Heat transmission coefficients in the scrape-off layer using PARASOL

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Hot plasma lost from the core of a tokamak travels along the open field lines in the scrape-off layer (SOL) to the divertor plates. To evaluate the heat load on the plates, fluid models are commonly used, but their accuracy falls off when the plasma deviates strongly from a Maxwellian distribution. Such deviation can occur when the collisionality is low or there is an electric field, such as in the sheath region. Modern SOL fluid codes apply external models that attempt to correct for the loss of kinetic effects. These models can be developed from experimental data or fully kinetic simulations. Kinetic effects that must be accounted for include closure parameters and boundary conditions at the sheath entrance. In this work, the behaviour of the heat transmission coefficients (HTCs) is examined with the PARASOL-1D simulation, a particle-in-cell code with a Monte-Carlo binary collision model [1].

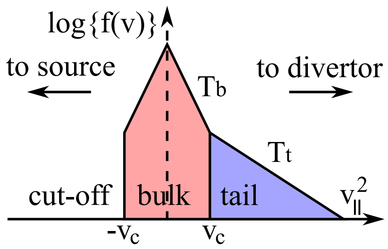
The total heat transmission coefficient relates the total energy flux of all plasma species $Q^{se} = \sum_j Q_j^{se}$ at the plasma-wall interface (sheath entrance) to the temperature T_j and particle flux $\Gamma_j^{se} = n_j V_j$, macroscopic quantities that are accessible in the fluid model. The contribution of species j is defined as $Q_j^{se} = \gamma_j / T_e \Gamma_i^{se}$ in experimental papers [2] and $Q_j^{se} = \gamma_j / T_j \Gamma_j^{se}$ in theoretical papers [3, 4]. We shall adopt the former in this paper because it is simpler to measure ion current and electron temperature in experiments. Theoretical treatment produces typical values in the ranges $\gamma_e = 4.5 - 5.5$ and $\gamma_i = 2 - 3 \times T_i / T_e$. However, the total HTC $\gamma = \gamma_i + \gamma_e$ measured in tokamaks falls within a larger range of 2-20 [2]. PARASOL simulations are used to show that the experimental results can be explained entirely by electron radiation energy loss, henceforth referred to just as radiation.

The classical expressions for the electron and ion HTCs are

$$\gamma_e = 2 + \frac{e\phi^{se}}{T_e}, \quad (1) \qquad\qquad \gamma_i = 2.5\frac{T_i}{T_e} + \frac{m_i V_{i||}^2}{2T_e}, \quad (2)$$

where ϕ^{se} is the potential at the sheath entrance and $V_{i||} = \int d\mathbf{v} v_{||} f_i(\mathbf{v}) / \int d\mathbf{v} f_i(\mathbf{v})$ is the ion parallel fluid velocity [3, 4]. Often only the first term of Eq. (2) is used to estimate the ion HTC, but the convective correction is found to be necessary in the collisional regime. Equation (1) was found to not match the electron HTC for all cases with radiation.

If the plasma is collisional, then there is strong diffusion in velocity space and the electron energy distribution function (EDF) tends towards a Maxwellian distribution. However, if the plasma is weakly collisional or collisionless, simulations have shown that the electron EDF in the SOL has a low-energy symmetrical bulk population and a high-energy tail traveling towards the divertor plate [1], as shown in Fig. 1. The symmetric bulk will not contribute to the particle or energy fluxes, so that they are determined almost entirely by the high-energy tail in this situation. Even so, the tail is usually too small to measure experimentally.



$$f(\mathbf{v}) = \begin{cases} 0 & v_{||} < -v_c \\ \frac{n_b}{\pi^{3/2} v_{t||} v_{t\perp}^2 \mathrm{erf}(v_c/v_{b||})} \exp\left(\frac{-v_{||}^2}{v_{b||}^2} - \frac{v_{\perp}^2}{v_{b\perp}^2}\right) & \left|v_{||}\right| < v_c \\ \frac{n_t}{\pi^{3/2} v_{t||} v_{t\perp}^2 [\mathrm{erf}(v_c/v_{t||}) - 1]} \exp\left(\frac{-v_{||}^2}{v_{t||}^2} - \frac{v_{\perp}^2}{v_{t\perp}^2}\right) & v_c < v_{||} \end{cases}$$

Figure 1: The electron energy distribution function is made up of a symmetric bulk and a high energy tail moving towards the divertor plate with thermal velocities v_b and v_t, respectively. The total electron density is equal to the sum of the bulk and tail densities $n_e = n_b + n_t$.

The electron HTC for this EDF can be readily calculated as

$$\gamma_e = \frac{m_e(v_{t||}^2 + v_{t\perp}^2 + v_c^2)}{2T_e} = \frac{\frac{1}{2}T_{t||} + T_{t\perp} + e\phi^{se}}{T_e}, \quad (3)$$

where $T_{t||}$ and $T_{t\perp}$ are the parallel and perpendicular temperature of the high-energy tail. The tail electrons travel directly from the source to the divertor plate without being trapped, so they have not yet experienced energy loss at the sheath entrance. Therefore, the tail temperature is typically isotropic and close to the electron source temperature, $T_{t||} \sim 0.7$ and $T_{t\perp} \sim 1$. By assuming that $T_{t||} \approx T_{t\perp} \approx T_{e0}$, Eq. (3) can be approximated as

$$\gamma_e \approx \frac{\frac{3}{2}T_{e0} + e\phi^{se}}{T_e}. \quad (4)$$

The PARASOL-1D code employs a self-consistent electrostatic particle-in-cell model with a binary collision model [1]. A slab geometry is used, such that motion is given by coordinate s along a magnetic field line with connection length $L_{||}$. The ratio of toroidal to total magnetic field strength is set such that the angle of incidence with the divertor is oblique $B_\phi/B = 0.2$. The amplitude of the magnetic field B is specified by the ion gyro-radius normalized to the poloidal circumference $\rho_i/L = 5 \times 10^{-3}$ The ions are fully traced (1d3v) and electrons are guiding center traced (1d2v). There is a single species of ions with a mass of $m_i/m_e = 1800$. The domain is symmetric and each half has three major regions: source, intermediate, and radiation. The range of the source region is $s/L_{||} = [0.4 : 0.5]$, the radiation region is $s/L_{||} = [0.01L : 0.21L]$, and the intermediate region lies between them. The source region supplies particles at fixed temperatures, T_{e0} and T_{i0} at a rate equal to the ion loss to the divertor plates. Radiation is implemented by decelerating all electrons in the radiation region while leaving their direction of travel unchanged. Each electron loses a fraction of the incoming energy flux directly proportional to its own kinetic energy. The desired radiation energy-loss flux to the energy flux from the source is given as an input parameter $f_{rad} = Q_{rad}/Q_{src}$.

Spatial profiles of the electron and ion HTC produced by PARASOL are shown in Figs. 2(a) and (b), respectively. The four cases are taken from the collisional and collisionless regimes without radiation $f_{rad} = 0.0$ and again with high radiation $f_{rad} = 0.6$. In the case without radiation, both γ_e and γ_i increase smoothly to the divertor plate. Their values are measured at the sheath entrance as defined by the quasineutrality condition. In the high radiation case, γ_e increases by an order of magnitude and γ_i increases by at least three orders of magnitude in the radiation region. Radiation rates of $f_{rad} = 0.2$ and higher remove so much energy from the plasma that the sheath entrance moves inside the radiation region.

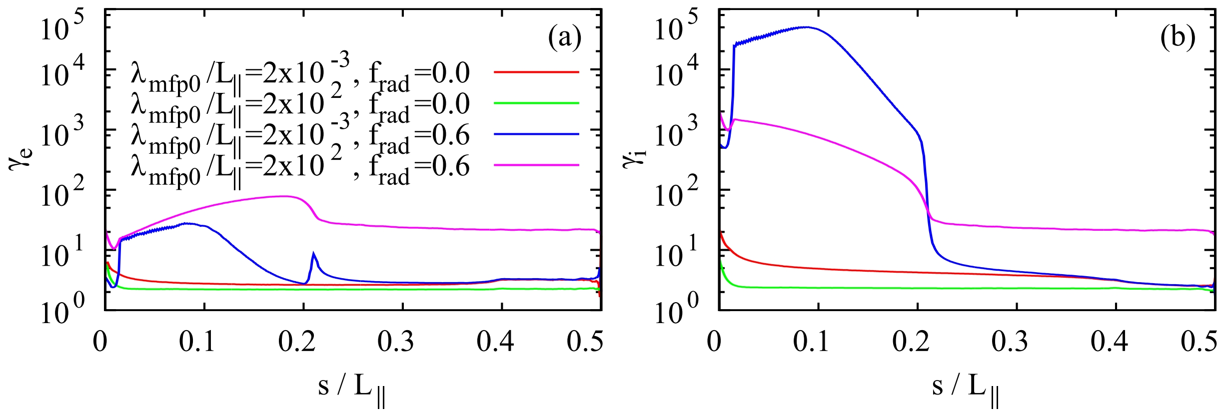


Figure 2: Spatial profiles of the electron and ion HTC for four cases: collisionless and collisional with and without radiation.

Values of the electron and ion HTCs are surveyed over collisionality, radiation rate, and ion-electron source temperature ratio and the results are shown in Fig. 3. Three models for γ_e are compared to the simulation results: the classical expression in Eq. (1), the expression derived from the realistic EDF in Eq. (3), and its approximation in Eq. (4). Simulation results for γ_i are compared to the first term of the classical expression in Eq. (2), and the full expression including the convective correction.

Figure 3(a) shows that the classical expression underestimates γ_e by about 20%, but Eq. (3) overestimates it by about 30% in the weakly collisional regime from $0.1 < \lambda_{mfp} < 10$. Approximating the tail temperature matches the data even more poorly. Figure 3(b) shows that the classical expression matches γ_i very well in the collisionless regime, but deviates in the collisional regime. Inclusion of the convective correction term reduces the error to a maximum of 25%, although typically it is less than 10%. Figure 3(c) shows that raising the radiation rate increases the electon HTC by an amount related to the mean free path. Radiation decreases the temperature of the trapped electrons, but does not affect the tail because the sheath entrance moves closer to the source than the radiation region. This causes γ_e to become very large, but the classical expression does not reflect this behaviour because it has no temperature dependence. The predictions of Eq. (3) and Eq. (4) are very accurate, deviating only slightly from the exact solution. Comparing Figs. 3(c) and (d) shows that the ion HTC has the same radiation dependence as the electron HTC. The classical expression is accurate to within 25%.

The dependence of both HTCs on the radiation rate in the collisionless regime are shown in

Figs. 3(e) and (f). One can see that there is a sudden jump from $f_{rad} = 0.1$ to 0.2, above which the HTCs stay constant at about 35. The new expression for γ_e is very accurate, especially when the tail temperature is approximated. However, the value of γ_i is somewhat overestimated by the full classical expression.

The equality of γ_e and γ_i in the collisionless regime is broken when the ion and electron source temperatures are not equal, as shown in Figs 3(g) and (h). The electron HTC is not affected by the source temperature ratio, but the ion HTC is nearly proportional to the temperature. The mean free path is long, but at very small temperature ratios, the ions can still collide several times before reaching the divertor plate. In this case, γ_i tends towards its higher collisional value and the convective correction term is necessary because the conductive energy (given by the first term of Eq. (2)) becomes a negligible fraction of the total energy flux.

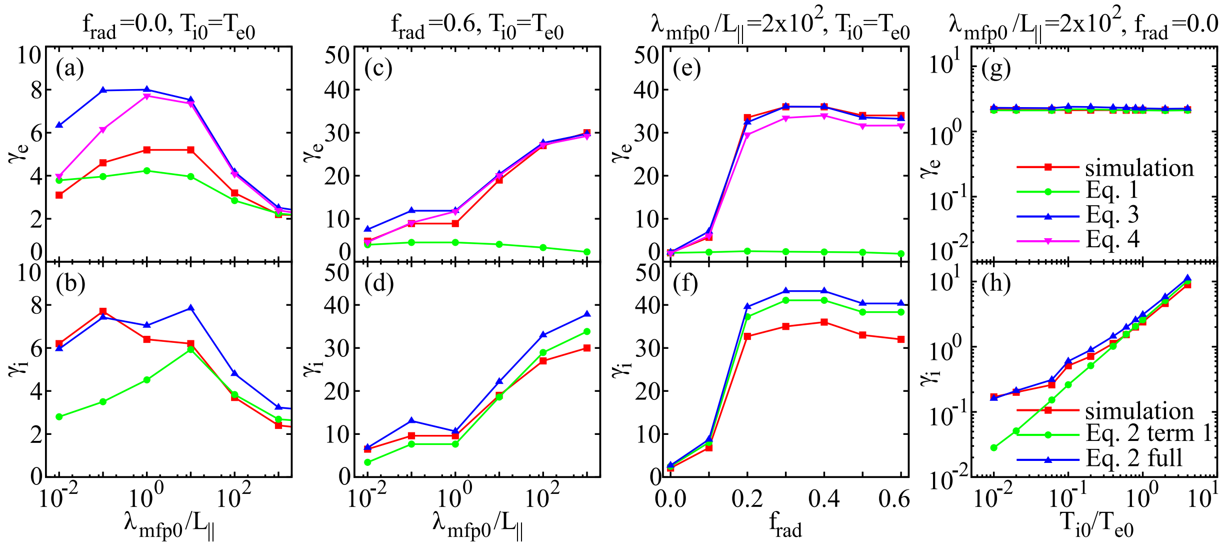


Figure 3: Electron and ion HTC surveyed over (a,b) mean free path without radiation, (c,d) mean free path with radiation, (e,f) radiation rate in the collisionless regime, and (g,h) ion-electron temperature ratio in the collisionless regime. Simulation results for γ_e are compared to Eqs. (1), (3), and (4), while results for γ_i are compared to the classical expression given in Eq. (2) with and without the convective correction.

In summary, we have shown that both the electron and ion HTC can become larger than 30 in the collisionless regime when the radiation rate is greater than $f_{rad} = 0.2$. A new formulation for γ_e that can account for radiation was developed, but it requires knowledge of the sheath potential, which may be unavailable in a fluid code. Therefore, when the electrons and ions are in equilibrium, the most efficient technique is to simply assume that the electron and ion HTC are equal and use the ion classical expression to estimate both of them.

References

[1] A. Froese et al., Contrib. Plasma Phys. **50**, 285 (2010).

[2] J. Marki et al., J. Nucl. Mater. **363**, 382 (2007).

[3] W. Fundamenski, Plasma Phys. Control. Fusion **47**, R163 (2005).

[4] D. Tskhakaya et al., Contrib. Plasma Phys. **46**, 649 (2006).