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学位（専攻分野）	博士（工学）
学 位 記 番 号	総研大甲第 1708 号
学位授与の日付	平成26年9月29日
学位授与の要件	物理科学研究科　核融合科学専攻 学位規則第6条第1項該当
学 位 論 文 題 目	A study on bi-directional hydrogen isotopes permeation through the first wall of a magnetic fusion power reactor
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論文内容の要旨
Summary of thesis contents

A study on bi-directional hydrogen isotopes permeation through the first wall of a magnetic fusion power reactor

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For the construction of magnetic fusion reactors, reduced activation ferritic steels (RAFSs) such as F82H are currently considered to be the candidate materials for the first wall. In this PhD thesis research, one of the technical issues related to hydrogen isotopes transport through the first wall has been studied. 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 hinder the recovery of tritium and 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. Despite its critical importance, there have been neither experimental nor theoretical studies on bi-directional permeation of hydrogen isotopes through reduced activation alloys. This PhD thesis research aims to understand the physical mechanisms driving hydrogen isotopes permeation processes and to establish fundamental knowledge databases for designing fusion power reactors.

Hydrogen permeation through a reduced activation ferritic steel alloy: F82H has been investigated in a steady state laboratory-scale plasma device: VEHICLE-1 under some of the reactor-relevant conditions. In PDP experiments, the hydrogen permeation flux is measured by a quadrupole mass spectrometer (QMS) at the downstream side. The plasma density is of the order of 10^9-10^{10} cm^{-3} and the electron temperature is ~3 eV. The particle bombarding energy is controlled by a negative bias voltage applied on the membrane flange. The net hydrogen implantation flux is estimated by taking into account the hydrogen species mix and reflection coefficient data. In GDP experiments, the upstream hydrogen gas pressure is 1.3×10^4-10^5 Pa measured by an absolute pressure gauge and the hydrogen permeation flux is measured by another QMS in VEHICLE-1 chamber. For all the permeation experiments, the membrane samples made of F82H and SUS304 are prepared in the same dimensions as those commercially available conflat flanges with an outer diameter of 70 mm, except that a circular area of 35 mm in diameter inside the knife-edge is machined down to thicknesses of 0.5 to 5 mm. A resistive heater is set beneath the membrane and the sample temperature varies from 220 ^oC to 520 ^oC.

The hydrogen transport parameter data taken for SUS304 have been found to be in good agreement with the literature data, which means that the experimental setup on VEHICLE-1 is valid for the evaluation of other first wall candidate materials. Both GDP and PDP data through F82H show thickness dependence, suggesting that hydrogen

permeation is diffusion-limited under some of the reactor-relevant conditions. The hydrogen transport parameters such as permeability, solubility, diffusion coefficient and surface recombination coefficient have been successfully measured for F82H. In particular, the surface recombination coefficient, which is essential to correctly predict the hydrogen isotopes permeation flux through the first wall, has been experimentally measured for the first time. Using the measured parameters and the steady state permeation model, hydrogen isotopes permeation flux and the dynamic wall inventory under some of the reactor-relevant conditions have been evaluated.

The surface effects on hydrogen PDP have been investigated from two aspects: surface contamination and morphology. A new model has been proposed to interpret the surface condition effects. Thick surface impurity film has been found to act as a second layer for diffusion and reduce the permeation flux in both laboratory and tokamak experiments. A decrease in steady state permeation flux has been measured when increasing plasma-facing surface area, which is in agreement with the theoretical prediction, i.e., the steady state permeation flux is inversely proportional to the square root of surface area. Experiments indicate that the permeation flux can be further reduced by simultaneous surface oxidization and area modification.

As a proof-of-principle experiment, first wall particle flux measurements in the QUEST spherical tokamak have been conducted, using a permeation probe that employs F82H as the membrane and also SUS304 as a comparative reference membrane. Permeation measurements have been done during the conditioning steady state discharges heated with 2.45 GHz and 8.2 GHz ECR. Diffusion and surface recombination coefficients measured in VEHICLE-1 are used to interpret the results from the permeation probe measurements in QUEST. A much shorter PDP breakthrough time and higher steady state permeation flux have been found for F82H than SUS304, which is consistent with the results from VEHICLE-1 experiments. The effect of plasma heating power indicates that the steady state permeation flux is roughly proportional to the square root of the implantation flux. The F82H permeation probe shows good sensitivity to the variation of plasma parameters.

Bi-directional hydrogen (H) permeation has actually been demonstrated for the first time in a laboratory-scale steady state plasma facility. Gas-driven permeation hydrogen flows from the gas-facing surface into helium, argon and hydrogen plasmas have been measured. For the bi-directional hydrogen permeation experiments, the membrane temperature is set between 550 and 600 ^{o}C, the hydrogen gas pressure for GDP is increased to 9.3×10^{4} Pa. At the plasma side, the electron temperature is raised up to ~10 eV for the improved sensitivity of H_{α} spectroscopy. Experiments indicate that gas-driven permeation can take place in the opposite direction of plasma-driven permeation, which then results in an unwanted increase in edge plasma density. A one-dimensional diffusion code: DIFFUSE has been utilized to simulate the experiment. The modelling result has been found to be in relatively good agreement with the experimental data. Hydrogen PDP flow from the plasma side to the gas side has been detected as well. The driving pressure for GDP has been found to decrease slower when a bias is applied to the sample, suggesting a PDP flow into the gas side.

DIFFUSE-code has extensively been executed, employing multiple hydrogen isotopes (D/T) for bi-directional permeation. The input data for DIFFUSE are such that the thickness of a membrane made of α-Fe (used as a surrogate of F82H) is 5 mm, the D/T inflows from the upstream (plasma-facing) side are driven by PDP with D/T implantation fluxes of 5×10^{15} D/cm^2/s and 5×10^{15} T/cm^2/s at a bombarding energy of 100 eV. The T inflow from the downstream (gas-facing) side is driven by GDP. Results indicate that the same isotopic species interact with each other in the two counter flows. Deuterium flow appears to be independent of these tritium flows, driven by its own concentration gradient.

Re-analysis of the tritium flows in a FLiBe loop has been performed, taking into account tritium leakage from the first wall. The tritium pressure has been found to be $\sim 1.1 \times 10^3$ Pa, which is ~10% of the tritium equilibrium pressure in FLiBe at a temperature of 527 ^{o}C. Under these conditions, ~68% of the bred tritium will be released at the plasma side by GDP. Assuming a particle reflection coefficient of 0.5 and a total incident flux of 2.0×10^{16} D&T/cm^2/s, the first wall recycling rate has been estimated to be 1.006.

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博士論文の審査結果の要旨

Summary of the results of the doctoral thesis screening

A study on bi-directional hydrogen isotopes permeation through the first wall of a magnetic fusion power reactor

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核融合原型炉および商用炉に於ける第一壁はブランケット要素のプラズマ対向壁として炉心プラズマ（D^+, T^+）に曝される。一方、ブランケット内ではトリチウム増殖材によって生成されるトリチウム（T_2）に曝されるため、水素同位体が双方向的に第一壁を透過する可能性がある。ブランケットは高い温度（500℃程度）での運転が要請され、熱応力緩和のため第一壁は5㎜以下の厚みとなる。この薄肉の第一壁を通しての双方向水素同位体輸送はプラズマ及びブランケット側への影響を含め、炉設計研究において重要な課題の一つである。申請者は既存のプラズマ生成装置に水素透過挙動観測系を追加装着することによって、低放射化フェライト鋼（F82H）を用いた双方向水素透過の原理実証に世界で初めて成功した。また、水素透過挙動の解析に重要な水素輸送パラメータ（特に、これまで文献値が見当たらなかった表面再結合係数）を実験データから評価し、核融合炉条件下での第一壁における水素同位体輸送を評価する基礎を構築した。

本研究では、水素同位体の金属壁を通しての水素同位体透過過程として良く知られているプラズマ誘起透過（PDP: Plasma-Driven permeation）とガス誘起透過（GDP: Gas-Driven Permeation）の核融合炉第一壁での輸送特性を明らかにするために、プラズマ壁相互作用研究に用いられてきたプラズマ生成装置（PWI実験装置）と水素透過挙動観測系を組み合わせ、双方向水素（H）透過実験が可能なシステムを開発した。先ず、ステンレス鋼中の水素輸送パラメータをPDP及びGDP実験結果から求め、文献値との比較検証を以て、上記PWI実験装置に追加改造した水素透過挙動観測系の本研究に対しての性能妥当性を確認した。その上で、核融合炉ブランケット材に想定されている低放射化材（F82H）に関する水素拡散係数・溶解度・表面再結合係数等を求め、特に、F82Hの表面再結合係数を実験的に初めて明らかにした。また、核融合炉第一壁相当の厚材（5 ㎜）においては、PDP及びGDPが共に拡散律速過程（Diffusion Limited Process）で決まることを明らかにした。次に、薄肉材料の両側に定常水素プラズマ（$T_e \sim 10$ eV, $n_e \sim 10^{10}$ cm^{-3}）と水素ガス（$\sim 10^5$ Pa）を配置して、双方向水素透過実験を行い、水素ガス側からの水素透過によるプラズマへの顕著な影響及びプラズマ側からの水素透過によるガス圧上昇を観測した。また、実験的に求められた水素輸送パラメータを用いた1次元水素拡散モデリングの結果とも良く一致することを示した。

さらに、第一壁材料表面での酸化膜生成や表面凹凸効果が水素同位体輸送に及ぼす影響について調査した。特に、表面凹凸効果に関しては、材料表面を三角形状に加工し、表面積の違いによるPDPによる水素透過束の変化を調べ、平坦表面との表面積比の平方根に反比例するという新たな知見を得た。この現象の物理的機構は表面での再結合による水素粒子放出が増加するというモデルによって説明できると結論している。

核融合炉第一壁でのケーススタディとしては、F82HFLiBe相当の水素同位体輸送パラメータを持つ純鉄（α-Fe）を第一壁に仮定し、水素実験で得られた知見を用いて、液体FLiBe冷却ブランケットの燃料回収ループの動特性解析を行い、ループ内のトリチウム圧力が従来値（熱力学的平衡圧力）の約10分の1であることを見出した。また、この値を用いて、ブランケットからのT_2ガスの周辺プラズマへの流入量を評価し、第一壁からの水素同位体（D及びT）全体のリサイクリング率が100%を超える（D[100%], T[101.2%]）ことを明らかにした。最終的には、この水素同位体輸送研究を炉設計研究へ統合することが今後の

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課題である。
　以上のように、これまで観測されていなかった双方向水素透過挙動の実験的・理論的検討を行い、核融合炉構造材の水素輸送特性及び水素輸送パラメータを明らかにしたことは学術的にも高く評価できる。また、第一壁の表面凹凸効果は水素輸送の制御という観点でも重要な成果である。さらに、磁気閉じ込め核融合炉とその燃料回収系の運転に新しい知見を与えるものであり、炉心プラズマとブランケットの境界領域を接続する上で工学的意義が大きい。結論として、新規性に富み、学術的にも高く評価でき、工学的意義および今後の発展性を高く評価できるので、本論文を博士（工学）学位論文として十分価値があると判断した。