J. Plasma Fusion Res. SERIES, Vol. 3 (2000) 316–319

Transient Hydrogen Release from Graphite just after High Flux Beam Irradiation

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(Received: 18 January 2000 / Accepted: 10 May 2000)

Abstract

The pebble divertor concept is proposed for compact and high power density fusion reactors. In this concept, fuel gas can be pumped out by streams of the free falling pebbles with the hydrogen getter surface layer through the divertor plasma. To investigate its fuel gas pumping function, the transient hydrogen release becomes important. In this study, the hydrogen release from the graphite just after the high flux irradiation was measured for estimating the pumping performance of the pebble divertor. The detailed hydrogen release behavior for 5 s after the end of the irradiation was calculated by solving the mass balance equations.

Keywords:
Pebble Divertor, Graphite, High Flux Irradiation, Hydrogen Retention

1. Introduction

The pebble divertor system [1,2] is one of the divertor concepts for the future fusion reactors, in which the important issues are the heat removal and the erosion of the divertor wall loaded with high heat flux and particle flux. In this system, the multi-layer coated pebbles are falling into the divertor space to form the divertor wall. The multi-layer pebble consists of the kernel (SiC or graphite) with good thermal characteristics, the plasma facing layer (graphite coated by chemical vapor deposition (CVD)) with low-Z and hydrogen retention characteristics, and the intermediate layer (SiC coated by CVD) with a very low tritium diffusivity and solubility.

By using the pebbles with the hydrogen getter surface, this system also has a fuel gas pumping function like as the carbon sheet pump [3] and the moving-belt plasma-facing components [4]. In the pebble divertor, the pebbles are heated up by the irradiation from plasma, and retain fuel particles. The temperature of the pebble reaches the maximum at the end of the irradiation. This temperature is called the "operational temperature". Then, the pebbles are transferred to the regeneration stage, and the pebbles are heated for the desorption of retained gas. This temperature is called the "regeneration temperature". In the previous wall pumping process, the temperature dependence of saturated amount of retained hydrogen in graphite is used. The difference between the saturated amount of retained hydrogen at the operational temperature and that at the regeneration temperature is the pumping capacity of the graphite surface, because the amount of retained hydrogen in graphite decreases with increase in the temperature [5]. So, the regeneration temperature must be higher than the operational temperature for the fuel gas pumping.

In the pebble divertor, another wall pumping process is considered. Under the high flux irradiation such as particle loading on the divertor plate, graphite

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retains more hydrogen than the saturated amount of retained hydrogen in graphite. After the irradiation, the supersaturated hydrogen is transiently released from the graphite by keeping the temperature of the pebbles at the operational temperature. This pumping process does not need the additional heating energy to raise the temperature of the pebbles above the operational temperature. Therefore, we are interested in the pumping of the pebble divertor by using the transient hydrogen release. However, there is no experimental data about the transient hydrogen release just after the high particle flux irradiation, in conditions comparable to the particle loading on the divertor plates.

In this study, we estimated the pumping performance of the pebble divertor by using the transient hydrogen release in the condition that the regeneration temperature and the operational temperature are the same. In the experiment, the hydrogen release from the graphite samples just after the high flux hydrogen beam irradiation with a maximum flux of 1×10^{22} atoms/m^{2}s (5 keV H_3^+ (1.7 keV per H)) was measured at the operational temperature of 573–973 K. Then the detailed hydrogen release behavior for 5 s after the end of the irradiation was calculated by solving the mass balance equations.

2. Experimental

Figure 1 shows the experimental device, which consisted of the high flux beam source [6], the irradiation chamber and the TDS chamber. The pulsed neutral beam (5 keV H_3^+ (1.7 keV per H)) with maximum particle flux of 1×10^{22} /m^{2}s can be generated for up to 4 s.

In this experiment, the samples are made of isotropic graphite PD-330s of $10 \times 20 \times 1$ mm^3. A Mo plate with a hole of 5 mm in diameter was placed at 7 mm from the graphite sample to limit the irradiated area. The temperature of the sample was monitored by the thermocouples, which were attached to the opposite side of the irradiated surface of the sample.

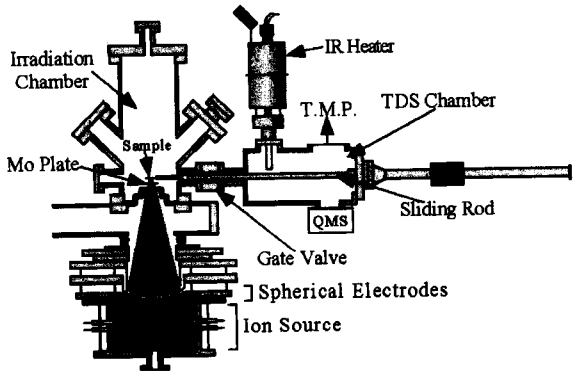

Fig. 1 Schematic view of the experimental device

It was difficult to measure the hydrogen release from the sample in the irradiation chamber, because working gas of the ion source was flowing into the irradiation chamber during the irradiation, and the pressure increased up to 3×10^{-2} Pa. Therefore, the graphite sample was transferred to the TDS chamber after the irradiation, and the gate valve was closed to prevent the gas flow to the TDS chamber. During the irradiation, the gas flow from the irradiation chamber to the TDS chamber was prevented by the plug on the sliding rod.

The TDS chamber was equipped with a 350 l/s turbo molecular pump, an infrared heater (IR heater) and a quadrupole mass spectrometer (QMS). The base pressure of the TDS chamber was 2×10^{-6} Pa.

In the experiment, the sample was irradiated for 4.0 s. The sample temperature rose up during the irradiation and reached the maximum temperature (the operational temperature) at the end of the irradiation. The values of the operational temperature were 573, 773, 973 K for the fluxes of 2.5, 4.5, 6.5×10^{21} H/m^{2}s, respectively. The end of the irradiation was defined as t = 0. Just after the irradiation, the sample was transferred to the TDS chamber within 1 s, and the gate valve was closed at t = 1 s. The period for the transfer was shorter than one forth of the recovery time of the vacuum condition degraded by the gas flow from the irradiation chamber during the transfer. After the transfer, the sample temperature was regulated to the same temperature with the operational temperature by the IR heater, and the QMS signal (M/e = 2) was measured until t = 200 s. However, the hydrogen release until t = 5 s was unable to be measured during the recovery time. The release of hydro-carbon was neglected, because the release of hydro-carbon just after the irradiation was less than 20 % of the hydrogen release.

For subtracting the background with the hydrogen released from the TDS chamber and the hydrogen gas flow from the irradiation chamber, we measured the background in the above experimental sequence without the ion extraction with the same gas feed into the ion source.

3. Results and Discussion

Figure 2 shows the measured hydrogen release rate at the various operational temperatures. Although the

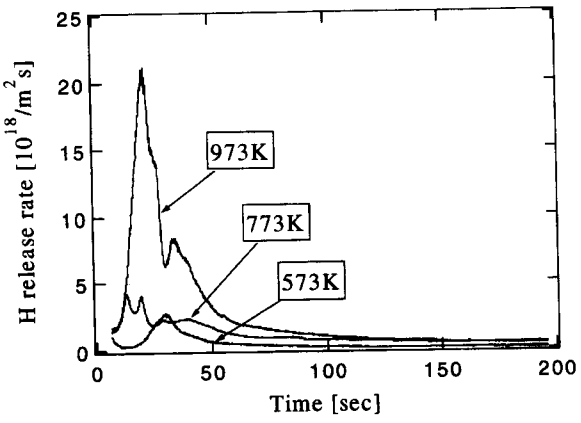

Fig. 2 The hydrogen release rate for the various operational temperatures.

hydrogen release behavior was affected by the temporal evolution of the sample temperature, the transient hydrogen release at the operational temperature of 973 K was larger than at the other cases. The amount of hydrogen release between 5 and 55 s at the operational temperature of 973 K was 4.0×10^{21} H/m^{2}s.

To calculate the pumping performance of the pebble divertor from this result, we assumed that a pebble stream was a moving flat surface, and its moving speed was 4.5 m/s [1]. This calculation showed that the pumping performance was 8.2 Pa·m^3/s for 300 K per 1 meter of the toroidal length of the divertor. Furthermore, the pumping performance of the pebble divertor of the tokamak associated with the ITER (major radius: 8.1 m) was 380 Pa·m^3/s. This was larger than the amount of the fuel gas feed of 200 Pa·m^3/s needed in steady state operation of ITER.

In the conditions of the divertor of fusion reactor, the energy of the particle to the pebble will be about 0.2 keV [7], which is lower than 1.7 keV in the experiment. The saturated amount of retained hydrogen in graphite for 0.3 keV deuterium implantation was about one third of one for 1.5 keV deuterium implantation [5]. If the transient hydrogen release is proportional to the saturated amount of retained hydrogen, the pumping performance of the pebble divertor will be lower than one third of the experimental results. However, the pebble divertor shares more fuel gas pumping capacity than a half of the ITER specification.

To estimate the more detailed pumping performance of the pebble divertor, we calculated the hydrogen release from the graphite by solving the mass balance equations of hydrogen in the graphite expressed as follows [8]:

$$\frac{\partial n(z,t)}{\partial t} = D\frac{\partial^2 n(z,t)}{\partial z^2} + P\phi\frac{\partial n(z,t)}{\partial z} + S(z) - \Sigma_T(C_0 - n_T(z,t))\,n(z,t) + (\sigma_T(z)\phi + \Sigma_d)\,n_T(z,t) - Kn(z,t)\,n_T(z,t) - 2K_1 n(z,t)^2 \quad (1)$$

$$\frac{\partial n_T(z,t)}{\partial t} = P\phi\frac{\partial n_T(z,t)}{\partial z} + \Sigma_T(C_0 - n_T(z,t))n(z,t) - (\sigma_T(z)\phi + \Sigma_d)\,n_T(z,t) - Kn(z,t)\,n_T(z,t) \quad (2)$$

Where z is the depth from the surface, n and n_T are the atomic density of activated (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 local molecular recombination rate constant of free hydrogen atom with trapped one, K_1 the local molecular recombination rate constant between free hydrogen atoms and C_0 the trap density in the graphite. These value except Σ_d and K_1 were obtained from the reference [1].

K_1 and Σ_d were obtained by $(K_1/C_0)\,(\Sigma_d/\Sigma_T)^2 = 45\exp(-1.2\ \text{eV/kT})$, which was evaluated from the temporal evolution of retained hydrogen in the isothermal annealing experiments [9]. Fig. 3 shows the Σ_d values used for the simulations with mass balance equations model. We varied the Σ_d as the calculated hydrogen release behavior agreed with the experimental one. When Σ_d was $5 \times 10^5 \exp(-1.2\ \text{eV/kT})$, the calculated hydrogen release behavior agreed with the experimental one. This result is shown in Fig. 4.

Using this result, the gas release before t = 5 sec can be calculated. In the pebble divertor, it is assumed that the pebbles drop from 2.5 m above the conductance barrier. Therefore, the gas release after t = 0.265 s may be corresponded to the pumping capacity. The unmeasurable hydrogen release from t = 0.265 to 5 s will be found to be about 5 % of the experimental result from t = 5 to 55 s.

In order to obtain the optimal operational temperature for the pumping performance of the pebble divertor, we also calculated the hydrogen release under the conditions simulated in the pebble divertor operation. The conditions were heat flux of 15 MW/m^{2}s, particle flux of 10^{23} H/m^{2}s, irradiation time of about 23 ms, pebble of 1 mm diameter with graphite kernel. If the pebble surface is uniformly irradiated, the surface temperature rises 386 K. So, the hydrogen release was

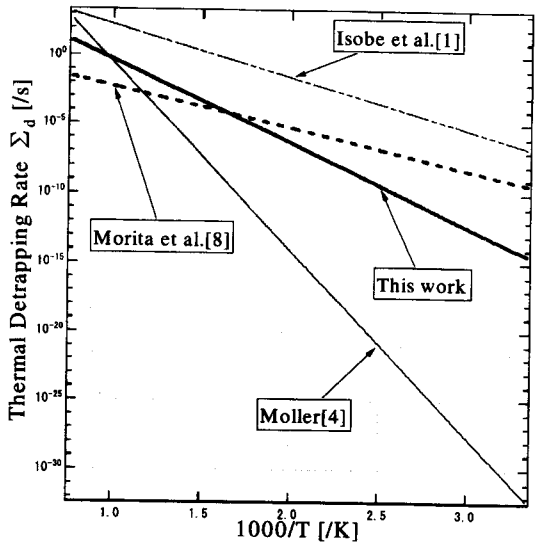

Fig. 3 The temperature dependence of the thermal detrapping constants for the simulations with mass balance equations model.

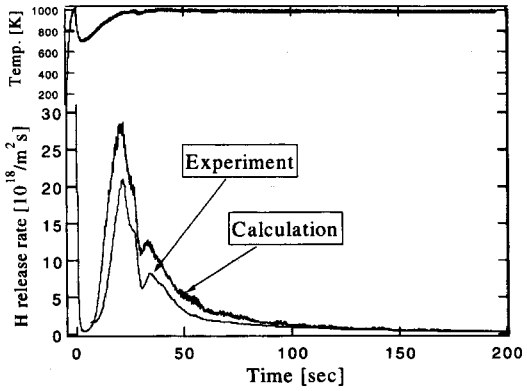

Fig. 4 The calculated hydrogen release behavior, the experimental one and experimental temperature behavior.

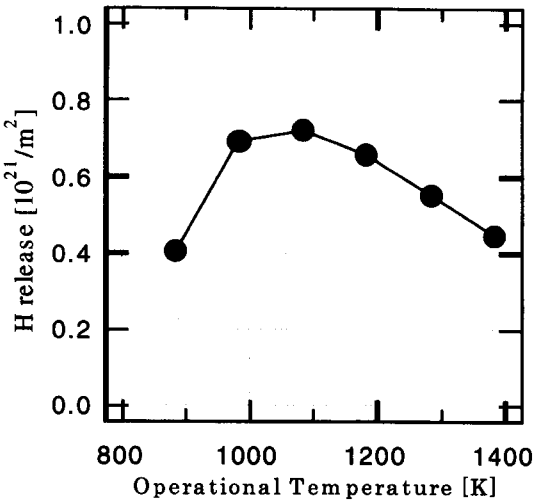

Fig. 5 The calculated amount of the hydrogen release for the different operational temperature.

calculated at the operational temperature from 878 K to 1378 K. Figure 5 shows the calculated hydrogen release rate for the different operational temperature. As shown Figure 5, the hydrogen release had a maximum value at the operational temperature of 1078 K. From this result, it was found that the optimal operational temperature was near 1100 K.

4. Summary

The transient hydrogen release from the graphite was experimentally measured just after the high flux irradiation. For more detail estimation, we calculated the hydrogen release rate by solving the mass balance equations. Using this calculation, the unmeasurable hydrogen release from t = 0.265 to 5 sec will be found to be about 5 % of the experimental result from t = 5 to 55 sec. By calculating the operational temperature dependence of the hydrogen release rate in the conditions simulated in the pebble divertor operation, it was found that the optimal operational temperature for the pumping performance of the pebble divertor was near 1100 K.

The experiment about the retention and release behavior of He ash is also needed to estimate the pumping performance of the pebble divertor. This issue should be discussed in the future.

References

[1] M. Isobe *et al.*, J. Nucl. Mater. **258-263**, 745 (1998).
[2] M. Isobe *et al.*, Nucl. Fusion **40**, 647 (2000).
[3] A. Sagara *et al.*, J. Nucl. Mater. **220-222**, 627 (1995).
[4] Y. Hirooka *et al.*, *Proceedings Symposium on Fusion Engineering* **2**, 906 (1998).
[5] W. Möller, J. Nucl. Mater. **162-164**, 138 (1989).
[6] M. Nishikawa *et al.*, Fusion Engrg. Des. **16**, 351 (1991).
[7] N.B. Morley *et al.*, Fusion Engrg Des. **28**, 176 (1995).
[8] K. Morita *et al.*, J. Nucl. Mater. **176-177**, 213 (1990).
[9] K. Morita *et al.*, J. Nucl. Mater. **196-198**, 963 (1992).