Fusion Engineering and Design xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Deuterium transport in a Lorentz-force convected liquid metal GaInSn under steady state plasma bombardment

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ARTICLE INFO

Article history:
Received 1 November 2016
Received in revised form 19 April 2017
Accepted 25 April 2017
Available online xxx

Keywords:
Liquid metal
Hydrogen diffusion
Forced convection
Hydrogen recycling
Plasma facing material

ABSTRACT

A series of experiments on deuterium plasma interaction with a liquid metal GaInSn alloy have been carried out to investigate the Lorentz-force (J × B-force) convection effects on particle recycling behavior over liquid metals under plasma bombardment. It has been found that deuterium recycling from the liquid is reduced, when forced convection is applied to the liquid. And deuterium recycling is reduced more as the current increases. A finite element analysis method has been applied to simulate the motion of the liquid and the deuterium transport process in the liquid. As a result, the deuterium transport in the liquid is accelerated by the convection.

1. Introduction

It has been widely recognized that solid plasma-facing components (PFCs) would suffer from erosion and cracking when they are submitted to high power loads in fusion devices [1]. As a possible solution, liquid metals have been proposed as plasma-facing materials because of their self-cooling and self-healing properties [2]. At present, lithium, tin and gallium are the primary liquid metal candidates for plasma-facing materials. Liquid lithium covered divertor was tested on NSTX [3], and continuously flowing liquid lithium limiter with a loop was performed in EAST [4], both of which yielded improved plasma performance. Free-falling liquid gallium drops were tested on the T–3 M [5] and ISTTOK [6] tokamaks, where no severe effects on the main plasma parameters have been found.

Among all the efforts on developing liquid metal PFCs, a new concept to enhance the interaction between the liquid metal in a pool with the divertor plasma by active J × B-force convection was proposed [7], which is referred to as the ACLMD (Actively Convected Liquid Metal Divertor). The proposal is to fill the lower part of the vacuum vessel with liquid metals such as Gallium or Tin. And electrodes and cooling tubes are immersed in the liquid metal. The J × B-force due to the current between the electrodes and the module provides a rotating motion for the liquid metal. A series of proof-of-principle experiments have been successfully conducted, and the J × B-force convection effects on hydrogen and helium recycling behavior have been preliminarily studied [8]. However, numerical study on the motion of the liquid metal and particle transport in liquid metal has not been performed yet.

The knowledge about hydrogen isotopes properties in liquid metals is essential to study hydrogen recycling, tritium retention and tritium recovery from liquid metals [9,10]. For solid plasma-facing materials, the database on hydrogen transport parameters have been enriched by a lot of experimental works, and the numerical study could be well aided by some of the hydrogen transport codes like TMAP [11] and DIFFUSE [12]. In contrast, the database for liquid metals is far from adequate, and there is no specialized code for simulation on particles transport in flowing liquid PFCs.

$Ga_{67}In_{20.5}Sn_{12.5}$ is an alloy with the melting point of 10.5 °C [13]. In the present work, it is chosen as a surrogate material for studying pure Ga and Sn, as well as liquid Li for their application with the concept of ACLMD diverotor. A mini-ACLMD setup employed GaInSn is installed in a linear plasma device VEHICLE-1 [14]. The deuterium recycling behavior over the liquid metal under J × B-force convection by different currents has been experimentally investigated. In addition, the motion of the liquid and the deuterium transport process in the liquid are simulated by finite element analysis.

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http://dx.doi.org/10.1016/j.fusengdes.2017.04.107
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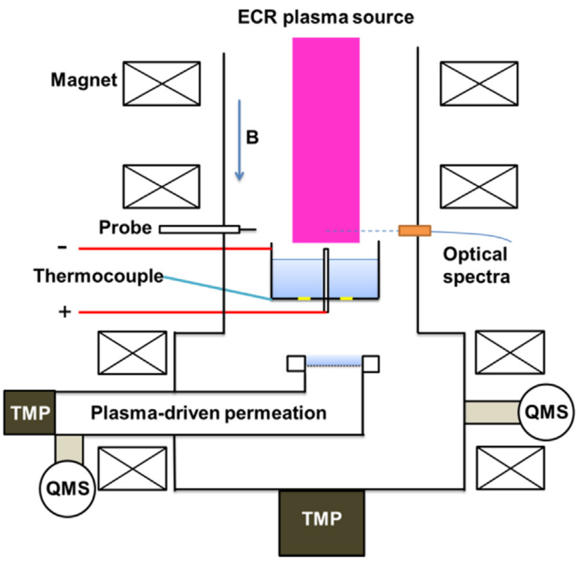

Fig. 1. Schematic diagram of the mini-ACLMD setup in VEHICLE-1. (TMP: turbo-molecular pump; QMS: quadrupole mass spectrometer).

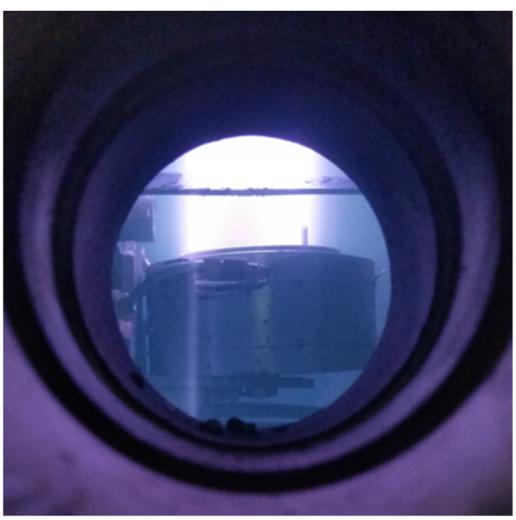

Fig. 2. A photo of the liquid metal exposed to the deuterium plasma.

2. Experimental setup

Shown in Fig. 1 is the schematic diagram of the mini-ACLMD setup in a liner plasma device, VEHICLE-1. The plasma is generated by a 2.45 GHz ECR source with the resonance magnetic field of 875 G. Liquid metal GaInSn is put in a stainless steel cup with an inner diameter of 50 mm and a depth of 25 mm. The depth of the liquid metal is 13 mm. A central electrode made of stainless steel is isolated with the sidewall by a ceramic ring. The bottom side of the central electrode is connected to the anode of a DC power supply, and the side wall is connected to the cathode. 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, as shown in Fig. 2. The temperature is measured by a thermocouple attached to the bottom of the cup. The neutral deuterium gas pressure during plasma operation are typically ~0.05 Pa. The deuterium plasma parameters measured by a moveable Langmuir probe positioned in the immediate upstream of the mini-ACLMD setup are: the electron temperature is ~5 eV and the plasma density is $\sim 10^{10}\ \mathrm{cm}^{-3}$, whereby the ion bombarding flux is $\sim 10^{16} D^+/\mathrm{cm}^2\mathrm{s}$. During the plasma experiments, visible spectroscopy measurements are performed, taking the intensity of Dα signal as the measurement of deuterium recycling over the liquid metal. The plasma bombarding energy is controlled by applying a negative DC bias voltage on the

mini-ACLMD setup. The line radiation intensities of Ga-I at 780.00 nm, In-I at 451.13 nm and Sn-I at 380.0 nm are monitored in parallel with the Dα intensity.

3. Results and discussion

3.1. Hydrogen isotopes transport in liquid metals

In general, incident hydrogen atoms in a solid material are trapped by defects at the implantation range [15]. After the trapping sites eventually getting saturated, the untrapped hydrogen atoms diffuse either deeper into the material or to the front surface. At the front surface, the recombination occurs for the atoms and hydrogen releases from the material as molecules. This process is generally described by the mass balance Eq. (1), consisting of diffusion term, trap term and source term, together with the boundary condition Eq. (2):

$$\frac{\partial C}{\partial t} = \nabla \cdot (D \nabla C) - \frac{\partial C_T}{\partial t} + G \tag{1}$$

Diffusion trap Source

$$\Gamma_{\mathrm{re}} = K_r \times C_0^2 \tag{2}$$

where C is the concentration of hydrogen, D is the diffusion coefficient, C_T is the concentration of trapped hydrogen, G is the source term, Γ_{re} is the reemission flux, K_r is the recombination coefficient, C_0 is the concentration hydrogen at the front surface.

For liquid metals, due to the mobility or flowing property, the incident hydrogen atoms transport not only by diffusion but also convection [16]. Then the mass balance equation is modified to be Eq. (3), where the trap effect is omitted:

$$\frac{\partial C}{\partial t} = \nabla \cdot (D \nabla C) - \boldsymbol{u} \cdot \nabla C + G \tag{3}$$

Diffusion Convection Source

In this equation, the second term describes the diffusive transport, while the third term accounts for the convective transport due to a velocity field **u**. Thus it is envisaged the external controllable velocity field **u** may provide a possibility to affect the hydrogen transport behavior, seeking for reduced recycling.

3.2. Liquid convection by Lorentz-force

By using the electrical conductivity $3.1 \times 10^6\ \Omega^{-1}\mathrm{m}^{-1}$ for GaInSn [16], and $1.4 \times 10^6\ \Omega^{-1}\ \mathrm{m}^{-1}$ for stainless steel, the current density in the liquid have been obtained by using a finite element analysis software COMSOL, as shown in Fig. 3, where the total DC current is 70A. And the current data are saved in the form of vector $\mathbf{J} = [J_x, J_y, J_z]$.

The magnetic field at the liquid target position in VEHICLE-1 has been measured to be about 350 G, i.e. B = [0,0, −0.035] T. When the DC current is applied in the liquid, a J × B-force $\mathbf{F} = [F_x, F_y, F_z]$ is generated in the bulk of the liquid metal, as shown in Fig. 4, where

$$F_x = -J_y \times 0.035\,[\mathrm{T}]\,,\ F_y = J_x \times 0.035\,[\mathrm{T}]\,,\ F_z = 0 \tag{4}$$

The convection motion of the liquid metal have been obtained by solving the Navier-Stokes equations with the CFD (Computational Fluid Dynamic) module, with the viscosity $2.98 \times 10^{-7}\mathrm{m}^2/\mathrm{s}$ for GaInSn [17] and the volume force $\mathbf{F} = [F_x, F_y, F_z]$. All the boundary conditions are set as no sliding wall, although the top surface is a free surface in the experiment. As a result, the velocity field vector $\mathbf{u} = [u_x, u_y, u_z]$ have been obtained, as shown in Fig. 5, where the