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Hydrogen and helium recycling from a **JxB**-force convected liquid metal $Ga_{67}In_{20.5}Sn_{12.5}$ under steady state plasma bombardment

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ABSTRACT

A series of first-of-a-kind laboratory-scale experiments on the **JxB**-force convected liquid metal divertor concept have been carried out in the temperature range from room temperature to ~200 °C, employing a eutectic alloy: $Ga_{67}In_{20.5}Sn_{12.5}$, the melting point of which is 10.5 °C. The electrical current conducted through the alloy is set at about 70A and the magnetic field is set at about 700 G. It has reproducibly been observed that hydrogen as well as helium particle recycling is noticeably reduced under steady state plasma bombardment when the liquid is convected by the **JxB** force.

1. Introduction

It has widely been recognized that exhaust power and particle handling by plasma-facing components (to be referred to as PFCs) is a critical issue for the successful operation of a steady state magnetic fusion power reactor. With the scaling law revaluated recently, based on the heuristic drift model [1], the thickness of the scraped-off layer (to be referred to as SOL) for ITER is predicted to be ~1 mm [2], indicating that PFCs could be exposed to the power and particle fluxes, respectively, reaching the orders of 100 MW/m^2 and 10^{24} D + T/m^2/s. The same scaling law generally predicts that the thickness of SOL decreases with increasing plasma current and major radius. It follows immediately from this that in the case of fusion power reactors the handling of exhaust power and particles by PFCs in any designs will truly be a challenge from the engineering physics point of view.

Although it is envisaged to be used as the divertor target material in ITER, tungsten is unlikely to survive these harsh conditions. It would be even more unlikely if a reduced activation ferritic steel alloy such as F82H with a thermal conductivity, typically one third of that of copper, is employed as the heat sink material of the divertor structure, as seen in recent fusion power reactor design studies such as SLIM-CS [3].

Nonetheless, the ductile-brittle transition temperature (to be referred to as DBTT) of tungsten is ~400 °C, substantially higher than most of the widely used engineering metals, so that the reactor operation including repeated plasma current ramp ups and downs will unavoidably result in thermal stress cracking in tungsten whether it is prepared by chemical vapour deposition or powder metallurgy [4]. All these arguments clearly point to a need for innovative PFC concepts development.

As a possible solution to this situation, the idea of using a liquid metal as a plasma-facing material covering to protect a solid PFC has been proposed, and proof-of-principle (to be referred to as PoP) experiments have been conducted over the past decade or so in some of the major plasma confinement devices [5–8] as well as in laboratory-scale plasma facilities [9], essentially all of which have been successful.

The evolution of the liquid metal PFCs is briefly reviewed as follows. The first generation may be represented by the capillary porous system (to be referred to as CPS) [10]. This CPS concept employs a molybdenum mesh wetted with molten lithium as a plasma-facing material, so that surface tension will keep the liq-

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uid from moving even with a transient electrical current running through it in a strong magnetic field. This concept has successfully been implemented as the main limiters in T-10 [5], FTU [6] and TJ-II [7], etc.

Following these CPS experiments, NSTX stepped up to the next generation, employing "semi-free" surface liquid lithium [8], sitting on a high-friction porous substrate [11] so that reduced deuterium recycling lasts longer than observed when lithium coatings were applied over the divertor target tiles, but this intent was not quite granted. It is believed that in addition to the high-friction porous substrate effect, because the top surface of the liquid facing the divertor plasma was probably warmer than the bottom of it and perhaps because the depth of liquid lithium was not sufficient, no effective natural convection occurred to desaturate solute deuterium and lithium deuteride precipitates in the surface region.

Motivated by these, a series of laboratory experiments have recently been conducted to investigate the effects of convection of molten lithium on the behavior of hydrogen and helium recycling under steady state plasma bombardment [12]. Results indicate that hydrogen recycling is reduced when molten lithium is mechanically stirred, resulting in "forced convection". Interestingly, opposite is true with helium recycling. This is because the solubility of helium in molten lithium decreases with decreasing temperature [13], which occurs upon liquid stirring.

In parallel with these experiments, a new concept to provide an electrically conductive liquid with **JxB-**forced convection has been proposed, where **J** is the electrical current and **B** is the magnetic field [14]. A series of PoP experiments have successfully been conducted [15,16] although several technical issues are pointed out, including the electrochemical effect to induce electrode corrosion and the joule heating effect on liquid temperature control. In the remainder of the present paper, this is referred to as the ACLMD (for the Actively Convected Liquid Metal Divertor) concept.

In the present work, a series of PoP experiments are conducted for the ACLMD concept, using a linearly magnetized steady state ECR plasma facility: VEHICLE-1 [17]. Employed as a liquid metal for this concept is a commercially available eutectic metal alloy: $Ga_{67}In_{20.5}Sn_{12.5}$, the melting point of which is 10.5 °C [18].

2. Experimental

The VEHICLE-1 facility details have already been presented elsewhere [17]. In this section, the PoP test setups and experimental conditions to examine the ACLMD concept are described.

Two ACLMD test setups have been prepared, as shown in Fig. 1(a) and (b). Shown in Fig. 1(a) is the table top test (ex-situ) setup, employing a pair of permanent magnets to provide ~800 G, simulating the resonance magnetic field for the plasma generation with 2.45 GHz ECR. The plasma exposure (in-situ) setup to be mounted on VEHICLE-1 is shown in Fig. 1(b), employing a "water wheel" with an LED rotation indicator. The temperature can be measured by two thermocouples: one attached at the bottom and the other on the sidewall of the liquid cup with a diameter of ~5 cm and a depth of ~3 cm, wound with a resistive heater.

Steady state hydrogen and helium plasma exposure experiments are done in VEHICLE-1 with the initial liquid metal temperature in the ACLMD test setup at room temperature. In the present work, no resistive heating is done to externally control the temperature of the liquid metal. Plasma exposure is controlled by a pneumatically operated shutter made of molybdenum, the opening time constant of which is ~20 ms.

The neutral hydrogen and helium gas pressures during plasma operation are typically of the order of 10^{-3} Torr. The hydrogen plasma parameters measured by a moveable Langmuir probe positioned in the immediate upstream of the ACLMD test setup are:

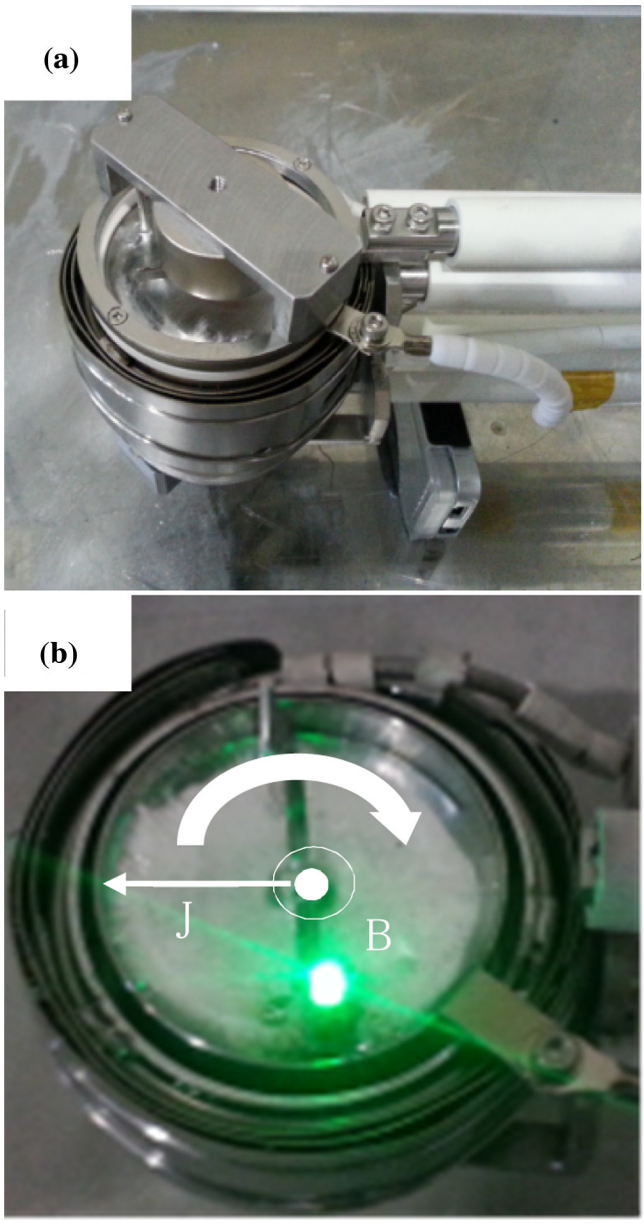

Fig. 1. The ACLMD concept test setups (a) the ex-situ setup; and (b) the in-situ setup with a "waterwheel" marked by an LED lamp. The directions of **J**, **B** and liquid motion are indicated.

the electron temperature is ~5.5 eV; and the plasma density is $\sim 1.2 \times 10^9$ 1/cm^3, in which case the ion bombarding flux is estimated to be $\sim 1.7 \times 10^{15}$ ions/cm^2/s. The helium plasma parameters are: the electron temperature is ~6.8 eV; and the plasma density is $\sim 1.6 \times 10^9$ 1/cm^3, whereby the ion bombarding flux is $\sim 4.1 \times 10^{15}$ ions/cm^2/s.

During these plasma experiments, visible spectroscopy measurements are performed, taking the intensities of Hα and He-I signals as the measures of hydrogen and helium recycling over the liquid metal, respectively. No DC-bias voltage is applied on to the ACLMD test setup, so that the actual plasma ion bombarding energy is ~20 V, a floating potential estimated from $-3k_BT_e$, where k_B is Boltzmann's constant and T_e is the electron temperature. To ensure no significant sputtering of $Ga_{67}In_{20.5}Sn_{12.5}$ by plasma bombardment, the line radiation intensities of Ga-I at 780.00 nm, In-I

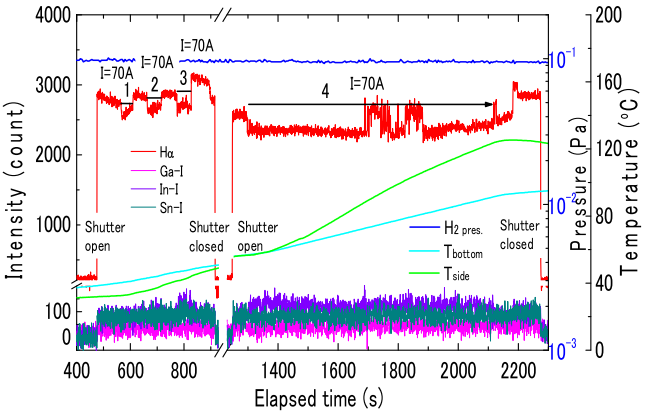

Fig. 2. Effects of the liquid convection induced by the JxB force on the hydrogen recycling behavior over a eutectic alloy: $Ga_{67}In_{20.5}Sn_{12.5}$.

at 451.13 nm and Sn-I at 380.01 nm are monitored in parallel with Hα and He-I intensity measurements.

3. Results and discussion

3.1. Ex-situ table top experiments

Ex-situ examinations are done first, using the ACLMD test setup with a pair of permanent magnets. The DC-current conducted across the liquid metal from the center electrode to the periphery of the liquid cup is increased gradually. When the current has reached ~40 A, the liquid surface appears to start waving, indicative of **JxB**-forced convection. At this point, however, the liquid metal as a whole does not clearly exhibit rotating movement, as illustrated in Fig. 1(b), presumably due to the flow resistance by the presence of the water wheel.

The bulk liquid starts rotating along with the water wheel when the current has reached ~70 A at which point the voltage between the center electrode and the liquid cup is ~3 V. Under these conditions, the averaged **JxB**-force is estimated to be ~3.7 g/cm^2 at half the radius of the liquid cup, which has led to a steady state speed of ~60 rpm. It is thus decided to run the in-situ ACLMD experiments under these **JxB**-forced convection conditions.

3.2. Hydrogen recycling behavior

Except for the very first in-situ test to confirm the **JxB** liquid rotation with the axial magnetic field of VEHICLE-1, which is about 700 G at around the ACLMD test setup position, the water wheel has been removed to minimize the liquid flow resistance and also to avoid any unwanted damage to the LED lamp and/or related complications by plasma bombardment. It follows from this that the actual liquid rotation speed will be somewhat higher during the particle recycling experiments to be described as follows. Unfortunately, however, at present there is no means to measure in-situ the actual rotation speed without the LED lamp in VEHICLE-1.

Shown in Fig. 2 are the Hα signal intensity and liquid cup temperature plotted as a function of time. The line radiation intensity data taken for Ga-I, In-I and Sn-I data are also plotted in the same fashion for comparison.

In this experiment, the **JxB**-forced convection effect on hydrogen recycling has been examined for four times. For the first three times, each ~1 min long, the radial DC current has been set at I = 70 A, as indicated in Fig. 2. Recognized that, every time **JxB**-forced convection occurs, the signal intensity of Hα, i.e. hydrogen recycling, is reduced by 10 ~ 15% relative to the steady state level, defined as 100% recycling.

It is important to mention here that the signal intensities of Ga-I, In-I and Sn-I appear to be minimal and do not show any changes, correlated to those observed for Hα. One may thus assume that JxB-forced convection would neither affect the reflection of visible lights nor splash the liquid metal, misleading plasma spectroscopy measurements. Also, one assumes that there is neither significant sputtering nor evaporation of the eutectic alloy constituents under the present plasma bombardment conditions. Meanwhile, the liquid temperature is seen to increase from room temperature to about 60 °C.

To investigate the joule heating effect, **JxB**-forced convection is applied continuously for ~12 min. During this time the temperatures measured by the two thermocouples have increased up to 80 °C and 120 °C, respectively, at the bottom and at the side wall of the liquid cup. For the first 6 min the Hα signal intensity has been found to be reduced down to 85 ~ 90% of the steady state level in the same manner, as observed for the first three times. After ~6 min, however, the Hα signal appears to "burst" two times, both temporarily gone back to the steady state level as if surface saturation has occurred, the mechanism of which is still unclear.

It has never been reported whether or not $Ga_{67}In_{20.5}Sn_{12.5}$ absorbs hydrogen to form any hydride(s), to the best of our knowledge, although the alloying constituents: Ga, In and Sn are known to form their respective hydrides [19–21]. The hydrogen recycling behavior shown in Fig. 2 suggests the following possibilities:

(1) Suppose that $Ga_{67}In_{20.5}Sn_{12.5}$ forms hydride(s) under hydrogen plasma bombardment. Then, solute hydrogen and hydride precipitates would be desaturated in the surface region when JxB-forced convection occurs;
(2) Hydrogen implanted by plasma bombardment might simply form gas bubbles without forming hydride(s) during JxB-forced convection; and
(3) Both (1) and (2) can take place simultaneously, which would lead to a decrease in Hα signal intensity, namely, reduced hydrogen recycling.

It is known that SnH_4 decomposes even at temperatures below 100 °C [21]. One then speculates that the hydrogen recycling bursts seen in Fig. 1 might be related to the thermal decomposition of SnH_4. Unfortunately, there are no literature data available on the thermal decomposition characteristics of Ga_2H_6 and InH_3 which, however, could contribute to hydrogen recycling burst as well. If none of these hydrides is formed in $Ga_{67}In_{20.5}Sn_{12.5}$, gas bubbles formed by JxB-forced convection might burst at a certain pressure, releasing hydrogen gas to lead to an increase in Hα signal. Nonetheless, much is yet to be explored on the interactions between hydrogen plasma and $Ga_{67}In_{20.5}Sn_{12.5}$.

3.3. Helium recycling behavior

The He-I signal intensity and liquid cup temperatures measured during steady state helium recycling experiments are shown in Fig. 3 as a function of time. During the course of these measurements, **JxB**-forced convection effects have been examined for four times under essentially identical conditions to those employed for the hydrogen recycling experiments.

Notice that every time **JxB**-forced convection occurs, helium recycling is reduced by 20 ~ 30% from the steady state level, even more noticeable than in the case of hydrogen recycling. Interestingly, the reduction in helium recycling becomes more and more significant as **JxB**-forced convection is repeated, namely, as the liquid metal temperature increases via joule heating. This is consistent

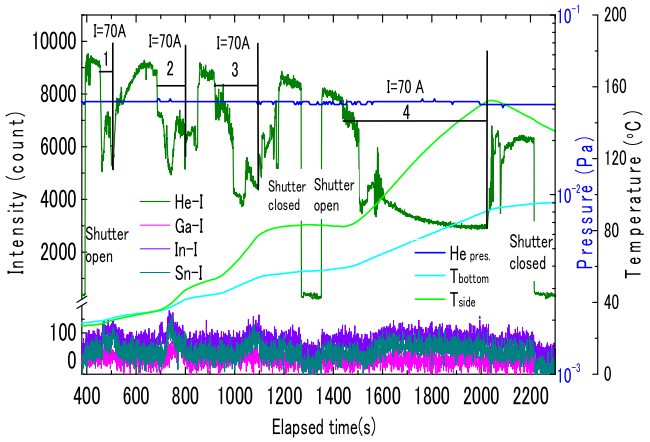

Fig. 3. Effects of the **JxB**-forced convection on helium recycling over $Ga_{67}In_{20.5}Sn_{12.5}$ under steady state plasma exposure.

Fig. 4. The surface of $Ga_{67}In_{20.5}Sn_{12.5}$ after plasma exposure experiments, showing a buoying contamination film.

with the literature data that the solubility of inert gases in a liquid metal increases with increasing temperature [13].

It should be pointed out here that, as can be seen in Fig. 3, the line radiation intensities of Ga-I, In-I and Sn-I exhibit a mild increase when helium recycling is reduced. One speculates that this might be associated with helium bubble formation in the liquid, followed by immediate burst, resulting in a splash to be detected by plasma spectroscopy although details are unclear at this point.

Finally, **JxB**-forced convection is maintained for ~10 min during which time the measured temperatures have increased from room temperature up to 100 and 120 °C, respectively, at the bottom and at the side wall of the liquid cup. Along with the temperature rise, helium recycling is further reduced whilst a mild burst is seen at around 100 °C. At the end of **JxB**-forced convection, helium recycling has been found to reach ~50% of that is observed at steady state.

3.4. Post-exposure surface film analysis

Shown in Fig. 4 is the surface of $Ga_{67}In_{20.5}Sn_{12.5}$ after plasma exposure experiments. As can be seen, there is a buoying contamination film which, however, can easily be scraped off. From the EDX analysis with generally minimal air exposure effect, this film has been found to be composed of 69 wt% Ga, 17.4 wt% In, 8.9 wt% Sn, 3.7 wt% O, 0.7 wt% C, indicating the formation of oxides and perhaps hydroxides as well.

A question may be asked here whether or not this contaminated film has affected the behavior of hydrogen and helium recycling, but cannot readily be answered at this point because such a thin film is predicted to sink into the bulk of the liquid metal, when JxB-forced convection occurs. Nonetheless, the question about the surface contamination effect remains open until further investigation has been done.

4. Conclusion

In the present work, a series of plasma-surface interaction experiments have been conducted to evaluate the ACLMD concept, employing a eutectic alloy $Ga_{67}In_{20.5}Sn_{12.5}$ as a plasma-facing liquid.

Results indicate that both hydrogen and helium recycling is noticeably reduced when **JxB**-forced convection occurs, which is encouraging from the particle control point of view. Also, the recycling burst has been observed when the liquid is subjected to **JxB**-forced convection continuously for an extended period. After plasma exposure, the liquid surface has been found to be covered with an oxygen-containing film, the effect of which is yet to be investigated.

As such, the details of hydrogen and helium absorption and desorption characteristics by $Ga_{67}In_{20.5}Sn_{12.5}$ are still unknown, which clearly warrants further work in this area of research.

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