Fusion Engineering and Design 89 (2014) 16–24

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Impact of nuclear irradiation on helium bubble nucleation at interfaces in liquid metals coupled to permeation through stainless steels

J. Fradera*, S. Cuesta-López*

Advanced Materials, Nuclear Technology, Applied Nanotechnology, University of Burgos (UBU), Science and Technology Park, I+D+I Building, Room 63, Plaza Misael Bañuelos, s/n, 09001 Burgos, Spain

ARTICLE INFO

Article history:
Received 9 March 2013
Received in revised form 31 October 2013
Accepted 6 November 2013
Available online 8 December 2013

ABSTRACT

The impact of nucleating gas bubbles in the form of a dispersed gas phase on hydrogen isotope permeation at interfaces between liquid metals, like LLE, and structural materials, like stainless steel, has been studied. Liquid metal to structural material interfaces involving surfaces, may lower the nucleation barrier promoting bubble nucleation at active sites. Hence, hydrogen isotope absorption into gas bubbles modelling and control at interfaces may have a capital importance regarding design, operation and safety.

He bubbles as a permeation barrier principle is analysed showing a significant impact on hydrogen isotope permeation, which may have a significant effect on liquid metal systems, e.g., tritium extraction systems. Liquid metals like LLE under nuclear irradiation in, e.g., breeding blankets of a nuclear fusion reactor would generate tritium which is to be extracted and recirculated as fuel. At the same time that tritium is bred, helium is also generated and may precipitate in the form of nano bubbles.

Phenomena modelling is exposed and implemented in openFROM® CFD tool for 0D to 3D simulations. Results for a 1D case show the impact of a He dispersed phase of nano bubbles on hydrogen isotopes permeation at an interface. In addition, a simple permeator simulation, consisting in a straight 3D pipe is exposed showing the effect of a He dispersed gas phase on hydrogen isotope permeation through different stainless steels. Results show the permeation reduction as a function of the interface area covered by He bubbles.

Our work highlights the effect of gas bubble nucleation at interfaces and the importance of controlling these phenomena in nuclear technology applications.

1. Introduction

Hydrogen isotope transport in matter is a critical issue in current nuclear technologies, from the point of view of design, operation and safety issues. For example, tritium inventory control and confinement is a key issue in nuclear fusion D–T reactors, concerning safety and the fuel cycle. Abundant literature can be found on hydrogen isotopes transport processes and on permeation barrier coatings, but there are no studies on the effect of nucleated bubbles at interfaces on hydrogen isotope permeation. The present work intends to give insight on impact of gas bubbles at interfaces on hydrogen permeation, that is bubbles as a permeation barrier.

Helium nucleated bubbles at interfaces, e.g. at LLE – structural material interfaces of a breeding blanket, can modify the permeation rates significantly. This work assesses this phenomenon, concluding that the impact on hydrogen isotope permeation is not negligible (Fig. 1).

The model described across Section 2 has taken into account the following phenomena:

- Helium nucleation at liquid metals–structural materials interfaces (Section 2.1).
- Hydrogen isotopes permeation through liquid metals–structural materials interfaces in the presence of gas bubbles (Section 2.2).

The availability of a computational tool for tritium inventory evaluation within each sub-system of a fusion reactor, particularly in breeding units, is of great importance regarding design and operation. Key parameters affecting the fuel cycle design may be detected and, after experimental validation, models could be adjusted and T inventory quantified. The TMAP7 code has proven to be helpful for 0D and 1D simulations involving permeation processes and has been validated for tritium transport (see Longhurst

* Corresponding authors.
E-mail addresses: jfradera@ubu.es (J. Fradera), scuesta@ubu.es (S. Cuesta-López).

0920-3796/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.fusengdes.2013.11.002

CFD	computational fluid dynamics
CC	cooling channels
CP	cooling plates
EoS	equation of state
EU'97	EUROFER'97
FEM	finite element method
FVM	finite volume method
HCLL	helium–cooled lithium lead
LLE	lithium lead eutectic alloy
LM	liquid metal
RAFM	reduced activation ferritic martensitic
SM	structural material
SP	stiffening plates
T	tritium

Greek characters

θ	contact angle
κ	effective solubility ratio
π	number pi
ρ	density
σ	surface tension
υ_0	volume of one atom or molecule
ψ	supersaturation ratio

Latin characters

a	specific area
$f(\theta)$	shape factor
Δg	nucleation driving force
k_B	Boltzmann's constant
k_r	recombination coefficient
k_S	Sievert's coefficient
m_0	mass of one atom or molecule
n	material depending exponent
r	radial coordinate
r_b	bubble radius
t	time
$\mathbf{u}$	fluid velocity
C	concentration
D	diffusivity
G	Gibbs free energy
M	molar mass
N_b	concentration of bubbles
P	pressure
R	gas constant
S	source term
T	temperature

Subscripts

abs	absorption into helium bubbles
i	hydrogen isotopes
EU	EU'97
F	fluid
G	gas phase
He	helium
HEN	heterogeneous nucleation
HON	homogeneous nucleation
LM	liquid metal
LLE	lithium lead eutectic alloy
M	membrane
SM	structural material
T, T_2	atomic, molecular tritium

Superscripts

b	bubble
0	pre-exponential
*	critical

[1] and Ambrosek et al. [2]). However, TMAP7 lacks the capabilities and flexibility of a CFD code.

An extensive review of hydrogen isotopes permeation barriers for metal structural materials (SM) in fusion power plants can be found in Hollenberg et al. [3]. Measures of hydrogen permeation have been carried out in the ENEA research center at Brasimone, in the test sets Corelli II [4] and Vivaldi [5,6], where permeation barriers in contact with eutectic lead-lithium have been tested; experiments will continue in the TRIEX facility [7]. Sedano et al. [8] evaluated tritium permeation and extraction for the LIBRETTO-3 experiment (irradiation of LLE capsules coated with different permeation barriers). Tritium permeation barriers in contact with liquid LLE in stainless steel tubes was estudied by Forcey et al. [9], and Nakamichi et al. [10] conducted several in-pile experiments on tritium permeation with ceramic coatings at the research reactor IGV. 1 M, in Kazakhstan, using liquid LLE alloys as the T source.

In terms of theoretical modelling Fukada et al. [11] analytically modelled the permeation of hydrogen isotopes through a plate type metal window, for LM in laminar flow. Farabolini et al. [12] evaluated the main T flows in a fusion plant with HCLL breeding blankets, using a FEM code with a 2D simplified representation of the breeding unit to analyse the blanket system (see, as well, Gabriel et al. [13]). Gastaldi et al. [14] developed a general model to analyse tritium release to the secondary circuit in a HCLL; FEM models were used to determine shape factors in order to correct for geometrical simplifications.

In the present work a specific model for He bubble nucleation at interfaces and bubble growth is presented, which has been implemented in the openFROM® CFD open source code [15] as a new solver. Implemented code is used to analyse He bubbles at interfaces effect on hydrogen isotope permeation.

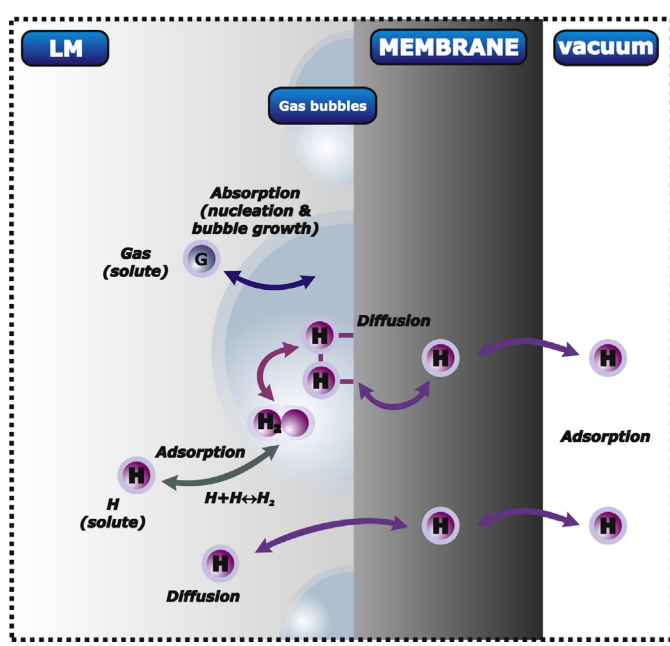

Fig. 1. Hydrogen isotope and helium transport phenomena in a permeation system.