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To cite this article: M. Nieto, D. N. Ruzic & J. P. Allain (2003) Experimental Measurements of Helium Retention in Flowing Liquid Lithium, Fusion Science and Technology, 44:1, 232-236, DOI: [10.13182/FST03-A339](https://doi.org/10.13182/FST03-A339)

To link to this article: <https://doi.org/10.13182/FST03-A339>



Published online: 12 May 2017.



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EXPERIMENTAL MEASUREMENTS OF HELIUM RETENTION IN FLOWING LIQUID LITHIUM

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The Flowing Liquid Surface Retention Experiment (FLIRE) has been built and designed at the University of Illinois at Urbana-Champaign to provide fundamental experimental data on the retention and pumping of He, H and other species in flowing liquid surfaces. These measurements are critical to the development of advanced plasma-facing components (PFCs) that apply flowing liquid metals to mitigate high heat loads encountered in the divertor region of next-step fusion reactors. The FLIRE facility currently uses an ion beam source, which injects ions into a flowing stream of liquid lithium. Its design allows the liquid lithium to flow between two vacuum chambers that become isolated from each other when the lithium flows. Recent results show retention of helium in flowing liquid lithium at 250-300 °C to be of the order 10^{-4} and diffusivities of 10^{-4} to 10^{-3} cm²/sec.

I. INTRODUCTION

One of the key challenges for the development of tokamak fusion reactors and fusion device technology is the ability for plasma-facing components (PFCs) to withstand peak thermal loads of the order of 10 MW/m² and up to 50 MW/m² for off-normal events such as edge-localized modes or disruptions for future next step fusion devices.¹⁻⁴ One alternative addressing this challenge is the use of free surface flowing liquids as plasma-facing components (PFCs). Some examples of free surface liquids include: liquid-metals such as liquid lithium and molten salts, such as flibe (LiF-BeF₂).⁵ Outstanding issues facing liquids as potential PFCs include: effective hydrogen/helium particle retention, plasma-liquid interaction mechanisms (evaporation, sputtering, spattering), chemical safety concerns (i.e. liquid lithium, flibe), interactions with other materials, tritium inventory, neutron irradiation, power extraction, vapor shielding, macroscopic liquid-metal removal and MHD

(magneto-hydrodynamic) effects on liquid-metal flow, transport and particle pumping. In addition to providing protection from high heat fluxes of future next-step fusion devices, free surface flowing liquids can enable existing fusion devices to achieve new confinement regimes.

For example, liquid lithium is known to pump hydrogen particles quite well and thus a new “low-recycling” regime can be attained.^{6,7} This could lead to steeper pedestal edge temperature profiles characteristic of higher confinement regimes. Lithium pellet injection in TFTR showed that conditioning of graphite walls with lithium led to higher confinement regimes.⁸⁻¹⁰ With low-recycling regimes though, lower density and pressure at the pump ducts will likely make helium pumping under standard vacuum pumping techniques nearly impossible, thus potential “low-recycling” liquids must also provide for sufficient helium pumping.^{11,12}

Currently the Flowing Liquid Surface Retention Experiment (FLIRE) facility is investigating

fundamental processes of the retention and pumping of He and hydrogen isotopes in flowing liquid lithium. These studies include the use of an ion beam source and particle retention measurements in flowing liquid lithium⁴ as opposed to studies of hydrogen retention in static liquid lithium.^{13, 14} In addition, the diffusion coefficient of the implanted species is calculated from measured retention data. This paper focuses on experimental measurements of He retention in flowing liquid lithium under a variety of experimental conditions namely: variation in the incident He energy and variation in the liquid lithium flow velocity.

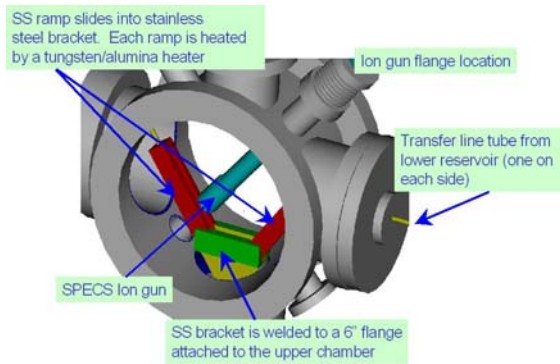


Figure 1. Internal ramp components and ion gun source of the FLIRE system.

II. EXPERIMENTAL SETUP

FLIRE is designed to measure the retention of flowing liquid lithium under a variety of experimental conditions. In its current design, FLIRE uses an ion beam to inject helium (or other) ions at near normal incidence into the flowing stream of liquid lithium. The SPECS IQE 11/35 ion source provides current densities in the order of 0.5 mA/cm^2 . The operating pressure is typically in the $10^{-6} - 10^{-5}$ Torr range, and ion energies up to 5000 V can be handled. The gun can also be moved to change the location of the striking point along the path of the flowing liquid. Base pressures of both the upper and bottom chambers range between 10^{-9} to 10^{-8} Torr.

Two quadrupole RGAs monitor the partial pressure of the incident particle species in the upper and lower vacuum chambers. The partial pressure of the injected ion species is measured in the bottom chamber, allowing for the calculation of retention characteristics. To improve the sensitivity of the RGA system, both instruments are equipped with channel electron multipliers that allow measurement of partial pressures as low as 10^{-12} Torr.

The flowing liquid lithium creates a vacuum seal at a 0.3-cm^2 aperture between the chambers when it is flowing down the plane. The ion gun is turned on only after the seal is established. Notice that there are two ramps over which liquid lithium is flowing as shown schematically in Fig. 1. If only one ramp were used, the surface layer in which the injected particles may be trapped would not necessarily flow smoothly into the bottom chamber. By having two flows meet at the opening, the surface layer is folded into the middle of the flow and must travel into the bottom vacuum chamber through the aperture. This concept was tested on a mock-up ramp system with the same specifications as the FLIRE ramp system with liquid gallium.³

A newly designed liquid-metal injection and storage system (LMISS) supplies the flowing liquid lithium in FLIRE. Two cylindrical liquid-metal reservoir chambers connected in series below the bottom chamber are the heart of the LMISS. Between the two liquid-metal reservoirs is a liquid-metal compatible inline valve used to transfer molten lithium between the two reservoirs when the whole lithium charge is in the upper reservoir. Lithium is initially melted under argon atmosphere in an external melt chamber; from there, it is transferred to the lower reservoir. The liquid is pumped using argon pressure on top of the liquid level, and it is transported through heated tubing averaging temperatures near $225 \text{ }^\circ\text{C}$. Once the lower reservoir is fully loaded, the metal is transported to the upper chamber and onto two heated internal ramps that guide the liquid to the lower chamber.

During lithium flow, both chambers are effectively isolated from each other by the flow itself as discussed earlier. When the flow stops, lithium remains in the aperture due to its high surface tension and continues to isolate the two chambers from each other. This unique feature makes the data analysis easier, since the signal from gas carried by the metal is completely separated from the background gas needed to operate the ion source. For safety precaution a stainless steel tray lies below the LMISS preventing any accidental spill of liquid lithium to touch the concrete below FLIRE. Further details of the experiment can be found in recent publications.^{3, 4} For each run the ion source can be varied in energy to study different penetration depths in flowing liquid lithium. The ramp heaters are varied by about $30\text{-}40 \text{ }^\circ\text{C}$ to measure any effect of the local liquid temperature on retention properties. Also, the flow velocity of liquid lithium is varied by careful variation of the pressure head measured by a diaphragm gauge at the

lower reservoir. For each variation, the partial pressure of He gas released from liquid lithium is measured and diffusivity calculated. A discussion on how the data is analyzed and error propagated is presented in the following section.

III. DATA ANALYSIS

A. RETENTION MEASUREMENTS

Retention measurements are obtained by analysis of the RGA data in the bottom vacuum chamber. The retention coefficient R is calculated by taking the ratio of particles release rate in the lower chamber q to the rate of injection from the ion gun j :

$$R = \frac{q}{j} \tag{1}$$

The release rate in the lower chamber is given by the steady state partial pressure P and the pumping speed S , just by balancing the release and the pump out:

$$q = \frac{P}{kT} S \tag{2}$$

To determine pumping speed, a pump out curve is obtained for the pumping conditions during the experiment. Generally, the pumping speed is kept to a minimum to increase the signal-to-noise ratio. The pumping curve for the set of experiments presented in this work is shown in Figure 2. The volume in the lower chamber is 7360 cm^3 , and hence the pumping speed value is $242 \pm 50 \text{ cm}^3/\text{s}$.

The ion current delivered from the gun to the metal gives the injection rate. Since no in-situ current diagnostic is available, the current measurements performed during an external gun calibration. Ion current is on the order of $3 \text{ }\mu\text{A}$, equivalent to 2×10^{13} particles/s.

A typical He signal in the lower chamber during a FLIRE run is shown in Figure 3. The pressure rises to an initial plateau (boxed in the Figure), and after that it increases. The increase in the pressure is indicative of a change in the flow regime (increased velocity, pooling effects, etc). The first pressure plateau is less likely to be affected by changes in the flow, so that is the value chosen to calculate the retention coefficient.

B. ANALYSIS OF DIFFUSIVITY

The retention coefficient is a quantity that can be measured directly on FLIRE. By making some simplifying assumptions, the retention coefficient measurement can be used to obtain an estimate of the diffusion coefficient. For the case of He, the fact that it is inert and insoluble in Li makes such model fairly simple. Then assumptions of the model are:

- One dimensional diffusion from bulk to surface
- Semi infinite domain
- All ions are implanted at the mean range r
- The size of the beam is much smaller than the width of the channel
- Convective transport is neglected

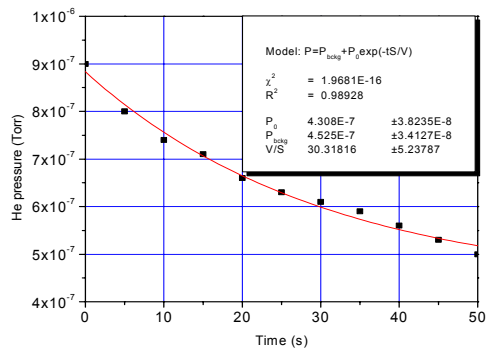


Figure 2: Pumping curve for the lower chamber. The pumping speed is obtained from the time constant

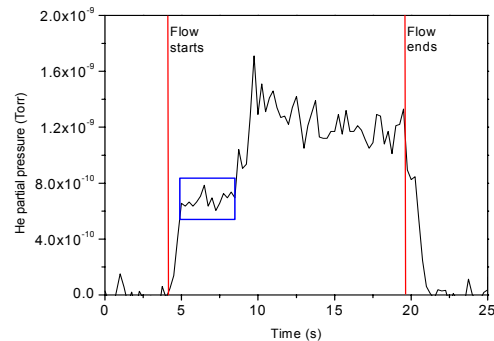


Figure 3: He trace in the lower chamber for a 1.5 keV He beam incident on a 60 cm/s Li flow. The box shows the initial pressure plateau

The retention coefficient can be calculated using this simple analytical model. The expression for R is:

$$R = \text{erf}\left(\frac{1}{2\sqrt{\theta}}\right) \tag{3}$$

The details of how this result is obtained can be found elsewhere.⁴ The dimensionless parameter θ is defined as the ratio of residence time to diffusion time:

$$\theta = \frac{DL}{vr^2} \quad (4)$$

Here, L is the path length from the beam striking point to the upper chamber exit, v is the flow velocity (L/v is the residence time in the upper chamber), D is the diffusion coefficient and r is the mean ion range (r^2/D is the diffusion time).

IV. RESULTS AND DISCUSSION

Results of He retention in flowing lithium are shown in Figures 4 and 5 for 260 ± 10 and 280 ± 10 °C, respectively. Retention coefficients on the order of 10^{-4} - 10^{-3} are obtained, and it increases as velocity and energy increase. At higher speeds, other effects such as lithium pooling during the passage between chambers increase the residence time in the upper chamber, reducing the retention coefficient.

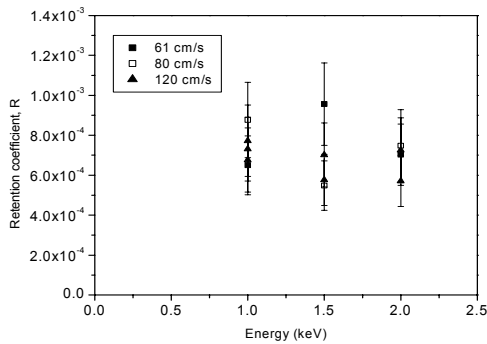


Figure 4. Retention coefficient as a function of energy for different flow velocities at 260 °C

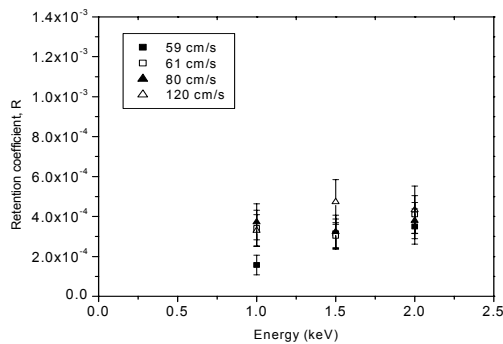


Figure 5. Retention coefficient as a function of energy for different flow velocities at 280 °C

Figures 6 and 7 present the diffusion coefficients calculated from the measured retention data using the analytical model mentioned previously. It can be observed that the calculated diffusion coefficient seems to go up with beam energy. This may be caused by the fact that the model assumes deposition of all particles at the mean range, hence neglecting the effect of the deposition profile. At high energy, some mixing may also be occurring. The fact that the surface is not flat but concave may also be playing a role. A more in-depth study is required to determine what is causing this behavior. The diffusion coefficient should not have an energy dependence.

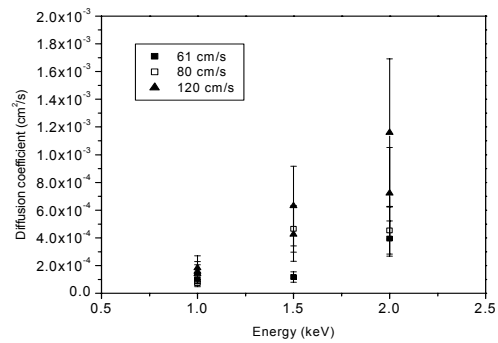


Figure 6. Diffusion coefficient for helium on liquid lithium at 260 °C.

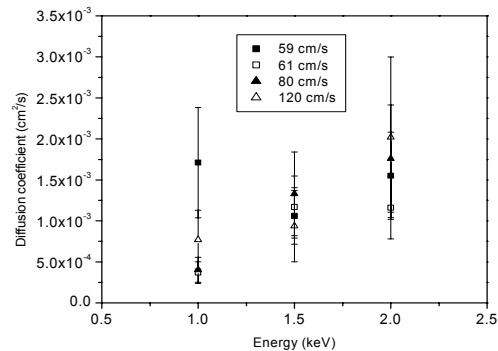


Figure 7. Diffusion coefficient for helium on liquid lithium at 280 °C.

By using the average value of D for each temperature to calculate θ , the plot shown in Figure 8 is generated. The solid line represents eq. (3), and the experimental points are shown for the two temperatures. As a guideline, a point was added for a reactor with Li flow speed of 10 m/s, 0.5 m of travel inside the reactor, bombarded by 10 keV He ions (with a mean range of 5000 Å) and a diffusion coefficient of 1×10^{-3} cm²/s, as determined from these experiments. Those parameters give a

retention coefficient of 0.004 (0.4 %), which is smaller than the lower limit suggested by some authors.¹¹

Notice that the effect of temperature is the displacement of the points along the line. For temperature increase, they are displaced down, and for a decrease they are displaced up. On the other hand, higher Li flow temperatures are required due to thermal cycle constrains. This means that retention will be even lower for high temperature operation. To obtain the complete temperature behavior and verify this fact, more retention measurements and diffusion calculations at different temperatures will be performed.

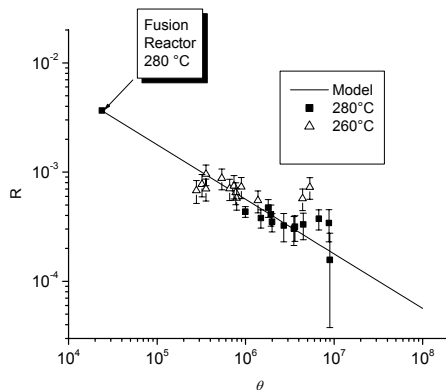


Figure 8. Retention coefficient as a function of the dimensionless parameter θ .

V. CONCLUSIONS

Retention coefficients in the order of 10^{-4} were obtained for He ions in flowing Li. From those measurements, the diffusion coefficients obtained were $(1.2 \pm 0.15) \times 10^{-3}$ cm²/s at 260 °C, and $(3.9 \pm 0.6) \times 10^{-4}$ cm²/s at 280 °C. The model used to estimate the diffusion coefficient from retention measurements will be improved so that the apparent energy dependence of the diffusion coefficient can be eliminated.

VI. ACKNOWLEDGEMENTS

The authors wish to acknowledge our funding sources, NPL Associates Inc. (subcontract DOEANL02-160) and the DOE ALPS program (contract DEFG0299ER54515). Special thanks to Sarfraz Taj, Gabe Burt, Jason Tillery and Matt Hendricks for their valuable contribution to the completion of this work

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