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Distribution of hydrogen isotopes retained in the divertor tiles used in JT-60U

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Abstract

Distribution of deuterium and hydrogen retained in graphite tiles placed in the divertor region of JT-60U with the dual side pumping geometry was investigated by thermal desorption spectroscopy. The retention of hydrogen isotopes was nearly proportional to the thickness of the carbon redeposited layers, though their concentration changes with the poloidal location and orientation of the surface tiles. The least concentration of $(H + D)/C$ ($\sim$0.02) was found in the redeposited layers on the inner divertor tile. Rather high hydrogen concentration was found in the redeposited layers on plasma shadowed area. In particular, the redeposited layers on the bottom side of the outer dome wing tile shadowed from plasma and facing to the pumping slot showed the highest concentration of 0.13 in $(H + D)/C$. In JT-60U, however, the carbon deposition in the shadowed area is very small, resulting in a smaller total retention in the divertor area compared to other large tokamaks.

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1. Introduction

It is a very important issue to evaluate retention properties of tritium and deuterium in in-vessel components of current devices from a viewpoint of safety for the next fusion reactor [1–4]. We have been studying the retention of hydrogen isotopes (H, D, T) in plasma facing graphite tiles used in the W-shaped divertor of JT-60U with the inner side pumping system [3,5–9] and with the dual side pumping system [10–12]. We found that most of the tritium produced by D–D reactions was implanted into graphite tiles in the micrometer depth range, while hydrogen and deuterium were retained in the near surface region and the retention was influenced by the carbon deposition as well as

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the surface temperature of the tiles. It is known that for JT-60U, erosion is dominant in the outer divertor region and redeposition in the inner divertor region and the outer wing of the dome unit [13].

In this study, hydrogen and deuterium retention on plasma facing surfaces and plasma shadowed surfaces of the graphite tiles used in the divertor region of JT-60U with the dual side pumping geometry was investigated by thermal desorption spectroscopy (TDS).

2. Experiments

Fig. 1(a) shows a cross sectional view of the JT-60U W-shaped divertor with the dual side pumping system. The tiles were exposed to 6700 shots of deuterium discharges with deuterium NBI heating (referred to as DD discharges hereafter), except the tiles of outer wing and top in the dome unit (2400 shots). For the June 1997–October 1999 experimental period, after 4300 shots of DD discharges with the inner side pumping system, 2400 shots of DD discharges were performed with the dual side pumping system. Before air ventilation, 350 shots of hydrogen discharges with hydrogen NBI (HH discharges) were performed to remove surface tritium. The NBI power for the HH discharges was about half that compared to the DD discharges. Hence the tile temperature increase during the HH discharges would be much less than that during the DD discharges. The operational temperature of the vacuum vessel and the base temperature of the tiles were ~573 K. Fig. 1(b) shows the sampling position. Samples (8 mm × 8 mm × 0.5 mm) were cut from the tiles to include the tile surface; five samples (#1–5) taken from the inner divertor tile, four samples (#6–9) from the dome units, and four samples (#10–13) from the outer divertor tile. The side surface was divided into three samples (Fig. 1(c)). For TDS measurements, the sample was heated from room temperature to 1273 K with a constant heating rate of 0.42 K/s and hold at 1273 K for 10 min. The dominant mass numbers observed by a quadrupole mass spectrometer during the heating were 2(H_2), 3(HD), 4(D_2), 16(CH_4), 19(CD_3H), 20(CD_4), 26(C_2H_4), 30(C_2H_6), 32(C_2D_4), 36(C_2D_6) and 39(C_3H_8) [9].

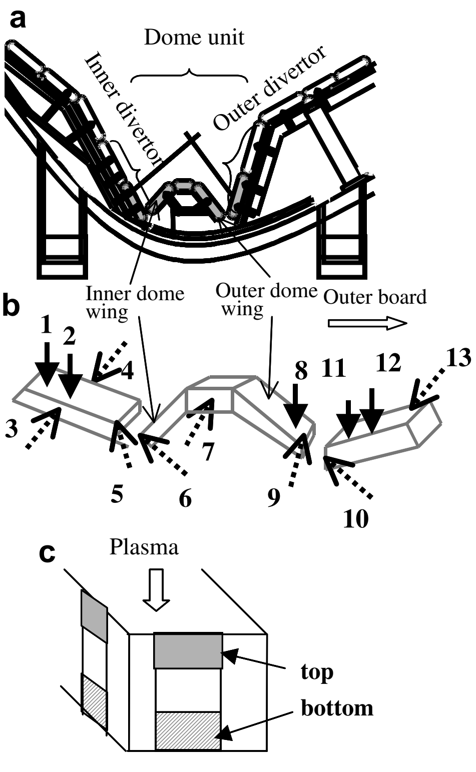

Fig. 1. Cross sectional view of the W-shaped divertor region of JT-60U with dual side pumping system (a), sampling position (b) and that of the side surface sample (c).

The thickness of the redeposited layers was evaluated by a scanning electron microscope (SEM). The depth profiles of hydrogen and deuterium retained in the samples were analyzed by secondary ion mass spectrometry (SIMS). Five kiloelectron volts cesium ions (Cs^+) were used as the primary ions. The sputtering rate was nearly 1 μm/h. The negative signal intensities of H and D were normalized by ^{12}C for comparison.

3. Results

Fig. 2 compares thermal desorption spectra of H_2, HD, D_2 and CH_4 for sample #2 from the plasma facing surface of the inner divertor tiles (a), sample #11 from the plasma facing surface of the outer divertor tiles eroded to a depth of about 15 μm [11] (b) and sample #9 from the top side surface of the outer dome wing tile facing toward the pumping slot (c). Samples #2 and #9 were respectively covered by redeposited layers of 85 and 32 μm in thickness. For sample #2, the main desorption peak of H_2 appeared around 1050 K, while the desorption of HD and D_2 were peaked at higher temperatures than that of H_2. Similar tendencies were observed in the TDS spectra of sample #9 and #11. Two desorption peaks of CH_4 were observed in sample #2 and #11 around 600 and 800 K. One can see that although both samples #2 and #9 were covered by thick rede-

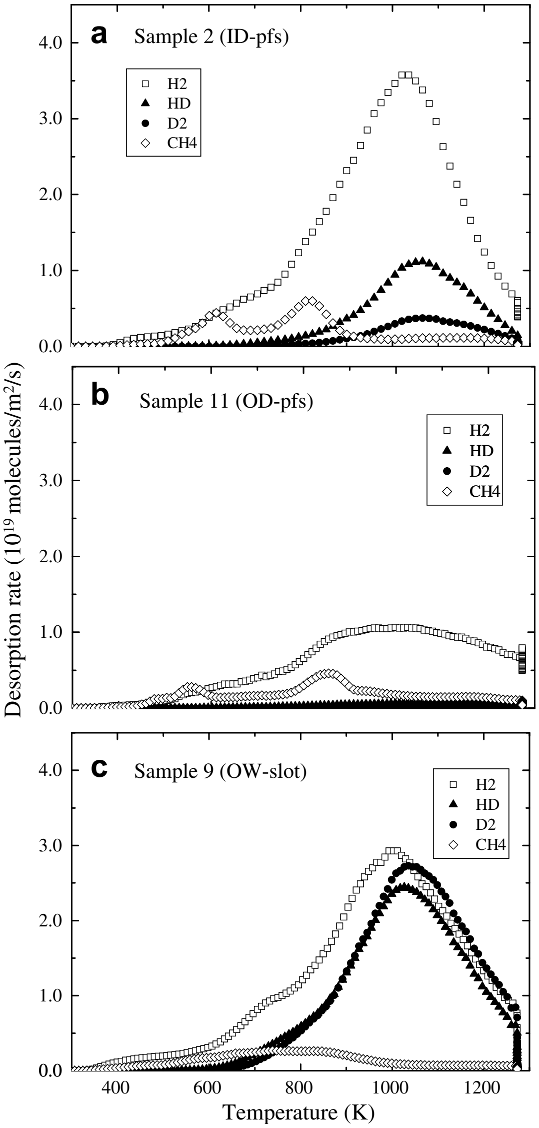

Fig. 2. Thermal desorption spectra of H_2, HD, D_2 and CH_4 desorbed from the sample 2 (a), the sample 11 (b) and the sample 9 (c).

posited layers, H_2 desorption is significant for sample #2, while H_2, HD and D_2 are comparable for sample #9. The desorption of HD and D_2 for sample #9 were peaked at lower temperatures than those of sample #2.

The total retention of hydrogen isotopes (H + D retention) was determined by integrating all desorbing species including H and D atoms in mass spectra. The desorption rate of H_2 did not come back zero during holding at 1273 K because the degassing from the TDS chamber wall became high due to the heat load. Hence the total H + D retention was overestimated. The fraction of H amount due to this overestimation to the total H + D retention was ~1.3 % (sample #2), ~5% (sample #11) and ~0.5% (sample #9). Fig. 3 shows the total H + D retentions and atomic ratio of retained D and H (D/H) for all samples. In the retentions, the contribution of hydrogen retained in the bulk was not subtracted. As the bulk sample, two samples cut in 2 mm depth from the surface from the inside of the inner and outer divertor tiles used in the inner side pumping geometry. The amount of H retention in the bulk was almost 2×10^{22} atoms/m^2 (~4×10^{25} atoms/m^3 [14]).

In Fig. 4, the (H + D) retentions for all samples except the eroded ones are plotted as a function of the thickness of the redeposited layers. Although the data are widely scattered, they can be divided into two groups as indicated by two solid lines depending on the locations of the redeposited layers

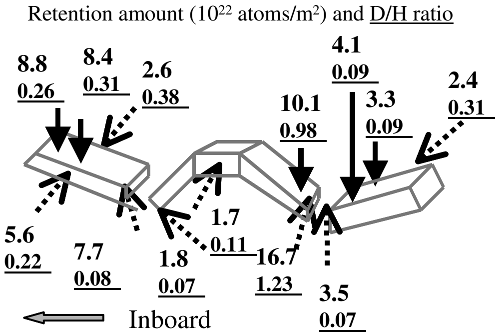

Fig. 3. Total amount of retained H and D in the samples and atomic ratio of retained D and H (D/H) for all samples. Numbers of bold letters are the total H + D retention in 10^{22} atoms/m^2. D/H ratios are presented as numbers underlined.

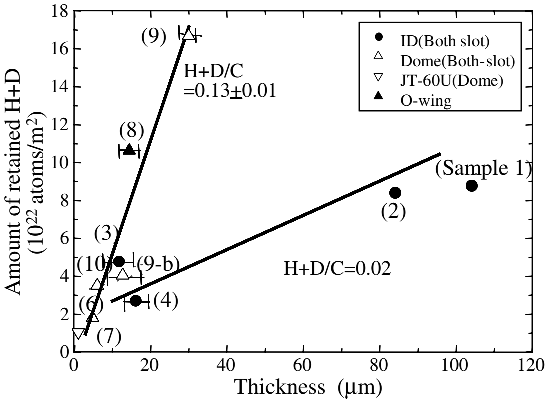

Fig. 4. Amount of retained H and D in the samples as a function of the thickness of the redeposited layer.

i.e. plasma facing surfaces and plasma shadowed tile sides, showing the retention increases with the thickness of the redeposited layers. The linear relationships indicate that hydrogen was retained uniformly in the redeposited layers with a relatively constant (but different depending on the location) hydrogen concentration irrespective of their thicknesses. This is quite consistent with hydrogen depth profiles by SIMS given in Fig. 5 which shows the depth profiles of H/C, D/C and (H + D)/C signal intensity ratio within the depth of 1.7 μm for sample #2 (a), sample #11 (b) and sample #9 (c). The H/C signal intensity ratio in near surface region was high and exponentially decreased with depth, while the D/C ratio was very small and then kept nearly constant with depth for samples #2 and #9 having thick redeposited layers. The (H + D)/C ratio for sample #9 was almost constant, while that for sample #2 was not constant within 1.7 μm. However, the (H + D)/C ratio for redeposited layers of inner divertor tiles became almost constant at deeper depth, according to previous study [5]. This is in agreement with the constant concentration throughout the layers as indicated above. From the linear relationship with a smaller slope, i.e. 8.9×10^{20} H + D/m^2 μm, the hydrogen isotope concentration, (H + D)/C, in the redeposited layers on the plasma facing surfaces (mostly on the inner divertor tiles) was determined to be ~0.02 assuming a carbon density of the redeposited layer to be 0.91 g/cm^3 [15]. This value agrees well with H/C of ~0.030 observed for the redeposited layers on the divertor tiles exposed to HH discharges in the JT-60 open divertor [16], and (H + D)/C of ~0.032 in the inner divertor tiles exposed to the DD discharges in the JT-60U with the inner side pumping system [9,14]. From the other linear relationship with a larger slope, the hydrogen isotope concentration in the redeposited layers on the plasma shadowed surfaces was determined to be 0.13 ± 0.01 in (H + D)/C.

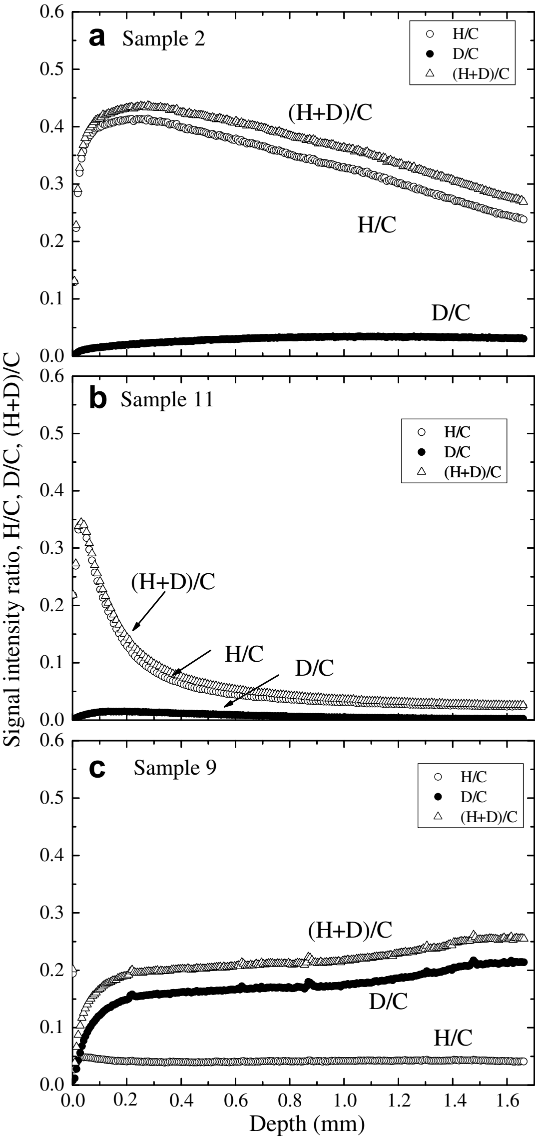

Fig. 5. Depth profile of H/C, D/C and (H + D)/C ratios measured by SIMS for the sample 2 (a), the sample 11 (b) and the sample 9 (c).

Fig. 5(b) shows the depth profiles of H/C, D/C and (H + D)/C for erosion dominated sample #11. The H/C signal intensity ratio in near surface region was high and exponentially decreased in depth, while D/C ratio was very small and was peaked at the depth of ~0.2 μm and then gradually decreased in depth.

4. Discussion

In previous studies, we have demonstrated that, in JT-60 and JT-60U, hydrogen is uniformly retained in the redeposited layers on plasma facing surfaces of the inner divertor with nearly constant concentration throughout the layers with much smaller H/C (0.02–0.03) ratios compared to other tokamaks with a carbon plasma facing surface [4,17,18]. We have attributed this lower hydrogen retention to the higher temperature of plasma facing surfaces in JT-60/JT-60U. The present study confirms this. It is shown that hydrogen retention in the redeposited layers on other plasma facing surfaces like the dome area is also small. Even in the redeposited layers on the plasma shadowed tile side area, hydrogen is retained uniformly with the concentration of 0.13 in (H + D)/C, still much smaller than the 0.4 for hydrogen saturated carbon layers observed at lower temperatures.

We discuss the cause of the small (H + D)/C ratio and small D/H ratio in the redeposited layers of the JT-60U divertor area. As is well known from previous studies, the saturated hydrogen concentration in ion-implanted graphite decreases exponentially with increasing implant temperature above 500 K [19]. Based on this exponential concentration decay, the temperature of the redeposited layers with H/C 0.03 would be well above ~900 K. Usually the vacuum vessel of JT-60U is kept at 573 K during plasma operation and all carbon tiles are only inertially cooled. Hence the tile bulk temperatures of the inner divertor were about a few 10 s of K higher than 573 K in average and the highest surface temperature of ~1373 K [7] was recorded at the outer divertor target tile. In addition, the thermal contact of the redeposited layers to the substrate was very poor as shown by Ishimoto [15]. All these suggest a significant temperature increase of the redeposited layers during these discharges. The maximum temperature observed by thermocouples inserted into the tile at the inner divertor tile was 750 K. Based on this tile temperature, the maximum surface temperature estimated by using the finite element modeling (FEM) analysis [7] was ~1000 K. Tile temperatures increase during DD discharges result in the small (H + D)/C ratio.

In the present study, the D/H ratio in the redeposited layers gives additional information on the temperature effect. First of all, one can note that the D/H ratio in the redeposited layers is significantly smaller than the ratio of the shot numbers of DD and HH discharges. Taking the small (D + H)/C into account, one can conclude that only a small fraction of the injected hydrogen isotopes were retained and most of the D retained during the DD discharge shots was replaced with H by successive HH discharges. Lower temperature desorption of H_2 compared to D_2 in Fig. 2 indicates either shallower depth profile for H_2 or less trapping energy of H than D (or both). The latter is not likely the cause of the significantly small D/H ratio. Since the heat load during HH discharges was only a half of that during DD discharges, the surface temperatures must be less for the former case because the tile temperature measured by thermocouples was low [14]. This indicates that the near surface layers must be saturated with D during DD discharge, and succeeding HH discharges would add H retention because of the lower temperature (allowing a higher concentration). Furthermore, during HH discharges, D near surface layers must be replaced by H, because the temperature is still high enough to allow isotopic exchange. This could result in deeper deuterium retention with lower concentration and a little higher binding energy as appeared in the SIMS profile and the TDS peak structure. One can note a tendency for the hydrogen retention and D/H ratio to be correlated i.e. larger retention gives a higher D/H ratio (see Fig. 3). According to the above discussion, that is because larger D retention implies a lower temperature during the DD discharges for this location, and correspondingly the amount replaced D by H during HH is smaller compared to remaining D. Consequently the larger concentration of 0.13 in (H + D)/C for the redeposited layers on the plasmas shadowed area can be attributed to a lower temperature increase during the discharges. The constant concentration in the redeposited layers corresponds to the homogeneous temperature rise of the layers, which was caused by the poor thermal contact of the layers to the substrate. Consequently, the hydrogen concentration in the redeposited layers in JT-60U is controlled by the highest temperature achieved before removal and gives little information on discharge history.

It should be mentioned that although the rather larger concentration of 0.13 in (H + D)/C was observed in the redeposited layers on the plasma shadowed area (still well below the saturation level), the redeposition on the shadowed area in JT-60U is quite small compared to other machines. The reason for the small redeposition could be either or all of (1) higher temperature, (2) fine alignment of neighboring tiles and (3) different divertor geometry and divertor plasma compared to other machines [20]. Anyhow, the total hydrogen retention in the divertor area of JT-60U remains quite small.

5. Conclusion

H + D retention in the graphite tiles exposed to DD and HH discharges in JT-60U W-shaped divertor with dual side pumping was investigated by TDS. In this study, not only the plasma facing surfaces but also the plasma shadowed tile sides were measured for the first time in JT-60U.

The total hydrogen isotope retention in the tile surfaces is widely distributed depending on the sample position. However, it is clearly correlated to the thickness of the redeposited layer and hydrogen is uniformly retained in the redeposited layer, except for the very near surface. The hydrogen concentration in the redeposited layers shows two different values dependent on their location, most probably owing to the temperatures of the surfaces obtained during discharges. The lowest concentration of ~0.02 in (H + D)/C was found in the redeposited layers on the plasma facing surfaces, which is nearly the same as that found for the redeposited layers on the same place with the inner side pumping system. Rather high hydrogen concentration was found in the redeposited layers on the plasma shadowed area. In particular, the redeposited layers on the bottom side of the outer wing tile facing to the pumping slot shows the highest concentration of 0.13 in (H + D)/C. This is six times higher than that for the redeposited layers on the inner divertor tile, but still lower than those observed in JET and other tokamaks. The reason for the small retention is confirmed to be the temperature increase of the redeposited layers during discharges, and the hydrogen concentration is likely controlled by the highest temperature which the redeposited layers attain during the discharges, but not by the concentration at the time of deposition.

In JT-60U, redeposition is dominated on plasma facing surfaces and that on the shadowed area is quite small. Several reasons have been mentioned, i.e. character of divertor plasma, geometry of divertor structure, tile alignment, tile temperature and so on [20]. Anyhow, the total hydrogen retention in the divertor area in JT-60U is quite smaller than those found in other large tokamaks currently operated.

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