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COMPREHENSIVE STUDY OF THE TRANSPORT
AND KINETIC SOURCE OF HELIUM ASH FROM
ALPHA PARTICLES

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Abstract

Future deuterium–tritium (D–T) burning plasmas will produce energetic alpha (α) particles that heat the background main plasmas, and then α particles are slowed down and thermalized as helium ash. The accumulation of helium ash in the core region degrades fusion performance by diluting the fuel ions and enhancing radiation losses, making efficient He ash exhaust essential for ITER and future reactors. Collisionless trapped electron mode (CTEM) turbulence may dominate under ITER-relevant conditions of low collisionality and strong electron heating. The results in this paper firstly show that convection of helium ash driven by CTEM turbulence is negligible compared with convection, and the normalized removal efficiency, labelled as the helium ash diffusivity to effective electron thermal conductivity, remains below unity. But, the presence of α particles destabilizes CTEM and further significantly enhance He ash diffusivity, finally improving the efficiency of helium ash exhaust more than 50% when the density gradient of 3% α particles is twice that of electrons. In parallel, progress has also been made in redefining the kinetic source of helium ash. The inclusion of energy diffusion in the Fokker Planck equation modifies the low-energy distribution of α particles, producing indirect and direct contributions that yield a net enhancement of the helium ash source. With including both kinetic description of helium ash sources and turbulent driven transport, the paper then predicts helium ash profiles under different sources, i.e, kinetic and fluid sources. The results indicate that fluid theory is accurate enough to describe the source effects and predict the helium ash density profile. These findings provide useful physics guidance for helium ash removal in ITER and future burning plasma experiments.

1. INTRODUCTION

In burning deuterium–tritium (D–T) plasmas, 3.5 MeV alpha (α) particles are produced in fusion reactions, slow down through collisions with bulk plasmas, and eventually thermalize as helium ash [1]. While α particles provide essential self-heating, helium ash acts as a detrimental impurity that dilutes fuel ions and increases radiative losses. To sustain ignition, International Thermonuclear Experimental Reactor (ITER) [2, 3] and China Fusion Engineering Test Reactor (CFETR) [4, 5] require the helium ash concentration in the core below 5–10% [6–8]. Experiments on TFTR, JET and DIII-D have revealed that helium ash transport is much stronger than neoclassical predictions [9], implying a dominant contribution from drift wave (DW) turbulence [10]. Under ITER-relevant conditions of low collisionality and strong electron heating, collisionless trapped electron mode (CTEM) turbulence is expected to be one of the dominate candidates of DW turbulence [11]. Recent linear stability analyses indicate that energetic α particles can destabilize the electron-density-gradient (∇n_e) driven CTEM instability through dilution effects [12]. This naturally raises the question of whether α particles can also modify the turbulent transport of helium ash driven by CTEM, which is one of the primary motivations of this study.

Beyond transport, an equally important challenge lies in accurately defining the helium ash source. Different levels of approximation have been adopted in the literature. In the fluid description, Angioni et al. [13] introduced a simplified source term, which is calculated by the density of α particles over slowing down time, and this density is obtained by integrating the slowing-down distribution of α particles. By contrast, Huo [14] formulated a kinetic description directly from the distribution function of α particles, but the contribution of energy diffusion was neglected in the Fokker-Planck equation. The energy diffusion effects may become non-negligible for the distribution function in the low energy. Recently, it is indeed found that when energy diffusion is included, the helium distribution function f_{He} in the low-energy region is lifted toward Maxwellian form [15, 16]. This modification implies that the kinetic description of helium ash source term defined from the underlying

distribution is inevitably altered. Therefore, a reliable evaluation of this source and the corresponding helium ash density require incorporation of energy diffusion effects.

In this paper, we attempt to review and extend the understanding of helium ash dynamics in burning plasmas by combining these two perspectives. Specifically, we emphasize (a) helium ash transport under CTEM turbulence and its modification by α particles, and (b) the kinetic definition of helium ash sources with energy diffusion and the prediction of helium ash density for ITER plasmas. It includes the main conclusions as follows:

- Under the parameters used in this work, convection of helium ash is negligible as compared to its diffusion. For long-wavelength ∇n_e driven CTEM, the normalized removal efficiency $D_{\text{He}}/\chi_{\text{eff}}$ is less than unity, which indicate a less efficient helium ash removal compared to the ITG turbulence [13]. Nevertheless, it is found that 3% α particles can enhance $D_{\text{He}}/\chi_{\text{eff}}$ by more than 50% when their density gradient is twice that of electrons, and this enhancement can be further strengthened by steeper density profile of α particles. This is mainly because the enhancement of helium ash diffusivity by α particles is stronger than that of effective electron thermal conductivity.
- Energy diffusion modifies the α distribution function in low energy, producing competing indirect (enhancing) and direct (reducing) contributions. Their combined effect yields a net source enhancement compared with slowing-down models. Meanwhile, the demarcation energy for distinguish helium ash and energetic α particles is quantified as $E^d \approx 5.3T_i$ in the core. Based on the f_{He} and E^d , the predicted helium ash density using the kinetic source with energy diffusion term is higher than that predicted by using slowing down distribution function, and is in agreement with results from fluid model.

2. EFFECTS OF ALPHA PARTICLES ON HELIUM ASH TRANSPORT DRIVEN BY CTEM TURBULENCE

This section focuses on the transport of helium ash under CTEM turbulence. The quasi-linear flux of helium ash is formulated and decomposed into diffusion and convection terms. Then, the normalized helium ash transport efficiency $D_{\text{He}}/\chi_{\text{eff}}$ is derived and compared with the ITG case. Finally, the influence of α particles is systematically examined.

In the quasi-linear framework, the turbulent flux of helium ash is written as

$$\Gamma_{\text{ash}} = \text{Re} \langle \delta n_{\text{ash}} \delta v_{\vec{E} \times \vec{B}} \rangle = -D_{\text{ash}} \nabla n_{\text{ash}} + V_{\text{ash}} n_{\text{ash}}. \quad (1)$$

The specific forms of the transport coefficients are given by

$$D_{\text{ash}} = \sum_k \Gamma_{0\text{ash}} \sqrt{\tau_{eH}} k_y^2 \rho_{sH}^2 c_{sH} R \frac{\hat{\gamma}_k}{\hat{\omega}_r^2} |\hat{\phi}_k|^2, \quad (2)$$

$$V_{\text{ash}} = \sum_k \frac{R}{L_{T,\text{ash}}} b_{\text{ash}} (\Gamma_{1\text{ash}} - \Gamma_{0\text{ash}}) \sqrt{\tau_{eH}} k_y^2 \rho_{sH}^2 c_{sH} R \frac{\hat{\gamma}_k}{\hat{\omega}_r^2} |\hat{\phi}_k|^2. \quad (3)$$

Alpha particles modify the CTEM real frequency $\hat{\omega}_r$ and growth rate $\hat{\gamma}_k$, and then further affect the diffusivity D_{ash} and convective velocity V_{ash} . Analytical scaling shows that $RV_{\text{ash}}/D_{\text{ash}} \approx -b_{\text{ash}} R/L_{T,\text{ash}} \sim \varepsilon_0^2$ due to weak finite Larmor radius and temperature gradient, so diffusion dominates over convection. The ambipolarity condition $\sum_{j=D,T,\text{He}} Z_j \Gamma_j + Z_\alpha \Gamma_\alpha = \Gamma_e$ is also self-consistently verified.

For an intensity-independent measure of helium ash removal, the diffusivity is normalized to the effective electron thermal conductivity:

$$\frac{D_{ash}}{\chi_{eff}} = \frac{\Gamma_{0ash}}{\hat{\chi}_e^{Res} + \hat{\chi}_e^{NR}} \quad (4)$$

where χ_{eff} includes resonant and non-resonant trapped electron contributions. The explicit expression of $\hat{\chi}_e^{Res}$ and $\hat{\chi}_e^{NR}$ can be found in [17].

Without α particles, the normalized helium ash transport efficiency under CTEM turbulence is less than unity, in contrast to ITG turbulence where typical values reach 2–3 [13], as shown in Fig. 1. When α particles are introduced, their dilution reduces the stabilizing contribution of D–T ions, which increases CTEM growth rates and enhances helium ash transport. At an α particle concentration of 3% with their density gradient being twice that of electrons, the normalized diffusivity increases by about 55%. Furthermore, with steeper α particle density profiles, the enhancement becomes stronger. Also shown in Fig. 1, the transport level of helium ash, D and T ions and α particles satisfies:

$$D_{ash} > D_D > D_T \gg D_\alpha \quad (5)$$

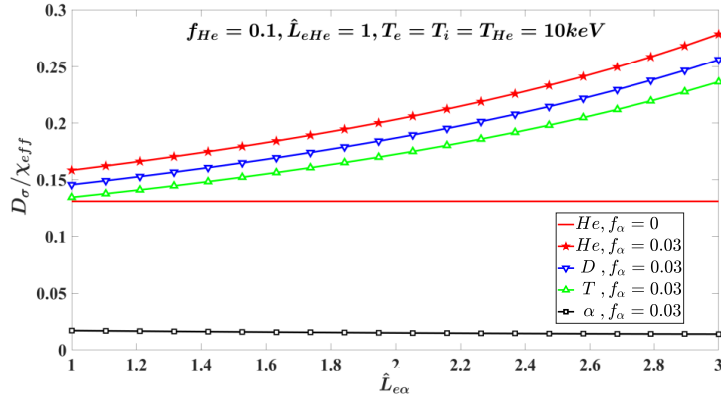


FIG. 1. Normalized diffusivity D_σ / χ_{eff} of helium ash, D–T ions and α particles as a function of $\hat{L}_{e\alpha}$ with different concentrations of α particles

3. KINETIC SOURCE OF HELIUM ASH: INCLUSION OF ENERGY DIFFUSION EFFECTS

This section develops a kinetic description of the helium ash source based on the Fokker–Planck equation with both drag and energy diffusion terms. The solution procedure is outlined to show how energy diffusion reshapes the low-energy part of the α distribution, leading to indirect enhancement and direct reduction effects on the source. Subsequently, the demarcation energy between α particles and thermalized helium ash is defined, and the source term is quantitatively obtained. Finally, the kinetic source is coupled to the continuity equation with ITG-based transport coefficients, and the resulting helium ash profiles are presented comparing with that from the fluid model.

As introduced, the Fokker–Planck equation with both drag and energy diffusion terms is [14]

$$\frac{\partial F_{He}}{\partial t} = \frac{\partial}{\partial E} (C_{drag} + C_{ed}) + S_0 \delta(E - E_0) \quad (6)$$

Here $F_{He} = (4\pi v / m_{He}) f_{He}$ is the normalized distribution function in energy space [14, 18], and S_0 is the alpha source, with the birth energy $E_0 = 3.5$ MeV. The collision operators can be separated into drag and energy diffusion contributions. The drag term is written as:

$$C_{drag} = -K_1 F_{He} \quad (7)$$

with $K_1 = -dE/dt$ being the slowing-down rate. The energy diffusion term is expressed as:

$$C_{ed} = \frac{1}{2} \frac{\partial}{\partial E} (K_2 F_{He}) \quad (8)$$

with K_2 being the energy diffusion rate.

To solve the Fokker–Planck equation, appropriate boundary conditions and source terms must be imposed. Integrating over energy yields $\left[C_{drag} + C_{ed} \right] \Big|_{E_0}^{\infty} = -S_0$, which ensures no contribution at $E = \infty$. At the source energy, where $|C_{drag}|/|C_{ed}| \gg 1$, the drag term dominates and satisfies $C_{drag}|_{E=E_0} = S_0$. At low energies, the distribution is required to approach a Maxwellian, giving $\frac{\partial f_{\alpha}}{\partial v} \Big|_{v=0} = 0$. Under ITER base-case parameters, the source strength is specified as:

$$S_0 = n_D n_T \langle \sigma u \rangle_{DT} \approx \frac{n_e^2}{4} \left(\frac{T_i}{10 \text{ keV}} \right)^2 \langle \sigma u \rangle_{DT-10} \quad (9)$$

where $\langle \sigma u \rangle_{DT-10} = 1.0 \times 10^{-22} \text{ m}^3 \text{ s}^{-1}$ at $T_i = 10 \text{ keV}$. With these sets, we can get the solution of distribution function.

The solution shows that at a characteristic time of $t = 2\tau_{sd,0}$, when the slowing-down of α particles is essentially completed and thermalization is already underway. In this stage, the slowing-down distribution forms in the high-energy region ($E/T_i > 10$), while in the low-energy region ($E/T_i < 5$) it approaches a Maxwellian due to energy diffusion. In the intermediate range, the distribution can be approximated by the sum of a slowing-down component and a Maxwellian tail. This overall evolution indicates that energy diffusion significantly modifies the low-energy distribution function of helium ions. This indicates that a pure slowing-down model is insufficient to capture helium ash formation.

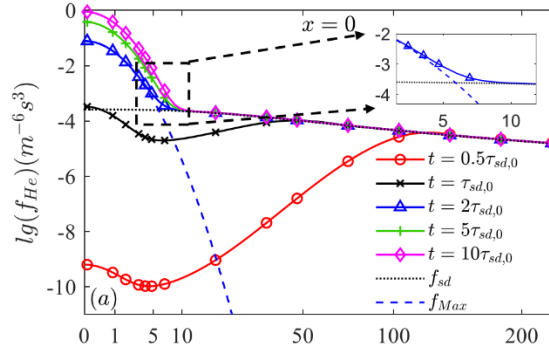


FIG. 2. The time evolution of f_{He} in the energy space at $x = 0$, f_{sd} at $t = \tau_{sd}$ (black solid line), and the Maxwellian distribution f_{Max} at $t = 2\tau_{sd}$ (blue dotted line) is also plotted for comparison. τ_{sd} is the slowing down time at each position and $\tau_{sd,0}$ is the slowing down time at specific position $x = 0$

Further analysis allows for a quantitative definition of the separation energy E^d , which distinguishes energetic α particles from thermalized helium ash. By imposing the condition $T_i = T_{ash}$, as shown in Fig. 3, we obtain $E^d/T_i = 5.3$ in the core, which is close to the conventional estimate of $E^d/T_i = 5$ used in earlier work [14]. Toward the edge, the separation energy increases to $E^d/T_i = 7.2$, because thermalization is faster in the outer plasma region.

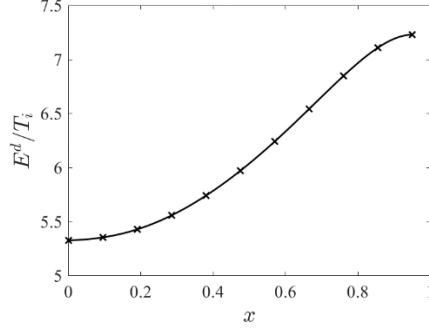


FIG. 3. The normalized demarcation energy E_d/T_i varies with the radial position

By integrating the kinetic equation, the helium ash source term $S_{ash,t}^F$ can be obtained. As illustrated in Fig. 4, the results demonstrate that indirect effect, $S_{ash,drag}^F = C_{drag} \big|_{E=E^d}$ (blue line), tends to increase the source, compared to the kinetic source calculated by slowing down distribution $S_{ash,sd}^F$ (black dashed line), while direct effect $S_{ash,ed}^F = C_{ed} \big|_{E=E^d}$ (green line) reduces it. Their combined effects (red line) produce a net source close to fluid sources S_{ash}^n (black solid line).

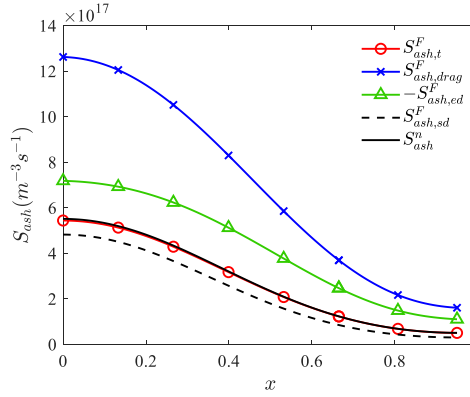


FIG. 4. Different sources at $t = 2\tau_{sd,0}$. The red solid line with circles, blue solid line with crosses, and green solid line with triangles are the total source, source without direct effect of energy diffusion, and with the direct effect, respectively. The black dashed line shows the source through f_{he} with neither the direct nor indirect effect, and the black solid line is the source defined by n_α

Finally, inserting this kinetic source into the continuity equation,

$$\frac{\partial n_{ash}}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[r \left(D_{ash} \frac{\partial}{\partial r} n_{ash} - V_{ash} n_{ash} \right) \right] + S_{ash} \quad (10)$$

together with ITG-based transport coefficients, $D_{ash} \approx \chi_{eff,t}$. And at the magnetic axis, symmetry requires

$\frac{\partial n_{ash}}{\partial x} \bigg|_{x=0} = 0$. At the outer edge, the density profile is assumed to decrease linearly toward the scrape-off layer,

and the gradient at the normalized radius $x = 0.76$ is fixed as $\frac{\partial n_{ash}}{\partial x} \bigg|_{x=0.76} = -\frac{n_{ash}|_{x=0.76}}{\hat{L}}$ following Angioni et al [13]. Beyond the separatrix ($x = 1.025$), the helium ash density is set to vanish.

The helium ash density by balancing the source and transport term is shown in Fig. 5. It can be seen that in comparison with the density profile predicted by slowing down distribution $S_{ash,sd}^F$ (black dashed line), the indirect effect of energy diffusion enhances the helium ash density (blue line), while the direct effect reduces it.

As a result, the total source (red line) with both contributions satisfies $S_{ash,t}^F > S_{ash,ed}^F$, where the kinetic source with both drag and energy diffusion effects is close to the fluid model (black solid line). This demonstrates that energy diffusion effects, when properly included, lead to a higher and more accurate estimate of n_{ash} .

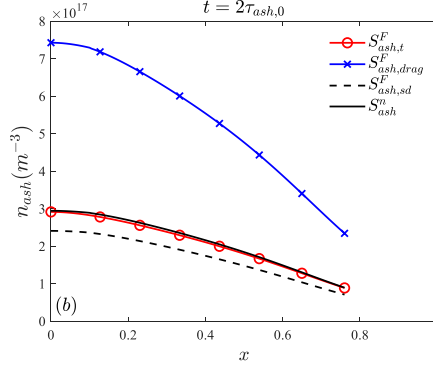


FIG. 5. n_{ash} with different sources at $t = \tau_{ash,0}$. The red line with circles, blue line with crosses, and black dashed line are n_{ash} with $S_{ash,t}^F$, $S_{ash,drag}^F$, $S_{ash,sd}^F$, respectively. The black solid line is n_{ash} with S_{ash}^n .

4. SUMMARY

The paper first investigates the transport of helium ash driven by CTEM turbulence [17]. The normalized efficiency parameter, D_{He}/χ_{eff} , is found to be less than unity, indicating that less efficient helium ash removal compared to ITG [13]. The presence of 3% α concentration, D_{He}/χ_{eff} increases 55% when their density gradient is twice that of electrons, and steeper α particle profiles further enhance the effect. Parametric scans confirm that higher T fraction, larger electron-to-ion temperature ratio, and flatter electron density profiles all are favourable for helium ash removal, and alpha particles amplify these favourable effects. The ambipolarity of turbulent fluxes is satisfied, with helium ash diffusivity exceeding that of D–T ions, and the α particle transport level by CTEM remains minimal.

In parallel, a kinetic treatment of the helium ash source based on the Fokker–Planck equation with explicit energy diffusion provides a more accurate description of the helium ion distribution function. Then, energy diffusion introduces both indirect enhancement and direct reduction of the kinetic source, and their combined outcome increases the total kinetic source and yields a steeper helium ash density profile, compared to the case with slowing down distribution function. The helium ash density with total kinetic source is close to that calculated from the simplified fluid source.

Future work should extend the analysis to include the coupling of energetic particles, drift waves, Alfvén eigenmodes, and zonal flows, in order to establish a deeper description of helium ions' evolution in burning plasmas.

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