Progress in Nuclear Energy 99 (2017) 1–10

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

Experimental study on thermal-hydraulic behaviour of LBE and water interface

Wangli Huang, Danna Zhou*, Rongyuan Sa, Hualei Jiang

Key Laboratory of Neutronics and Radiation Safety, Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, Hefei, Anhui 230031, China

A R T I C L E I N F O

Article history:
Received 4 August 2016
Received in revised form
17 March 2017
Accepted 4 April 2017

Keywords:
Steam generator tube rupture
Molten LBE
Fragmentation
Steam explosion
Interfacial instability

A B S T R A C T

For the design and safety studies of steam generator in the China LEAd-based Reactor (CLEAR) project, it is necessary to investigate the consequences of a Steam Generator Tube Rupture (SGTR) accident which could result in a reaction between Lead-Bismuth Eutectic (LBE) and highly pressurised water. Some experiments have been conducted to investigate the thermal-hydraulic behaviour of the molten LBE/water interface; the whole fragmentation processes of these experiments were visually observed with a high-speed video camera, and the transient pressure histories were measured by high-frequency piezoelectric pressure sensors. The effects of LBE temperature, water temperature, nozzle diameter and injection velocity were investigated. Visualisation films indicated that the explosion phenomenon happened readily at lower water temperature. The peak pressure decreased with increasing water temperature, nozzle diameter and injection velocity. However, the peak pressure first increased and then decreased as the LBE temperature increased. The shape of the debris became round at higher water temperature, and a needle-like shape was observed at lower temperatures. Debris analysis results showed that the debris sizes of 2.8–6.7 mm had the largest mass fraction. By comparison with the theoretical calculation, it was found that the fragment diameters measured in the present study agreed well with Weber number theory. Thus, it was demonstrated that the fragmentation mechanism was controlled by shearing stress under the present experimental conditions.

1. Introduction

Lead-bismuth eutectic (LBE), due to its favourable properties, such as the low melting point, excellent neutron performance, high thermal conductivity and low chemical activity, has been considered as one of the most promising candidate materials for primary coolant and spallation target in accelerator driven systems (ADSs) (Zhan and Xu, 2012). In recent years, the research and development for ADS programs has been launched by the Chinese Academy of Sciences (CAS), and the Institute of Nuclear Energy Safety Technology (INEST) has undertaken the responsibility to design the reactor, named the China LEAd-based Reactor (CLEAR) and to adopt LBE as the coolant (Wu et al., 2016). With plenty of experience in the design and technology of fusion reactors (Wu et al., 2006, 2011; Qiu et al., 2000; Wu, 2007; Wu et al., 2008; Chen and Wu, 2000; Wu et al., 2007a,b) as well as in the related design and simulation analysis of the Dual-Functional Lithium Lead (DFLL) blanket (Wu, 2002; Wu et al., 2007a,b, 2009a,b, 2015) and materials research (Wu et al., 2009a,b; Huang et al., 2007; Wu et al., 2002; Li et al., 2007; Huang et al., 2004, 2009), a series of LBE test facilities, named KYLIN loops, have been constructed to investigate specific topics, such as the corrosion behaviour of structural materials and thermal-hydraulic and safety features (Wang et al., 2014; Lyu et al., 2016; Liu et al., 2016; Lu et al., 2014; Yao et al., 2015).

Based on the concept design of CLEAR, Steam Generator Units (SGUs) are put inside the reactor vessel in direct contact with the LBE coolant. Due to the tough working conditions (i.e. high temperature, high pressure, corrosion risk etc.) in the secondary water loop, the probability of a tube rupture in the SGU is not negligible. Therefore, it is important to investigate the effect of a Steam Generator Tube Rupture (SGTR) accident in the design and safety assessment of CLEAR. Within the postulated accident, highly pressurised water directly contacts the primary coolant, forming a dynamic thermal Coolant-Coolant Interaction (CCI), which could trigger various transients and enhance the risk to structural integrity. The rapid vaporisation of the discharged water can lead to sloshing of the LBE pool with strong mechanical impact of the

* Corresponding author.
E-mail address: danna.zhou@fds.org.cn (D. Zhou).

http://dx.doi.org/10.1016/j.pnucene.2017.04.005

heavy liquid on structures. Besides, a severe pressure build-up can lead to radial core compaction processes as well (Wang et al., 2008). For a complete understanding of the evolution process of a SGTR accident, the initial phase of the accident, when the molten LBE and water initially contact each other, is very important and should be investigated with high priority.

Some experiments and simulations have been carried out to investigate the interaction of lead-alloy with water. Flory et al. (1969). conducted some experiments to investigate the interaction of lead with water. It was found that concentric rings were formed on the surface of lead droplets and then an outward burst occurred when the lead temperature reached 500 °C. The hypothesis of surface instability as a mechanism was supported by the experiments. Witte et al. (1973). investigated the fragmentation phenomena quenching pure lead, zinc and bismuth in water and liquid nitrogen. No fragmentation was observed when molten lead droplets (427–589 °C) were dropped into water (26.7–35.0 °C). Abe et al. (2002). conducted two kinds of experiments to identify the process of vapour explosion, and investigated the trigger mechanisms of vapour explosion using an external pressure pulse. The results showed that no spontaneous vapour film collapsed and no large pressure was generated even under an external pressure pulse. Sa et al. (2011a, 2011b) studied the thermal interaction zone (TIZ) related to the lead-alloy/water interaction by conducting some small-scale experiments to clarify the effect of the temperatures of lead-alloy and water. Ciampichetti et al. (2009, 2011). injected pressurised water into an LBE pool to simulate the SGTR accident in the LIFUS 5 facility, and a rapid system pressurisation was detected. Sibamoto et al. (2007). and Park et al. (1999). applied high-frame-rate neutron radiography techniques to research the penetration and boiling behaviours of a plunging water jet into a molten LBE pool. Pesetti et al., 2016a,b). performed experiments to investigate the postulated SGTR event in LIFUS5/Mod2. They injected pressurised subcooled water into the reaction tank partially filled with LBE at 400 °C, and fast-pressure transducers, thermocouples and strain gauges were used to provide high-quality measurement data. In addition, assessment and analysis of the SGTR experiments in the LIFUS5/MOD2 facility was carried out by SIMMER-III code (Pesetti et al., 2016a,b). The numerical analysis provided injection line and reaction tank pressurisation in agreement with the experimental data. The SIMMER-III also analysed the volume fraction point of view and the energy released in the total reaction tank and in its cover gas. Del Nevo et al (Del Nevo et al., 2016). using the SIMMER-III code to investigate the safety issues raised for the operation of CIRCE-ICE facility, and some LBE/water reaction experiments were executed in the LIFUS-5 test facility. Wang et al. (2008). used the SIMMER-III code to investigate the phenomenology and physics of thermal and hydraulic interactions between water and liquid LBE. Cheng et al. (2015). used the SIMMER-III code to investigate the metal/water interaction, interaction characteristics including the pressure buildup, as well as the release of mechanical energy and its conversion efficiency. Lu et al. (2016). used lead and bismuth as the metal samples to investigate the breakup process when highly superheated molten metal falls into the subcooled coolant during the FCI process. They found that the breakup process was significantly restricted by the high melting point of the metal, and the high surface tension, viscosity, and thermal conductivity, and low specific heat of the molten metal. Meanwhile, increasing the coolant temperature and the temperature of molten lead could obviously restrict or prevent the breakup process. Pillai et al. (2016). studied the fragmentation of molten aluminium and lead jets in bulk coolant and compared the particle size from experiments with theoretical analysis. It was found that the predicted values agreed well with the experimental results Moreover, the thermophysical properties of the metals play a crucial role in the fragmentation.

The above study provided some knowledge and experience on the interaction of lead-alloy and water, but the molten LBE/water interaction has rarely been studied in medium-scaled experiments, and the breakup process and physical mechanism is also unclear. Some preliminary work related to the LBE/water interaction at a medium scale has been done by Huang et al. (2015), but it was not enough to understand comprehensively the interaction between molten LBE and water, or the underlying physical mechanism. The interfacial dynamic behaviours of LBE/water in direct contact play a major role in LBE jet breakup and it may further trigger a violent vapour explosion, so it is very important to investigate the interfacial behaviour in details. Consequently, more experiments should be conducted, and the interfacial behaviour of LBE/water in direct contact, which would be the origin of the accident, should be investigated in detail to understand mechanisms of rapid violent boiling.

In this study, experiments of LBE/water interaction have been conducted and the transient pressure histories were measured by high-frequency piezoelectric pressure sensor. The effects of LBE temperature, water temperature, nozzle diameter and injection velocity were observed and investigated. The debris was collected and sieved, and the results compared with existing fragmentation theories.

2. Experiment

2.1. Experimental apparatus

The test facility for molten LBE and water interaction was designed as shown in Fig. 1. The main components are an electric furnace, a water tank and a data acquisition system. The design temperatures of molten LBE and water are 250–600 °C and 20–80 °C, respectively. The temperatures of LBE were set based on the design specification of CLEAR-I. To examine the effect of coolant subcooling, the water temperature was kept the same as the subcooled water based on the design values of CLEAR-I (230 °C, 4 MPa), which represents the same water subcooling as a water temperature of 80 °C at normal atmospheric pressure. The whole process of LBE/water interaction was monitored by a high-speed video camera. The change of pressure and temperature was recorded by transducers at the same time. The electric furnace was designed to heat solid LBE to different temperatures. A crucible was located inside the furnace with an inner diameter and height of 90 mm and 190 mm, respectively. A nozzle with its opening being plugged by a conical-shaped rod was designed at the bottom of the crucible, and the rod was used to prevent the leakage of molten LBE and also to control the free fall of molten LBE. A continuous flow of Ar gas was supplied to protect the molten LBE against oxidation during heating. The water tank is composed of stainless steel and a transparent quartz glass window (ø 250 mm × 800 mm) allowed the observation and recording of the process of molten LBE/water interaction. The bottom plate of the tank collected the debris produced.

2.2. Instrumentation

A cylindrical heater furnace (1 kW rating) was used to heat the molten LBE. The melting temperature was monitored by a sheathed K-type thermocouple on the top cover of the crucible. A 4 kW electric immersion heater was used to heat the water, and temperature controller with a thermocouple sensor was used to control the water temperature at the desired level.

A Kistler quartz piezoelectric pressure transducer with a frequency of 80 kHz was applied to measure the transient pressure signals for the LBE/water interaction. The pressure transducer was