Journal of Nuclear Materials 307–311 (2002) 1517–1519

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Hydrogen and helium entrapment in flowing liquid metal plasma-facing surfaces

Ahmed Hassanein [*]

Argonne National Laboratory, Bldg. 362, 9700 South Cass Avenue, Argonne, IL 60439, USA

Abstract

The ability to use liquids as plasma-facing component (PFCs) depends on their interaction with the plasma and the magnetic field. One important issue for the moving liquid is the ability to entrain particles that strike the PFC surface (helium and hydrogen isotopes) while accommodating high heat loads. To study this problem, a numerical model has been developed using the HEIGHTS computer simulation package. The model was used to investigate pumping of He particles by the flowing liquid rather than requiring a standard vacuum system. Hydrogen isotope (DT) particles are likely be trapped in the liquid metal surface (e.g., lithium) due to the high chemical solubility of hydrogen. The incident He particles in the established low-recycling regime at PFCs could be harder to pump using standard vacuum pumping techniques. The analysis results indicate, however, a reasonable chance of adequate helium self-trapping in flowing lithium as PFC without active pumping.

1. Introduction

One of the most challenging areas for fusion power production in a tokamak device is the development of plasma-facing components (PFCs) that can withstand high heat and particle fluxes during normal and abnormal events. Renewable liquid metal surfaces offer significant advantages over the standard solid components. However, the ability to use liquids as divertor surfaces depends on their interaction with the plasma and the reactor's strong magnetic field. One important issue that will influence the selection of liquid surfaces is whether the moving liquid will entrain particles that strike the surface while still accommodating high heat loads. Particle entrapment, in particular, could determine the viability of specific liquid candidates as renewable divertor surfaces. Hydrogen isotope (DT) particles striking the surface will most likely be trapped in the lithium surface because of the high chemical solubility of the hydrogen in liquid lithium. This will result in a low-recycling divertor and a high edge temperature (several hundred eV).

There are several implications of a low-recycling divertor on plasma performance. An important issue is whether He can be pumped at low density by a standard vacuum system. If helium particles are not entrained in the surface and must be pumped out of the divertor, then standard vacuum pumping techniques must be used. However, the low-recycling regime also results in a low density and pressure at the pump ducts. Because helium is a difficult species to vacuum pump, it may be more difficult or impossible to obtain adequate pumping in this situation.

The potential for any of the liquid candidates (e.g., Li, Sn, Ga, flibe) to work satisfactorily depends on whether particles with negligible chemical solubility (for example, He in Li and DT in flibe) become entrained in the surface for a long enough time to be removed from the divertor chamber. If He is entrained in lithium and so removed, the lithium system would eliminate the need for separate vacuum pumping and, therefore, would become more attractive. On the other hand, complete recycling (little or no entrapment) would make He removal from the lithium system difficult or impossible.

---

[*] Tel.: +1-630 252 5889; fax: +1-630 252 3250/5287.
E-mail address: hassanein@anl.gov (A. Hassanein).

0022-3115/02/$ - see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0022-3115(02)01270-9

The overall understanding of particle dynamic entrapment in liquid surfaces is crucial to assessing their viability for divertor operation. The purpose of this study is to investigate whether a lithium-layer pump/absorb the incoming flux of helium, deuterium, and tritium. The numerical model is implemented with the HEIGHTS package [1], which takes into account the kinetics of particle injection, motion, interactions with the liquid lattice, and the ultimate release from the moving surface [2].

The produced helium ash from the thermonuclear reaction in a fusion reactor needs to be removed at its production rate [2]. For example, in a 2000 MW fusion power reactor operating in the low-recycle regime, the alpha-production rate $I_{\mathrm{Fus}} = 2000\ \mathrm{MW} \approx 7.1 \times 10^{20}$ He/s. For a DT current to the divertor, $I_{\mathrm{DT}} \approx 1.6 \times 10^{23}\ \mathrm{s}^{-1}$, and for the 10% $\mathrm{He}/(\mathrm{D}+\mathrm{T})$ fraction in the core plasma, the helium current to the divertor is $I_{\mathrm{He}} \approx 1.6 \times 10^{22}\ \mathrm{s}^{-1}$. Therefore, the required removal efficiency is $I_{\mathrm{Fus}}/I_{\mathrm{He}} \approx 0.04$, or approximately 4–5%.

2. Computational model

The development of a model describing absorption of helium and deuterium–tritium particles by a layer of liquid metal entails solving a time-independent, two-dimensional diffusion equation in the x–y poloidal plane with various boundary conditions.

The basic general equation can be written as:

$$v_0 \frac{\partial c(x,y)}{\partial y} = -\frac{\partial}{\partial x} J(x,y) - Q_0 Q(x,y) c(x,y) + G_0 G(x,y,l_0),$$
$$0 \leqslant x \leqslant L_x, \quad 0 \leqslant y \leqslant L_y, \tag{1}$$

where $c(x,y)$ is the particle concentration at depth x along flow distance y, J is the particle flux, v_0 is the velocity of liquid, l_0 is the maximum particle implantation depth, L_x is the depth of the liquid layer, and L_y is the exposed length of liquid surface to the plasma. The functions $Q(x,y)$ and $G(x,y)$ are for particle absorption and implantation fluxes, respectively. The flux, J, is determined as follows:

$$J(x,y) = -D_0 D(T(x,y)) \frac{\partial c(x,y)}{\partial x}. \tag{2}$$

The values D_0, Q_0 and G_0 are dimensional constants that characterize the rates of diffusion, absorption, and implantation, respectively [2].

The boundary condition is:

$$c(x,0) = c_0(x), \tag{3}$$

where usually $c_0(x) = 0$. Two kinds of boundary conditions are considered at the surface. The first is:

$$c(0,y) = 0, \tag{4}$$

where zero surface concentration is assumed for the helium implantation case. The second boundary condition,

$$D \frac{\partial}{\partial x} c(0,y) = K_{\mathrm{r}} c^2(0,y), \tag{5}$$

which predicts the surface recombination of a diatomic molecule (for D_2 and T_2), where the molecular recombination constant K_{r} can be calculated in various ways [3].

The particle diffusivity D is a measure of particle mobility in the liquid and generally has the form:

$$D = D_0 \exp(-E_{\mathrm{d}}/kT), \tag{6}$$

where D_0 is a material constant, and E_{d} is the migration energy [3].

The details of the implantation of the incident helium and hydrogen isotopes in the near surface layer of liquid Li as plasma-facing material are calculated by using the 3D ITMC Monte Carlo code, which is part of the HEIGHTS package [4]. The mesh size of the implantation zone can be as small as one monolayer thick to accurately predict the effect of the near surface area [2]. The incident particle energy is determined by a number of factors. Higher incident energies than 10 keV will help trap more He particles in the moving Li due to the deeper implantation [2].

Fig. 1 shows the He pumping coefficient calculated as a function of Li flow velocity and He diffusion coefficient for He particles with an incident energy of 1.0 keV [2]. To achieve an adequate He removal rate (approximately 5% removal efficiency, as defined earlier), with a Li diffusion coefficient of $D_0 = 10^{-10}\ \mathrm{m}^2/\mathrm{s}$, the Li velocity should be >20–30 m/s. At higher diffusion coefficients, the required Li velocity is very high, exceeding 100 m/s. To achieve adequate He pumping at higher implantation energies (resulting from the low-recycle regime), reasonable Li velocities of ≈10 m/s could be sufficient [2].

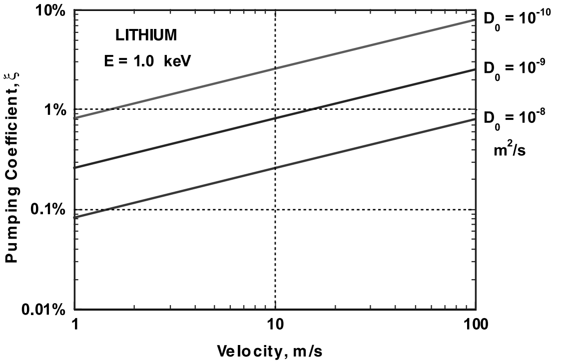

Fig. 1. HEIGHTS calculations of He pumping coefficient as a function of Li velocity at 1-keV incident particle energy.

However, if He bubbles are formed in the flowing Li near the surface layer, significant He trapping can occur [2].

Although the range of the implanted hydrogen isotopes in Li is less than 0.1 μm for an incident particle kinetic energy as high as 1 keV, the calculated rate of surface recombination into hydrogen isotope molecules (and therefore the release rate) is very small. Therefore, in the case of a moving liquid surface, almost all the incident hydrogen isotope is retained in the flowing Li [2].

3. Summary

To pump He at the minimum required rate of about 4–5% of impinging current, one needs a He diffusion coefficient $<10^{-8}$ m^2/s for reasonable liquid velocities. Recent studies suggest that such diffusion values may be feasible. A more important trapping mechanism, suggested by the present author, is bubble formation in the near implantation region. These bubbles (if developed) will trap helium, deuterium, and tritium and effectively enhance the pumping ratio. However, rapid bubble growth and explosion can lead to He detrapping from the moving liquid.

HEIGHTS numerical calculations also indicate that deuterium and tritium particles will be completely pumped by the flowing Li. However, because of several uncertainties, more data are urgently needed on He diffusion and trapping, such as bubble formation and growth in liquids that could significantly alter the kinetics of particle recycling at the liquid surface.

Acknowledgement

Work is supported by the US Department of Energy, Office of Fusion Energy Science, under Contract W-31-109-Eng-38.

References

[1] A. Hassanein, I. Konkashbaev, J. Nucl. Mater. 273 (1999) 326.
[2] A. Hassanein, J. Nucl. Mater. 302 (2002) 41.
[3] K.L. Wilson, Data Compendium for Plasma–Surface Interactions, Nucl. Fusion, Special Issue 1984, IAEA, Vienna, 1984, Chapter 3.
[4] A. Hassanein, J. Nucl. Inst. Meth. Phys. Res. B 13 (1985) 225.