Nuclear Engineering and Design 294 (2015) 16–23

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Detection of gas entrainment into liquid metals

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HIGHLIGHTS

- We present liquid metal experiments dedicated to gas entrainment on the free surface.
- Ultrasonic and X-ray attenuation techniques have been used to study the mechanisms of gas entrainment.
- A comparison between bubbly flow in water and GaInSn showed substantial differences.
- Our results emphasize the importance of liquid metal experiments which are able to provide a suitable data base for numerical code validation.

ARTICLE INFO

Article history:
Received 29 January 2015
Received in revised form 29 May 2015
Accepted 4 July 2015
Available online 21 September 2015

ABSTRACT

Entrainment of cover gas into the liquid metal coolant is one of the principal safety issues in the design of innovative liquid metal-cooled fast reactors. We present generic experimental studies of this phenomenon in low-melting metals. Ultrasonic and X-ray diagnostic tools were considered for a visualization of gas entrainment at the free surface of the melt. Laboratory experiments were conducted using the eutectic alloy GaInSn, which is liquid at room temperature. Vortex-activated entrainment of air at the free surface of a rotating flow was revealed by ultrasonic techniques. X-ray radioscopy was used to visualize the behavior of argon bubbles inside a slit geometry. The measurements reveal distinct differences between water and GaInSn, especially with respect to the process of bubble formation and the coalescence and breakup of bubbles. Our results emphasize the importance of liquid metal experiments which are able to provide a suitable data base for numerical code validation.

1. Introduction

Controlling gas entrainment at the free surface of the liquid pool is one of the thermo-hydraulic challenges for operating liquid metal cooled fast reactors (Tenchine, 2010). The entrainment of a significant amount of cover gas by the liquid metal flow carries the risk that bursts of gas bubbles may run through the reactor core, causing a change in reactivity. Moreover, the occurrence of bubbles near the fuel rods impairs heat removal, or the gas may cause other operational problems, such as fluctuations in the pump discharge. Several mechanisms for bubble entrainment are possible in liquid metal cooled reactors (Baum and Cook, 1975; Madarame and Chiba, 1990): vortex activated entrainment, entrainment due to surface waves, and liquid fall entrainment. The main source of entrapped gas is the presence of either van-Karman vortices behind immersed structures or so-called "bathtub" vortices developing in rotating flows. A great deal of work has been conducted so far by many research groups to study the mechanisms of gas entrainment and identify efficient measures for mitigating this phenomenon (see, for instance, Banerjee and Padmakumar, 2009; Baum and Cook, 1975; Eguchi et al., 1994; Madarame and Chiba, 1990; Patwardhan et al., 2012; Satpathy et al., 2011; Yamaguchi et al., 2011). The majority of publications deal with numerical simulations and experimental studies using water models. Because of the lack of suitable measuring techniques, the number of experimental studies providing data from liquid metal flows is relatively low. However, new, innovative diagnostic tools based on ultrasonic, inductive and radiation techniques have been developed in the last decade, which enables effective studies of real liquid metal flows (Eckert et al., 2007, 2011).

In this paper we want to demonstrate the capabilities of ultrasonic techniques and X-ray radioscopy to detect gas entrainment at the free surface of liquid metal flows. We present two experiments here. The first considers a liquid metal flow that forms a tornado-like vortex with a funnel-shaped surface depression and

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http://dx.doi.org/10.1016/j.nucengdes.2015.07.072
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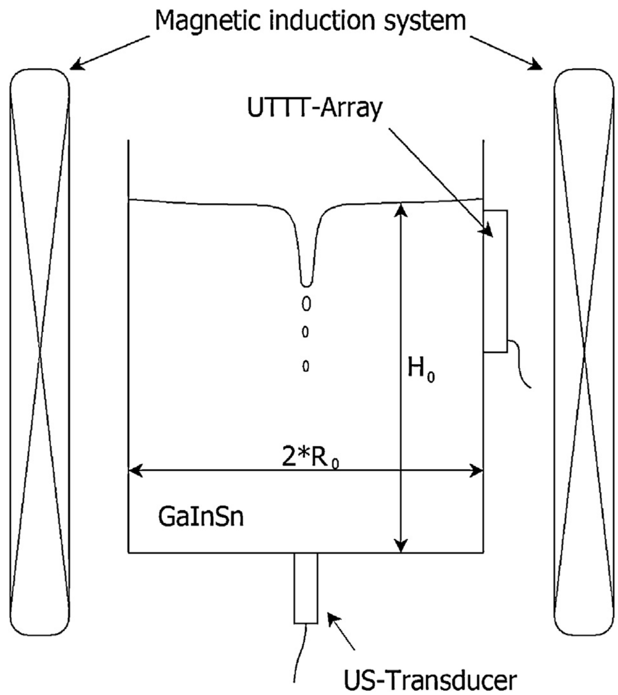

Fig. 1. Schematic drawing of the experimental setup.

incidental gas entrainment. Such vortex flows can be generated in liquid metals by the combined action of a rotating and a traveling magnetic field. The flow configuration is similar to that described in Vogt et al. (2013). Two different ultrasonic methods were used to track the position of the free surface and to detect gas bubbles entrapped inside the bulk liquid. Another experiment employs X-ray radioscopy to visualize rising gas bubbles in a rectangular box. The bubbles drive an intensive jet-like flow, which generates perturbations and waves at the free surface. The X-ray images show the entrainment of individual bubbles at outlying positions with respect to the bubble jet.

2. Vortex-induced gas entrainment

The spin-up of a concentrated, tornado-like vortex in a liquid metal bath was realized experimentally on a laboratory scale by using two independent magnetic body forces provided by a rotating magnetic field (RMF) and a vertically traveling magnetic field (TMF). The continuously applied RMF provides the source of angular momentum. A TMF pulse, about one order of magnitude stronger than the RMF, focuses this angular momentum toward the rotational axis and forms an intense, tornado-like vortex that induces gas entrainment at the bottom of this vortex funnel. The surface deformation and the gas entrainment into the liquid metal were observed by both the ultrasound Doppler method (Section 2.2) and the ultrasound transit-time-technique (UTTT, Section 2.3).

2.1. Experimental description

Fig. 1 shows a schematic drawing of the experimental setup. The experiments were carried out in the PERM magnetic induction system at Helmholtz-Zentrum Dresden-Rossendorf. The PERM stirrer provides a 200 mm bore and is designed to create a RMF with magnetic induction up to $B_R = 17$ mT and a TMF up to $B_T = 20$ mT. The actual magnetic induction applied in this experiment is on the order of $B_R \sim 1$ mT and $B_T \sim 10$ mT. The frequency of the RMF is $\omega_R/2\pi = 30$ Hz, while that of the TMF is $\omega_T/2\pi = 60$ Hz. These different frequencies were chosen in order to keep the interaction between the RMF and TMF low. Two cylindrical vessels made of Perspex were placed alternatively in the middle of the 200 mm bore of the induction coils. The first cylinder had an inner diameter of $D_0 = 2 \times R_0 = 170$ mm and was filled up to a height of $H_0 = 170$ mm with the eutectic alloy GaInSn, which is liquid at room temperature. Material properties of the GaInSn alloy can be found in Plevachuk et al. (2014). The UTTT measurements require the attachment of a sensor array at the sidewall of the vessel. Because of the limited size of the induction system a smaller cylinder with an inner diameter of $D_0 = 90$ mm was used for that purpose and filled up to a height of $H_0 = 140$ mm. The free surface of the liquid metal in both cylinders was covered with a thin hydrochloric acid layer in order to avoid oxidation of the GaInSn alloy.

At the beginning of each measurement the liquid metal was set into a quasi-stationary swirling motion by the RMF. At time $t = 0$ s the rotating liquid metal is exposed to a strong, upwards-directed TMF. The following transient flow pattern is dominated by the formation of a tornado-like flow pattern along the rotational axis of the liquid metal. An example of the vortex funnel is shown in Fig. 2 The tornado can be clearly observed only during the first couple of seconds where the flow field is laminar and axisymmetric. After a few seconds, the flow becomes highly turbulent and the liquid metal tornado breaks down into turbulent spots. The vortex features mainly depend on the magnetic induction ratio of the TMF to the RMF. This ratio can be expressed in terms of non-dimensional parameters (F and Ta) as follows:

$$\frac{F}{Ta} = \frac{\omega_T}{\omega_R} * \frac{B_T^2}{B_R^2} * \frac{\kappa R_0}{2}$$

In this equation, ω_T and B_T stand for the frequency and amplitude of the TMF, respectively. Accordingly, ω_R and B_R denote the frequency and amplitude of the RMF. $\kappa = 21.8\ \mathrm{m}^{-1}$ is the wave number of the TMF. The higher the F/Ta ratio, the deeper the tornados funnel. But also, the deeper the tornados funnel, the narrow it becomes. In addition to the force ratio F/Ta, the absolute value of F plays an important role as well. If F is sufficiently high (on the order of 10^{10}), bubbles are formed at the bottom of the vortex funnel. After their formation, the bubbles are dragged into the liquid since the liquid metal flows downwards along the axis of the vortex.

Immediately after the TMF is switched off, the bubbles emerge at the free surface (Fig. 3(b)) For a more detailed description of the underlying fluid dynamics, we refer to Vogt et al. (2013), since we will focus on the detection of the bubbles in this flow configuration.

2.2. Interface detection by ultrasound impulse echo technique

The surface deformation and the detection of the entrained bubbles were realized using a modified ultrasound Doppler velocimetry (UDV) system. The UDV technique is based on an impulse echo technique and is suitable for measuring instantaneous velocity profiles in opaque fluids. It was adopted by Takeda (1991) for experimental fluid dynamics. These days, ultrasound Doppler velocimetry has become an accepted measuring technique for flow investigations in various liquid metals such as mercury (Takeda et al., 1998), sodium (Eckert and Gerbeth, 2002) or alloys up to temperatures of about 700 °C (Eckert et al., 2003). In the present study, we used the DOP2000 velocimeter (model 2125, Signal Processing SA, Lausanne) equipped with a 4 MHz (TypeTR0411SS, acoustic active diameter 10 mm) transducer that was placed at the bottom wall of the vessel such that the ultrasonic beam coincides with the rotational axis of the cylindrical vessel. Instead of measuring fluid velocities, we used the UDV-device to detect the liquid metal interface by recording the ultrasound echo of the free surface and the echoes from the entrained gas bubbles. Therefore, the sensitivity of the UDV device was reduced significantly in order to