flux produced at the neutralizer plate that either is pumped (f_p) or escapes the divertor channel back toward the main plasma (f_E).

The geometry used in the neutral transport model is shown in Fig. 4. Only the region in the vicinity of the neutralizer plate (between points B and D in Fig. 4) is included in this model since the neutral density falls off rapidly with distance from the neutralizing surface.¹⁷ The scrape-off plasma enters the divertor channel with a width Δ and is incident on the neutralizer plate after a distance X_c along the channel. The neutralizing surface is oriented at an angle θ to the plasma flow, which produces a wedge-shaped plasma poloidal cross section adjacent to the neutralizer plate. A void region of thickness X_{TH} exists between the scrape-off and the chamber wall. The neutral transport model in ref. 11 involves finding the average probability that a neutral produced on the plate can escape through the wedge-shaped profile. The net neutral flux leaving the scrape-off is determined, accounting for

multiple reflections off the chamber walls and passes through the scrape-off plasma [see Eqs. (35)–(44) in ref. 11]. The portion of this neutral flux that is pumped, f_p , is governed through a balance of the effective area of the pumps, A_{pump}^* , and the surface area of the plasma in the divertor channel, A_p . Equation (42) from ref. 11 (which depends on the pump speed S , duct conductance C , and number of pumps N) is used for A_{pump}^* :

$$A_{\text{pump}}^* = 4/C_0 \times S_{\text{eff}}, \quad (12)$$

$$A_p = 2\pi R_p (X_c + \Delta/\sin \theta), \quad (13)$$

where S_{eff} is the effective pump speed $[N(S^{-1} + C^{-1})^{-1}]$, C_0 is the average wall temperature (300 K) molecular speed, and R_p is the major plasma radius (= 3.5 m).

The fraction of the neutral flux exiting the scrape-off that escapes toward the main plasma, f_E , is

$$f_E = \frac{A_E}{A_p} \exp(-X_c/\Delta_z), \quad (14)$$

where A_E is the escape area = $2\pi R(X_{\text{TH}} + \Delta)$ and Δ_z is the attenuation factor given by Eq. (51) in ref. 11.

In the following results, the pumped and escaping fractions of neutrals (f_p and f_E) are multiplied by the correcting factors C_p and C_E , respectively. These factors are determined through checks with the Monte Carlo neutral transport code DEGAS¹⁵ as described in the following paragraphs. Also, when used in conjunction with ZEPHYR, the average density and temperatures between the throat (point B) and neutralizer plate are used to evaluate MFPs.

The iteration procedure between ZEPHYR and the neutral transport model involves changing the coefficient n_0 in Eq. (9) to satisfy the steady-state neutral particle balance:

$$\text{ionization rate} + \text{pumping rate} + \text{escape rate} = \text{production rate} . \quad (15)$$

Provided with an initial guess for the neutral density profile in the plasma [see Eq. (9)], ZEPHYR calculates the plasma conditions at the neutralizer plate. With the additional knowledge of the scrape-off width (from the radial profile model), the total neutral production rate, $(2\pi R_p B_p / B_T) \Delta(nv)_p$, can be determined, and the fractions that are pumped and that escape are provided by the neutral transport model. Also, the neutral ionization rate is provided by Eq. (11). The neutral density coefficient n_0 is adjusted so that the total sink rate of neutral particles [left-hand side of Eq. (15)] balances the production rate. This iteration process is complicated by the fact that modifications of the neutral density change the plasma conditions at the plate and hence change the neutral production rate.

2.4 BENCHMARKING THE NEUTRAL TRANSPORT MODEL

Before applications of the iteration procedure between the plasma transport and the neutral transport are presented, a benchmarking of the neutral transport model previously discussed, henceforth referred to as the simple neutral transport model (SNTM), with the DEGAS code is discussed. The DEGAS code can account for the detailed geometry of the limiter (divertor) configuration and the effects of plasma variation to a much greater extent than the SNTM. Some reference comparison cases between the two models are discussed in the following paragraphs.

The geometry used in the DEGAS modeling of the limiter region is shown in Fig. 5. Solid lines represent material walls, and dotted lines represent computational boundaries. The upper zones contain plasma, and the bottom zone is void. A uniform source of plasma is initiated along the neutralizer plate, and pumping is simulated by modeling some wall zones as pump ducts and specifying that a fraction of the neutrals hitting these zones is absorbed. The absorbed fraction is

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Fig. 5. Geometry used in DEGAS for modeling of neutral transport below limiter.

$$f_{abs} = \frac{A_{pump}^*}{2\pi R_p \times l_{abs}}, \quad (16)$$

where l_{abs} is the length of the wall segments modeled as pump ducts. Neutrals that leave through the opening at the left-hand side of the configuration in Fig. 5 are escaping neutrals. The corresponding parameters used in the simple neutral transport model are $X_c = 50$ cm, $X_{TH} = 9$ cm, $\Delta = 3$ cm, and $\theta = 5^\circ$. For the limiter case, a uniform plasma density and temperature are used in the DEGAS calculations. Table 1 compares the pumping and escaping fractions as calculated for some typical plasma conditions below the limiter. Results from DEGAS are averaged over runs done with pumping at various wall segments. The results from SNTM are found using the factors $C_p = 0.8$ and $C_E = 1.5$ for the pumping and escaping fractions. With the values, the pumping fractions found with SNTM are within $\sim 10\%$ of these predicted by DEGAS, and the escaping fractions are within $\sim 20\%$ of the DEGAS results. The preceding values for C_p and C_E are used for all the limiter cases throughout this work.

The method of modeling the neutral transport for the divertor case is slightly different from that for the limiter cases. For TFCX, the flux surfaces in the divertor chamber are expanded by about a factor of 3 compared to the spacing at the midplane. To account for this, the S.O. thickness provided by the radial profile code is increased by three in the SNTM, and to conserve the total number of particles the density used in the neutral transport calculations is taken to be one-third of that predicted, assuming a constant cross-sectional area S.O. Also, for the divertor cases, the S.O. thickness used in the SNTM is increased an additional 30% to account for the spreading of the plasma across the main plasma side of the separatrix in the divertor chamber, where it is unopposed by a confined plasma.

The geometry used in DEGAS for the divertor option is shown in Fig. 6. With the preceding considerations in mind, the corresponding inputs used in the SNTM are $X_c = 50$ cm, $X_{TH} = 20$ cm, $\Delta = 5$ cm, and

Table 1. Comparison of pumped and escaping fractions of the neutral flux produced at the plate for the limiter option, as predicted by DEGAS and the SNTM

Case		Pumped fraction (%)		Escaping fraction (%)	
Plasma conditions	Pump speed	DEGAS	SNTM	DEGAS	SNTM
$n = 8.2 \times 10^{12} \text{ cm}^{-3}$					
$T_e = 18 \text{ eV}$	$1.6 \times 10^5 \text{ L/s}$	8.6	9.6	6.9	8.7
$T_i = 13 \text{ eV}$	$2.2 \times 10^5 \text{ L/s}$	12.8	12.6	7.3	7.8
$n = 5 \times 10^{12} \text{ cm}^{-3}$					
$T_e = 30 \text{ eV}$	$1.6 \times 10^5 \text{ L/s}$	8.3	8.9	8.8	7.4
$T_i = 20 \text{ eV}$	$2.2 \times 10^5 \text{ L/s}$	11.6	11.6	8.2	7.14

^aUsing 16 ducts with $C = 19 \text{ m}^3/\text{s}$ and $S = 50 \text{ m}^3/\text{s}$.

^bUsing 16 ducts with $C = 15 \text{ m}^3/\text{s}$ and $S = 30 \text{ m}^3/\text{s}$.

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Fig. 6. Geometry used in DEGAS for modeling of neutral transport in divertor.

$\theta = 15^\circ$. For the divertor case, the plasma parameters vary greatly in the radial direction in the area of interest for pumping calculations. In the limiter case, only the outer portion of the S.O. that is incident on the bottom of the limiter is of concern for neutral pumping calculations. To take some account of the large variations in plasma parameters for the divertor case, simple profiles for temperature and density are included in the DEGAS calculations. Higher densities and temperatures ("peak" values) are used in the zone above the separatrix (see Fig. 6) compared with the plasma in the zones above and below it ("low" values). The average value of the profiles is used in the SNTM for these comparisons. Table 2 shows the pumping and escaping fractions of the neutrals as calculated with the two neutral transport models for several cases. For these runs, the coefficients $C_p = 0.47$ and $C_E = 0.48$ are used in the SNTM, and good agreement between the results of the two models is observed. These values for C_E and C_p are also used for the rest of the divertor cases discussed in this work.

Even though the SNTM cannot be expected to provide detailed information on the neutral transport, the preceding comparisons indicate that it can be used to provide estimates on overall quantities, such as the fraction of neutrals being pumped or the fraction escaping the divertor chamber. However, the simple model does need to be checked for each geometry, as indicated in the different correction factors (C_E and C_p) found for the preceding limiter and divertor examples. We note that even with $C_E = C_p = 1.0$, the simple model results show good agreement with those from DEGAS for the fraction of neutrals that are ionized (i.e., $1 - f_p - f_E$), which is about 80% for the preceding cases. It is the lower fractions of pumping and escaping neutrals, which are of particular interest, that require calibration with sophisticated models. The importance of coupling the neutral and plasma transport is also evident in the preceding comparisons with the observation that large percentages of the neutrals produced on the plate are ultimately ionized in the S.O. (i.e., high neutral recycling). A final comment on the neutral transport modeling is that only hydrogen neutrals are considered. Throughout this work, transport of helium is assumed to be equivalent to that of hydrogen.

Table 2. Comparison of pumping and escaping fractions of the neutral flux produced at the plate for the divertor option as predicted by DEGAS and the SNTM

Case		Pumping fraction (%)		Escaping fraction (%)	
Plasma conditions	Pump speed	DEGAS	SNTM	DEGAS	SNTM
$n = \begin{matrix} 3 \times 10^{12} \text{ cm}^{-3} \text{ peak} \\ 7 \times 10^{12} \text{ cm}^{-3} \text{ low} \end{matrix}$	$1.1 \times 10^5 \text{ L/s}^a$	1.7	1.6	16	1.6
$T = \begin{matrix} 120 \text{ eV peak} \\ 30 \text{ eV low} \end{matrix}$	$2.1 \times 10^5 \text{ L/s}^b$	3.1	3.2	16	16
$n = \begin{matrix} 5 \times 10^{12} \text{ cm}^{-3} \text{ peak} \\ 2 \times 10^{12} \text{ cm}^{-3} \text{ low} \end{matrix}$	$1.1 \times 10^5 \text{ L/s}$	1.7	1.7	19	18
$T = \begin{matrix} 150 \text{ eV peak} \\ 30 \text{ eV low} \end{matrix}$	$2.1 \times 10^5 \text{ L/s}$	3.0	3.4	18	17

$^a_N = 16, C = 10 \text{ m}^3/\text{s}, S = 20 \text{ m}^3/\text{s}.$

$^b_N = 16, C = 20 \text{ m}^3/\text{s}, S = 10 \text{ m}^3/\text{s}.$

3. RESULTS

The modeling technique described in Sect. 2 is applied here to study the neutral pumping rates for pump-limiter and divertor configurations. In order to illustrate the modeling technique, the iteration process used for the first example in Sect. 3.1 is described in detail. Subsequently, the results and the trends they exhibit are emphasized. The results in this section also address the sensitivity of the calculated pumping rates to changes in various assumptions and boundary conditions.

3.1 PUMP-LIMITER CASE

The first step in the S.O. modeling technique involves using the radial profile model to find the average density and temperature in region 1 of the S.O. (see Fig. 2) and the S.O. thickness. Figure 7 shows the temperature and density in region 1 vs distance from the main plasma. This case is for a density of $5 \times 10^{13} \text{ cm}^{-3}$ and a temperature of 140 eV at the main plasma scrape-off interface (edge) and uses $D = \chi = 10^4 \text{ cm}^2/\text{s}$ for the particle and energy transport coefficients. Also shown is the assumed neutral recycling profile, R , which is determined in the following manner.

For the limiter case, recycling in the S.O. plasma is divided into two radial categories: (1) the S.O. portion incident on the top of the limiter and (2) the outer part of the S.O. that is incident on the bottom face of the limiter. Recycling in the first region is assumed to be small since the neutrals are not restrained by any material surface from entering the closed-field region. Recycling in the latter category is high since the geometry is "closed" and the neutrals are unlikely to penetrate back toward the main plasma. Sensitivity to changes in the low recycling assumption in the first region is addressed later. The location of the limiter's leading edge, which is the demarcation for the portion of the S.O. that flows below the limiter, is determined by the criterion that the heat flux has fallen to 200 W/cm^2 . For this example, the leading edge is 2.2 cm into the scrape-off. The recycling coefficient

Fig. 7. Density n , temperature T , and neutral recycle coefficient R vs radial distance from main plasma for a limiter case.

is increased to the prescribed value underneath the limiter, beginning 1 cm from the leading edge. Also, the recycling coefficient is ramped down to zero after the plasma temperature (average of the throat and plate values) falls below 20 eV since the neutral ionization probability begins to rapidly drop below this temperature.¹⁸ The range over which the recycling is decreased to zero is taken to be between the points where the temperature lies between 20 eV and 10 eV. Proper treatment of the cold (<10-eV) outer edge of the scrape-off requires a more detailed neutral transport model than the method used here, which relies on average densities and temperatures. The sensitivity of the results to variation in the recycle cutoff in the cold outer extent of the S.O. is addressed later. Finally, we note that in practice the actual determination of where to ramp the recycling coefficient up and down to satisfy the preceding criteria requires several iterations.

The distinguishing feature in Fig. 7 is the reduced rate of density falloff in the region of high neutral recycling, similar to the trend noticed in Fig. 3. Also, it is evident that the temperature falloff is not reduced in this region because heat conduction allows energy transport along the field lines even though the particle flow rate in that direction is reduced. The integrated heat flux (Q) onto the limiter is 48 MW (including the outboard half of the scrape-off that is assumed to be the same as the inboard half modeled here). To arrive at a different integrated value for total heat flux, the starting values for n and/or T at the edge of the main plasma must be changed accordingly and the preceding process repeated.

The information displayed in Fig. 7 includes the thickness of the scrape-off plasma that flows behind the limiter Δ and the average throat density $\bar{n}$ and temperature $\bar{T}$ of the plasma that flows behind the limiter. The thickness Δ is taken to be the radial distance from the leading edge to the point where the neutral recycling is assumed to go to zero. This information is used as input for the coupled ZEPHYR-neutral transport model calculation. Results for the plasma profiles along the field lines calculated with this model are shown in Fig. 8. The plasma density n , temperature T , and flow speed V are relatively constant in

Fig. 8. Ion temperature T_i , electron temperature T_e , density n , and flow speed V vs distance along the field line from the neutralizer plate for a limiter case.

the region adjacent to the main plasma [$4 \text{ m} \leq \ell \leq 20 \text{ m}$] with the gradients occurring predominantly in the "divertor" region [$0 \text{ m} \leq \ell \leq 4 \text{ m}$]. The localization of the gradients near the neutralizer plate supports the approximation made in Sect. 2.1 with regard to the use of constant plasma parameters along the field lines in region 1. The neutral transport calculations done in the ZEPHYR loop use the average of the plate and throat values for density and temperature and use the pump-limiter geometry described in Sect. 2.3. For this example, a pumping system of 16 pumps with speeds $= 5 \times 10^4 \text{ L/s}$ and ducts with conductance $= 1.9 \times 10^4 \text{ L/s}$ corresponding to $S_{\text{eff}} = 2.2 \times 10^5 \text{ L/s}$ is modeled. The net plasma current entering the limiter shadow region for this case is $7.4 \times 10^{21} \text{ s}^{-1}$, of which $4.7 \times 10^{21} \text{ s}^{-1}$ (63%) are pumped as neutrals. Also, the neutral recycling in the divertor channel [Eq. (6)] for these plasma conditions is 0.8, which is consistent with the assumed recycling in the preceding radial profile calculation. In practice, several iterations between the radial profile model and the ZEPHYR-neutral model are needed to reach a consistent neutral recycling value.

Table 3 shows results for several other cases found using the procedure previously described. These cases investigate the effects on the calculated neutral pumping rates caused by variations in the assumed conditions at the main plasma-S.O. interface and by changes in the assumptions used in the model. Values provided by the radial profile model (Q , $\bar{n}$, $\bar{T}$, $\Delta_{\text{S.O.}}$, Δ , f_{BL}) are indicated in the left-hand columns. Here $\Delta_{\text{S.O.}}$ is the total S.O. width, including the portion incident on the front surface of the limiter, and f_{BL} is the fraction of the plasma flow out of the S.O. region (along the field line) that flows below the limiter. Output from the coupled ZEPHYR-neutral model for the recycling value R , the neutral pumping rate Γ_p , and the fraction of the plasma flow into the throat that is pumped f are shown in the right-hand columns. All cases in Table 3 use the same pump speed as the case just described (case 1).

In comparing the neutral pumping rates in Table 3, the following scalings should be kept in mind. The neutral pumping rate is proportional to the total particle flow underneath the limiter (into the

Table 3. Results for coupled plasma-neutral transport modeling procedure for the limiter case

Case		Radical profile model							Coupled ZEPHYR-neutral model		
Description	n_{edge} (10^{13} cm^{-3})	T_{edge} (eV)	Q (MW)	$\bar{n}$ (10^{13} cm^{-3})	$\bar{T}$ (eV)	$\Delta_{\text{S.O.}}$	Δ (cm)	f_{BL} (%)	R	Γ_{p} (10^{21} s^{-1})	f (%)
1. Base	5.0	140	48	1.15	24.5	5.6	3.3	11	0.80	4.7	63
2. $\chi = 3 \times 10^4 \text{ cm}^2/\text{s}$	5.0	116	49	0.80	26.5	8.1	5.4	9	0.87	2.8	52
3. $D = 3 \times 10^4 \text{ cm}^2/\text{s}$	5.0	103	49	1.60	21.0	7.0	4.1	19	0.71	8.6	52
4. Low Q, low T_{edge}	4.6	100	30	1.30	23.0	5.3	3.0	17	0.76	5.8	61
5. Low Q, moderate T_{edge}	4.0	112	30	1.10	24.0	5.3	3.3	15	0.80	4.5	62
6. Lower temperature for recycling cutoff	4.0	112	30	0.92	21.2	7.6	5.6	19	0.80	4.2	48
7. High neutral recycling on front of limiter	4.0	116	30	1.20	23.5	5.5	3.3	19	0.78	5.2	62

throat). For the pump-limiter case considered here, about one-half to two-thirds of this flow is pumped. The plasma flow under the limiter is

$$\Gamma_T \sim \Delta \times \bar{n}_t \times V_t, \quad (17)$$

where V_t is the plasma flow speed at the throat. For conditions typical of the plasma considered here, the plasma flow speed at the throat is most strongly affected by the neutral recycling that occurs near the neutralizer plate, R. Increases in R tend to decrease the throat flow speed (see ref. 13). Variations of the pumping rates shown in Table 3 are explained by variations in the three parameters on the right-hand side of Eq. (17) as discussed in the following paragraphs.

Increasing χ (case 2 compared to case 1) results in a wider S.O., which tends to increase the neutral recycling. The increased recycling slows the plasma flow rate into the throat, which overwhelms the effects of a larger Δ in Eq. (17) and results in a net decrease of the neutral pumping. Increasing D (case 3 compared to case 1) only slightly changes Δ , but in this case there are stronger gradients along the field line and a lower plate temperature (<20 eV). This condition results in a slightly lower recycling than case 1 because of the reduced neutral ionization probability. The lower recycling in case 3 coupled with the higher average density at the throat results in the highest pumping rate of any of the cases shown in Table 3. Rather than specify the fraction of the S.O. that flows below the limiter, the location of the leading edge is determined here by the criterion that the heat flux has fallen to 200 W/cm^2 . As seen in Table 3, the fraction of plasma flowing out at the S.O. that goes below the limiter f_{BL} is $\approx 10\text{-}20\%$. This fraction tends to increase as the neutral recycling below the limiter, R, decreases.

Cases 4-7 in Table 3 use edge densities and temperatures that result in integrated heat fluxes Q of 30 MW. These cases generally have a smaller portion of the S.O. impinging on the front surface of the limiter, but the parameters for the part of the S.O. flowing behind the limiter are similar to those of Cases 1-3. The largest pumping rate

found in cases 4-7 is for the low edge temperature example (case 4), which has the lowest recycling. The lower input for the edge temperature has the consequence of a lower average throat temperature (and even lower temperatures near the neutralizer plate) than the other cases, which is responsible for the small recycling value. The last two examples in Table 3 indicate little effect on the neutral pumping rates from changes in the assumptions about the recycling profile used in the radial profile model. Case 6 uses a lower temperature (5 eV) for the neutral recycling cutoff in the radial profile model, and case 7 assumes that high neutral recycling also occurs on the front surface of the limiter. It is interesting to note that the pumping rate tends to increase with high recycling on the front surface of the limiter (case 7 compared to case 5). High neutral recycling on the front surface is desirable as a mechanism for reducing erosion rates.⁷ With high neutral recycling on the front surface of the limiter (case 7), the average density of the plasma beneath the limiter is slightly higher than that of case 5, and the temperature is slightly lower (hence lower neutral recycling). These effects result in an increased plasma flow rate underneath the limiter, which produces a larger pumping rate.

In general, the cases in Table 3 with the lowest recycling have the highest neutral pumping rates. Also, it is seen that variations in the assumptions inherent to the model show factors of uncertainty in the neutral pumping rates on the order of 2. The neutral pumping rate required for the exhaust in TFCX¹⁶ is $\sim 2 \times 10^{21} \text{ s}^{-1}$. This rate corresponds to 250 MW of fusion power and a 5% helium density ratio and assumes that helium transport (neutral and plasma) is equivalent to that of hydrogen. The neutral pumping rates shown in Table 3 indicate that adequate neutral particle removal rates for the exhaust requirements are possible for the pump-limiter configuration with $S_{\text{eff}} = 2.2 \times 10^5 \text{ L/s}$.

All results to this point have been calculated using the same pump speed. Figure 9 shows the variation of the neutral pumping rate with different pump speeds. These results are for the same input conditions as case 5 in Table 3. The increase in neutral pumping rates with higher pumping speeds is primarily due to two effects: (1) lower neutral

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Fig. 9. Neutral pumping rate and neutral recycling vs effective pump speed for a limiter case.

recycling and (2) a larger fraction of the plasma flowing into the throat being subsequently pumped as neutrals (pumping fraction) instead of escaping back toward the main plasma. The plasma flow into the throat for the 4.5×10^5 -L/s example is approximately twice that of 6×10^4 -L/s example, and this difference is related to the higher neutral recycling for the latter case. Also, the pumping fraction of the plasma flow into the throat is 2.5 times higher for the 4.5×10^5 -L/s case compared to the 6×10^4 -L/s case. The combination of the two effects results in a pumping rate that is ≈ 5 times higher for the 4.5×10^5 -L/s case.

Although the plasma flow rate into the throat for the case with $S_{\text{eff}} = 4.5 \times 10^5$ L/s is approximately twice that for the 6×10^4 -L/s case, the plasma flow rate onto the bottom of the limiter (i.e., the neutral production rate) is larger for the case with lower pump speed. The additional source of plasma flow onto the limiter for the 6×10^4 -L/s case arises from the larger neutral recycling. The fraction of the neutrals produced at the plate that are pumped is relatively small (i.e., 8% for $S_{\text{eff}} = 6 \times 10^4$ L/s and 21% for $S_{\text{eff}} = 4.5 \times 10^5$ L/s), with the bulk of the neutrals produced at the plate being ionized for both cases.

3.2 DIVERTORS

For the divertor case, the entire radial extent of the S.O. is included in the neutral pumping calculations, as opposed to the limiter case in which only the outer portion was involved. Consequently, much larger temperature and density variations are involved in the divertor case. To take some account of the larger probability of neutral ionization in the higher density and higher temperature portion of the S.O., the recycling profile $R(r)$, which is used in the radial profile model, is chosen in the following manner. The recycling is decreased linearly from a peak value at $r = 0$ to a lower value at the point where $T = 20$ eV. The peak (lower) value is taken so that the amount of recycling is doubled (halved) compared the reference value. The intermediate value is used for comparison with that predicted by the coupled ZEPHYR-neutral model. Otherwise the modeling procedure is the same as that

described for the limiter cases. Figure 10 shows the density and temperature profiles found with the radial profile model and the associated neutral recycling profile for a divertor case using an edge temperature (density) of 165 eV ($4.5 \times 10^{13} \text{ cm}^{-3}$). The integrated heat flux Q for this case is 30 MW. Also, $S_{\text{eff}} = 2.1 \times 10^5 \text{ L/s}$ and $\chi = D = 10^4 \text{ L/s}$ are used.

Figure 11 shows the profiles for density, temperature, and flow speed along the scrape-off field lines found with the ZEPHYR-neutral code using input from the information displayed in Figure 10. A neutral pumping rate of $5.8 \times 10^{21} \text{ s}^{-1}$ is found in this case, and the neutral recycling coefficient is 0.86. The divertor channel geometry (Fig. 6) is more open for neutral penetration toward the main plasma than the limiter-channel geometry. As a result, a larger fraction of the neutral flux leaving the divertor channel exits as neutrals escaping toward the main plasma rather than as pumped neutrals. In this case, only about one-fifth of the neutrals leaving the divertor channel are pumped, compared to corresponding fractions of more than one-half for the pump-limiter cases in Table 3.

Variation of the neutral pumping rate vs S_{eff} for the conditions used in the preceding case is shown in Fig. 12. The increase in neutral pumping rates with larger S_{eff} is caused by the pumping of a larger fraction (f) of the plasma flow into the divertor channel. Unlike the pump-limiter cases, the recycling is insensitive to changes in S_{eff} (see Fig. 12), and the total plasma flow rate into the divertor only changes slightly with S_{eff} . The lack of sensitivity of R to changes in S_{eff} is due to the small percentage of neutrals leaving the divertor channel as pumped neutrals. Also, it is evident that the neutral pumping rates for divertors are comparable to those of pump-limiters. Although the divertor case has more plasma flowing into the divertor channel than the limiter case, the smaller percentage of it that is pumped tends to even out the net pumping rate. To satisfy the exhaust requirement of a particle removal rate $\geq 2 \times 10^{21} \text{ s}^{-1}$ from Fig. 12, it is seen that S_{eff} must be $\geq 10^5 \text{ L/s}$.

Fig. 10. Density n , temperature T , and neutral recycle coefficient R vs radial distance from main plasma for a divertor case.

Fig. 11. Ion temperature T_i , electron temperature T_e , density n , and flow speed V vs distance along the field line from the neutralizer plate for a divertor case.

Fig. 12. Neutral pumping rate and neutral recycling vs effective pump speed for a divertor case.

4. CONCLUSIONS

4.1 SUMMARY

Investigation of the scrape-off region requires modeling the plasma transport across field lines and including the associated effects of neutral recycling. The method used in this work involves the use of separate models for each of these aspects that are coupled through an iteration procedure that checks the assumptions of one component with the output from another. This approach is a first step for the study of the scrape-off region including two-dimensional (2-D) plasma transport effects and those of the coupled neutral transport and requires only minimal numerical effort. The method was applied here to the study of neutral pumping rates in the pump-limiter and divertor options for the proposed TFCX experiment. It was found that high neutral recycling in the vicinity of the neutralizer plate has important ramifications on the evaluation of pumping rates for both the pump-limiter and the divertor. In both cases, the plasma flow into the channel surrounding the neutralizer plate is greatly reduced by the neutral recycling. The fraction of this flow that is pumped can be large (>50%), but in general it is dependent on the particular geometry and plasma conditions. It was found that pumping speeds $\geq 10^5$ L/s are adequate for the exhaust requirements in the pump limiter and the divertor cases.

4.2 LIMITATIONS OF MODEL AND FUTURE DIRECTIONS

The primary limitation of the technique used here is the use of averaged results from one component of the iteration procedure as input for calculations of other components. For instance, the simple neutral transport model used here provides a single recycling coefficient based on calculations using averaged plasma parameters and a scrape-off width provided by the radial profile model. A possible next step, which would provide a more accurate treatment of the transport along the field lines at each radial location, would be to use a Monte Carlo neutral transport model to provide the recycling coefficient as a function of radial position. This information could then be coupled to a method similar to

the radial profile model used here to permit a better treatment of the outer radial extent of the scrape-off plasma (with temperatures ≤ 20 eV), which could have a large contribution to the total plasma flow rate toward the neutralizer plate due to its transparency to neutral recycling.

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ABSTRACT

Analysis of the scrape-off region requires treatment of the plasma transport along and across the field lines and inclusion of the neutral transport effects. A method for modeling the scrape-off region that is presented here uses separate models for each of these aspects that are coupled together through an iteration procedure that requires only minimal numerical effort. The method is applied here to estimate the neutral pumping rates in the pump-limiter and divertor options for a proposed deuterium-tritium (D-T) ignition experiment. High neutral recycling in the vicinity of the neutralizer plate dramatically affects pumping rates for both the pump-limiter and divertor. In both cases, the plasma flow into the channel surrounding the neutralizer plate is greatly reduced by the neutral recycling. The fraction of this flow that is pumped can be large ($>50\%$), but in general it is dependent on the particular geometry and plasma conditions. It is estimated that pumping speeds $\geq 10^5$ L/s are adequate for the exhaust requirements in the pump-limiter and the divertor cases. Also, high neutral recycling on the front surface of the limiter tends to increase the neutral pumping rate.