PFC/JA-96-6

Two-Body Similarity and Its Violation in Tokamak Edge Plasmas

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March 1996

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This work was supported by the US Department of Energy under contract DE-FG02-91ER-54109.

Submitted for publication in: Physics of Plasmas

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Abstract

Scaling laws found under the assumption that two-body collisions dominate can be effectively used to benchmark complex multi-dimensional codes dedicated to investigating tokamak edge plasmas. The applicability of such scaling laws to the interpretation of experimental data, however, is found to be restricted to the relatively low plasma densities ($<10^{19}$ m^{-3}) at which multi-step processes, that break the two-body collision approximation, are unimportant.

PACS numbers: 52.30.-q, 52.25.Fi

The physics of edge plasmas plays a very important role in tokamak performance by strongly affecting global plasma confinement (e.g. L- and H-modes) and determining the plasma-wall interaction regime and first wall heat load. All of these factors have substantial impact on tokamak reactor design. Edge plasma physics, however, is complicated and involves many different disciplines including plasma turbulence, plasma-neutral interactions, impurity dynamics, atomic physics, radiation transport, wall interactions, and kinetic features. Two dimensional (2D) transport codes developed for modeling edge plasmas (see, for example, Ref. 1 and the references therein) have becomed quite complex and it is often difficult to identify the underlying physical phenomena. As a result, efforts have been made to determine key dimensionless parameters and scaling laws for edge plasmas from the first principles. These scaling laws can be compared with experimental results to provide insight into the importance of the various physical processes at work. Moreover, the edge plasma scaling laws can be used to help benchmark large 2D codes.

General dimensionless analyses were given in Refs. 2-4 that identified all dimensionless plasma parameters. The similarity of different devices is insured by keeping the key dimensionless parameters fixed[3]. Lackner[5] considered the similarity of tokamak edge plasmas by making some assumptions about the relative importance of the various physical processes (in particular dominance of two-body collisions). In Ref. 6 the scaling laws for different regimes of plasma (treated as a fluid) interacting with neutrals, including the boundary conditions at the walls, were analyzed in the two-body collision approximation.

The main goal of our investigation is into the applicability of the two-body collision approximation for tokamak edge plasmas for the parameters relevant to current experiments. We begin by recalling the neutral kinetic equation retaining multi-step transitions between all possible quantum states $\vec{\alpha}$ in the absence of three-body interactions:

$$\vec{v}\cdot\nabla f_N(\vec{v},\vec{r},\vec{\alpha}) = C_{N,N} + C_{N,p} + C_{N,\hbar\omega} \ . \qquad (1)$$

In Eq. (1), $f_N(\vec{v},\vec{r},\vec{\alpha})$ is the neutral distribution function, $\vec{v}$ is the velocity, and $\vec{r}$ is the spatial variable; the terms $C_{N,N}$ and $C_{N,p}$ describe two-body neutral-neutral and neutral-plasma interactions, while the term $C_{N,\hbar\omega}$ accounts for radiation effects (absorption of radiation, induced emission, and spontaneous decay of excited states). Often only spontaneous decay is retained in $C_{N,\hbar\omega}$ by assuming an optically thin plasma. However, spontaneous decay of excited states is a one-body process. Therefore, neutral transport can only be described in terms of two-body processes if either a) $C_{N,\hbar\omega}$ is much smaller than other terms in Eq. (1), or b) the spontaneous decay of the excited states of the neutrals occurs before they are able to have significant impact on the processes important in edge plasmas (e. g. energy radiation loss, ionization of the neutrals, etc.). For both these limits two-body collisional scaling can be recovered.

We investigate the applicability of the two-body interaction approximation in a tokamak scrape-off layer with a modified rectangular version of the 2D UEDGE plasma fluid code coupled to Navier-Stokes neutral transport package [1]. To benchmark the code against two-body scalings, we first neglect the effect on the ionization rate of multi-step atomic processes involving the excited states of atomic hydrogen. Then we retain multi-step processes in the ionization rate to investigate the significance of non-two-body effects. Violation of two-body scaling due to multi-step transitions occurs if ionization of a significant population of excited atoms takes place before they are able to spontaneously decay to the ground state.

We consider a rectangular divertor region between the X-point and target with a prescribed energy flux profile and zero particle flux condition on the upstream boundary, and complete plasma recycling at the walls. We perform the simulations for a reference case with Alcator C-Mod edge plasma parameters[7] (B_{pol}/B=0.06, 25 cm poloidal distance between the X and strike points, and a 5 cm radial width). For the reference case the peak parallel energy flux and plasma pressure at the divertor entrance are taken to be 150 MW/m^2 and 800 Pa, respectively, and anomalous plasma particle and heat diffusivities of 0.5 m^2/s are employed; resulting in a peak upstream plasma density and temperature of $\sim 6\times 10^{19}$ m^{-3} and ~ 40 eV. The contour plot of the plasma density found for the reference case are shown in Figs. 1a for the 5 cm nearest the target.

Next we perform the scaled simulation. Following the scaling law procedure of Ref. 6 we quadruple all dimensions of our computational domain (including the grid spacing) and the anomalous transport coefficients, and reduce the upstream pressure and energy flux by a factor of four to obtain the same normalized solution. Notice, that to preserve two-body scalings we must scale anomalous transport coefficients and lengths the same way, and omit the plasma density dependences in the atomic hydrogen rate constants caused by multi-step processes. The contour plot of the plasma density for the scaled case shown in Figs. 1b are multiplied by four to illustrate exact two-body similarity (all other plasma quantities also obey exact similarity). This test of two-body similarity provides an important benchmarking of the UEDGE code.

Figures 2 a and b show the plasma density for the same benchmarking test, but with multi-step processes turned on in the atomic hydrogen ionization and radiation rate constants. Notice that two-body similarity is no longer satisfied. Moreover, differences occur even for the low plasma densities cases (Figs. 1b and 2b), for which the effect of multi-step processes is weaker (see Ref. 8 and the references therein). The reason for these differences is that the effect of multi-step processes on the atomic hydrogen rate constants can only be neglected, roughly speaking, below 10^{19} m^{-3} (for optically thin plasma), while even our lower density simulations exceed 5×10^{19} m^{-3} in some regions. The violation of two-body similarity is also apparent from the appropriately normalized heat fluxes onto the target, as illustrated in Fig. 3. It follows from Fig. 3 that at higher plasma densities multi-step processes result in higher heat loads than would be predicted by two-body scaling laws.

To summarize we have demonstrated the following:

i) The scaling laws found in Refs. 5, 6 by assuming two-body interactions dominate provide a useful benchmarking technique for the complex multi-dimensional codes employed to investigate tokamak edge plasmas.

ii) The applicability of two-body scaling laws for interpreting experimental data is restricted to the relatively low plasma densities ($<10^{19}$ m^{-3}) for which multi-step processes are unimportant.

Acknowledgments

Research was supported by U.S. DoE, under grant DE-FG02-91ER-54109 at MIT and by contract DE-AC07-94ID13223 at INEL.

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Figure Captions

Fig. 1. Figures 1 (a) and (b) show the plasma density for the benchmarking test in which the multi-step processes are turned off in the atomic hydrogen ionization and radiation rate constants. Figure 1 (a) is the contour plot of the plasma density found for the reference case for the 5 cm nearest the target. Figure 1 (b) is the contour plot of the plasma density for the scaled case multiplied by four to illustrate exact two-body similarity.

Fig. 2. Figures 2 (a) and (b) show the plasma density for the same benchmarking test as in Figs. 1 but with multi-step processes turned on in the atomic hydrogen ionization and radiation rate constants.

Fig. 3. Figure 3 illustrates one consequence of the violation of two-body similarity by plotting the heat fluxes onto the target for the cases shown in Figs. 2. The heat flux of the case of Fig. 2 (a) is compared to four times the heat flux of the case of Fig. 2 (b).

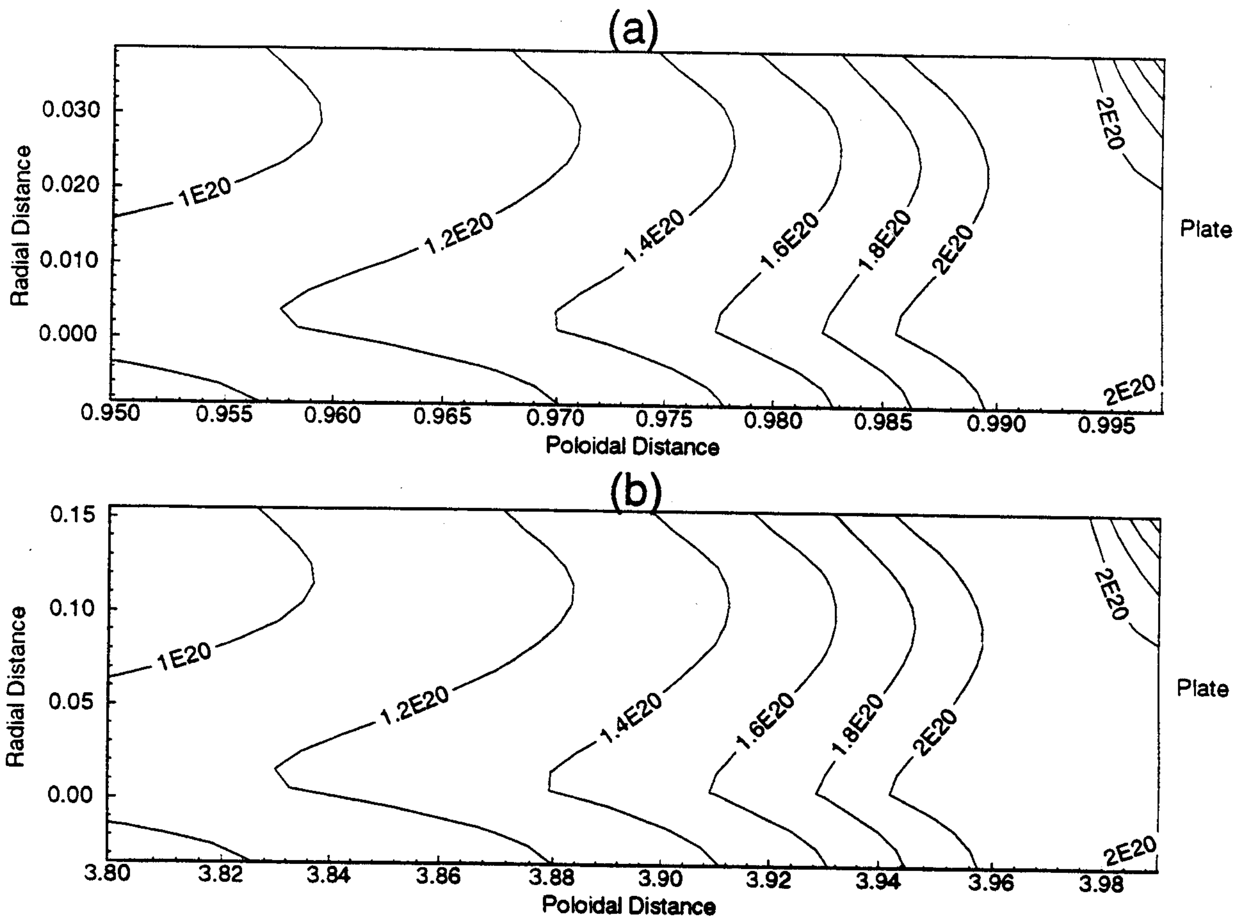
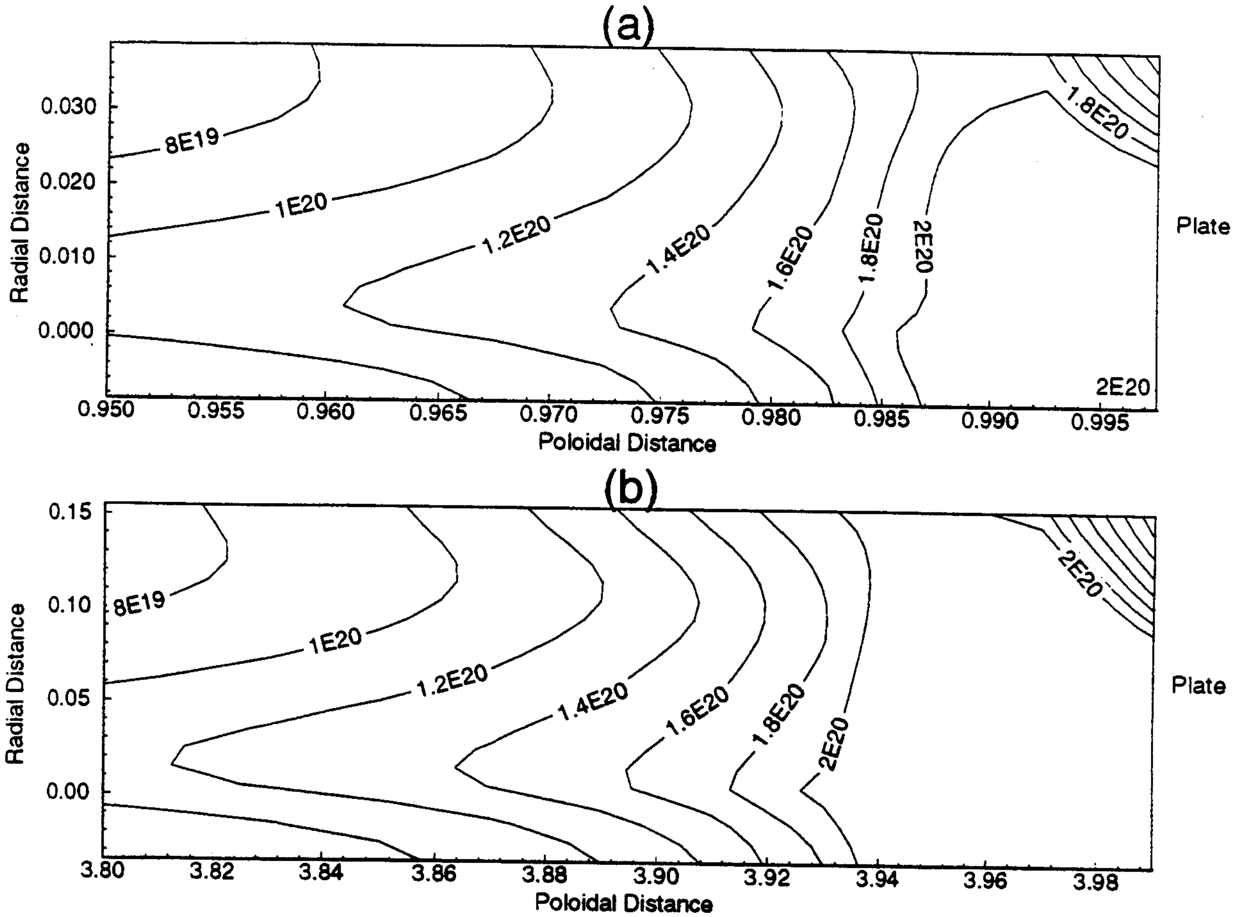

(a)
0.030
0.020
0.010
0.000
Radial Distance
1E20
1.2E20
1.4E20
1.6E20
1.8E20
2E20
2E20
2E20
Plate
0.950
0.955
0.960
0.965
0.970
0.975
0.980
0.985
0.990
0.995
Poloidal Distance
(b)
0.15
0.10
0.05
0.00
Radial Distance
1E20
1.2E20
1.4E20
1.6E20
1.8E20
2E20
2E20
2E20
Plate
3.80
3.82
3.84
3.86
3.88
3.90
3.92
3.94
3.96
3.98
Poloidal Distance

Fig. 1 a,b.



(a)
Radial Distance
0.030
0.020
0.010
0.000
8E19
1E20
1.2E20
1.4E20
1.6E20
1.8E20
2E20
1.8E20
2E20
Plate
0.950
0.955
0.960
0.965
0.970
0.975
0.980
0.985
0.990
0.995
Poloidal Distance
(b)
Radial Distance
0.15
0.10
0.05
0.00
8E19
1E20
1.2E20
1.4E20
1.6E20
1.8E20
2E20
2E20
Plate
3.80
3.82
3.84
3.86
3.88
3.90
3.92
3.94
3.96
3.98
Poloidal Distance

Fig. 2 a,b.

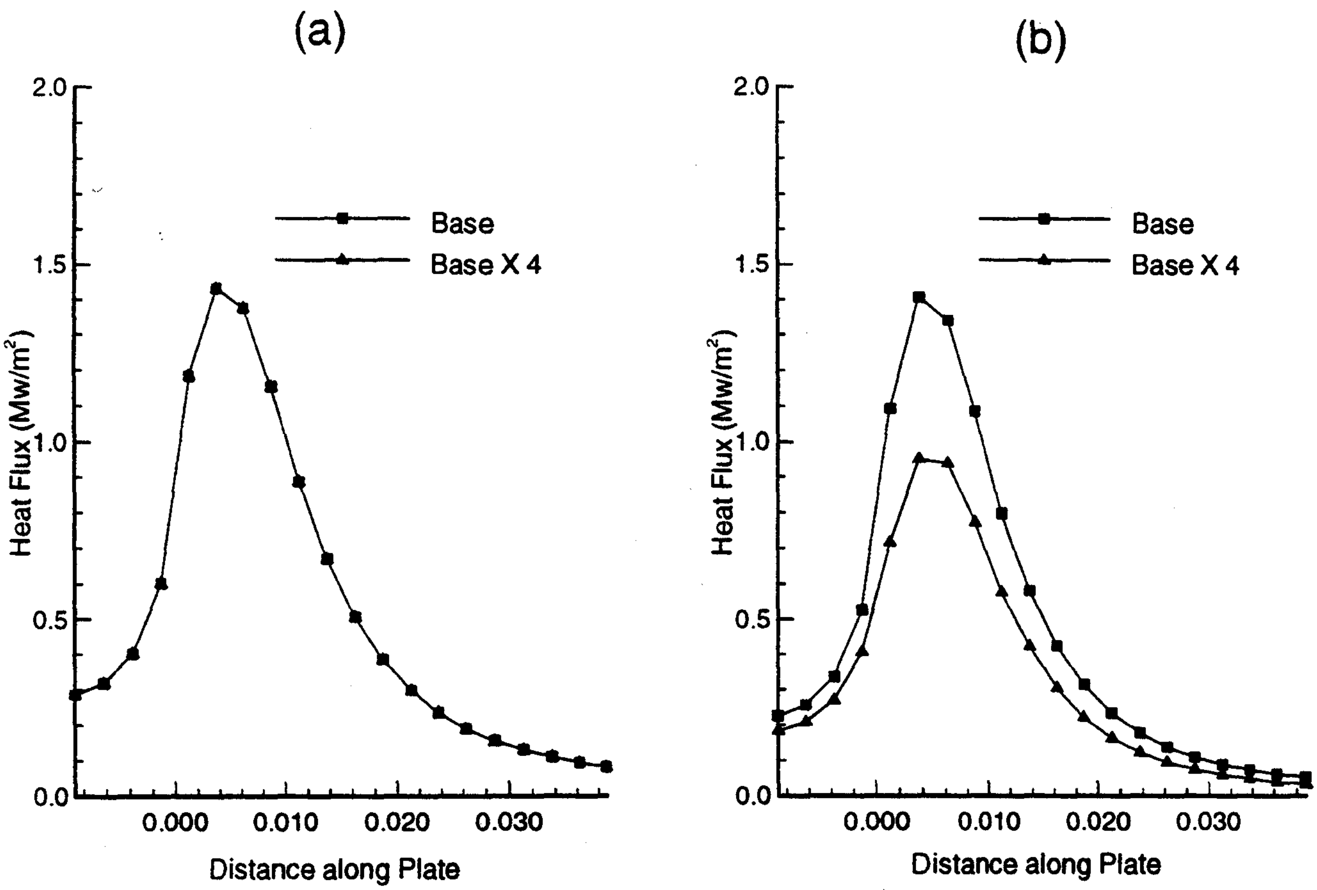

(a)
(b)
Base
Base X 4
Heat Flux (Mw/m²)
2.0
1.5
1.0
0.5
0.0
0.000
0.010
0.020
0.030
Distance along Plate

Fig. 3.