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Bi-Directional Hydrogen Isotopes Permeation through the First Wall of a Magnetic Fusion Power Reactor

磁気核融合炉第一壁の双方向水素同位体透過に関する研究

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Plasma-driven permeation (PDP) and gas-driven permeation (GDP) through a first wall candidate material F82H have been investigated using a laboratory-scale steady state plasma facility. Experiments indicate that GDP can take place in the opposite direction of PDP, which then results in an unwanted increase in edge plasma density. A hydrogen flow from the plasma side into the gas side has also been detected. A one-dimensional code: DIFFUSE has been utilized to simulate the experiments. Multiple hydrogen isotopes (D/T) bi-directional permeation has been studied by DIFFUSE-code modelling as well.

1. Introduction

The first wall of a fusion power reactor is defined as the plasma-facing surfaces of the blanket units, which are required to operate at elevated temperatures for an efficient heat exchange. For the blankets employing self-cooled breeder, the first wall is exposed to the edge plasma, containing energetic D^+ and T^+ on the one side and on the other side it is exposed to T_2 gas bred in blankets. Under these conditions, it is highly possible that these hydrogen isotopes would penetrate the first wall by a phenomenon called "bi-directional permeation": (1) deuterium as well as tritium would transport into the blanket by plasma-driven permeation (PDP), which will probably necessitate isotope separation; and (2) tritium would flow in the counter direction to the edge plasma by gas-driven permeation (GDP), which will affect edge plasma density [1,2].

In the present work, bi-directional hydrogen permeation experiments has been performed by exposing membrane samples made of a first wall candidate material F82H to plasma and gas simultaneously. Both of the PDP flow and GDP flow have been successfully identified in these experiments. A one-dimensional diffusion code: DIFFUSE [3,4] has been utilized to analyze the bi-directional permeation processes. For D-T fusion reactor studies, isotope effects must be taken into account because both D and T are the fuels. DIFFUSE code has been extensively executed to deal with the multiple hydrogen isotopes (D, T) permeation cases as well.

2. Experimental

Shown in Fig. 1 is the schematic diagram of the bi-directional permeation setup in VEHICLE-1 [5]. F82H membranes are fixed in such a way that the upstream surface is exposed to hydrogen plasma, while the other side is exposed to hydrogen gas. At the plasma side, a separately pumped quadrupole mass spectrometer (QMS) is used to measure the H_2 partial pressure. The electron density is of the order of 10^{10} cm^{-3}. The electron temperature is raised up to ~10 eV for the improved sensitivity of H_α spectroscopy. At the gas side, the hydrogen gas pressure is measured by an absolute pressure gauge. The thicknesses of the F82H sample membrane varied from 0.5 mm to 5 mm. The sample membranes can be heated up to >500 ℃ by plasma bombardment and heat from a resistive heater. SUS304 are utilized as a reference material to validate the experimental setup.

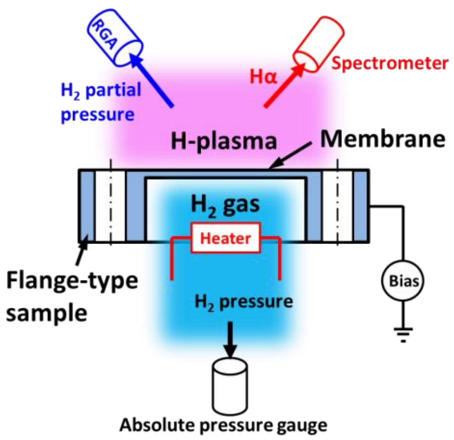

Fig.1 A schematic diagram of the bi-directional permeation setup in VEHICLE-1.

3. Hydrogen flow from the gas side to the plasma side (GDP flow)

Gas-driven permeation of hydrogen has been identified in the upstream hydrogen plasma, as shown in Fig.2. In this case, the ion bombarding energy is set at 50 V. Also, the temperatures on the gas-facing and plasma-facing sides are ~580 ^{o}C and ~550 ^{o}C, respectively. Taking into account the ion species mix in the low temperature hydrogen plasma and the particle reflection at the plasma-facing surface, the net implantation flux is estimated to be ~8.5×10^{15} H /cm^2/s. Notice that the P_{H2} and H_α signals keep track of each other. Also seen here is the initial transient kick-up, which is exhibited by both P_{H2} and H_α, presumably due to ion-induced desorption or thermal desorption, although the detail is unclear at this point. The GDP hydrogen flow rate in this case has been evaluated to be about 9.9×10^{15} H-atoms/cm^2/s.

DIFFUSE code has been used to solve the diffusion equations with the input data exactly the same as the experiment. A GDP backflow of 1.3×10^{16} H/cm^2/s is predicted by the calculation, which is relatively close to the experimental data.

4. Hydrogen flow from the plasma side to the gas side (PDP flow)

Hydrogen PDP flow from the plasma side to the gas side has been detected as well, as shown in Fig.3. Bi-directional hydrogen PDP experiments have been performed with and without a bias. Hydrogen gas is introduced to a closed volume (PDP downstream) with an initial hydrogen gas pressure of 520 Torr. After the transient phases, the hydrogen pressures decrease linearly, indicating steady state hydrogen outflows to the plasma side. The total remaining hydrogen particle numbers in the closed volume at time t are given as $N_1(t)$ and $N_2(t)$ for the cases with and without PDP as:

$$N_0 - N_t - J_{\mathrm{GDP}}ts + J_{\mathrm{PDP}}ts = N_1(t) \tag{1}$$

and $$N_0 - N_t - J_{\mathrm{GDP}}ts = N_2(t), \tag{2}$$

where N_0 is the initial particle number, N_t is the number of particles trapped in the membrane, s is the surface area, J_{GDP} and J_{PDP} are the steady state GDP and PDP flux, respectively. Then the PDP flux can be evaluated by:

$$J_{\mathrm{PDP}} = \frac{1}{s}\left(\frac{dN_1(t)}{dt} - \frac{dN_2(t)}{dt}\right). \tag{3}$$

Using the steady state portion of the curves shown in Fig.3, the PDP flux is estimated to be ~2.3×10^{14} H/cm^2/s, which is about 30% higher than theoretical prediction.

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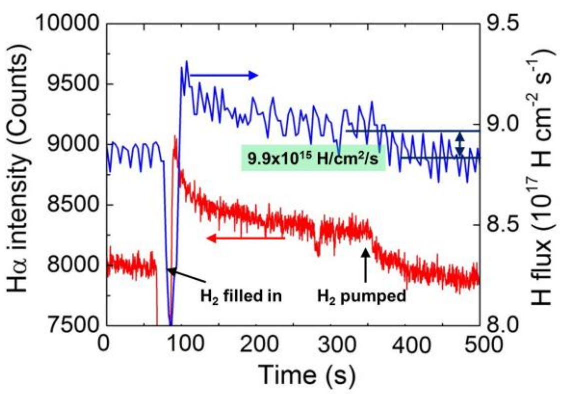

Fig.2 Hydrogen flux and H_α signals detected in the upstream hydrogen plasma in VEHICLE-1.

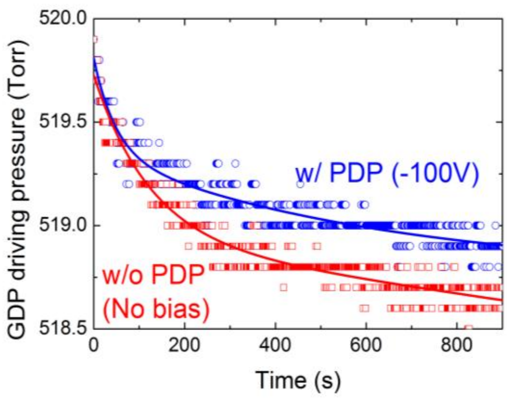

Fig.3 Variation of hydrogen gas pressures measured by an absolute pressure gauge at the gas side.