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学位（専攻分野）	博士（工学）
学位記番号	総研大甲第 1966 号
学位授与の日付	平成29年9月28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	Hydrogen isotopes transport in liquid metals under steady state plasma bombardment
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論文の要旨

Summary (Abstract) of doctoral thesis contents

Hydrogen isotopes transport in liquid metals under steady state plasma bombardment

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It has been widely recognized that solid plasma-facing components (PFCs) would suffer from erosion and cracking when they are subjected to high power loads and particle fluxes in fusion devices. As a possible solution, the use of liquid metals for PFCs has been proposed because of their self-cooling and self-healing properties. At present, lithium, tin and gallium are the possible candidates. The liquid lithium covered divertor was tested in NSTX, and a continuously flowing liquid lithium limiter with a loop was performed in EAST, both of which have resulted in improved plasma performance. Free-falling liquid gallium drops have been tested on the T–3 M and ISTTOK tokamaks, where no severe effects on the main plasma parameters have been observed. In this PhD thesis research, one of the technical issues related to hydrogen isotopes transport in liquid metals has been studied extensively.

The understanding of hydrogen isotopes properties in liquid metals is essential for studying particle control in the edge plasma. And to evaluate liquid metals as the PFCs in a fusion reactor, the interactions between plasma and liquid metals should be studied experimentally. However, the information on this subject is far from adequate. This PhD thesis research is intended to provide the understanding of the mechanism of hydrogen transport in liquid metals under plasma bombardment, and to establish a database on hydrogen transport parameters such as diffusivity, recombination coefficient, solubility and retention for liquid metals, and to investigate the natural and forced convection effects, if any, on the hydrogen transport behavior in liquid metals.

To evaluate hydrogen isotopes transport parameters in liquid metals, plasma-driven permeation (PDP) experiments have been conducted in a steady state laboratory-scale linear plasma device: VEHICLE-1. In the PDP experiments, the hydrogen permeation flux is measured by a quadrupole mass spectrometer (QMS) in the downstream side. The electron temperature is typically Te~3eV and the plasma density is n~1016m-3. The particle bombarding flux is ~1020m-2s-1, and the bombarding energy is controlled by a negative bias voltage applied to the target. An innovative technique employing surface tension to hold a liquid metal using a mesh sheet has been proposed and implemented in the PDP experiments. A liquid metal sample is fixed in such a way that the upstream surface is exposed to hydrogen plasma, while the downstream side is exposed to an ultrahigh vacuum (10−6-10−5 Pa) chamber. Using this technique, the upstream chamber and downstream chamber are separated by the liquid metal on the mesh. A resistive heater is set beneath the mesh sheet to control the temperature of the liquid metal. The melting point of GaInSn alloy is 10.5°C, which means that it is a liquid at room temperature. In the present work, this alloy is chosen as a surrogate for gallium, tin and lithium.

For lithium, hydrogen and deuterium PDP experiments through a 2mm deep lithium membrane have been conducted from 323oC to 402oC, and steady state PDP fluxes have been obtained. From the H-Li phase diagram, it is derived that lithium would transform from αliq phase to αliq+βsol phase during PDP. And the dissolved hydrogen concentration remains unchanged even after passing the phase boundary Cs. As a result, the hydrogen and deuterium recombination coefficients for lithium have been obtained for the first time. For GaInSn, hydrogen PDP experiments have been conducted with 2 mm deep GaInSn from 330°C to 437 °C. Deuterium PDP experiments have been conducted with 2 mm and 4 mm deep GaInSn from 280°C to 496 °C. The PDP data show depth effects, suggesting that hydrogen isotopes PDP through liquid GaInSn are diffusion-limited. Hydrogen and deuterium diffusivities and recombination coefficients have been successfully measured for GaInSn. Deuterium retention in GaInSn after PDP has been measured by (thermal desorption spectrometry) TDS. A one-dimension diffusion code: DIFFUSE has been utilized to simulate the experiments by using the measured parameters. The modeling results are consistent with the experimental data. Using the same method for GaInSn, hydrogen isotopes diffusivities and recombination coefficients for pure liquid Ga and Sn have been obtained. And the deuterium dynamic and static retentions for liquid Ga and Sn have been evaluated and compared.

Natural convection is a phenomenon commonly present in liquids under thermal expansion induced density variation. In order to investigate natural convection effects on hydrogen PDP, two cases (A, B) of experiment have been prepared in VEHICLE-1. For Case A, the depth of liquid GaInSn is 15mm, and natural convection is supposed to take place judged from the Rayleigh number; For the Case B, a convection preventing mesh (CPM) is set in the middle of the liquid GaInSn to reduce the effective depth of the liquid, and natural convection is not supposed to take place. The natural convection motion and particle transport behavior for both cases have been simulated with a finite element analysis software COMSOL by solving the Navier-Stokes equations, heat transfer equation, and mass balance equations. The simulation results predict that natural convection only takes place for Case A, and particle transport is much faster under natural convection. Deuterium PDP experiments have been conducted for both cases. In Case A, the deuterium permeation flux rapidly increases to a quasi-steady state level as the plasma bombardment starts. In Case B, the permeation flux gradually increases to a steady state level, which is about one order of magnitude lower than that in Case A. The different PDP behaviors in these two cases indicate that deuterium permeation through the liquid can be intensely enhanced by the natural convection.

JxB-forced convection effects on hydrogen isotopes recycling have been investigated. From the study of the natural convection effect, it has been found that convection could enhance particle transport and heat transfer in a liquid. However, natural convection may not take place in a liquid divertor situation, where the liquid is warmer at the top. To get actively controlled convection in a liquid divertor, JxB-forced convection has been proposed by M. Shimada et al. In this concept, electrodes are immersed in the liquid and DC currents are applied among the electrodes. Taking advantage of the toroidal magnetic field, a JxB-force could be produced to convect the liquid. In our work, this concept has been demonstrated with a mini JxB setup installed in VEHICLE-1 by using liquid GaInSn. Liquid GaInSn is put in a stainless steel cup with an inner diameter of 50mm. The depth of the liquid metal is set to 13mm. A central electrode made of stainless steel is isolated from

the sidewall by a ceramic ring. DC currents (0-100A) are applied between the central electrode and the sidewall. A “water wheel” made of stainless steel is installed on the central electrode as an indicator for the motion of the liquid metal during plasma operation. And visible spectroscopy measurements are performed, taking the intensity of the Hα (Dα) signal as the indication of hydrogen (deuterium) recycling from the liquid metal. Simulations of particle transport in the liquid metal under JxB-forced convection have been performed by COMSOL. The modeling results indicate that particle transport in a liquid under JxB-forced convection is much faster than that in a static liquid. And with higher DC currents, more particles are retained in the liquid with less particle recycling from the liquid. In the experiments, it has been found that the flow speed of the liquid increases as the DC current increases. And hydrogen (deuterium) recycling is reduced when the JxB-force is applied in the liquid. Liquid flow speed effects on the recycling have also been observed, which are in agreement with the simulation results.

This PhD thesis work has established some fundamental knowledge database for the applications of liquid metals as plasma facing components. Using forced convection in the liquid to enhance the particle transport and heat transfer can be a possible idea for the engineering design. Using the hydrogen transport parameters, it is possible to calculate hydrogen isotopes dynamic retention in the liquid PFCs, and hydrogen isotopes recycling flux back to the edge plasma. More efforts are still required to investigate hydrogen isotopes transport behavior in liquid metals under reactor relevant conditions. Experimental proof of enhanced heat transfer by convection also warrants further investigation.

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博士論文審査結果の要旨

Summary of the results of the doctoral thesis screening

It has recently been pointed out that the current plasma-facing component (PFC) design, employing refractory materials such as tungsten, may not serve as expected in removing high heat fluxes associated with the power and particle flows due to confinement loss. Not only that, tungsten is predicted to suffer from thermomechanical cracking due to its exceptionally high DBTT (Ductile-Brittle Transition Temperature) of around 400°C. To resolve these technical issues, the use of liquid metals for PFCs has been proposed over the past decade. However, little is known about the behavior of hydrogen isotopes transport through liquid metals exposed to steady state plasma.

From this point of view, Mr. BI HAILIN has carried out experimental and modelling work on the permeation and recycling of hydrogen isotopes (H, D) through/from selected liquid metals including Li, Sn, Ga, and GaInSn under steady state plasma bombardment. For the permeation experiments, first he came up with an innovative method, utilizing surface tension to suspend a liquid metal on a metal mesh sheet. Using this method, he has successfully measured H and D plasma-driven permeation (PDP) fluxes through these liquid metals at temperatures between 250°C and 500°C. He has evaluated the diffusion coefficients of these hydrogen isotopes in liquid metals in this temperature range by fitting the time evolution curves of these PDP flux data. Using these diffusivity data, he has evaluated the surface recombination coefficients of these liquid metals. Also, he has measured static deuterium retention in these liquid metals. Particularly for liquid lithium, a hydride-forming metal, he has found that hydrogen isotopes PDP is not limited by diffusion but by surface recombination. From this finding, the surface recombination coefficients of liquid lithium for H and D have been directly evaluated from the phase diagram data for the Li-H system. As such, he has established the database of hydrogen isotopes transport parameters: diffusion and surface recombination coefficients, a significant contribution to the liquid metal PFC development for DEMO reactors beyond ITER.

In conducting these systematic experiments, he has observed that liquid convection, either natural convection or forced convection, significantly accelerates hydrogen isotopes transport in liquid metals. He has successfully analyzed these observations, using the finite element method to solve the Navier-Stokes equation for fluid dynamics modelling. Of particular importance is his finding of the effect of electromagnetically (**J**x**B**) induced convection on hydrogen isotopes recycling from liquid metals, measured by plasma spectroscopy, resulting in reduced recycling which has been recognized to be a key to achieving high-performance core plasma confinement in a number of existing experimental fusion devices.

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Throughout these research activities he has clearly demonstrated his ability to conduct original research independently. He has attended several international conferences where he gave oral presentations and also has published 4 papers in journals circulated worldwide, demonstrating his capability to communicate in English with others. Based on all these, the thesis committee unanimously agreed to recommend that a PhD degree be granted to him.

At the thesis evaluation committee meeting held on Aug. 8th, Mr. BI HAILIN presented some of the most important results from his research over the past three years of the SOKENDAI PhD program. He was asked numerous questions, but answered these questions in the most appropriate fashion. Having learned from this Q&A, he gave a significantly improved presentation at the public oral defense held on Aug. 29th. He answered all the questions asked carefully and correctly.

Throughout these presentations and Q&A sessions, he clearly demonstrated his ability of communicating in English with the thesis evaluation committee members and people in the audience at the public oral defense. Particularly, the fluid dynamics modelling results turned out to be so convincing that one should develop liquid metal PFCs provided with forced convection in order to enhance power and particle removal.

As such, Mr. BI HAILIN has demonstrated his suitability for the degree of Doctor of Philosophy from SOKENDAI.