Experimental study on fragmentation behaviors of molten LBE and water contact interface (Postprint)

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Abstract

Based on the design of CLEAR (China LEAd-based Reactor), it is important to study the molten LBE (Lead-Bismuth Eutectic)/water interaction following an incidental steam generator tube rupture (SGTR) accident. Experiments were carried out to investigate the fragmentation behavior of the molten LBE/water contacting interface, with a high-speed video camera to record the fragmentation behavior of 300-600 ℃ LBE at 20 ℃ and 80 ℃ of water temperature. Violent explosion phenomenon occurred at water temperature of 20 ℃, while no explosion occurred at 80 ℃. Shapes of the LBE debris became round at 80 ℃ of water temperature, whereas the debris was of the needle-like shape at 20 ℃. For all the molten LBE and water temperatures in the present study, the debris sized at 2.8-5.0 mm had the largest mass fraction. The results indicate that the dominant physical mechanism of the molten LBE fragmentation was the Kelvin-Helmholtz instability between LBE/water direct contact interface.

Full Text

Preamble

Experimental Study on Fragmentation Behaviors of Molten LBE and Water Contact Interface

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Abstract: Based on the design of CLEAR (China LEAd-based Reactor), studying the molten LBE (Lead-Bismuth Eutectic)/water interaction following an incidental steam generator tube rupture (SGTR) accident is important. Experiments were carried out to investigate the fragmentation behavior of the molten LBE/water contacting interface, using a high-speed video camera to record the behavior of 300–600 °C LBE in water at 20 °C and 80 °C. A violent explosion phenomenon occurred at a water temperature of 20 °C, while no explosion occurred at 80 °C. The shapes of LBE debris became round at 80 °C water temperature, whereas the debris exhibited needle-like shapes at 20 °C. For all molten LBE and water temperatures in the present study, debris in the size range of 2.8–5.0 mm had the largest mass fraction. The results indicate that the dominant physical mechanism of molten LBE fragmentation was Kelvin-Helmholtz instability at the LBE/water direct contact interface.

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

The Accelerator Driven System (ADS) was motivated by remarkable potentialities for transmutation of long-lived nuclear wastes from the operation of nuclear power plants (NPPs) [**?**]. A project has been implemented to develop ADS technology in China. Based on experiences of designing fusion reactors and the successful design and development of a series of PbLi test facilities named DRAGON series, the FDS team has undertaken the ADS project and proposed and developed the concept of China LEAd-based Reactor (CLEAR). Lead-bismuth eutectic (LBE), due to its good thermal-physical and chemical properties, was chosen as the spallation target and primary coolant material [**?**]. LBE test facilities named KYLIN loops have been built to explore related technologies such as compatibility with structural materials, thermal-hydraulic characteristics, and safety features \cite{3-15}.

In order to extract thermal power from the main vessel, steam generator units (SGU) of CLEAR are placed inside the reactor vessel and immersed in the primary coolant (LBE). Housed in the SGU under harsh working conditions (i.e., high temperature, high pressure, corrosion, etc.), the secondary water loop and large number of pipes necessitate investigation of steam generator tube rupture (SGTR) accident impacts in design and safety studies. In this postulated accident, highly pressurized water blasts into the low-pressure primary coolant, forming a thermal coolant-coolant interaction (CCI), similar to a fuel-coolant interaction (FCI) during a severe NPP accident, which triggers various transients and evokes structural risks, causing escalation of the accident. A CCI with sudden vaporization of discharged water can initiate sloshing motion of the heavy primary coolant, inducing strong impact pressures that may challenge vessel integrity. Severe pressure build-up can also lead to radial core compaction processes [?]. Therefore, it is significant to investigate the SGTR accident in the design and construction of China LEAd-based Research Reactor (CLEAR-I) and to explore protection and mitigation measures against the accident. To better understand the SGTR accident, the fragmentation procedure of molten LBE when it contacts water should be studied because it may form a large-scale accident. This study can help disclose local heat transfer behavior in micro-interactions between the two liquids.

The interaction of molten lead-alloy with water has been investigated in different experiments. Flory et al. [?] reported direct contact interaction of lead with water to support the hypothesis of surface instability as a mechanism. Outward burst was observed for lead droplets at 500 °C. Furuya et al. [?] investigated trigger mechanisms of vapor explosions by impinging water droplets on lead-bismuth and lead; however, vapor explosion phenomenon was not observed when a water droplet was dropped into molten lead and lead-alloy. Sa et al. [?, ?] poured small-scale molten lead-alloy droplets into subcooled water and found that peak pressure in fragmentation of LBE droplets increased with droplet temperature, but no difference was observed with increasing water subcooling temperature. Li et al. [?, ?] obtained particle size distribution in water from LBE fragmentation at lower molten temperatures. Park et al. [?] and Sibamoto et al. [?] applied high-frame-rate neutron radiography technique to observe penetration and boiling behavior of a plunging water jet in a molten LBE liquid pool. Ciampichetti et al. [?, ?] injected water into LBE to simulate the SGTR accident in the LIFUS 5 facility, and fast system pressurization was detected. On the other hand, using SIMMER-III code, Wang et al. [?] evaluated a postulated SGTR accident in a lead-cooled accelerator driven system.

However, molten LBE and water interaction was rarely studied in medium-scale experiments. The interfacial behavior of LBE/water direct contact should be investigated in detail to understand mechanisms of rapid violent boiling and the consequent accident. In the present study, thermal-hydraulic behavior of the molten LBE/water interface was visually observed with a high-speed video camera at different temperatures of LBE and water. The visual information was analyzed to determine fragmentation behavior and steam explosion characteristics. The results were compared with existing theories, and it was found that Kelvin-Helmholtz instability could be the most probable reason for molten LBE/water interface breakup.

II. Experiment

A. Experimental Apparatus

Figure 1 [Figure 1: see original paper] shows schematically the experimental apparatus consisting mainly of an electric furnace, a crucible, and a water tank. The crucible, made of stainless steel, is located inside the furnace of $ $190 mm × 90 mm. LBE was melted in the crucible with an electric heater. At the crucible bottom there is a nozzle with its opening plugged by a conical-shaped rod, which is raised by a stepping motor actuator at the time of melt delivery. Ar gas is supplied via a regulator to protect molten LBE from oxidation. The water tank, of $ $250 mm × 800 mm, is composed of stainless steel with a quartz glass window to observe molten LBE/water interaction behavior using the camera. A plate at the tank bottom is used to collect post-test debris products.

B. Instrumentation

A cylindrical radiant heater furnace (1 kW rating) was used to heat molten LBE. Temperature was monitored by a sheathed K-type thermocouple on the top cover of the crucible. A 4 kW immersion electric heater was used to heat water whenever needed, with a thermocouple sensor to control water temperature. A high-speed video camera was installed to record video images of the molten LBE breakup process at 5740 frames per second.

C. Experimental Procedure and Test Conditions

When the furnace and water tank were heated to desired temperature setpoints, the stepping motor raised the plug to open the nozzle and inject the melt jet into water. Fragmentation and breakup behavior of molten LBE in water was observed by the video camera. After each test, water was drained from the tank and debris was collected and dried. Particle size distribution of fragmented debris was obtained by mechanical sieving using a stack of sieves from 0.5–10 mm. The inventory of poured metal was about 450 g. Molten LBE temperatures were 300, 400, 500, and 600 °C. Water temperatures were 20–80 °C, ranging from room temperature to temperatures related to design specifications of CLEAR-I, which is to be operated at 230 °C and 4 MPa, equivalent to water subcooling temperature of 80 °C in normal atmosphere. The nozzle diameter was 300 mm, the initial jet velocity was 2.42 m/s, and the free fall distance from nozzle to water surface was 5 mm. All experiments were performed in atmosphere.

III. Results and Discussion

Temperature effects on melt fragmentation were studied with LBE at 300, 400, 500, and 600 °C, at water temperatures of 20 °C and 80 °C. Figure 2 [Figure 2: see original paper] shows fragmentation behaviors, solidified fragments, and debris size distributions at water temperature of 20 °C.

In Fig. 2(a), extensive explosion was observed at 400, 500, and 600 °C. Taking the 400 °C LBE case as an example, instability can be seen clearly at the melt side at 3.484 ms, and slight expansion and explosion can be observed from the melt front extending upward at 6.968 ms. As the center column of molten LBE decreased and disappeared, violent explosion occurred at 14.634 ms. This is because when molten LBE at higher temperatures was injected into water, steam produced at the contact interface was immediately broken up due to the 20 °C water. This induced disturbances of the contact interface, leading to further contact of molten LBE with more unstable steam and finally resulting in vapor explosion. Additionally, molten LBE at higher temperatures, due to its lower viscosity and surface tension, is easier to break up into fine particles through the coupling interaction of hydrodynamics and unstable disturbances. However, no explosion was observed throughout the whole course at 300 °C.

The debris shown in Fig. 2(b) exhibits flake and needle shapes for LBE at 400, 500, and 600 °C, while long strip and helix shapes appear for LBE at 300 °C. This is because internal energy of 300 °C molten LBE is too low to produce unstable steam at the contact interface, so unstable disturbances induced by vapor film collapse are very small. Besides, the shear force produced by relative velocity between 300 °C melt and water was lower than the viscosity and surface tension of molten LBE, and only deformation behavior occurred on the surface of the molten LBE jet by shear force during interaction. Thus, the debris is in long strip and helix shapes.

Figure 2(c) shows debris size distributions for LBE temperatures of 300, 400, 500, and 600 °C at 20 °C water temperature. The largest mass fraction of debris almost lies in the size range of 2.8–5.0 mm. In the size range of 0.5–2.8 mm, mass fraction increased with molten LBE temperature. However, the largest mass fraction for 300 °C LBE was higher than at other LBE temperatures because no significant fragmentation occurred and debris was mostly in long strip and spiral shapes sized at about 3 mm.

At 80 °C water temperature, no explosion could be observed either. Figure 3(a) [Figure 3: see original paper] shows typical fragmentation behaviors of 500 °C molten LBE at 80 °C. Areas enclosed by circles express the fragmentation process of molten LBE, and some spherical fragments stripped from the leading edge of molten LBE can be seen roughly. The reason is that a stable vapor film could be easily formed at the leading edge in high-temperature water, which lowers the latent heat of vaporization of water when molten LBE contacts water, and this decreases heat transfer ability and hinders further contact between molten LBE and water.

Fragments are shown in Fig. 3(b). In general, fragments were round with smooth surfaces in all cases, and debris shapes at different LBE temperatures did not change significantly. In Fig. 3(c), the largest mass fraction of debris was still in the size range of 2.8–5.0 mm, similar to water temperature of 20 °C, and debris sizes corresponding to the largest mass fraction at different LBE temperatures did not change significantly.

Debris at each water temperature, shown in Figs. 2(b) and 3(b), differs significantly from each other. At 20 °C, debris was generally fluffy needles and flakes due to violent explosions when molten LBE plunged into water, whereas at 80 °C debris has round and smooth surfaces generally, owing to presence of stable vapor films formed during fragmentation, in which fragmented particles were entrained and solidified inside vapor films.

Comparing debris weight percentage distributions at water temperatures of 20 °C and 80 °C (Figs. 2(c) and 3(c)), the debris size of the highest mass fraction can be considered the most probable debris size in molten alloy jet breakup, and as results of dominant jet breakup mechanisms [**?**]. The largest mass fraction lay in the size range of 2.8-5.0 mm, with the largest mass fraction of about 40% and 20% for 20 °C and 80 °C, respectively.

IV. Theoretical Comparison of Experimental Results

It is well-known that fragmentation is related to the wavelength of unstable interface. Several theories have been proposed for fragmentation of molten alloys, such as Rayleigh-Taylor instability, Kelvin-Helmholtz instability, Critical Weber number criteria, and instability of surface waves on gas-liquid interface [**?**]. By Rayleigh-Taylor instability, fragmentation of a cylindrical jet is caused at the jet leading edge due to acceleration normal to the melt-water interface, while by Kelvin–Helmholtz instability it occurs at the jet surface due to relative velocity of melt and water parallel to the interface [**?**].

The wavelength of the fastest growth rate, λ_1, is expressed by Eq. (1) based on Rayleigh-Taylor instability [**?**]:

$$\lambda_1 = 2\pi \left\{3\sigma/[(\rho_j - \rho_w)g]\right\}^{1/2}$$

where σ is surface tension; and _w are density of jet and density of water, respectively; and g is acceleration. Using physical properties of molten LBE, we have $\lambda_1 = 23$ mm, which is far greater than the most probable fragment size of 2.8–5.0 mm.

In Kelvin–Helmholtz instability on the interface parallel to the direction of gravity, a critical relative velocity, U, above which some initial disturbances of large wavelength are unstable is given by [**?**]:

$$U = \left[2\pi\sigma(\rho_j - \rho_w)/(\lambda\rho_j\rho_w)g\right]^{1/2}$$

Given the relative velocity, the minimum unstable wavelength, λ_2, can be obtained by:

$$\lambda_2 = 2\pi\sigma(\rho_j - \rho_w)/\left(U^2\rho_j\rho_w\right)$$

Using physical properties of molten LBE and the initial jet velocity, the minimum wavelength could be calculated. The results in Fig. 4 [Figure 4: see original paper] were calculated with Eqs. (1) and (3) using the following physical properties of LBE: melting temperature, 125 °C; density, 10,380 kg/cm^3; specific heat, 148 J/(kg • K); thermal conductivity, 9.65 W/(m • K), and surface tension N/m. The symbols in Fig. 4 show the most probable fragment size. Comparing experimental data with calculation results of Kelvin-Helmholtz instability, the most probable experimental fragment size was in the range of 2.8-5.0 mm. Therefore, Kelvin-Helmholtz instability is the dominant physical mechanism of molten LBE fragmentation under the present experimental conditions.

V. Conclusion

In order to investigate fragmentation behavior of the molten LBE/water contacting interface, experiments were initiated utilizing a visualization experimental facility with a high-speed video camera to observe fragmentation behavior and unstable wavelength on the LBE/water interface, and solidified fragment shapes and mass fraction distributions were analyzed after experiments. These data yielded the following results:

1) Visualization pictures present obvious violent explosion phenomenon of LBE in water when water temperature is 20 °C, and no explosion occurred in water at 80 °C.
2) Shape of LBE debris became round with increasing water temperature, and debris shape did not change significantly with increasing molten LBE temperature. Debris size of the highest mass fraction was 2.8-5.0 mm, which was not influenced by water temperature or molten LBE temperature in the present study.
3) The dominant physical mechanism of molten LBE fragmentation was Kelvin-Helmholtz instability at the LBE/water contacting interface.

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Note: Figure translations are in progress. See original paper for figures.