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Steady state wall pumping performance of pebble drop divertor

M. Isobe *, Y. Ohtsuka, Y. Ueda, M. Nishikawa

Graduate School of Engineering, Osaka University, 2-1 Yamada-Oka, Suita-shi, Osaka 565-0871, Japan

Abstract

A pebble drop divertor concept is proposed for future fusion reactor. By using multi-layer coated pebbles, this system can be expected to provide the fuel gas pumping function. In this paper, the pumping performance of the pebble drop divertor is estimated. The transient behavior of hydrogen retained in the surface layer of pebbles in divertor irradiation is calculated using a mass balance equation of hydrogen atoms in the graphite surface. In this calculation, the incident hydrogen flux of 1×10^{23} atoms/m^2 s (1.5 keV) and the heat flux of 35 MW/m^2, and the width of strike zone of 5 cm are assumed. Range distribution of 1.5 keV hydrogen and ion-induced detrapping cross-section is calculated by TRIM code. From the calculated dynamic hydrogen retention, it is shown that the pebble drop divertor using the pebble with graphite surface layer and BeO kernel can pump out hydrogen by $4.3 \times 10^{22} - 2.2 \times 10^{23}$ atoms/s from the ITER scale fusion reactor.

1. Introduction

The pebble drop divertor concept is proposed for the compact and high power density fusion reactor. In the basic pebble drop divertor [1], huge number of small (1–2 mm in diameter) spherical refractory pebbles (i.e. divertor pebbles) are falling in the divertor space and cover the strike zone of heat flux as a pebble curtain. The divertor pebbles are heated up by divertor heat load and then cooled outside of the divertor. This system can remove high heat flux effectively like other moving divertor systems that use liquid metal flow, moving belt and rotating drum as divertor surface.

The pebble drop divertor also has potential that fills the engineering "gap" between fusion technology for current pulse operating device and that for future steady state reactor. For example, carbon based material is widely used as plasma facing material of current fusion devices. However, it cannot be expected to be applied for high power and steady state fusion reactor because of it's high sputtering yield and high tritium inventory. Similarly, various wall conditioning techniques to make high performance fusion plasma will be unavailable in steady state system.

In the pebble drop divertor, each divertor pebble is irradiated for less than 0.1 s per cycle and it can be regenerated outside of divertor. This operating condition is same as that of current plasma facing component. Therefore material database and wall conditioning techniques for current fusion devices can be applied to the pebble drop divertor system.

We study pebble drop divertor system using multi-layer coating pebbles. Multi-layer coating pebble adds many beneficial functions to the pebble drop divertor system. By selecting appropriate material of surface layer (i.e. Plasma Facing Layer: PFL), the pebble drop divertor can control plama density and impurity. An intermediate coating layer for tritium permeation barrier enables to keep low bulk tritium retention. And the kernel material can be selected considering thermal and mechanical properties.

One of the expected functions of pebble drop divertor is the fuel gas pumping. The divertor pebbles irradiated in the divertor strike zone are saturated their PFL with incident hydrogen, then they drop out of divertor with retained fuel. The retained fuel gas is desorbed in the circulating process and the regenerated divertor pebbles drop in divertor space again. In this way, the pebble drop divertor can pump out fuel particles continuously.

* Corresponding author. Tel.: +81 6 877 5111; fax: +81 6 879 7867; e-mail: mi@ppl.eng.osaka-u.ac.jp.

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In this paper, the feasibility of pumping function of pebble drop divertor is investigated. Because the divertor pebbles will be irradiated by very high particle load (about 10^{23} atoms/m^{3}s) and heat load (about 30 MW/m^2), it is needed to estimate dynamic behavior of retained hydrogen under quickly rising temperature. So that the numerical simulation using mass balance equations of retained hydrogen in graphite was performed.

2. Irradiation condition of divertor pebbles

Fig. 1 shows the schematic view of the pebble drop divertor system and a multi-layer coated pebble. To determine the irradiation condition of pebble drop divertor system; the size of pebbles, flow rate and the velocity of dropping pebble and the heat/particle load to the divertor pebbles at strike zone must be assumed.

According to ITER EDA design, the power flow to divertor region is 150 MW in 1.5 GW of fusion power. The pebble drop divertor that provides pumping function will form low recycling plasma-surface interface. Therefore the load reduction by charge exchange and radiation in the divertor region will not be expected and the heat load to divertor will concentrate to the strike zone of divertor surface.

The width of strike zone obtained from current large tokamak experiment is about 50 mm [2]. Because this heat load profile is measured on little inclined divertor plate, it can be applied to pebble drop divertor that does not reduce heat load reduction with an inclined surface. If the major radius of torus is assumed to be 7 m, the area of strike zone is estimated about 4.4 m^2 (including inboard and outboard area) and the heat load to each divertor pebble will be 35 MW/m^2. When the contribution of ion is about half of this heat load and the incident ion energy assumed to be 1 keV, the particle load will be about 1×10^{23}/m^{2}s. If these heat and particle load uniformly distributed on one side of a pebble, the load becomes 17.5 MW/m^2 and 5×10^{22}/m^{2}s on the surface of pebbles.

The maximum allowable heat load to divertor pebbles is limited by internal thermal stress induced by incident heat flux. The thermal stress is determined from various parameters; the size of pebbles, thermoelastic

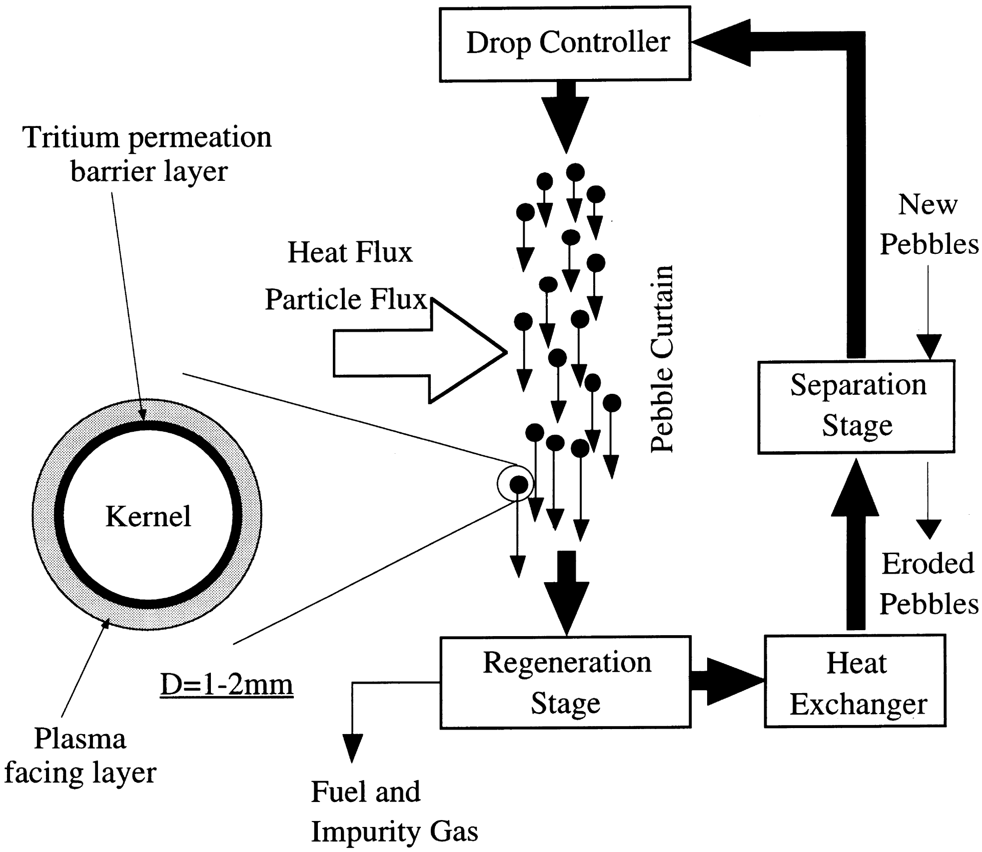

Fig. 1. Schematic diagram of the pebble drop divertor system and a multi-layer coated pebble.

parameters of kernel materials, the duration of irradiation. The irradiation conditions of divertor pebble should not exceed this limit. In addition it is preferred to be lower the surface temperature rise during irradiation from the viewpoint of pumping performance. The stress analysis of irradiated pebble shows the divertor pebble with BeO kernel of 1 mm in diameter or with graphite kernel of 2 mm in diameter that dropped from 1 m upper than strike zone can bear the divertor heat flux described above. At this operating condition, the velocity of pebbles passing through strike zone is about 4.5 m/s and the irradiation time is about 10 ms.

3. Mass balance equations of retained hydrogen

Graphite is the most widely used plasma facing material in present-day fusion devices. Its low Z character and good compatibility with high confinement core plasma are proven for a fusion reactor. And its drawbacks such as high erosion yield by particle impact and high hydrogen retention are not problems in pebble drop divertor system. Therefore the graphite is a candidate material of PFL of a divertor pebble.

The mass balance equations of hydrogen in the graphite PFL are expressed as follows:

$$\begin{aligned}\frac{\partial n}{\partial t}(z,t) = {} & D\frac{\partial^2 n}{\partial z^2}(z,t) + P\phi\frac{\partial n}{\partial z}(z,t) + S(z) \\ & - \Sigma_{\mathrm{T}}(C_0 - n_{\mathrm{T}}(z,t))n(z,t) + (\sigma_{\mathrm{d}}(z)\phi \\ & + \Sigma_{\mathrm{d}})n_{\mathrm{T}}(z,t) - Kn(z,t)n_{\mathrm{T}}(z,t) \\ & - 2K_1 n^2(z,t), \end{aligned} \tag{1}$$

$$\begin{aligned}\frac{\partial n_{\mathrm{T}}}{\partial t}(z,t) = {} & P\phi\frac{\partial n_T}{\partial z}(z,t) + \Sigma_{\mathrm{T}}(C_0 \\ & - n_{\mathrm{T}}(z,t))n(z,t) - (\sigma_{\mathrm{d}}(z)\phi + \Sigma_{\mathrm{d}})n_{\mathrm{T}}(z,t) \\ & - Kn(z,t)n_{\mathrm{T}}(z,t), \end{aligned} \tag{2}$$

where z is the depth from the surface, n and n_{T} are the atomic density of free and trapped hydrogen, Σ_{d} the thermal detrapping rate constant, Σ_{T} the trapping rate constant, σ_{d} the ion-induced detrapping cross-section, ϕ the incident particle flux, S implantation rate, D the diffusion constant, P the particle impact erosion rate of surface layer, K the molecular recombination rate constant of free hydrogen atom with trapped one, K_1 the molecular recombination rate constant between free hydrogen atoms and C_0 the trap density in the graphite.

As described in Section 2, the irradiation time of the divertor pebble is very short. So that the diffusion effect can be neglected in the estimation of retained hydrogen in the surface layer of the divertor pebble. The remaining parameters are needed for numerical evaluation of hydrogen retention of the divertor pebble. In this work, the recombination rate K was taken from the function of the temperature, which is determined by Morita and Hasebe [3] from the fluence dependence of ion induced release of retained hydrogen measured by elastic recoil detection method. The value of C_0 and Σ_{T} were obtained from the same reference.

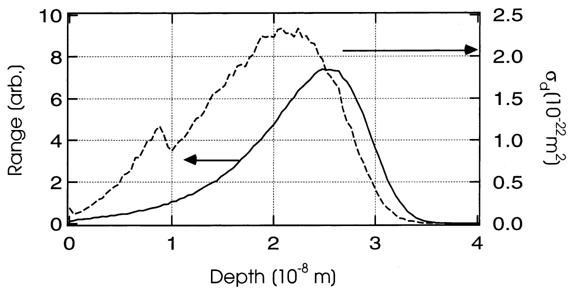

Fig. 2. The range distribution of incident hydrogen and the depth profile of ion-induced detrapping cross-section; σ_{d}, by 1.5 keV H^+ irradiation to graphite.

The surface erosion rate P was calculated from the physical sputtering yield of graphite by hydrogen irradiation. The effect of chemical erosion can be neglected because of chemical erosion is expected to be reduced in irradiation of very high particle flux [4].

The implantation rate S and the ion-induced detrapping cross-section σ_d determined from the range of incident hydrogen ion and the number of displacement hydrogen atoms. These values were calculated with TRIM code under the condition that hydrogen saturated graphite was irradiated by hydrogen ion beam. Fig. 2 shows the depth profiles of range and σ_{d} of 1.5 keV H^+ irradiation.

The thermal detrapping rate Σ_{d} and the molecular recombination rate constant between free hydrogen atoms K_1 are determined as the combination of $K_1/C_0(\Sigma_d/\Sigma_T)^2$ from the time evolution of retained hydrogen of isothermal annealing experiments [5]. These parameters were obtained from curve fitting to the experimental temperature dependence of in-irradiation hydrogen saturation concentration by 1.5 keV H^+ beam [6]. Fig. 3 demonstrates a satisfactory agreement of this calculation and experimental data from Ref. [6]. In this calculation the incident flux was set to $1 \times 10^{20}/\mathrm{m}^2$ s.

4. Results

The numerical simulation was performed about divertor pebbles with graphite PFL/BeO kernel and graphite PFL/graphite kernel. The diameter of the pebble with BeO kernel was set to 1.0 mm and that with graphite kernel was set to 2.0 mm. The operating parameters and divertor load were set as described in Section 2. To simplify the evaluation of surface temperature, it was assumed the heat load of 17.5 $\mathrm{MW/m^2}$ was uniformly distribute on all over the pebble surface.

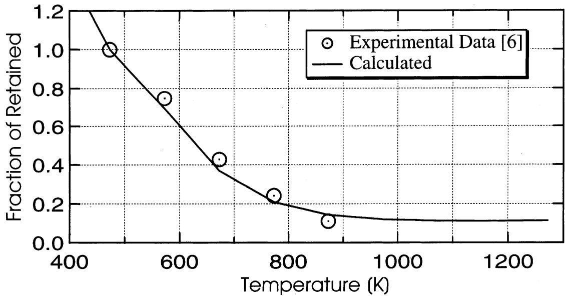

Fig. 3. Normalized saturated amount of hydrogen implanted into graphite. The open circle is experimental data from Ref. [6] and the line is numerical result. The calculation were performed for an ion flux of 1×10^{20} /m^2 s.

This assumption is the worst case for the pumping performance because the higher surface temperature makes lower the retained hydrogen that carry away from divertor as shown in Fig. 3. The inlet pebble temperature T_i was set to 500 K and 1000 K. The surface temperature of pebble rise during divertor irradiation and the surface temperature at outlet point ($t = 11.2$ ms) T_o was higher than T_i by about 220 K for pebbles with BeO kernel and by 260 K for pebbles with graphite kernel. The cooling of the pebble's surface by radiation after irradiation was neglected.

Fig. 4 shows the time evolution of retained hydrogen in graphite PFL with BeO kernel. The solid line is the result of $T_{in} = 500$ K and dotted line is that of $T_{in} = 1000$ K. At the outlet point, the retained hydrogen density is 5.5×10^{20}/m^2 and the amount does not depend on inlet or outlet temperature. This is because, in very high flux irradiation, ion impact detrapping rate is much larger than thermal detrapping rate even at high temperature.

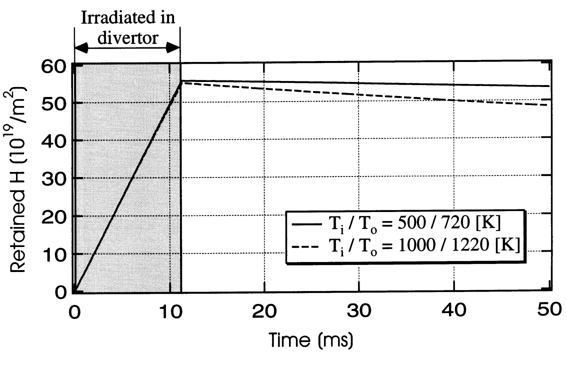

Fig. 4. Time evolution of retained hydrogen concentration in PFL of free falling divertor pebbles. The incident heat flux: 35 MW, particle flux 1×10^{23} /m^2 s, the width of strike point: 5 cm, the velocity at strike point: 4.4 m/s, diameter of pebble: 1 mm, PFL material: graphite, kernel material: BeO.

When T_{in} is set to 500 K, retained hydrogen decrease slowly after the pebbles pass through the strike zone. From the isochronal annealing experiment of hydrogen saturated graphite in room temperature, the graphite at 700 K retains the same hydrogen concentration as that at room temperature and the saturation concentration at room temperature is about 3×10^{21}/m^2 [6,7]. Therefore at this operating condition, retained hydrogen at outlet point remains in PFL until it is desorbed in regeneration process.

When T_{in} is set to 1000 K, retained hydrogen decreased rapidly after irradiation as shown in Fig. 5. While the divertor pebbles dropping 1 m from divertor strike zone (it takes about 0.2 s), 39% of retained hydrogen is desorbed spontaneously. And almost all the retained hydrogen is released within 10 s after irradiation. This means that when pebble drop divertor operate in very high temperature, little additional heating is needed for regeneration of irradiated pebbles. If divertor pebbles are drop out of divertor region to some pumping chamber within 1 second after irradiation, 20% of retained hydrogen (1.1×10^{20}/m^2) can be pumped out from divertor.

The pumping performance can be estimated from this retained hydrogen concentration, the effective area of divertor surface and the drop velocity of the pebbles at strike zone (about 4.4 m^2 and 4.5 m/s, as described in Section 2). At the low inlet temperature, $T_{in} = 500$ K, the pumping performance is varied by the regeneration condition and when all retained hydrogen desorbed in the regeneration process, the pumping rate is 2.1×10^{23} hydrogen atoms/s. At the high inlet temperature, $T_{in} = 1000$ K, the pumping rate is 4.3×10^{23} hydrogen atoms/s.

When 5% of fuel gas contributes to nuclear fusion, the reactor whose fusion power is 1.5 GW requires pumping rate of about 2×10^{22} hydrogen atoms/s. The pebble drop divertor can satisfy this requirement.

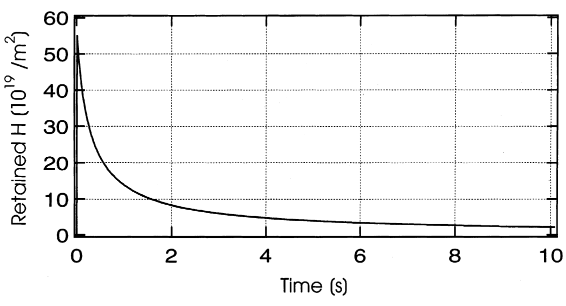

Fig. 5. Decrease of retained hydrogen in PFL at high temperature operation ($T_i = 1000$ K). The inlet/outlet temperature: 1000 K/1220 K, the velocity at strike point: 4.4 m/s, diameter of pebble: 1 mm, PFL material: graphite, kernel material: BeO.

5. Discussion

As described in Section 3, the diffusion effect was neglected in this work. This is not wrong assumption during irradiation because irradiation time is shorter than typical diffusion time, that is about 1000 s, and the bulk diffusion effect is reduced by large surface erosion rate. However, the estimation of the desorption behavior after divertor irradiation needs to consider the diffusion effect. The following is a raw estimation of effect of the diffusion.

Fig. 6 shows the free and trapped hydrogen profile at outlet point ($t = 11.2$ ms) when inlet temperature is 1000 K. The solid line is free hydrogen profile and the dotted line is that of trapped hydrogen. The free hydrogen profile shows that the maximum free hydrogen concentration is about $3.5 \times 10^{28}/\mathrm{m}^3$ and the typical length of the profile is about 250 Å. The diffusion constant of free hydrogen during irradiation is obtained from Ref. [2]. It is expressed as a function of temperature; $D = 10^{15}$ $\mathrm{e}^{-0.25\ \mathrm{eV/kT}}$. Therefore the estimated diffusion flux to the bulk graphite at 1000 K is about $2.0 \times 10^{20}/\mathrm{m}^2$ s.

The diffused free hydrogen atoms to bulk graphite will trap at that point and the local molecular formation will be decreased. It means that as taking diffusion effect mentioned above into account, the spontaneous desorption will be reduced.

Therefore more detailed analysis including diffusion effect are needed for the estimation of pumping performance and regeneration condition at high temperature operation. The investigation of He ash pumping is also needed to evaluate the performance of the pebble drop divertor system. These subjects should be discussed in the future.

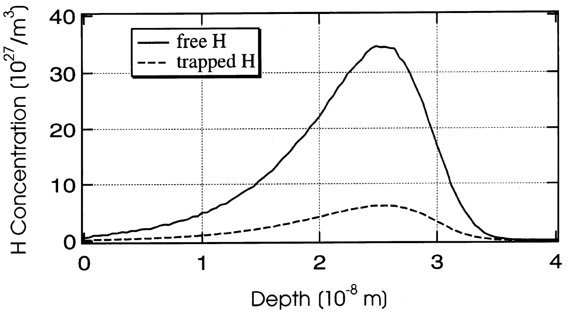

Fig. 6. The depth profile of free and trapped hydrogen immediately after the divertor irradiation. The inlet/outlet temperature: 1000 K/1220 K, the velocity at strike point: 4.4 m/s, diameter of pebble: 1 mm, PFL material: graphite, kernel material: BeO.

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