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## Desorption behavior of H<sub>2</sub>O from isotropic graphites dipped in water

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### Abstract

H<sub>2</sub>O desorption behavior of isotropic graphites dipped in water was investigated by a technique of thermal desorption spectroscopy (TDS). Gas species, H<sub>2</sub>, H<sub>2</sub>O, CO, CO<sub>2</sub> and numerous hydrocarbons, were found to be desorbed from the graphite. The temperature with the maximum desorption rate of H<sub>2</sub>O was around 873 K, for the ramp rate ranging from 0.083 to 0.83 K/s. The peak temperature of H<sub>2</sub>O became again around 873 K, even after the heat treatment for the graphite sample at 625 K for 7 hrs prior to the TDS measurement. Apparent activation energy of the desorption for H<sub>2</sub>O was obtained as  $252 \pm 24$  kJ/mole. From the evaluation for value of the activation energy, it is presumed that the H<sub>2</sub>O desorb due to the recombination between -H and -OH groups adsorbed on edge surfaces of the graphite.

### 1. INTRODUCTION

Graphite, because of its low atomic number, low vapor pressure and high thermal shock resistance, has been widely used for first wall protective tiles and limiter in the entire inner wall of the present-day nuclear fusion devices [1-7]. In particular, the isotropic graphite with isotropic properties on electrical resistance and thermal conductivity, has been often employed as first wall materials. Performance of fusion plasma confinement was remarkably improved by using the graphite material, because of the low radiation loss power [8].

However, it was reported that impurities such as oxygen and carbon in a plasma increased in stead of metal impurities, because of the gas desorption from the very porous structure [9-12]. Since the first wall material is often exposed in air in the case of the maintenance, the element gases of air, such as CO<sub>2</sub>, H<sub>2</sub>O and O<sub>2</sub>, can easily adsorb on the graphite. The oxide formed on the graphite surfaces desorbs mainly in the form of CO and CO<sub>2</sub> due to the thermal and plasma irradiation during the plasma discharge shot. Then, the emitted CO and CO<sub>2</sub> dissociate to energetic ions or neutral species in the plasma. These species again bombard the graphite wall and sputter the carbons. The erosion yield of carbon due to energetic oxygen atom or ion is extremely high [13]. Therefore, the graphite wall is largely eroded by these processes. Thus, elucidation of desorption behavior of graphite after air exposure is a very important issue for the application to fusion devices. In

numerous studies, examined were the desorption behavior such as the amount of desorbed gases [14–21] and adsorbed gases [15,16,17,20]. It is well known that H<sub>2</sub>O molecules reversibly bound to the carbon surface and desorb at low temperature [22,23]. Recently, it is reported that H<sub>2</sub>O desorbs from graphite tiles exposed in air during long time period at a considerable high temperature [14,17,24]. However, the desorption behavior of H<sub>2</sub>O emitted at such high temperature has not been systematically studied.

In a process of H<sub>2</sub>O-desorption, it is not clarified yet either the H<sub>2</sub>O desorbs by the surface reaction due to the recombination between -H and -OH groups or by the diffusion process of physically adsorbed H<sub>2</sub>O molecules through micro pores. So, in this study, we investigated the desorption characteristics of H<sub>2</sub>O emitted at the high temperature, such as activation energy for H<sub>2</sub>O-desorption. For this purpose, the isotropic graphite dipped in water for a long time period was employed. We used a TDS technique [25,26] to evaluate the apparent activation energy and the amount of desorbed H<sub>2</sub>O molecules. In addition, the effective surface area was measured by using a gas adsorption method to estimate the coverage of gases adsorbed on the graphite surface.

## 2. EXPERIMENTAL

A TDS vacuum system used in this work is shown schematically in Fig. 1. The system was evacuated both by a turbo molecular pump (TMP) and a Ti-sublimation pump. An orifice with diameter of 10 mm was attached between the vacuum chamber and the pumping system. In this pumping system, a base pressure of  $3 \times 10^{-7}$  Pa was achieved after bakeout at 443 K for 12 hrs. During the measurement of the thermal desorption spectrum, the chamber was evacuated only by the TMP. Thermally desorbed gases were analyzed by a quadrupole mass spectrometer (QMS), for the mass range from 2 amu to 45 amu. The change of total pressure was continuously monitored by using a Bayard-Alpert ionization gauge (BA).

The graphite sample was placed on a Ta-heater with resistive heating. The temperature was measured by a chromel-alumel thermocouple spot-welded to the heater. Before the TDS measurement for the graphite sample, only the Ta-heater was heated up to 1273 K, to obtain the TDS spectrum of a background level. The temperature ramp rate was adjusted by changing a current of power supply controlled with a PID controller. The temperature of the Ta-heater was linearly increased, i.e.,  $T = T_0 + \beta t$ . Here,  $\beta$  is the ramp rate which was changed from 0.083 to 0.83 K/s.

An isotropic graphite, fine grain graphite (IG-110U), supplied by Toyo Tanso Co., Inc. was employed as the sample. The apparent density, average pore diameter and pore volume of IG-110U are 1.77 g/cm<sup>3</sup>, 3  $\mu$ m and 14–18 volume percents, respectively. A graphite sheet with a thickness of 1 mm was cut into the size of 10 $\times$ 10 $\times$ 1 mm. The sample was treated in the following way : (1) degassed under UHV at 1273 K for 30 min in the TDS apparatus, (2) taken out from chamber and placed in atmosphere, (3) immediately dipped into water and hold for two days, (4) taken out from the water and immediately placed into the sample

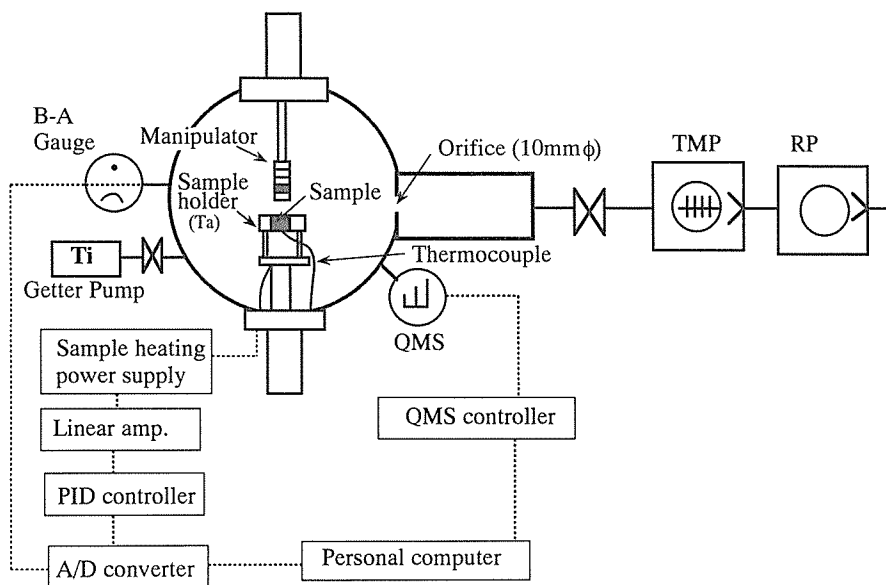


Fig. 1 Schematic diagram of experimental apparatus

holder, and (5) the chamber was pumped out. After this treatment, the TDS chamber was baked at 373 K, and then the sample was heated at the temperature lower than this baking temperature.

Before the above experiment, we also measured the desorption spectra of H<sub>2</sub>O from the isotropic graphites dipped into the water for only 5 min and exposed to air for two days. The amount of H<sub>2</sub>O desorbed from the wetted sample was approximately twice larger than that of the air exposed sample [15]. Thus, it is presumed that a large quantity of water is adsorbed on the graphite surface, because it is dipped into water for two days.

Surface area of IG-110U was measured by using a surface area measurement apparatus. The details of this apparatus are reported elsewhere [27]. In order to obtain adsorption isotherms, physical adsorption of xenon at liquid nitrogen temperature was utilized. Before the adsorption measurement, IG-110U was degassed at 573 K for one day under a pressure of about  $1 \times 10^{-5}$  Pa.

### 3. RESULTS AND DISCUSSION

#### (1) Desorbed gas species and the desorption temperatures

A typical TDS spectrum of isotropic graphite dipped in water is shown in Fig. 2. After the subtraction of the background level, all signal intensities were presented. Major thermally desorbed gas species were H<sub>2</sub>, H<sub>2</sub>O, CO and CO<sub>2</sub>. These desorption spectra show that the temperature with the maximum desorption rate ( $T_p$ ), is around 873 K, except H<sub>2</sub>. Numerous hydrocarbons were also observed in the spectra. The signal intensities of hydrocarbons were one or two orders of magnitude smaller than those of the others. The peak temperatures of hydrocarbons were observed around 980 K, close to that of H<sub>2</sub>. Figure 3

shows a mass spectrum when the sample temperature was about 880 K. Cracking ions of masses which correspond to  $C_1$ ,  $C_2$ ,  $C_3$  and  $C_4$  hydrocarbons [28], were clearly observed. If the QMS is widely scanned to a higher range, other hydrocarbons ( $> C_4$ ) [29] might be observed.

In the present TDS apparatus, it is possible to admit the  $H_2O$  vapor through the variable leak valve from the reservoir. So, the thermal desorption spectrum from the graphite sample exposed to  $H_2O$  vapor was also studied. Although the sample had been contacted with the  $H_2O$  vapor at the exposure level up to  $1 \times 10^7$  L, peak temperature of  $H_2O$ -desorption was not observed around 873K. It was reported by Fukui et.al. [30] that the desorption peak

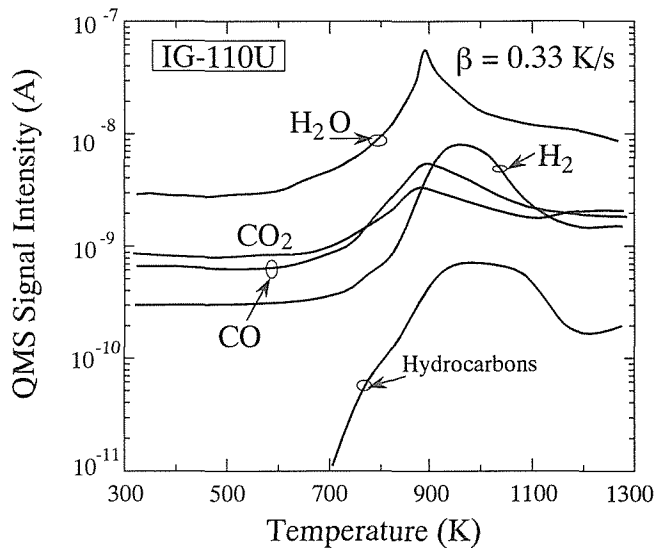


Fig. 2 Typical TDS spectrum of isotropic graphite after dipping in a water

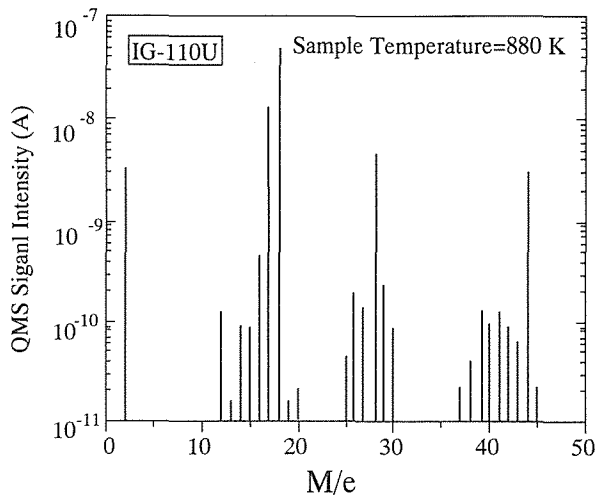


Fig. 3 Mass spectrum of isotropic graphite

of H<sub>2</sub>O was not observed from graphite film made on nickel after H<sub>2</sub>O exposure at 570 L, but peak temperature of H<sub>2</sub>O was observed around 500 K after air exposure for one day. These results suggest that the H<sub>2</sub>O desorption at the high temperature considerably depends on the exposure level.

## (2) Activation energy of the desorption

The activation energy of the desorption ( $E_a$ ) is estimated from the TDS spectra taken with different ramp rates. Figure 4 shows the plot of  $\ln(T_p^2/\beta)$  against  $1/T_p$  for H<sub>2</sub>O, CO, CO<sub>2</sub> and H<sub>2</sub>. The linearity between  $\ln(T_p^2/\beta)$  and  $1/T_p$  was found in the figure. If these gases desorb due to either first-order reactions or second-order reactions, the activation energy,  $E_a$ , can be evaluated from the slope of the straight line [25]. The activation energies of desorption for CO, CO<sub>2</sub> and H<sub>2</sub> were obtained as  $235 \pm 20$ ,  $212 \pm 10$  kJ/mole and  $95 \pm 14$  kJ/mole, respectively. The values of  $E_a$  for CO and CO<sub>2</sub> agree with those reported by Marchon et.al, [29]. They concluded that a lactone group and a semiquinone group were precursors of CO<sub>2</sub> and CO, respectively. Although  $T_p$  of H<sub>2</sub> was higher than those of the others, the value of  $E_a$  became small.

The activation energy of H<sub>2</sub>O was obtained as  $252 \pm 24$  kJ/mole. The present value was larger than those reported, e.g., the heat of condensation of H<sub>2</sub>O (= 55 kJ/mole) and  $E_a$  of H<sub>2</sub>O-desorption from graphite films (= 11.5–35.6 kJ/mole) [23] and the binding energy between a H<sub>2</sub>O molecule and edge carbon atoms of graphite powder (= 146 kJ/mole) [29]. The present value was rather close to the heat of H<sub>2</sub>O formation ( $H_2 + 1/2 O_2 \rightarrow H_2O$ ;  $\Delta H = -242$  kJ/mole).

On the other hand, the activation energy due to diffusion of physically adsorbed H<sub>2</sub>O molecules through micro pores has been estimated as 22.6 and 38.1 kJ/mole (25–75 °C) [32]. Sevenster also measured the activation energy of diffusion,  $E_b$ , and diffusion constant ( $D_0$ ) of H<sub>2</sub>O in a coal as 8.8–11.7 kJ/mole,  $(4.8-6.4) \times 10^{-13}$  cm<sup>2</sup>/s, respectively at low temperature region (25–60 °C) [33]. The activation energy obtained in the present study was also larger than that of the diffusion process.

## (3) TDS spectra of H<sub>2</sub>O after preheating

We examined the TDS spectra for the sample preheated with different heating condition, prior to the TDS measurement. After the heat treatment, the sample temperature was

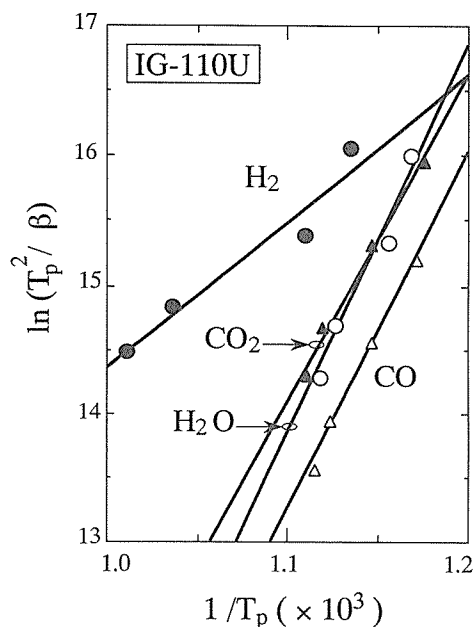


Fig. 4 Reciprocal peak temperature ( $T_p$ ) versus  $\ln(T_p^2/\beta)$

continuously risen up to 1273 K with 0.17 K/s. The TDS spectra of H<sub>2</sub>O are shown in Fig. 5. The TDS spectrum of preheated sample for 7 hrs at 623 K, was very similar to that for 1 hr. The peak temperatures were observed again at the high temperature close to 870 K. Dubinin reported [22] that most of adsorbed water was removed by only evacuating the active carbon at 20 °C. The residual quantity, however, could not be desorbed by only evacuating, after the carbon sample was left more than several months. In order to desorb most of the residual quantity, the heating at the temperature of 623 K was needed in the experiment of Dubinin.

Even if samples were preheated at 723 K and 773 K for 2 hrs, the desorption peaks were also observed at around 850 K. Therefore, if isotropic graphite has a lot of maicro pores, H<sub>2</sub>O molecules physically adsorbed on the carbon atoms of intersurface of micro pores might be already desorbed during these preheating.

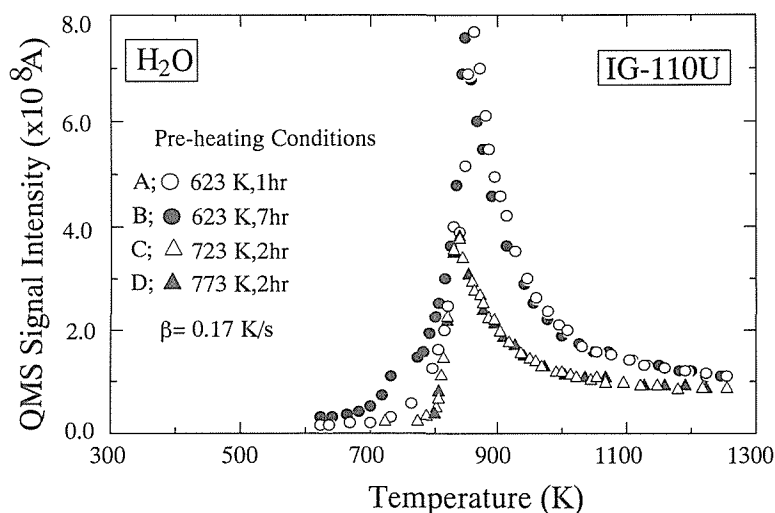


Fig. 5 H<sub>2</sub>O desorption spectra after preheating of wetted sample

#### (4) TDS spectra of H<sub>2</sub>O for samples with different thickness

Figure 6 shows TDS spectra of H<sub>2</sub>O desorbed from IG-110U with different thickness. In these curves, the background level was not subtracted. If H<sub>2</sub>O desorbs due to diffusion process, the peak temperature might be shift to lower temperature with decrease of thickness. However, all of the peak temperatures were observed around 870 K. This result supports the previous conclusion, e.g., the recombination between -H and -OH groups adsorbed on the edge surfaces of graphite occurs around the peak temperature.

Tremblay et.al, reported that phenol (hydroxyl), hydroquinone, aldehyde and carboxylic acid are regarded as the function groups produced a H<sub>2</sub>O molecules [34]. Yamabe and Takahashi proposed that H<sub>2</sub>O is produced from -COOH groups and -OH groups [35]. Kelemen [36], Marchon [29] and Herman and Huttinger [37] proposed that -OH or ether

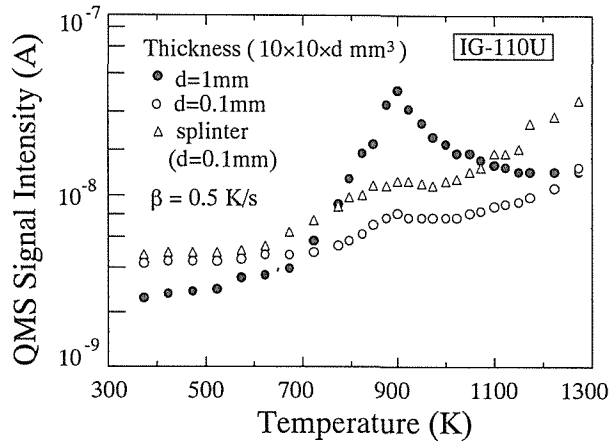


Fig. 6 TDS spectra of H<sub>2</sub>O desorption of wetted graphite with different thickness

groups exist on graphite or active carbon surface after wetting. However, Smith and coauthors reported that phenolic -OH bond remained on the graphite surface after heating at a temperature of 953 K [38]. So we guessed that H<sub>2</sub>O molecules are desorbed at high temperature due to the recombination between C-H group and hydroxylic -OH group on the graphite surface.

The total amount of the desorption for H<sub>2</sub>O molecules was estimated by using pumping speed and sensitivity of QMS of H<sub>2</sub>O as  $(1.5-4.0) \times 10^{17}$  molecules/g. Since surface area of IG-110U was obtained as 0.7 m<sup>2</sup>/g, surface density of carbon atoms was roughly estimated as  $2 \times 10^{19}$  atoms/m<sup>2</sup>. From the value of desorption amount and surface density of carbon atoms, the coverage of precursors of H<sub>2</sub>O is estimated from 0.01 to 0.025, when H<sub>2</sub>O desorbs due to the recombination between a -H and a -OH group.

#### 4. SUMMARY

We investigated the desorption of H<sub>2</sub>O observed at high temperature. There were two possibilities, i.e., the surface reaction due to the recombination between -H and -OH groups or the diffusion process of physically adsorbed H<sub>2</sub>O molecules through micro pores. The apparent activation energy for H<sub>2</sub>O emitted around at 873 K was obtained as 252+24 kJ/mole. From the value of activation energy and dependences of peak temperatures on thickness and preheating condition, it was presumed that H<sub>2</sub>O dissociatively adsorbed on edge surfaces of the graphite and desorbed due to the recombination between C-H and hydroxylic -OH groups.

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