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DIII-D edge plasma simulations with UEDGE code including non-diffusive anomalous cross-field transport

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Abstract

Recently, both Alcator C-Mod and DIII-D tokamaks observed fast anomalous cross-field plasma transport in the SOL. These observations supported by theoretical studies have indicated that such transport is essentially non-diffusive and intermittent. We present the results of macroscopic plasma simulations with the UEDGE transport code including anomalous cross-field outward-directed convection for a series of low-power DIII-D shots. Our analysis of experimental and simulation data supports the view that non-diffusive transport is important for the entire edge plasma behavior in both L- and H-mode discharges.

Keywords: Anomalous convection; Non-diffusive transport; Edge plasma; UEDGE code

1. Introduction

In the past few years much effort has been dedicated to the investigation of anomalous intermittent cross-field transport in the tokamak SOL. Such transport in plasma edges has been studied theoretically [1,2] as well as experimentally on both C-Mod [3] and DIII-D [4] tokamaks. These investigations have indicated that such transport produces plasma blob-like structures [1], causing infrequent but large transport events directed outwards. The intermittent transport is then not diffusive, but convective. Macroscopic plasma simulations accounting for fast non-diffusive transport have been performed with the 2D code UEDGE [5] for C-Mod [6] and DIII-D [7] edge plasmas. As shown, broad radial plasma profiles measured in the SOL are difficult to explain without non-diffusive transport. This transport strongly increases the plasma particle and power fluxes in the far SOL and enhances the recycling of neutral particles in the main chamber.

In the present study, we consider a series of shots obtained on DIII-D with the low power input due to Ohmic (OH) and neutral beam (NBI) heating. Based on our results of UEDGE simulations for these discharges, we describe the effect of anomalous non-diffusive transport on plasma parameters in both the SOL and divertor regions. We also compare the properties of anomalous transport in L- and H-mode plasmas.

2. UEDGE code model

The UEDGE code self-consistently solves the Braginskii plasma transport equations with anomalous cross-field transport and reduced Navier–Stokes equations for the deuterium atom transport [5]. The input

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parameters and boundary conditions for these equations, which match the recent experiments on DIII-D tokamak, are discussed in [7]. All DIII-D shots under consideration have a lower single-null magnetic configuration. The code simulates the SOL, outer and inner divertors, private flux region, and a narrow transition zone (TZ) of the core plasma (CP) adjacent to separatrix. Recent computations are done on non-orthogonal plasma mesh, which is constructed by using experimental magnetic equilibrium data and the detailed divertor geometry. This mesh covers the edge region, $\psi_N^c < \psi_N < \psi_N^w$, $\psi_N^c = 0.9$, $\psi_N^w = 1.15$, in the space of normalized poloidal magnetic flux ψ_N, where $\psi_N = 1$ corresponds to the magnetic separatrix. The input parameters at the core boundary ψ_N^c are the plasma density N_e^c and the plasma power P_c. In a series of UEDGE runs, the transport parameters are adjusted to match not only the radial plasma profiles measured upstream in the SOL by the Thomson scattering system (TSS), but also the particle flux balance for CP at ψ_N^c boundary: $\Phi_{cp} = G_c + \Phi_0^c$. Here, the net plasma flux through ψ_N^c, Φ_{cp}, is matched to the CP fueling rate which is the sum of the direct particle input G_c due to NBI and the recycling neutral influx Φ_0^c. Without gas puffing and cryopumping, the plasma particle balance is controlled by the albedo ξ_w, which is prescribed on the outer-most magnetic flux surface (MFS), ψ_N^w. The effect of plasma cooling by carbon impurity radiation is described by a simple model in which the spatially constant parameter γ_{imp} represents the ratio of impurity ion density to electron density. The value of γ_{imp} is adjusted to match the total radiated power loss P_{tot}^{rad} measured by bolometers as well as the plasma parameters and D_α radiation profiles measured in the divertor.

3. Anomalous cross-field convection

The cross-field plasma transport in tokamaks is known to be strongly anomalous and is usually handled in edge transport codes by using a simple diffusive model. This model introduces spatially constant coefficients for plasma diffusion ($D_\perp$) and heat conduction ($\chi_\perp$), whose values should be deduced from matching experimental data. However, a purely diffusive cross-field transport (PDCFT) model does not incorporate the effect of intermittent convective transport and in some cases it fails to match experimental data [7].

The non-diffusive, blobby plasma transport is modeled in UEDGE by a time-independent anomalous cross-field convective velocity V_{conv} directed outward. The model 2D profile of the V_{conv} term is described in [7]. The analytical profile is characterized by input parameters V_{conv}^c, V_{conv}^s, and V_{conv}^w which are the velocities at the outer mid-plane for ψ_N^c, $\psi_N = 1$, and ψ_N^w, respectively. To model the low-power plasmas, the V_{conv} profile in [7] has been modified for the divertor regions. Instead of poloidally self-similar radial profile, we assume that V_{conv} is zero around the X-point and monotonically increase along the MFS towards the divertor plates reaching V_{conv}^d at the strike points. The $D_\perp$ and $\chi_\perp$ coefficients, convective velocities V_{conv}^j (j = c, s, w, d), and albedo ξ_w are adjusted until the simulated plasma profiles agree with the measured profiles.

The radial particle flux, F_b, associated with plasma blobs in the SOL is $F_b = N_b V_b (R_b/V_b) f_b$, where N_b, V_b, and R_b, are the plasma density, cross-field velocity, and radial thickness of a blob, f_b is the blob birth frequency in CP. The convective flux at the wall is $F_w = N_e^w V_{conv}^w$. Hereafter, N_e^w and N_e^s are the plasma densities at ψ_N^w and $\psi_N = 1$. Assuming that blob parameters remain unchanged across the SOL and taking $N_b = N_e^{tz} = (N_e^c + N_e^s)/2$, the particle flux balance results in $f_b = (N_e^w/N_e^{tz}) V_{conv}^w / R_b$. We use this simple relation to represent anomalous convective flux in terms of 'blobs per second'. For $R_b = 0.005$ m, the typical values $N_e^w/N_e^{tz} = 0.05$–0.1, $V_{conv}^w = 100$–200 m/s inferred from UEDGE calculations correspond to $f_b = 1000$–4000 blobs/s at mid-plane that is in good agreement with intermittent transport measurements [4] on DIII-D.

4. Results

The L-mode shots selected for this paper provide experimental data over a range of edge-plasma densities at the same power input. The outer divertor is attached for all these shots, while the inner divertor detaches only in the highest density shot. The parameters at 3400 ms into the discharges are listed in Table 1, including: line-averaged plasma density, $\langle N_e \rangle$, measured by interferometers; density N_e^c obtained by the main-chamber TSS; time-averaged power inputs due to NBI ($\langle P_{NBI} \rangle$) and OH ($\langle P_{OH} \rangle$); CP particle input corrected for a long time scale density variation $G_c = -\Omega_c \, d\langle N_e \rangle/dt + G_{NBI}$ (Ω_c is the core volume, $G_{NBI} \approx \langle P_{NBI} \rangle \times 20$ A/MW is the NBI

Table 1
Parameters of DIII-D shots used in UEDGE simulations

	Shot number			
	105500	105512	105517	105188
Mode	L	L	L	H
$\langle N_e \rangle$ (10^{19} m^{-3})	2.4	3.5	4.5	5.8
N_e^c (10^{19} m^{-3})	1.1	2	3	5.0
G_c (A)	5	20	27	60
$\langle P_{NBI} \rangle$ (MW)	0.5	0.6	0.6	2.6
$\langle P_{OH} \rangle$ (MW)	0.6	0.7	0.9	0.4
P_c^{rad} (MW)	0.13	0.2	0.4	0.6
P_c (MW)	1.0	1.1	1.1	2.4
P_{tot}^{rad} (MW)	0.5	0.8	1.0	1.3
τ_E (s)	0.13	0.12	0.1	0.2

fueling rate); radiation power loss P_c^{rad} from CP calculated by using experimental radial profiles of N_e and T_e; and $P_c = -1.5\Omega_c \, d\langle N_e(T_e + T_i)\rangle/dt + \langle P_{NBI}\rangle + \langle P_{OH}\rangle - P_c^{rad}$. The terms $d\langle\rangle/dt$ are evaluated according to the time evolution of plasma profiles measured in CP. We model these shots using UEDGE with and without taking anomalous non-diffusive transport into account.

We find that PDCFT model does not match simultaneously experimental data on basic edge plasma parameters listed in Table 3. For the shot 105500, PDCFT model requires high values of $D_\perp = 0.25$–0.3 m^2/s to fit the radial plasma profiles in the CP and near SOL. At the same time, the calculated far-SOL density is less than that measured and the computed plasma flux to main chamber walls is negligibly small. For any $D_\perp$ consistent with particle flux balance at ψ_N^c boundary, neutral density at mid-plane due to leakage of neutrals from the divertor is small, so that the calculated D_α brightness for tangential and horizontal ($J_{D\alpha}^{fs12}$) FSSs at mid-plane is several times smaller than the measured brightness. As a result, the calculated CP source due to ionization of recycling neutrals is about half the source derived from D_α measurements. The deficiencies of PDCFT model are clearly seen in Fig. 1. In particular, without fast convection, the calculated D_α signals strongly decrease in the view away from the divertor, whereas the same signals measured by upper-viewing FSS even increase. Moreover, solutions only with both inner and outer divertor detachment were obtained for the highest density shot 105517 in matching the CP and SOL data under assumption of PDCFT.

Inclusion of fast non-diffusive transport allows us to obtain attached divertor solutions consistent with most experimental data for all L-mode shots under consideration. The anomalous transport data in Table 2 correspond to UEDGE solutions giving the best fit to experimental data. As seen, these shots can be modeled using the same values of $D_\perp$ and $\chi_\perp$. The higher the $\langle N_e\rangle$ of the shot, the higher is the convective velocity V_{conv}^w in the far SOL. For the CP and near SOL regions, anomalous velocities, V_{conv}^c and V_{conv}^s, decrease as plasma density increases. In this table, Φ_0^c, Φ_0^s, and Φ_0^w are the neutral fluxes through the ψ_N^c, $\psi_N = 1$, and ψ_N^w surfaces, respectively; the expression $\{A\}$ means the poloidal averaging of A over the outer SOL; $\eta_{conv} = \Phi_{conv}/\Phi_{total}$ is the ratio of anomalous convective flux to total flux. The plasma flux to chamber walls is predominantly due to anomalous convection: $\eta_{conv}(\psi_N^w) \approx 1$, whereas the fraction $\eta_{conv}(\psi_N = 1)$ of anomalous convection at the separatrix decreases as $\langle N_e\rangle$ increases. The neutral flux, Φ_0^w,

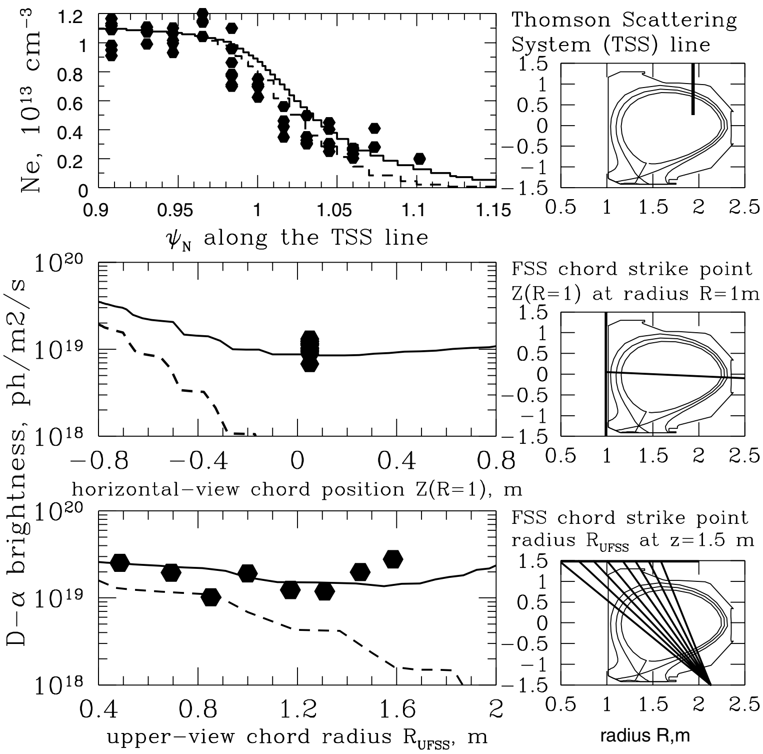

Fig. 1. Comparison between experimental profile data (points) and the profiles calculated with (solid lines) and without (broken lines) anomalous plasma convection is given in LHS panels for DIII-D shot 105500. Arrangement of corresponding diagnostics is shown on RHS panels.

Table 2
Anomalous cross-field transport data from UEDGE

	Shot number			
	105500	105512	105517	105188
$D_{\perp}$ (m^2/s)	0.15	0.15	0.15	0.08
$\chi_{\perp}$ (m^2/s)	0.8	0.8	0.8	0.25
$V^{w}_{conv}/\{V^{w}_{conv}\}$ (m/s)	100/56	137/76	170/95	100/60
$V^{s}_{conv}/\{V^{s}_{conv}\}$ (m/s)	13/7	8/4.8	5/3	2/1.2
$V^{c}_{conv}/\{V^{c}_{conv}\}$ (m/s)	9/3	3/1	2/0.7	0.8/0.3
V^{d}_{conv} (m/s)	13	11	9	17
$\eta_{conv}(\psi^{w}_{N})$	0.97	0.95	0.93	0.92
$\eta_{conv}(\psi_{N}=1)$	0.7	0.5	0.4	0.35
Φ^{c}_{0} (A)	260	253	240	200
Φ^{s}_{0} (A)	520	590	870	570
Φ^{w}_{0} (A)	260	590	1360	1300
ε_{wr}	0.4	0.8	0.9	0.9
ξ_{w}	0.99	0.98	0.98	0.96

which is mainly due to neutralization of convective plasma flux at the outer chamber wall, increases with $\langle N_e \rangle$. In low-density discharges, the SOL is relatively transparent for neutral atoms. The flux Φ^{s}_{0} through separatrix is then close to Φ^{w}_{0}, except for shot 105500 where there is a significant contribution from neutrals originating in the divertor. In all shots, the core influx Φ^{c}_{0} due to recycling neutrals is by more than order of magnitude higher than NBI fueling G_{NBI}. The chamber wall is close to being totally saturated by gas; only 1–2% (see ξ_w values in Table 2) of incident particle flux is deposited. The heat transport across the TZ and near SOL is dominated by heat conduction, but the heat convection dominates in the far SOL.

An important quantity is ε_{wr}, the fraction of neutral flux through the ψ^{c}_{N} MFS into the CP due to recycling of neutrals in the main chamber. For the lowest density shot 105500, this fraction is 40% (Table 2) indicating the importance of neutrals leaking from the divertor into the core for plasma fueling. However, divertors become rapidly opaque to neutral atoms with increase in the discharge density $\langle N_e \rangle$. For the higher density shots, the main chamber recycling dominates in CP fueling.

Comparison between experimental and simulated data is given in Table 3. As seen, UEDGE accurately matches the following chosen parameters: temperatures (T^{c}_{e}, T^{div}_{e}) and densities (N^{c}_{e}, N^{div}_{e}) measured by TSS in the TZ and in the outer divertor a few cm above the plate; peak values for ion saturation current (Φ^{p}_{d}) and temperature (T^{p}_{d}) measured by probes installed on divertor floor; horizontal D_{α} signals $J^{fs12}_{D\alpha}$; ion temperature T^{tz}_{i} and impurity content γ^{core}_{imp} in TZ obtained by CERS; mid-plane pressure P_{mid} measured by fast pressure gauge. The UEDGE simulations reproduce an important feature of this series of L-mode shots: main-chamber recycling quantities, $J^{fs12}_{D\alpha}$ and P_{mid}, strongly increase and impurity content γ^{core}_{imp} decreases with increase in the discharge density.

We also simulate the low-density H-mode shot 105188. Our modeling is related to the time slice 3300 ms taken just before an edge localized mode (ELM). Similar to the highest density L-mode shot, the PDCFT model gives the plasma temperature $T^{p}_{d} < 2$ eV at outer divertor plate, which is smaller than the measured temperature $\approx$9 eV. Then, we include anomalous convection in order to obtain attached solutions for this H-mode shot. According to experimental stored energy based on EFIT reconstruction as well as to diamagnetic measurements, the energy confinement time τ^{H}_{E} in H-mode at this time is about twice the τ^{L}_{E} in L-mode shots (Table 1). Correspondingly, 2–3 times smaller transport coefficients are used in simulation of this H-mode plasma compared to those used in L-mode modeling (Table 2). With respect to L-mode shot 105517, the convective velocities inferred from the simulations with good agreement to the measured H-mode profiles change differently in different edge regions: velocities in the pedestal region, V^{c}_{conv} and

Table 3
UEDGE data versus experimental data

	Shot number							
	105500		105512		105517		105188	
	UEDGE	EXP	UEDGE	EXP	UEDGE	EXP	UEDGE	EXP
N^{c}_{e} (10^{19} m^{-3})	1.1	1.1	2	2	3	3	5.0	5.0
T^{c}_{e} (eV)	310	300	240	240	200	200	600	600
T^{tz}_{i} (eV)	350	–	270	300	230	220	600	–
$J^{fs12}_{D\alpha}$ (10^{19} m^{-2}/s)	0.9	1.0	2.3	2.8	4	5	3	3
T^{div}_{e} (eV)	30	30	15	12–20	6	4–7	25	30
N^{div}_{e} (10^{19} m^{-3})	2	1.5	5	3–5	10	6–12		
γ^{core}_{imp} (%)	0.8	0.8	0.3	0.3	0.25	0.2	0.5	0.8
Φ^{p}_{d} (A/cm^2)	20	15–20	27	20–40	40	20–40		
T^{p}_{d} (eV)	28	30–40	13	13–20	3	5–10	5	9
P_{mid} (μTorr)	4	5–9	7.6	10	19	20	15	10

V^{s}_{conv} decrease roughly by factor $\tau^{H}_{E}/\tau^{L}_{E}$, V^{w}_{conv} decreases slowly, and V^{d}_{conv} in the divertor increases. The effect of anomalous convection on H-mode edge plasma in this shot (at least, from a numerical experiment viewpoint) has the same main features as in L-mode shots: the rapid cross-field transport results in a strong main chamber recycling, reduces and delocalizes the recycling of neutrals and plasma radiation near the strike points, and avoids false detached divertor solutions.

5. Conclusions and discussion

Using the UEDGE code, we simulate the non-diffusive, intermittent cross-field transport in DIII-D edge plasma by using a spatially dependent, time-averaged anomalous convective velocity. We model the plasma and neutral transports self-consistently in 2D by adjusting the transport parameters until the simulated radial plasma profiles and radiation agree with measurements in the SOL, CP, and divertor regions.

Inclusion of anomalous convection allows us to reproduce not only the individual properties of selected shots, but also important experimental features of a series of low-power L-mode shots: (i) radial plasma density profiles extend far into the SOL; (ii) horizontal chord D_α brightness (which is directly related to the plasma source in the main chamber) increases faster than linearly with discharge density; (iii) the concentration of impurities both in the CP and in the divertors decreases with edge plasma density, while the total plasma radiation loss increases. We find that anomalous convective velocity profile should vary with L-mode discharge density, whereas the plasma diffusivities may have the same values in all these discharges. Because of strong increase of D_α brightness measured from the main chamber with increase in $\langle N_e \rangle$, the calculated V^{w}_{conv} in the far SOL increases approximately linearly with $\langle N_e \rangle$.

The present UEDGE simulations show that experimental data can be successfully modeled by rapid convective cross-field transport in both L- and H-mode plasmas, and that such transport may lead to the main-chamber recycling regime, in which neutrals originated from the main chamber feed the CP predominantly.

More modeling, theoretical, and experimental efforts are required to validate the 2D profile of anomalous convective velocity. In particular, it is not ruled out that intermittent transport also occurs on the inboard part of the torus. In fact, the blob radial movement outward on the outboard side is a cause of strong MHD perturbations to magnetic flux tube that may result in this flux tube moving toward the inner wall on the inside of the torus. In this case, plasma-blob transport may also cause enhanced recycling of particles on the inner chamber wall. Inner chamber wall recycling due to fast radial transport has been observed on C-Mod [3].

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