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Reduction of Helium Ash in Fusion Plasma by Selective Helium Pumping

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Abstract

The concept for reduction of helium ash concentration in a fusion plasma, based on the selective pumping for helium ions, is described. In a case that this scheme is employed together with the pumping of divertor, the helium ash concentration can be considerably reduced. Thus, this method is helpful to sustain the burning plasma state or the ignition condition. The pumping condition required for the selective helium pumping metal is also discussed.

1. Introduction

In a fusion reactor, one of major concern is to effectively pump the helium ash produced by the fusion reaction, since it becomes difficult to sustain the ignition condition due to the fuel dilution if the helium concentration exceeds a some level. In addition, the radiation loss power due to helium impurities is also enhanced. In the design of International Thermonuclear Experimental Reactor, ITER1), it is pointed out that the size of plasma has to be significantly enlarged when the helium concentration increases from 10% to 20%.

For the removal of the helium ash, the pumping due to the magnetic divertor has been intended so far. However, the pumping efficiency of the magnetic divertor alone may not be satisfactory high. Thus, the additional pumping is needed to avoid the increase of the helium ash concentration.

Recently, it was shown that some metals such as nickel can trap or retain helium ions selectively2),3). Namely, the trapping efficiency for helium ions was observed to be much higher than that for fuel hydrogen ions. If the metal which selectively pumps the helium ions is used in the vicinity of the divertor, the helium ash concentration in a core plasma may be largely reduced. The concept for an use of the selective helium pumping metal may not been constructed yet. So, in this study, the concept for the scheme of the selective helium pumping is discussed. The requirement for the selective helium pumping is also suggested.

2. Helium Ash Concentration

In a fusion reactor, the density balance of helium ions in a core plasma is given by

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$$\frac{dn_{He}}{dt}=\frac{n_P^2}{4}\langle\sigma v\rangle_f-\frac{n_{He}}{\tau_{He}}(1-f_R^{He}), \tag{1}$$

where n_{He} is the helium density, n_p the fuel ion density ($n_p=n_D+n_T$), $\langle\sigma v\rangle_f$ the fusion reaction rate, τ_{He} the confinement time of helium ions in the core plasma, and f_R^{He} the fraction of helium returning to the core plasma, e.g. helium recycling ratio. In a steady state, we have

$$\frac{n_{He}}{n_t}=\frac{\tau_{He}}{1-f_R^{He}}\frac{n_P^2}{4}\langle\sigma v\rangle_f, \tag{2}$$

where $n_t=n_{He}+n_p$ the total ion density. Since the value of beta defined by $\beta=3n_tT/B_2/2\mu_o$, is limited by the criterion of mhd instability, n_t has to be kept constant if the plasma temepratur, T, is fixed. When the ratio of helium ion concentration is expressed as $g=n_{He}/n_t$, Eq.(2) can be written as

$$\frac{g}{1-g}=\frac{\tau_{He}}{4}\frac{n_p\langle\sigma v\rangle_f}{1-f_R^{He}}. \tag{3}$$

For the calculation of helium ash concentration, we now consider the following parameters of a fusion reactor

Major Radius, R=7 m,
Minor Radius (Plasma Radius), a=2 m,
Fusion Reaction Rate, $P_f=10^{-22}\ m^3/s$,
Alpha Particle Energy, $E\alpha=3.6\ MeV$,
Neutron Energy, $E_n=14\ MeV$,
Fuel Ion Density, $n_p=2\times10^{20}m^{-3}$,
Particle Confinement Time of Fuel Ion, $\tau_p=2s$,
Particle Confinement Time of Helium Ion $\tau_{He}=4s$,
Energy Confinement Time, $\tau_E=2s$.

The fusion power, P_f, and the fueling rate, Γ_f, become

$$P_f=\frac{n_P^2}{4}\langle\sigma v\rangle_f k(E_\alpha+E_n)=1\cdot8\ GW, \tag{4}$$

$$\begin{aligned}\Gamma_f&=\left\{\frac{n_P^2}{4}\langle\sigma v\rangle_f+\frac{n_P}{\tau_P}(1-f_R^P)\right\}V_c\\&\simeq\frac{n_p}{\tau_p}(1-f_R^P)\,V_c=3\times10^{21}\ fuel\ ions/s,\end{aligned} \tag{5}$$

where $V_c=2\pi R\cdot\pi a^2$ is the plasma volumn of the core plasma, and f_R^P the fraction of fuel ions returning to core plasma, e.g. recycling ratio of fuel ions. In Eq.(5), it is assumed that $f_R^P=0.95$.

From Eq.(3), the ratio of helium ash concentration to the total density is caluculated for the value of f_R^{He}, as shown in Fig. 1. It is observed that the ratio of helium ash concentration rapidly increases with the recycling ratio of helium when the value of f_R^{He} is close to unity. In the divertor region, the recyling flow of the helium may be smaller than that of the fuel ions since the friction force of fuel ion flow acting on the helium is larger. In a case that $f_R^{He}=0.9$, the ratio of helium ash concentration becomes approximately 20%, which may be too

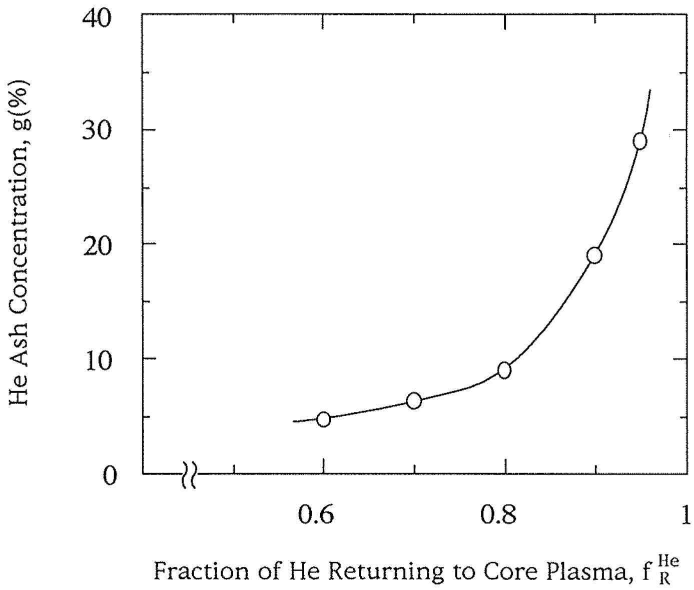

Fig. 1 Ratio of helium ash concentration, g, versus recycling ratio of helium, f_R^{He}.

large.

When the helium ash concentration is large, the plasma volumn has to be increased due to the reduction of alpha heating power. Now we consider the case that the ratio of the helium ash concentration is increased from g to $g+\Delta g$. The energy confinement time, τ_E, has to be increased from τ_E to $\tau_E+\Delta\tau_E$ for the ignition condition to be sustained. The increase of the plasma size can be estimated from the energy balance equation. When the ratio of the helium ash concentration is g, it is assumed that the following ignition condition is sustained

$$\frac{d}{dt}(3n_Pkt)=(1-g)^2\frac{n_t^2}{4}\langle\sigma v\rangle_f E\alpha-(1-g)\frac{3n_tkT}{\tau_E}-gc_bZ^2n_t^2\sqrt{T}=0, \tag{6}$$

where the radiation loss only due to the helium is considered. In Eq.(6), the term of the alpha heating is comparable with that of the heat conduction loss. The term of the radiation loss is much smaller than the other term. If the ratio, g, is increased to $g+\Delta g$, for the ignition condition to be sustained the increasing ratio of the energy confinement time becomes

$$\frac{\Delta\tau_E}{\tau_E}\sim\frac{\Delta g}{1-g}. \tag{7}$$

If the energy confinement time is proportional to $a\cdot I_p$, the plasma radius has to be $(1+\Delta\tau_E/\tau_E)$ times increased, and the fusion power also $(1+2\Delta\tau_E/\tau_E)$ times increased. Here, I_p is the plasma current (approximately 20 MA). For example, the plasma volumn is approximately 20% increased if Δg is 10%.

Thus, the helium ash concentration has to be kept low. If the pumping efficiency of the divertor is not so high, the additional pumping is required.

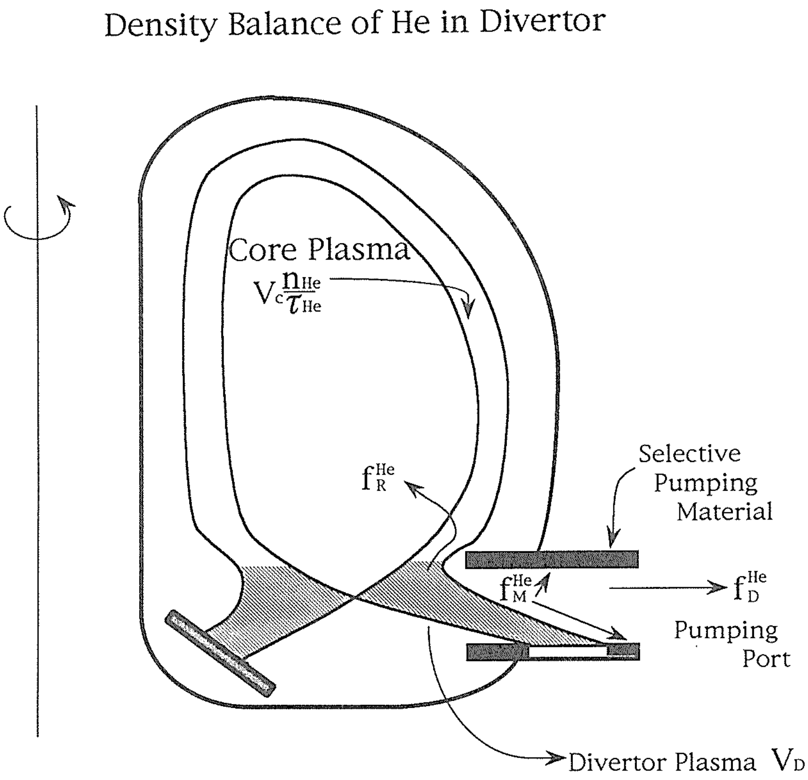

Fig. 2 Particle balance of helium ions in a fusion reactor.

3. Reduction of Helium Recycling Ratio by Selective Helium Pumping

In order to reduce the value of f_R^{He}, the use of metal which can selectively pumps the helium ash is considered. Figure 2 shows the balance of the helium ions in the fusion plasma. The helium flow from the core plasma to the divertor is $V_C n_{He}/\tau_{He}$, which is pumped to the port of the divertor with the ratio of f_D^{He}, pumped or trapped to the selective pumping metal with the ratio of f_M^{He}, or returned to the core plasma with the ratio of f_R^{He}. These parameters are related as

$$f_R^{He} + f_M^{He} + f_D^{He} = 1. \tag{8}$$

In the divertor region with the volumn of V_D, the balance equation can be written as

$$V_D \frac{dn_{He}^D}{dt} = -V_D\left(\frac{1}{\tau_R} + \frac{1}{\tau_M} + \frac{1}{\tau_D}\right) n_{He}^D + V_C \frac{n_{He}}{\tau_{He}} = 0, \tag{9}$$

where n_{He}^D is the helium density in the divertor, τ_R, τ_M and τ_D the time constants for recycling into core plasma, selective pumping and pumping to the port, respectively. From Eqs.(8) and (9), we have

$$f_R^{He} = \frac{\tau_{He}}{\tau_R} \frac{V_D}{V_C} \frac{n_{He}^D}{n_{He}}, \tag{10}$$

$$f_M^{He} = \frac{\tau_{He}}{\tau_M} \frac{V_D}{V_C} \frac{n_{He}^D}{n_{He}}, \tag{11}$$

$$f_D^{He} = \frac{\tau_{He}}{\tau_D} \frac{V_D}{V_C} \frac{n_{He}^D}{n_{He}}. \tag{12}$$

In a case that $n_{He}^D/n_{He}=10$ and $V_D/V_C=1/10$, $f_M{}^{He}=\tau_{He}/\tau_M$. If $f_M^{He}=0.1$ and $\tau_{He}=4s$, τ_M becomes 40 s. The time required to pump by the selective pumping metal is not too short. When the value of f_D^{He} is 0.1, the helium ash concentration becomes 10%, which may be acceptable. The selective pumping metal would be placed in the vicinity of the divertor. If the poloidal width of the selective pumping metal is L, the helium flux to be pumped is given by

$$\begin{aligned} \Gamma_{He} &= V_C \frac{n_{He}}{\tau_{He}} f_M^{He} \Big/ 2\pi RL \\ &= 7\times 10^{14}\ He/cm^2\cdot s. \end{aligned} \tag{13}$$

The saturation level of nickel for the trapping of helium is approximately $10^{17} He/cm^2$. Then, at least the surface of the metal has to be refreshed within every 100 s, by the evaporation. In order to keep the value of f_M^{He} constant, the contineous evaporation of such metal may be desirable. In the above case, the required deposition rate becomes a few monolayers per second.

4. Summary

The concept for the scheme of selective helium pumping is described. If this method is applied in addition to the divertor pumping, the helium ash concentration can be reduced to an acceptable level. The rate of the selective pumping is discussed. During the discharge of a burning plasma, the contineous or periodical evaporation of the selective metal is required since the trapping capability saturates.

Acknowledgement

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