

Hydrogen and helium recycling from a $\mathbf{J \times B}$ -force convected liquid metal $\text{Ga}_{67}\text{In}_{20.5}\text{Sn}_{12.5}$ under steady state plasma bombardment

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ABSTRACT

First-of-a-kind laboratory plasma interaction experiments on the $\mathbf{J \times B}$ -force convected liquid metal divertor concept have been carried out, employing a eutectic alloy: $\text{Ga}_{67}\text{In}_{20.5}\text{Sn}_{12.5}$, the melting point of which is 10.5°C , in the temperature range from room temperature to $\sim 200^\circ\text{C}$. The electrical current conducted through the alloy is set at about 70A and the magnetic field is set at about 700gauss. 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 $\mathbf{J \times B}$ force.

1. INTRODUCTION

It is widely 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 reevaluated recently [1], the thickness of the scraped-off layer (to be referred to as SOL) for ITER is predicted to be $\sim 1\text{mm}$, meaning that PFCs will probably be exposed to power and particle fluxes, respectively, of the order of $100\text{MW}/\text{m}^2$ and $10^{24} \text{ D}+\text{T}/\text{m}^2/\text{s}$. The same scaling law predicts that the thickness of SOL decreases with

increasing plasma current and major radius [2]. 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 low thermal conductivity, typically one third of that of copper, is employed as the heat sink material of the divertor structure, as

seen in modern fusion power reactor studies such as SLIM-CS [3].

Also, the ductile-brittle transition temperature (to be referred to as DBTT) of tungsten is $\sim 400^{\circ}\text{C}$, substantially higher than most of the engineering metals, so that reactor operation including plasma current ramp up and down will unavoidably result in thermal stress cracking in tungsten whether it is prepared by chemical vapor deposition or powder metallurgy [4]. All these arguments clearly point to the need for innovative PFC concepts development.

As a possible resolution to this situation, the use of liquid metals as the plasma-facing materials covering PFCs has been proposed, and proof-of-principle (to be referred to as PoP) experiments have been conducted over the past several decades in some of the plasma confinement devices [5, 6, 7, 8] as well as in laboratory-scale facilities [9], all of which are essentially successful.

The evolution of the liquid metal PFCs is briefly reviewed as follows. The first generation may well be represented by the capillary porous system (to be referred to as CPS) [10]. The CPS concept employs a tungsten mesh wetted with molten lithium as a plasma-facing material, so that the surface tension will keep liquid from moving even with a transient electrical current running through it in a strong magnetic field. This concept has been implemented in the

limiters in T-10 [5], FTU [6] and TJ-II [7].

Following the successful applications of the CPS concept, NSTX moved to the second step, employing “free surface” liquid lithium as the plasma-facing material [8], which may be called as the second generation, intending that reduced hydrogen recycling lasts longer than observed when lithium coatings were applied over the divertor target tiles, but this intent was not granted. One of the possible reasons may be that because the plasma-facing side of the liquid lithium is warmer than the bottom, due to the divertor heat flux, there is no natural convection, occurring to help desaturate implanted hydrogen in the surface region.

Motivated by these experiments, a series of laboratory experiments have recently been conducted to investigate the effects of forced convection of molten lithium on hydrogen and helium recycling under steady state plasma bombardment. Results indicate that hydrogen recycling is reduced when molten lithium is mechanically stirred, i.e. forced convection. Interestingly, opposite is found to be true with helium recycling. This is believed to be because helium solubility in molten lithium decreases with decreasing temperature, which occurs along with liquid stirring.

In parallel with these experiments, a new concept to provide an electrically

conductive liquid with forced convection has been proposed, employing the $\mathbf{J} \times \mathbf{B}$ force, where $\mathbf{J}$ is the electrical current and $\mathbf{B}$ is the magnetic field [11]. A series of PoP experiments have successfully been conducted [12, 13] although some of the technical issues are also pointed out, including the electrochemical effect on electrode erosion and the joule heating effect on liquid temperature control. In the remainder of this paper, this is referred to as the actively convected liquid metal divertor (ACLMD) concept.

In the present work, an experimental setup based on the ACLMD concept is installed in the VEHICLE-1 steady state plasma facility [14]. Evaluated for the first time as the plasma-facing material is a eutectic alloy: $\text{Ga}_{67}\text{In}_{20.5}\text{Sn}_{12.5}$, the melting point of which is 10.5°C [15].

2. EXPERIMENTAL

Used in this work for the steady state hydrogen and helium plasma interactions with liquid metals is the VEHICLE-1 facility, the details of which have already been presented elsewhere [14]. In this section, the liquid metal PFC test setup prepared on the ACLMD concept [11] is presented.

The ACLMD liquid metal PFC test setup is shown in Fig. 1(a), (b) and (c). Shown in Fig. 1(a) and (b), respectively, are the setup mounted on an insulated flange and a close-up of the $\mathbf{J} \times \mathbf{B}$ liquid metal rotation mechanism, employing a

pair of permanent magnets to provide at ~ 100 gauss for an off-line test, similar to (b) the resonance magnetic field for the plasma generation with 2.45GHz ECR. The actual setup mounted on VEHICLE-1, employing a “water wheel” with an LED rotation marker lamp is shown in Fig. 1(c). The temperature of the liquid cup can be measured at the bottom and on the sidewall by thermocouples.

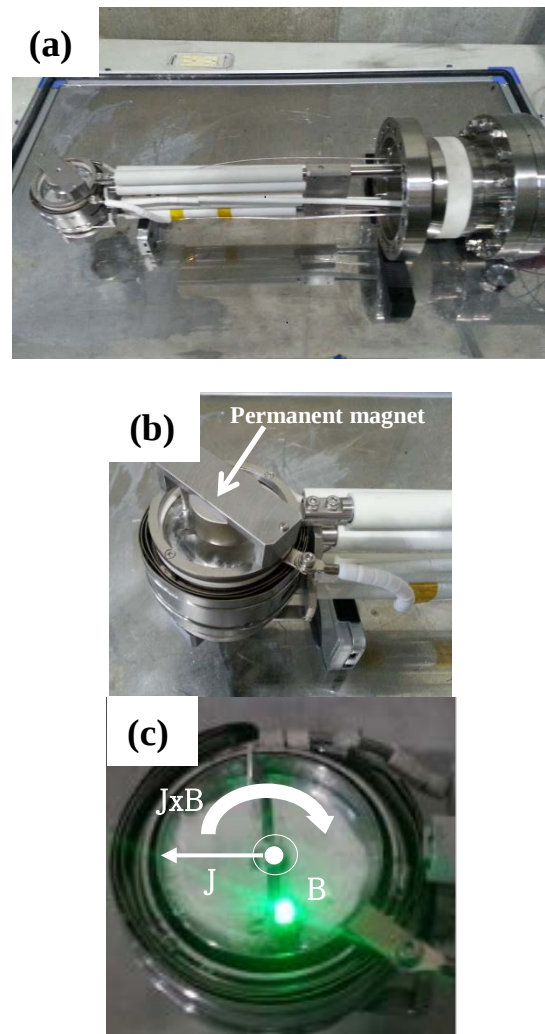


Fig. 1 The ACLMD test setup (a) an insulation flange-mounted setup; (b) a close-up on the off-line test setup; and (c) the setup mounted on VEHICLE-1 with a “waterwheel” marked by an LED lamp.

3. RESULTS AND DISCUSSION

3.1 Hydrogen recycling behavior

Steady state hydrogen plasma exposure experiments have been conducted with the initial temperature at room temperature. The plasma parameters are set such that the electron temperature is $\sim 5.5\text{eV}$ and the plasma density is $\sim 1.2 \times 10^9 \text{ 1/cm}^3$, whereby the ion bombarding flux is $\sim 1.7 \times 10^{15} \text{ ions/cm}^2/\text{s}$.

During these plasma experiments, visible spectroscopy measurements have been performed, taking H_α as the measure of hydrogen recycling over the liquid metal. No DC-bias voltage is applied on the ACLMD test setup, so that the actual plasma ion bombarding energy is 10~20V. To ensure no significant sputtering, the line intensities of Ga-I, In-I and Sn-I are also monitored in parallel with H_α signal measurements.

Shown in Fig. 2 are the H_α signal intensity and liquid cup temperature plotted as a function of time. The line intensity data taken for Ga-I, In-I and Sn-I data are also plotted for comparison. It is clear that the sputtering of alloy constituents is minimal.

In this series of experiments, liquid convection effects have been observed for four times. For the first three times, each about 1minute long, the electrical current is set about 70A and the voltage then is 3~4V. The axial magnetic field of VEHICLE-1 is measured to be about

700 gauss at the position where the ACLMD liquid metal PFC test setup is installed. Under these conditions, one estimates an average $\mathbf{J} \times \mathbf{B}$ rotating force of about 3.7g/cm^2 at half the radius, which has led to a rotation of about 60 revolutions per minute.

As can be seen in Fig. 2, when liquid convection is provided by the $\mathbf{J} \times \mathbf{B}$ force, hydrogen recycling has reproducibly been observed to be reduced by about 10~15% from the steady state level. Meanwhile, the liquid temperature is seen to increase from room temperature to about 60°C .

For the final test, the $\mathbf{J} \times \mathbf{B}$ -forced convection is applied continuously for about 12 minutes. For the first 6minutes hydrogen recycling has been found to be maintained at 85~90% of the steady state level in the same manner as observed for the first three times. After about 6 minutes, however, hydrogen recycling “burst” two times up to the steady state level, the mechanism of which is unclear.

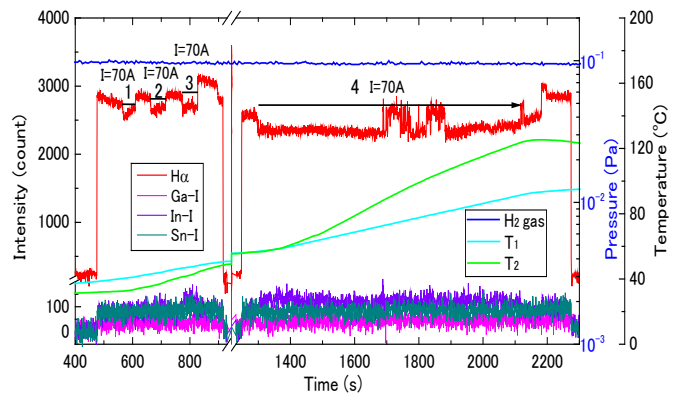


Fig. 2 Effects of the liquid convection induced by the $\mathbf{J} \times \mathbf{B}$ force on hydrogen recycling over the liquid state Ga67In20.5Sn12.5. During these measurements, the waterwheel with an LED lamp is not attached on the liquid cup to minimize the flow resistance.

It has never been reported whether or not $\text{Ga}_{67}\text{In}_{20.5}\text{Sn}_{12.5}$ absorbs hydrogen to form a hydride, to the best of our knowledge, although the alloying constituents: Ga, In and Sn are known to form their respective hydrides [16, 17, 18]. The hydrogen recycling behavior shown in Fig. 2 suggests three possibilities: (1) $\text{Ga}_{67}\text{In}_{20.5}\text{Sn}_{12.5}$ might absorb hydrogen to form a hydride via an exothermic reaction because when convection occurs, the liquid surface temperature decreases, leading to the absorption of hydrogen, i.e. reduced recycling. Also, liquid convection desaturates hydride in the surface region, as pointed out in our previous study on liquid lithium [19]; (2) Hydrogen might be absorbed into the convected liquid to form bubbles without chemical bonding; and (3) Both (1) and (2) are taking place.

Because SnH_4 is known to decompose at relatively low temperatures even below 100°C [18], the recycling bursts observed at between 80 and 120°C might be due to thermal decomposition. Unfortunately, there are virtually no literature data available on the thermal decomposition characteristics of Ga_2H_6 and InH_3 , which can contribute to the recycling burst as well, though. As such, the details are yet to be explored.

3.2 Helium recycling behavior

Similar steady state helium plasma experiments have been conducted, again,

with the initial temperature at room temperature. The plasma parameters are set such that the electron temperature is $\sim 6.8\text{eV}$ and the plasma density is $\sim 1.6 \times 10^9 \text{ 1/cm}^3$, whereby the ion bombarding flux is $\sim 4.1 \times 10^{15} \text{ ions/cm}^2/\text{s}$.

During these plasma experiments, visible spectroscopy measurements have been performed, taking He-I as the measure of helium recycling over the liquid metal. No DC-bias voltage is applied on the ACLMD test setup, so that the actual plasma ion bombarding energy is $10\sim 20\text{V}$. To ensure no significant sputtering, the line intensities of Ga-I, In-I and Sn-I are also monitored along with He-I signal measurements.

The He-I signal intensity and liquid cup temperature are shown in Fig. 3 as a function of time. The line intensity data taken for Ga-I, In-I and Sn-I data are also plotted for comparison. It is clear that the sputtering of alloy constituents is negligible.

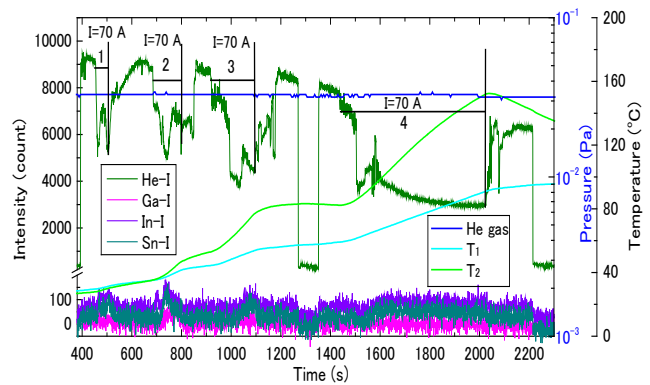


Fig. 3 Effects of the $\mathbf{J} \times \mathbf{B}$ -forced convection on helium recycling over $\text{Ga}_{67}\text{In}_{20.5}\text{Sn}_{12.5}$ under steady state plasma exposure. During these measurements, the waterwheel with an LED lamp is not attached on the liquid cup to minimize the flow resistance.

Similarly to the hydrogen recycling experiments, **JxB**-forced convection effects have been observed for four times. For the first three times, each about 1 minute long, the electrical current and the voltage are set in identical conditions to those employed for hydrogen recycling experiments.

Notice that each time **JxB**-forced convection occurs, helium recycling is reduced by about 20~30% from the steady state level, even more significant than hydrogen recycling. During these measurements, the liquid temperature has increased from room temperature up to between 100~150°C, measured by the two thermocouples. Interestingly enough, the reduction in helium recycling becomes more significant as liquid convection repeats, namely, as the temperature increases from room temperature up to about 80°C.

This behavior is opposite to that was observed for liquid lithium exposed to helium plasma in our previous study [19]. Generally, the solubility of inert gases in a liquid metal increases with increasing temperature, meaning that when the **JxB**-forced convection is applied, the surface temperature decreases. As a result, helium will be released, leading to an increase in He-I signal, which is not the case in the present work. Details are still unclear.

Finally, the **JxB**-forced convection is maintained for about 10 minutes. While

the liquid temperature increases from 90°C up to 150°C due to Joule heating, helium recycling is further reduced although a mild burst followed by some fluctuations is seen at around 100°C. Towards the end of measurements, helium recycling has been found to reach about 50% of the steady state. This trend is consistent with the general temperature dependence of helium solubility in liquid metals.

3.2 Post-exposure surface analysis

Shown in Fig. 4 is the surface of $\text{Ga}_{67}\text{In}_{20.5}\text{Sn}_{12.5}$ after plasma exposure experiments. Clearly, there is a buoying contamination layer which, however, can easily be scraped off. It has been found from EPMA analysis that this layer is composed of 69 at% Ga, 17.4 at% In, 8.9 at% Sn, 3.7 at% O, 0.7 at% C, indicating the formation of oxides.



Fig. 4 The surface of $\text{Ga}_{67}\text{In}_{20.5}\text{Sn}_{12.5}$ after plasma exposure, showing a buoying contamination film.

A question may be raised whether or not this contamination has affected the

hydrogen and helium recycling behavior, but cannot readily be answered either way at this point because it is highly possible that such a thin film sinks into the liquid, when JxB-forced convection is applied.

4. CONCLUSION

In the present work, a series of first-of-a-kind plasma-surface interaction experiments have been conducted, evaluate a eutectic alloy $\text{Ga}_{67}\text{In}_{20.5}\text{Sn}_{12.5}$ as a liquid plasma-facing material subject to the JxB-forced convection.

Results indicate that both hydrogen and helium recycling is noticeably reduced when forced convection applied to the liquid, which is all encouraging from the particle control point of view. Also, the formation of buoying oxides and perhaps hydroxides as well getters impurities to improve the cleanliness of vacuum.

Nonetheless, the details of hydrogen and helium absorption and desorption characteristics of $\text{Ga}_{67}\text{In}_{20.5}\text{Sn}_{12.5}$ are still unknown, which warrants further work.

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