Nuclear Engineering and Design 324 (2017) 171–180

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Scaled experiment investigating sonomechanically enhanced inert gas sparging mass transfer

Floren Rubio[a], Leonard Bond[b], Edward Blandford[a,*]

[a] Department of Nuclear Engineering, University of New Mexico, MSC01 1120, 1 University of New Mexico, Albuquerque, NM 87131-0001, United States
[b] Center for Nondestructive Evaluation, Iowa State University, Ames, IA 50011, United States

ARTICLE INFO

Keywords:
Keywords: Ultrasonics
Sonomechanical enhancement
Flibe
FHR
Tritium
Scaled experiment

ABSTRACT

One of the leading advanced reactor concepts is the fluoride salt high temperature reactor (FHR) currently under investigation. This design utilizes a fluoride molten salt, flibe ($2\ LiF/BeF_2$), as the primary coolant. One challenge of employing flibe as a coolant is the production and release of tritium. The FHR community is currently investigating various techniques to solve this tritium management challenge. One of the methods investigated is inert gas sparging which has been investigated during the Molten Salt Reactor Experiment (MSRE) in the 1960's and 1970's. To enhance the efficiency of this technique, high power ultrasonics can be employed to sonomechanically enhance the mass transfer performance. Initial experimental studies coupling ultrasonics and inert gas sparging have been performed in the scaled ultrasonic mass transfer (SUMATRA) experiment. The scaling was done by matching the *Sc* between a water/glycerol mixture and flibe at FHR temperatures. The SUMATRA experiment evaluated the performance of inert gas sparging with and without ultrasonic enhancement. The results show a significant performance enhancement due to the sonomechanical effect which is contributed to an increase in the diffusive mass transfer contribution due to bubble breakup and the subsequent increase interfacial area.

1. Introduction

The use of liquid fluoride salts has an extensive history of consideration for use as a working fluid in high temperature nuclear applications such as inertial confinement fusion reactor and molten salt reactor (MSR) (Cadwallader and Longhurst, 1999; McNeese, 1971; Rosenthal et al., 1970), including the fluoride salt high temperature reactor (FHR). Such FHRs differ from fluid-fueled MSRs in that they employ a solid fuel form (Andreades et al., 2014). Of all the possible candidate salts, a eutectic mixture of lithium fluoride and beryllium fluoride, flibe, was chosen for the Molten Salt Reactor Experiment (MSRE) and subsequently the FHR for its relatively high thermal conductivity and favorable neutronic performance (Robertson, 1965). However, when in a neutron flux, flibe is a significant source of tritium through the reaction pathways given in Eqs. (1)–(3).

$$^{6}_{3}\mathrm{Li} + ^{1}_{0}n \rightarrow ^{4}_{2}He + ^{3}_{1}H \tag{1}$$

$$^{7}_{3}Li + ^{1}_{0}n \rightarrow ^{4}_{2}He + ^{1}_{0}n + ^{3}_{1}H \tag{2}$$

$$\begin{gathered} ^{9}_{4}Be + ^{1}_{0}n \rightarrow ^{4}_{2}He + ^{6}_{2}He \\ ^{6}_{2}He \rightarrow ^{6}_{3}Li + \beta^{-} + \gamma \\ ^{6}_{3}Li + ^{1}_{0}n \rightarrow ^{4}_{2}He + ^{3}_{1}H \end{gathered} \tag{3}$$

In the Mark 1 Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor (PB-FHR) design, reported by the University of California, Berkeley in 2014 (Andreades et al., 2014), this mechanism is projected to result in a tritium production rate of 2508 Ci/day for a 236 MWth core, which is much larger than that seen for a current commercial pressurized water reactor (PWR) (1.99 Ci/day) (NRC; FHR, 2013). A crucial engineering challenge of the technology is to address tritium release mitigation. Key tritium escape regions and strategic tritium removal points can be identified for the Mark 1 PB-FHR as shown in Fig. 1. Various strategies that have been or are currently being investigated include graphite adsorption, mass permeators, barrier coatings, and inert gas sparging (Forsberg et al., 2017, 2014; Kress, 1972). Each proposed strategy has its own advantages and disadvantages. The use of inert gas sparging has the unique potential to not only remove, but also, sequester tritium through a process stream. The process efficiency is not as high as would be liked and options that can enhance the process are being sought, and one such approach is to use high power

---

* Corresponding author.
E-mail address: edb@unm.edu (E. Blandford).

http://dx.doi.org/10.1016/j.nucengdes.2017.08.016
Received 15 May 2017; Received in revised form 14 August 2017; Accepted 16 August 2017

Nomenclature

δ	Boundary layer thickness (m)
ε	Gas holdup
κ	Polytropic coefficient
$k_L a$	Volumetric mass transfer coefficient (1/s)
$\mathscr{D}$	Mass Diffusivity (m^2/s)
μ	Dynamic viscosity (Pa s)
ν	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
σ	surface tension (N/m)
a	Interfacial area (m^2/m^3)
C	DO Concentration (mg/L)
C_0	Initial DO concentration (mg/L)
d_{avg}	Average bubble diameter (m)
f	Frequency (hz)
fps	frames per second
k_L	Liquid side mass transfer coefficient (m/s)
L	Characteristic length (m)
N	Number density ($1/m^3$)
p_0	Ambient pressure (Pa)
Re	Reynolds number
S	Renewal Frequency (Hz)
Sc	Schmidt number
Sh	Sherwood number
t_e	Exposure time (s)
U	Velocity (m/s)

ultrasonics (Rubio et al., 2016).

High powered ultrasonics (in the cavitation regime) have been used and investigated for its enhancement for both degassing of metal melts (Naji Meidani and Hasan, 2004; Xu et al., 2008) and mass transfer properties in chemical reactors (Riera et al., 2009; Al Taweel et al., 2005; Gogate et al., 2010; Laugier et al., 2008; Rooze et al., 2013; Sainz Herrán et al., 2012; Ensminger and Bond, 2011). It would appear that there is potential for the use of high power ultrasonics to enhance the sparging mass transfer and tritium removal (Rubio et al., 2016). Although there are a diverse range of engineering challenges in implementing this technique for tritium removal, there would appear to be potential opportunities for the incorporation of high power ultrasonics for tritium removal in the FHR (Rubio et al., 2016, 2014).

This paper reports an exploratory reduced-scale investigation of sonomechanical enhancement of inert gas sparging, which is demonstrated over a range of Schmidt numbers (Sc), the ratio of momentum vs molecular diffusivity, that will encompass the planned operating temperature of the proposed the FHR facility. Visual and system and material process parameters for the dissolved oxygen (DO) measurements are used to investigate and quantify the mechanism of sparging enhancement could be determined. A working model was developed and is presented.

2. Theory

The governing phenomena utilized for this application is two-phase mass transfer, between the host sparging gas bubble and soluble tritium in liquid phase and changes in the behavior due to the imposition of an acoustic field, at some specific intensity and operating parameters (temperature and pressure). Analysis of the combination of these two fundamental topics is essential in understanding and quantification of the effectiveness of the specific phenomenology of the proposed potential sonomechanically enhanced mass transfer mechanism. In order to conveniently investigate phenomena at the FHR conditions, a scaled experiment is required.

2.1. Scaling approach

The scaling in the current study is rested on the demonstration of appropriate relationships in matching properties in the glycerol/water and flibe includes matching Sc, which is the ratio of the convective and diffusive forces on mass transfer, through the fluid properties, namely density ρ, dynamic viscosity μ, and diffusivity $\mathscr{D}$. The very basis of reduced-scaled experiment is establishing physical similitude between the model and the prototype through preserving geometric, kinematic, and dynamic similarity. This means that the general shape, flow profiles,

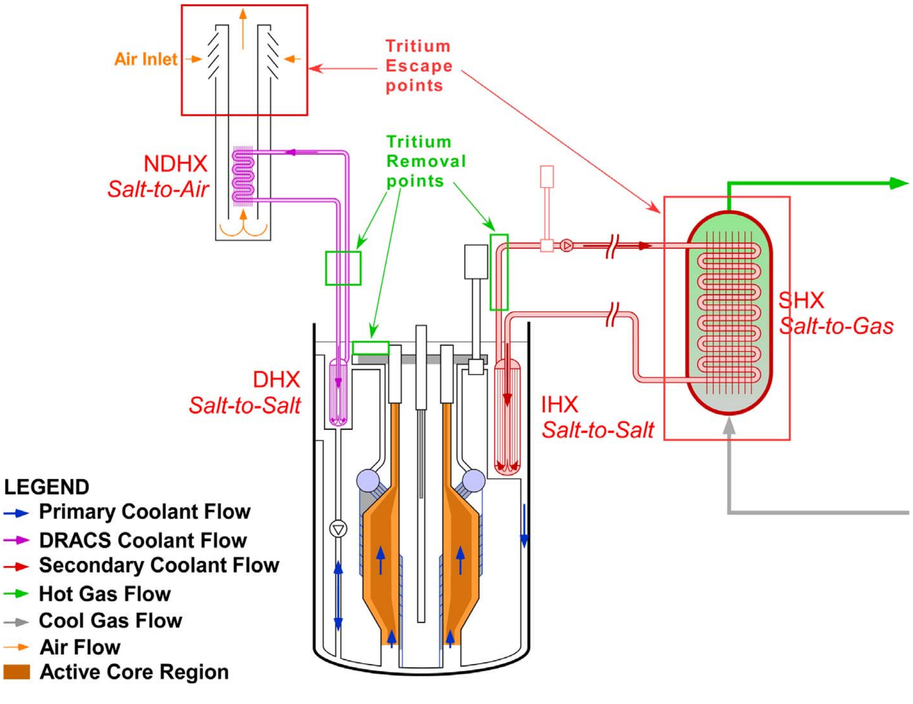

Fig. 1. Diagram of an FHR. Highlighted are areas where tritium has a high potential of release and areas where a tritium removal system can be most beneficial.