HELIUM ASH REMOVAL: COMPREHENSIVE EFFECTS OF ALPHA PARTICLES ON THE SOURCE AND TRANSPORT OF HELIUM ASH

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Avoiding helium (He) ash accumulation is important to achieve high fusion power in future burning plasma. Energetic alpha (α) particles can affect the density profile of He ash from affecting both source and transport terms. Ref. [1] calculated the kinetic source $S^k_{ash,sd} = -K_1 F_{sd}$ of He ash from energy of α particles, with K_1 being the slowing down rate and $F_{sd} = \frac{4\pi\sqrt{2E/m_{He}}}{m_{He}} f_{sd}$, based on the slowing down distribution f_{sd}. However, recent works [2, 3] finds energy diffusion term can lift the distribution function of He ions f_{He} in low energy region and bring the deviation from classical f_{sd}, and this would affect the source and transport of He ash, but have not been explored. This work reports the effects from energetic α particles not only on source term by including energy diffusion but also on transport through dilution, and predict the He ash density profile under ITER baseline scenario [4].

We start from the Fokker-Planck equation of He ions [1]:

$$\frac{\partial F_{He}}{\partial t} = \frac{\partial}{\partial E}\left(C_{drag} + C_{ed}\right) + S_0 \delta(E - E_0). \quad (1)$$

Here, $F_{He} = \frac{4\pi\sqrt{2E/m_{He}}}{m_{He}} f_{He}$ is the number of He ions in per volume and per energy interval, $C_{drag} = -K_1 F_{He}$ is the collision operator contributed by drag effect from background particles, and $C_{ed} = \frac{1}{2}\frac{\partial}{\partial E}(K_2 F_{He})$ represents energy diffusion effect also due to collision with K_2 being the energy diffusion rate, $S_0 = n_D n_T \langle \sigma u \rangle_{DT}$ with $\langle \sigma u \rangle_{DT}$ being the D-T reaction rate. By numerically solving the Fokker-Planck equation under ITER base case parameters, we obtain the distribution function of He ions f_{He} in full energy range and find a deviation from f_{sd} in the range of $E/T_i < 10$, where is closer to the Maxwellian distribution. This can *indirectly* affect the kinetic source. Besides, energy diffusion effect also introduces an extra term into the kinetic source, which is called the *direct* effect, which will be shown later.

By integrating both sides of Eq. (1) over E, we can obtain the evolution equation of He ash in the absence of radial transport $\frac{\partial n_{ash}}{\partial t} = S^k_{ash,t}$, where

$$S^k_{ash,t} = S^k_{ash,drag} + S^k_{ash,ed} \quad (2)$$

is the total kinetic source of He ash. $S^k_{ash,drag} = C_{drag}\big|_{E=E^d}$ is contributed from *drag* term in Eq. (1) and is corrected by the *indirect* effect of energy diffusion due to the modification of f_{He}. $S^k_{ash,ed} = C_{ed}\big|_{E=E^d}$ is contributed from the *direct* effects of *energy diffusion*. E^d is the demarcation energy to distinguish energetic α particles and He ash. $C_{drag}\big|_{E=E^d}$ and $C_{ed}\big|_{E=E^d}$ can be understanded as collision induced convective and diffusive fluxes in energy space across the demarcation energy surface at $E = E^d$, respectively. The positive sign of the flux means the direction of flux is from high to low energy region, and vice versa.

The kinetic sources depend on the demarcation energy E^d. We quantitatively propose E^d where the equivalent temperature of He ash $T_{ash} = T_i$. Then, we calculate the kinetic source of He ash as shown in Fig. 1

(a). The *indirect* effect of energy diffusion enhances the source as $S^k_{ash,drag}$ is about 3 times larger than $S^k_{ash,sd}$. On the other hand, $S^k_{ash,ed} < 0$ means the *direct* effect makes He ions diffuse from the low energy to high energy and plays a role of sink for He ash. The total kinetic source $S^k_{ash,t}$ is determined by the competition between the source and sink. It is positive and higher than $S^k_{ash,sd}$ in the core, which means considering both direct and indirect effects of energy diffusion can increase the source of He ash. Further comparison with fluid source $S^f_{ash} = n_\alpha/\tau_{sd}$ used in Ref. [5] is also shown, $S^k_{ash,t}$ is slightly higher than the S^f_{ash} in the core but lower in the edge, and $S^k_{ash,sd}$ is always lower than S^f_{ash}.

By balancing the source and ion temperature gradient (ITG)-driven transport [5, 6], we obtain the density profile of He ash as shown in Fig. 1 (b). n_{ash} with $S^k_{ash,drag}$ significantly higher than $S^k_{ash,sd}$, indicating that only considering the indirect effect of energy diffusion can significantly enhance the profile. However, it is reduced to n_{ash} with $S^k_{ash,t}$ by including the direct effect of energy diffusion as well. Finally, n_{ash} with is still slightly higher than that with $S^k_{ash,sd}$ and closer to that with the fluid source S^f_{ash}, which implies that neglecting the entire energy diffusion effects will underestimate n_{ash}.

Further, as the density of energetic α particles is too low under ITER baseline scenario (only 0.5% even in the core) to observe significant dilution effect on turbulence, we enhance the T_i to obtain a higher concentration of n_α. The result shows the energetic α particles can destabilize ITG turbulence, which in turn affects the ITG-dominant transport of He ash. Moreover, n_{ash} is comparable with n_α. Then, as shown in Fig. 1 (c), considering dilution effect from both energetic α particles and He ash on transport finally decrease n_{ash}.

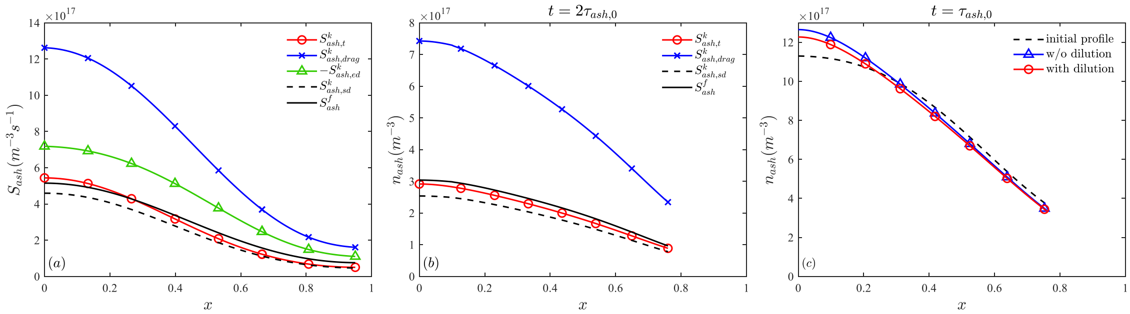

Figure 1. (a) Different sources of He ash. (b) He ash density profile by balance transport and source. (c) He ash density profile by including dilution effects from energetic α particles and He ash.

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