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Author(s)	Hino, Tomoaki
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Schemes for Reduction of Helium Ash in a Fusion Reactor

Tomoaki HINO[1,2]

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Abstract

For the reduction of helium ash in a fusion reactor, several methods have been proposed. These methods are systematically discussed based upon the density balance of heliums, e.g. the term of the helium flow from the divertor to the core plasma. In addition, it is shown that the emission of heliums retained in the wall may largely enhance the helium ash level. Then, the helium retention in the wall during the plasma discharge shot has to be sufficiently reduced.

1. Introduction

In a fusion reactor, the reduction of helium ash concentration is one of most important issues to achieve a burning plasma state with a long time period1). Since the helium ash causes the fuel dilution, α-heating power becomes smaller than the energy conduction loss power and then the ignition condition can not be sustained. If the helium ash concentration is not sufficiently reduced, the term of the energy conduction loss has to be decreased, e.g. the energy confinement time be lengthened. Since the energy confinement time, τ_E, is roughly proportional to the plasma radius, a, the plasma size has to be enlarged to obtain the ignition condition. Thus, the reduction of the helium ash is a critical issue to achieve the burning plasma.

In a fusion reactor of a tokamak1) or a helical type2), the helium ash is removed into the vacuum pumping port placed in the divertor region. However, the pumping efficiency of the helium is not sufficiently large, so that the additional methods such as the use of helium selective pumping material3) and the use of localized divertor4) have been proposed. The principles of these methods will be described based on the analysis for the density balance of the helium, e.g. in term of the helium flow from the divertor to the core plasma.

In the case of the burning plasma, the plasma facing walls may largely retain the heliums produced by the fusion reactions. The heliums may emit into the core plasma and then the helium ash level might be enhanced. This process has not been taken into account so far. The increase of the helium ash level due to this process is also discussed based on the density balance of the helium.

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[1] Department of Nuclear Engineering, Hokkaido University, Sapporo, 060 Japan
[2] National Institute for Fusion Science, Nagoya, 464-01 Japan

2. Density Balance of Helium Ash

In the single null divertor configuration shown in Fig.1, the helium densities in the core plasma and the divertor , n_c and n_d, respectively, are expressed as

$$\frac{dn_c}{dt} = -\frac{1-R_c}{\tau_c} n_c + \frac{n_{DT}^2}{4} \langle \sigma v \rangle_f = 0\,, \tag{1}$$

$$\frac{dn_d}{dt} = \frac{V_c}{V_d}\frac{n_c}{\tau_c}(1-R_c-R_p) = 0\,, \tag{2}$$

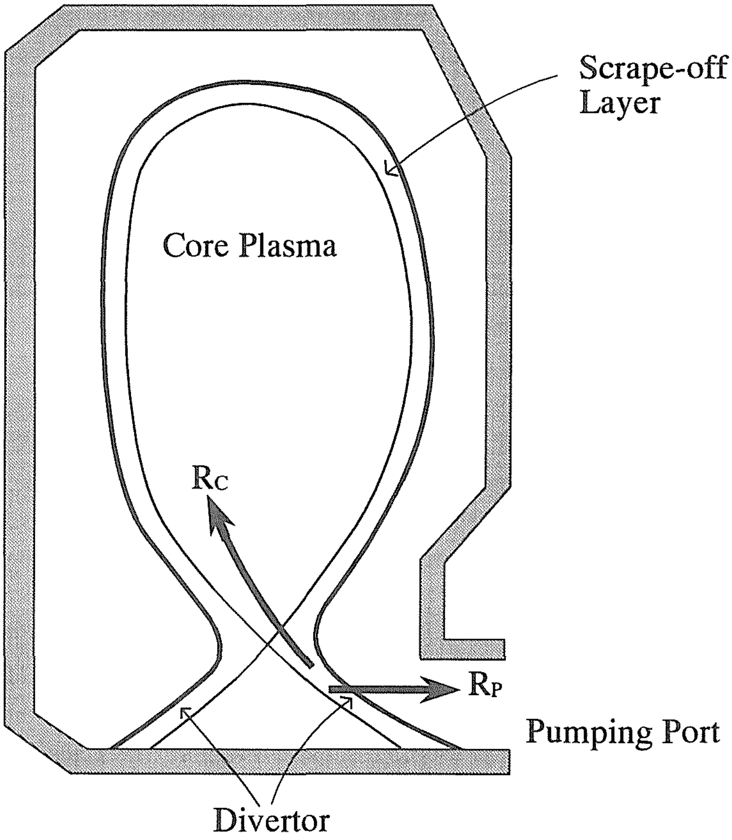

Fig. 1 Single null divertor configuration.

where τ_c is the helium confinement time, R_c the ratio of the helium returning to the core plasma from the divertor, n_{DT} the fuel deuterium and tritium ion density, $\langle \sigma v \rangle_f$ the fusion reaction rate, V_c and V_d the volumes of the core plasma and the divertor, respectively, and R_p the ratio of the helium pumped into the pumping port. From Eq.(2), we have

$$R_c + R_p = 1\,. \tag{3}$$

The time constants of the helium for the inward flow and the flow into the pumping port, $\tau_{d\to c}$ and $\tau_{d\to p}$, respectively, are defined as

$$\frac{n_c}{\tau_c} V_c R_c = \frac{n_d}{\tau_{d\to c}} V_d$$

$$\frac{n_c}{\tau_c} V_c R_p = \frac{n_d}{\tau_{d\to p}} V_d.$$

Then, we have

$$R_c = \frac{\tau_c}{\tau_{d\to c}} \frac{n_d}{n_c} \frac{V_d}{V_c}, \tag{4}$$

$$R_p = \frac{\tau_c}{\tau_{d\to p}} \frac{n_d}{n_c} \frac{V_d}{V_c}. \tag{5}$$

In a case that $n_d/n_c=10$, $V_d/V_c=1/10$, $R_c=0.9$ and $R_p=0.1$, the time constants, $\tau_{d\to c}$ and $\tau_{d\to p}$, become $\tau_{d\to c}\approx 1\cdot 1\tau_c$ and $\tau_{d\to p}=10\tau_c$, respectively. If $\tau_c=4$s, $\tau_{d\to c}$ and $\tau_{d\to p}$ are 4.4 s and 40 s, respectively. The time required for the helium to be pumped is very long but the inward flow takes place roughly within the time scale of the helium confinement time.

The helium ash concentration of the core plasma is obtained from Eq.(1). When the total ion density is expressed as $n_t=n_{DT}+n_c$, the ratio of the helium density to the total ion density becomes

$$\frac{g}{1-g} = \frac{\tau_c}{4} \frac{n_{DT}\langle\sigma v\rangle_f}{1-R_c}. \tag{6}$$

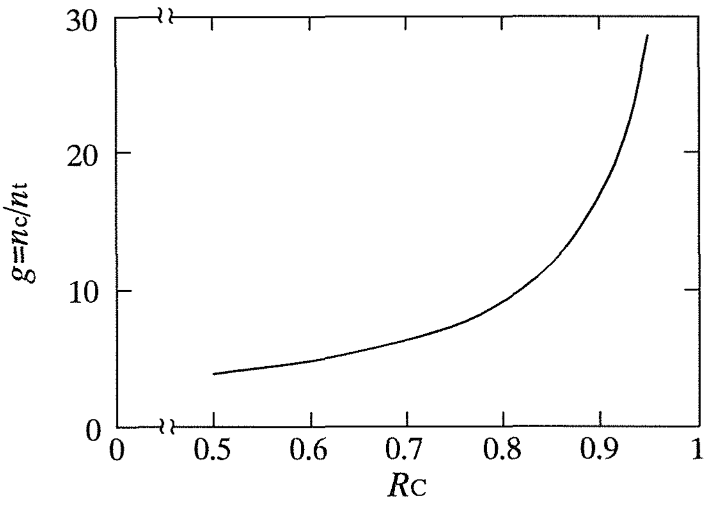

Fig. 2 Ratio of helium ash concentration versus ratio of inward flow, Rc.

The ratio of the helium density to the total ion density is plotted to the value of R_c in Fig. 2. In this figure, it is assumed that $\tau_c=4$ s, $n_{DT}=2\times10^{20}$ m^{-3} and $\langle\sigma v\rangle_f=10^{-22}$ m^3/s. The helium ash concentration largely increases as the ratio of the inward flow, R_c. For example, the value of g becomes ~20 % when $R_c=0.95$. It is known that the ratio of helium ash concentration has to be below approximately 10 %. In the case of ITER[1)], it is estimated that $R_c \sim 0.9$ and g~20 %. In this case, it is difficult to achieve the ignition condition and thus the plasma size was determined to be enlarged in the recent Engineering Design Activities, EDA. In the helical reactor, the connection length between the X point and the divertor wall is relatively shorter than that of the tokamak. Then, there may be a possibility that the value of R_c may become more close to unity. In order to reduce the helium ash concentration, the reduction of the value of R_c has to be conducted by using the additional methods and/or by changing the divertor configuration. In the following section, several methods are discussed in term of the value of R_c.

3. Methods of Helium Ash Reduction

One of the approach for the reduction of the helium ash is to enhance the friction force of the plasma flow from the core plasma, since the inward flow of the helium can be pushed back by the friction force. In order to enhance the friction force, the connection length has to be long and the plasma density has to be kept high. The other method is to enhance the pumping efficency, e.g. the value of R_p. If the cryopump is employed instead of the turbo molecular pump, the value of R_p may be increased. In addition, if the baffle plates are placed in the vicinity of the divertor, the pumping efficiency may be enhanced. Already these considerations have been taken into account in the design of ITER but such the reduction is not sufficiently large.

If the material which can selectively pump or trap only the helium is attached in the divertor region, the inward flow of the helium may be largely reduced[3)]. In this case, the ratio of the inward flow is given by

$$R_c = 1 - R_p - R_M, \tag{7}$$

where R_M is the ratio of the helium trapped by the selective pumping material. Since the helium in the divertor many times collides with the selective pumping material, the value of R_M can be taken larger than 0.1. Then, the helium ash concentration in the core plasma may be able to be reduced to ~10 %.

The other additional method is to place several localized limiters with the pumping port such as the ripple limiters[4)]. A fraction of the helium flow from the core plasma into the scrape-off layer can be removed by these localized divertors, and then the helium density in the divertor can be reduced. The ratio of the inward flow in this case becomes

$$R_c = 1 - R_p - R_{ad}, \tag{8}$$

where R_{ad} is the ratio of the helium pumped into the ports in the vicinity of the localized divertor. Preliminary analysis showed that $R_{ad} \sim 0.4$[4)]. Thus, the ratio of the helium ash can be largely reduced, e.g. g~6 %.

4. Effect of Heliums Retained in Walls on Helium Ash Concentration

The plasma facing walls can trap the heliums produced by the fusion reactions. During the discharge shot, these heliums may be desorbed both by ion/neutral impact desorption and the thermal desorption. In this section, these processes are taken into account in the density balance of the helium. If the plasma is sufficiently detached from the first wall, a major process of the helium desorption is due to the charge exchanged particles produced by the reaction between the neutral atoms and the plasma ions of the scrape-off layer. Thus, the density balance for the helium of the core plasma is given by

$$\frac{dn_c}{dt}=-\frac{1-R_c}{\tau_c}n_c+\frac{n_{DT}^2}{4}\langle\sigma v\rangle_f+f_c\Gamma_{cx}, \tag{9}$$

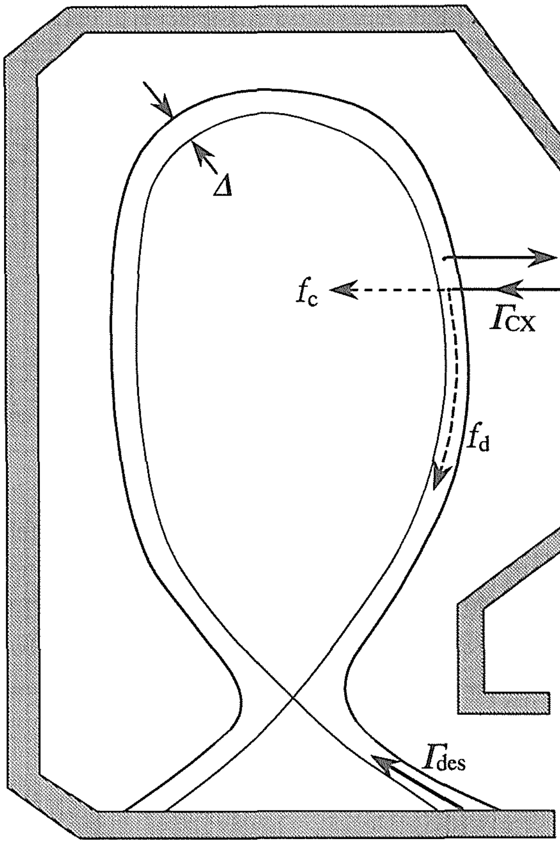

Fig. 3 Emissions of heliums retained in the first wall and the divertor.

where $\Gamma_{cx} \approx n_{DT}^{SOL} n_0 \langle\sigma v\rangle_{cx} g_{cx}(2\Delta/a)$ is the helium flow due to the charge exchanged particles, $f_c = \exp(-\Delta n_e \langle\sigma v_e\rangle_i / v_{He})$ the fraction penetrating into the core plasma as shown in Fig.3, n_{DT}^{SOL} the plasma density of the scrape-off layer, $n_0 = 3.5\times10^{22} P_0(\mathrm{Torr})\ \mathrm{m}^{-3}$ the neutral atom density, $\langle \sigma v \rangle_{cx}$ the charge exchange rate, g_{cx} the ratio of impact desorption, Δ the thickness of the scrape-off layer, n_e the electron density of the scrape-off layer, $\langle \sigma v_e \rangle_i$ the ionization rate and v_{He} the velocity of the emitted helium.

The helium density of the divertor may be expressed as

$$\frac{dn_d}{dt} = \frac{R_c}{\tau_c}(1-R_c-R_p)+f_d\Gamma_{cx}+\Gamma_{des}, \tag{10}$$

where $f_d = 1\text{-}f_c$, $\Gamma_{des} = \Gamma_W + \Gamma_{ion}$ the helium flow emitted from the divertor, Γ_W the helium flow due to the thermal desorption, $\Gamma_{ion} = n_{DT} V_c g_{ion} / V_d \tau_{DT}$ the helium flow due to the ion impact desorption, g_{ion} the ratio of the impact desorption and τ_{DT} the ion confinement time. If the divertor wall temperature is not elevated, it is regarded that $\Gamma_W \approx 0$.

In a case of steady state, Eqs.(9) and (10) become

$$n_c = \frac{\tau_c}{1-R_c}\left(\frac{n_{DT}^2}{4}\langle \sigma v \rangle_f + \underline{f_c \Gamma_{cx}}\right), \tag{11}$$

$$R_c = 1 - R_p + \underline{\frac{\tau_c}{n_c}(f_d\Gamma_{cx}+\Gamma_{ion})}. \tag{12}$$

The terms with the underlines are due to the heliums emitted from the wall. These terms have to be much smaller than those in the case without the helium emission. When $f_c \sim 0.1$, $n_{DT}^{SOL}/n_{DT} = 1/4$, $\langle \sigma v \rangle_f = 10^{-22}$ m^3/s, $\langle \sigma v \rangle_{cx} \sim 10^{-13}$ m^3/s, $\tau_{DT} = 2$ s and $V_c/V_d = 10$, these conditions become

$$g_{cx} P_0 \ll 10^{-9}\,(Torr),$$
$$g_{ion} \ll 5 \times 10^{-4}.$$

If the neutral gas pressure, P_0, is 10^{-6}Torr, g_{cx} or g_{ion} has to be much less than $\sim 10^{-3}$. This example shows that the ratio of ion or charge exchanged particle desorption should be kept extremely small. Then, the amount of the retained heliums in the wall has to be very largely reduced. In the case of ITER, the divertor wall temperature is estimated to be approximately 300 °C. Even if the heliums are trapped in the wall, there may be no problem only when the heliums thermally desorb at the temperature less than 300 °C. In order to avoid the helium emission from the wall, the material in which the helium can be thermally desorbed at the temperature less than the operation wall temperature, is desirable.

5. Summary

The density balances of the helium in the both the core plasma and the divertor are analyzed and then the schemes how to reduce the helium ash concentration are discussed. For the reduction of the helim ash concentration, the additional method is necessary in addition to the poloidal divertor. It is indicatated that the use of helium selective pumping material or the use of localized diertors may largely decrease the inward flow of the helium, e.g. the helium ash concentration.

The emission of the helium retained in the wall may largely enhance the helium ash concentration. Thus, this helium retention amount has to be kept extremely small by the choice of the material and/or the baking/operation temperature.

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