Systematic experimental investigation on pressure build-up characteristics of water jet injection into a molten LBE pool

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Abstract

In the scenario of a steam generator tube rupture (SGTR) accident in a lead-cooled fast reactor (LFR), high-pressure secondary-circuit subcooled water is injected into a primary vessel at ordinary pressure, where a molten lead-based alloy (typically pure lead or lead-bismuth eutectic (LBE)) is used as the coolant. To clarify the pressure build-up characteristics under water jet injection, this study conducted several experiments by injecting pressurized water into a molten LBE pool at Sun Yat-sen University. To obtain a further understanding, several new experimental parameters were adopted, including the melt temperature, water subcooling, injection pressure, injection duration, and nozzle diameter. Through detailed analyses, it was found that the pressure and temperature during the water-melt interaction exhibited a consistent variation trend with our previous water droplet injection mode LBE experiment. Similarly, the existence of a steam explosion was confirmed, which typically results in a much stronger pressure buildup. For the non-explosion cases, increasing the injection pressure, melt-pool temperature, nozzle diameter, and water subcooling promoted pressure build-up in the melt pool. However, a limited enhancement effect was observed when increasing the injection duration, which may be owing to the continually rising pressure in the interaction vessel or the isolation effect of the generated steam cavity. Regardless of whether a steam explosion occurred, the calculated mechanical and kinetic energy conversion efficiencies of the melt were relatively small (not exceeding 4.1% and 0.7%, respectively). Moreover, the range of the conversion efficiency was similar to that of previous water droplet experiments, although the upper limit of the jet mode was slightly lower.

Full Text

Preamble

Systematic Experimental Investigation on Pressure Build-Up Characteristics of Water Jet Injection into a Molten LBE Pool

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In the scenario of a steam generator tube rupture (SGTR) accident in a lead-cooled fast reactor (LFR), secondary circuit subcooled water under high pressure is injected into an ordinary-pressure primary vessel containing molten lead-based alloy (typically pure lead or lead-bismuth eutectic (LBE)) as coolant. To clarify the pressure build-up characteristics under water jet injection, this study conducted experiments by injecting pressurized water into a molten LBE pool at Sun Yat-sen University. To obtain further understanding, several new experimental parameters were adopted, including melt temperature, water subcooling, injection pressure, injection duration, and nozzle diameter. Through detailed analyses, it was found that the pressure and temperature during water-melt interaction exhibited a consistent variation trend with our previous water droplet injection mode LBE experiments. Similarly, the existence of a steam explosion was confirmed, which typically results in much stronger pressure buildup. For non-explosion cases, increasing the injection pressure, melt-pool temperature, nozzle diameter, and water subcooling promoted pressure build-up in the melt pool. However, a limited enhancement effect was observed when increasing injection duration, which may be due to the continually rising pressure in the interaction vessel or the isolation effect of the generated steam cavity. Regardless of whether a steam explosion occurred, the calculated mechanical and kinetic energy conversion efficiencies of the melt were relatively small (not exceeding 4.1% and 0.7%, respectively). Moreover, the range of conversion efficiency was similar to that of previous water droplet experiments, although the upper limit of the jet mode was slightly lower.

Keywords: Lead-cooled fast reactor; Steam generator tube rupture accident; Pressure build-up characteristics; Experimental study; Pressurized water jet injection.

Introduction

The lead-cooled fast reactor (LFR) is generally considered among the most promising candidates for Generation IV nuclear systems [1]. In these reactors, lead-based alloys (usually lead or lead–bismuth eutectic (LBE)) are applied as primary coolant owing to their excellent heat transport capability, high boiling point, and chemical inertness with air and water [2, 3]. Therefore, for a common pool-type LFR, an intermediate heat transport system need not be installed, and the primary pumps and steam generators (SG) can be installed directly in the primary circuit. This significantly simplifies the system structure and improves heat transfer efficiency [4]. However, extreme operational conditions (e.g., high temperature, high pressure difference between primary and secondary loops, and LBE corrosion risks) in such a configuration considerably increase the possibility of SG tube rupture (SGTR) accidents [5].

Based on previous research, the evolution of a typical LFR SGTR accident can be divided into four stages [6–9]. In Stage I, secondary water is injected into the primary loop from the rupture location owing to the large pressure difference between the two loops. The injection results in a discontinuity in the pressure field in the two-phase mixture region, where water evaporates and expands intensively due to rapid decrease in ambient pressure (flash evaporation phenomenon). This generates an instantaneous pressure shock wave that propagates in the molten lead-based alloy pool. Such a pressure wave applies a sudden load to surrounding structures and may even create new ruptures in neighboring SG tubes. In Stage II, owing to instability at the steam-water interface, a mixture of steam and liquid water breaks up and disperses in the melt pool, forming a multiphase flow configuration. Meanwhile, expansion of the mixing zone causes displacement of lead-based alloy from the outflow zone, which results in sloshing of the melt pool that could potentially cause mechanical damage to structures in the primary vessel. In Stage III, certain water droplets may become wrapped in a thin vapor layer. Owing to protection provided by this vapor layer, these water droplets evaporate slowly in the melt pool [9]. However, under certain triggering actions such as pressure waves, the vapor layer can collapse, causing long-lived water droplets to fragment and come into direct contact with surrounding molten lead-based alloy (i.e., coolant-coolant interaction (CCI)), which can facilitate drastic evaporation or even trigger an intense steam explosion. Finally, in Stage IV, under the effect of buoyancy force, driving force of the pumps, and drag force of the lead-based alloy flow, steam bubbles can become entrapped and transported toward the core, potentially causing core reactivity disturbances and inhibiting heat exchange. Among these evolution stages, Stages I and III pose potentially greater risk of causing destructive consequences during an LFR SGTR accident [6]; therefore, these two stages have been the focus of study for many researchers for over a decade.

In recent years, many experimental and numerical studies have concentrated on the scenario of secondary water injection into primary molten lead-based alloys in Stage I, wherein high-pressure subcooled water is injected into a vessel containing molten LBE. In general, these studies can be divided into three categories: mechanistic experiments, large-scale experiments under working conditions, and numerical simulations. In the first category, Sibamoto et al. [10, 11] conducted experimental investigations at the Japan Atomic Energy Agency (JAEA) by injecting water into a molten LBE pool while using high-frame-rate neutron radiography to visualize the interaction between water and LBE. Furthermore, Zhang et al. [12] conducted experiments at the Chinese Academy of Sciences by injecting air into a water pool to visually simulate water injection into an LBE pool in Stage I. Recently, Cheng et al. [13] performed simulant experiments at Sun Yat-sen University (SYSU) by injecting ethanol and water into an FC-40 fluorinert pool. These studies concentrated primarily on the penetration behavior of a water jet in a molten lead-based alloy pool. Regarding large-scale experiments, Ciampichetti et al. [14, 15] at ENEA in Italy injected high-pressure subcooled water (6–7 MPa, 130–235 °C) into an LBE pool (350–400 °C) through a 4 mm nozzle using the LIFUS 5 facility. In their study, pressure and temperature fluctuations during the interaction were investigated. In addition, Yu et al. [16] conducted several similar experiments using the LBE SGTR test facility (LEST) at Xi'an Jiaotong University, with a focus on pressure fluctuation and steam cavity migration.

Several researchers have conducted numerical studies on this topic. For example, in addition to experiments at the LIFUS5 and LIFUS5/Mod2 facilities, numerical simulations using the SIMMER-III code were also performed [14, 15, 17] at ENEA based on their experimental conditions. Further, researchers from Shenzhen University conducted numerical investigations to simulate the experiments of Sibamoto et al. [11] and Pesetti et al. [17] using the MC3D code. Iskhakov et al. [7] proposed two approaches for estimating forces acting on neighboring tubes using one-dimensional (1D) spherical coordinate models under the conditions of the steam generator of the BREST-OD-300 reactor.

Experimental and numerical studies were also conducted for Stage III, that is, a water droplet entrapped within a molten lead-based alloy pool. For example, Cheng et al. [19] conducted an experimental study by delivering several dozen milliliters of water lumps into a molten Bi-Sn-In pool at JAEA. Several studies have focused on pressure build-up characteristics during Stage III conducted at SYSU using an experimental facility called the pressurization characteristics in melt–coolant interaction (PMCI) [20–23]. This facility has proven capable of rectifying several defects in the JAEA design [19, 20, 23]. For example, Zhang et al. [23] conducted experiments by delivering water lumps to the bottom of a molten Bi-Sn-In alloy pool. Recently, Cheng et al. [21, 22] released water lumps of different volumes and shapes into a molten LBE pool. All three studies reported limited pressure build-up when water volume increased, because the isolation effect of the vapor layer at the water-melt interface is the primary cause. These results are consistent with a previous numerical study on water-melt interaction at JAEA using the SIMMER-III code performed by Cheng et al. [24]. Further, Iskhakov et al. [8] analyzed the steam explosion phenomenon using a model of multiphase thermal detonation and Hugoniot adiabats.

However, despite significant efforts, several defects have been observed in past studies on Stage I. For example, in the studies by Ciampichetti et al. [14, 15] and Yu et al. [16], experiments were conducted under working conditions of an actual LFR; however, the experimental parameters were limited to a relatively narrow range. In existing mechanistic studies, such as those of Sibamoto et al. [10, 11], Zhang et al. [12], and Cheng et al. [13], more experimental parameters were considered compared to large-scale experiments. Although the interaction behavior between the water jet and molten LBE can be effectively visualized using neutron radiography and transparent simulant materials, it remains difficult to determine pressure build-up characteristics during the interaction through a two-dimensional (2D) view of the mixing zone in an open interaction vessel connected to the atmosphere. Furthermore, in the studies by Zhang et al. [12] and Cheng et al. [13], certain reliability issues related to the simulant materials remain, such as whether the results obtained can be adopted directly under actual conditions. Therefore, current knowledge on the interaction mechanism of a water jet with molten LBE during Stage I remains limited, and clearer investigation through systematic experiments is urgently required.

Focusing on the interaction mechanism in Stage I, this study conducted several new experiments by injecting pressurized water into a molten LBE pool using the PMCI experimental facility at SYSU. To acquire deeper understanding of pressure build-up characteristics during Stage I, various experimental parameters, including injection pressure, injection duration, nozzle diameter, and temperature of both liquids, were considered. The remainder of this paper is organized as follows. In Sect. II, the PMCI facility and experimental conditions related to all experimental cases in this study are described in detail. In Sect. III, the history of both steam explosion and non-explosion cases in the transient state, the influence of experimental parameters on pressure build-up, and the energy conversion efficiency (including overall mechanical energy efficiency and kinetic energy efficiency of the melt) are analyzed and interpreted in detail. Specifically, to deepen understanding of water-melt interaction mechanisms, experimental results in this study are compared with those of our previous studies focusing on Stage III. The knowledge and experimental data accumulated in this study can be applied to validate numerical models in the future.

II. Experimental Details

As mentioned in Sect. I, the PMCI experimental facility was designed and established based on the original facility at JAEA, and has reduced uncertainties in experiments and enhanced operability compared to its predecessor [19, 20, 23]. Moreover, in contrast to previous studies, this study focused on Stage I instead of Stage III; thus, the water delivery system of the PMCI facility was replaced by a water jet injection system.

[Figure 1: see original paper] presents a schematic of the PMCI facility employed in this study. The interaction vessel of the PMCI facility is a rigid cylindrical vessel made of 316L stainless steel with an inner diameter of 250 mm and height of 750 mm, which is capable of resisting instantaneous pressure build-up (up to 40 MPa) during interaction. To measure transient temperature and pressure at different regions (i.e., the molten LBE pool and cover gas) during interaction, several K-type thermocouples and dynamic pressure sensors were installed at corresponding locations, as shown in Fig. 1. Detailed information on these instruments is provided in . For safety purposes, an outer vessel was used to contain and isolate the interaction vessel.

Before melting, a chemical composition test was performed on the LBE ingots, which showed that the oxidized part was negligible. To maintain the target liquid level in the melt pool during experiments, the mass of LBE was calculated at room temperature before being loaded into the interaction vessel. An inductive electromagnetic heater with a coil wrapped around the outer wall of the interaction vessel (Fig. 1) can produce approximately 40 kW heating power for heating and melting LBE. Before heating, inert gas was introduced into the interaction vessel to evacuate air and prevent oxidation of LBE.

The injection system, which included a stainless-steel container, solenoid valve, and injection tube, was installed on the top cover of the interaction vessel (Fig. 1). A rubber sealing ring was inserted between the top cover and interaction vessel to ensure airtightness during the experiment. Before each run, pure water was added to the stainless-steel container. A resistance heater attached to the outer wall of the container was used to heat the water, and water temperature was controlled using a digital heating device. When water temperature reached the set value, it was sustained by the control device in subsequent steps. During heating, inert gas was introduced to pressurize the water in the container. A solenoid valve connected to a release control device was installed below the container to control injection duration. One end of the injection tube was screwed to the solenoid valve, and the other end was a nozzle with different diameters. The tube was inserted into the melt pool (approximately 10 mm) through the top cover of the interaction vessel. After temperatures of the molten LBE and water reached desired values, the water jet was released into the molten LBE pool.

To clarify pressure build-up characteristics during Stage I (i.e., under the scenario of water jet injection into a molten LBE pool), several experimental parameters were considered, including water temperature (Tw) (or water subcooling (ΔTsub)), injection pressure (Pi), injection duration (ti), LBE temperature (Tm), and nozzle diameter (d). lists the specific conditions of all experimental cases in this study. The LBE temperature range was set based on working conditions of China's CLEAR-I, which uses LBE as primary coolant. The core inlet and outlet temperatures were 573 K and 673 K, respectively [25]. The water temperature range was set based on water subcooling in actual LFRs. In this study, water subcooling ranged from 20–80 K in the experimental pressure range, which is equivalent to the water subcooling range in design specifications of certain typical LFRs (e.g., CLEAR-I with designed water subcooling of 80 K) [26].

Furthermore, as mentioned by [27], the boiling mode during interaction of water with melt could also have significant influence on water evaporation rate and thus on pressure build-up characteristics. In previous studies [28–30], a criterion for boiling mode was proposed from a thermal perspective. During sudden contact between cold and hot liquids, if the instantaneous contact interface temperature Ti is higher than the homogeneous nucleation temperature Thn, then the cold liquid evaporates sufficiently violently to trigger a steam explosion [31]. These two temperatures can be calculated using the following equations [31, 32]:

$$T_i - T_c = \sqrt{\frac{K_h \rho_h C_h}{K_c \rho_c C_c}} (T_h - T_i)$$

$$T_{hn} = T_{sat} \left[0.905 - \left(\frac{T_{sat} + 273}{T_{crit} - 273} \right) + 0.095 \left(\frac{T_{sat} + 273}{T_{crit} - 273} \right)^8 \right] (T_{crit} + 273)$$

where K, , and C denote thermal conductivity, density, and specific heat, respectively. Subscripts ‘c’ and ‘h’ denote cold and hot liquids, respectively. Further, Tsat is the saturation temperature of water and Tcrit is the critical temperature of water (647 K). However, an upper temperature limit exists for this boiling mode. If the instantaneous contact interface temperature Ti is higher than the minimum film boiling temperature Tmfb, a stable vapor film forms at the interface of water and melt, which significantly inhibits heat transfer between the two materials. The minimum film boiling temperature was calculated using the following equation [33]:

$$T_{mfb} = T_{sat} + (101 + 8\Delta T_{sub})$$

where ΔTsub is water subcooling. Therefore, if the water-melt temperature combination is in the zone where Ti > Thn and Ti < Tmfb, a steam explosion might be triggered. Based on this criterion, it is possible to predict the boiling mode for each experimental case, as shown in [Figure 2: see original paper].

III. Experimental Analyses and Discussion

A. Transient Behavior of Representative Cases

Similar to studies by Cheng et al. [21, 22] that focused on Stage III, two interaction mechanisms (i.e., steam explosion and non-explosion) were observed, with corresponding conditions listed in . Because visualization methods (such as neutron radiography) were not applied in this study, water-melt interaction could not be directly observed. Therefore, pressure history was used to determine the interaction mechanism. Because these two different interaction mechanisms may cause transient behaviors with evident differences, two representative runs from each category are discussed separately in this section.

Among cases where steam explosion did not occur, case No. 17 was selected for analysis, and its measured transient temperature and pressure histories are shown in [Figure 3: see original paper]. In the pressure history, it can be clearly observed that after direct contact between the water jet and melt pool, water evaporated rapidly and created several pressure pulses in the melt pool. This trend was very similar to transient behavior of the water droplet mode in previous studies by Cheng et al. [21, 22], wherein a three-phase evolution could be distinguished. In Phase (1), in the water and melt premix, water evaporated and condensed simultaneously, and pressure increased slightly from the initial constant value. In Phase (2), water evaporated rapidly, leading to a spike in melt pressure history called the two-phase pressure [19], which was used to characterize pressure build-up in the melt pool. In Phase (3), the generated steam expanded, and pressure decreased gradually from a maximum value due to steam condensation.

In this case, the peak value of the two-phase pressure was relatively small (approximately 0.19 MPa), and the duration was quite short (several tens of milliseconds). In addition, because there is still large space in the interaction vessel, pressure in the cover gas region increased continuously at a relatively low rate. However, with respect to temperature history, there was no significant change in temperature in either the melt pool or cover gas region. This is because the melt pool and cover gas regions have a considerably larger scale than the volume of the water jet per run; therefore, temperature variation in both regions is negligible.

For steam explosion cases, case No. 19 was selected for analysis, and its measured transient temperature and pressure histories are shown in [Figure 4: see original paper]. Comparison of pressure histories with non-explosion cases in [Figure 3: see original paper] revealed a consistent overall trend despite different interaction mechanisms. However, a considerably more intensive two-phase pressure, with a peak value of 0.9 MPa and duration of several tens of milliseconds, was generated during water-melt interaction in this case, and the pressure increase rate in the cover gas region was also higher. In addition, because the volume of water injected into the melt pool remained almost unchanged, temperature variations in the melt pool and cover gas regions remained relatively minor.

B. Influence of Experimental Parameters on Pressure Build-Up Characteristics

To quantitatively analyze the influence of experimental parameters on pressure build-up characteristics, the method applied in previous studies [19–23, 27] was also used in this study. During Stage I of an SGTR accident, flash evaporation of the water jet occurs, creating a pressure wave in the melt pool that can cause mechanical damage to in-vessel structures. As mentioned in Section III.A, several pressure pulses are generated in the melt pool during water-melt interaction, among which the first two-phase pressure is the most intensive. Therefore, the impulse I applied to the melt pool by the first two-phase pressure was used to characterize the intensity of the pressure wave in the melt pool:

$$I = A \int P(t)dt$$

where A, P, and t represent the cross-section of the interaction vessel, pressure, and time, respectively. According to the original study [19], this method is more appropriate for analysis than the method that uses peak value. As shown in [Figure 3: see original paper] and [Figure 4: see original paper], there were many fluctuations in measured pressure history data; integration could greatly reduce the influence of noise and represent an overall variation trend.

In this section, the influence of experimental parameters on pressure build-up characteristics is discussed. As shown in , only a few experimental cases exhibited steam explosion; thus, the impulse of steam explosion cases was calculated in the subsection for each parameter. Instead, the influence of interaction mechanism was analyzed separately.

1. LBE Temperature To investigate the influence of molten LBE temperature on pressure build-up characteristics, the calculated impulses at different molten LBE temperatures are shown in [Figure 5: see original paper]. According to , all cases involved here were non-explosion cases. As shown in [Figure 5: see original paper], despite differences in injection pressure, increasing melt pool temperature increased pressure wave intensity. Theoretically, as melt-pool temperature increased, heat transfer between the water jet and molten LBE was promoted, and water evaporated more violently, consequently generating a more intense pressure wave in the melt pool.

2. Water Subcooling The influence of water subcooling on pressure build-up characteristics under melt temperatures of 623 K and 648 K is shown in [Figure 6: see original paper]. The figure indicates a consistent trend in the influence of water subcooling. As water subcooling temperature increased (or water temperature decreased), pressure wave intensity tended to increase. This influence pattern was completely different from that in previous water droplet mode studies [20–23], where water subcooling had no significant effect on pressure wave intensity. In theory, two possible factors could influence heat transfer efficiency and thus pressure wave intensity: the water-melt temperature difference and the boiling mode of water. However, it is noteworthy that the product of water heat capacity and water subcooling was significantly lower than the latent heat of water. Thus, despite increased water-melt temperature difference as water subcooling increased, the required energy for evaporation did not vary greatly. Therefore, this seems to conflict with the variation in pressure wave intensity shown in [Figure 6: see original paper], which is clearly observed to be more significant than that in Section III.B.1. This suggests that the water-melt temperature difference should not be the major influence factor.

Considering that phase change is involved in water-melt interaction, the boiling mode of water should be the definitive factor. Notably, during the experiment, cases with water subcooling of 20 K were very mild, whereas blast sounds occurred in other cases. Referring to [Figure 2: see original paper], although from the thermal aspect all experimental cases were not within the steam explosion zone or the film boiling zone (where Ti > Thn and Ti > Tmfb), their relative positions to these two zones could explain the phenomenon to a certain extent. In [Figure 2: see original paper], as water subcooling decreased, experimental conditions were closer to the film boiling zone. It is reasonable to presume that under such conditions, film boiling occurs at certain locations on the water-melt interface, and overall heat transfer is inhibited; thus, a pressure wave with reduced intensity is observed. Compared with previous water droplet mode studies [20–23], the water jet was more likely to be broken up into many smaller fragmented droplets, thereby introducing a larger water-melt contact area. Consequently, the overall possibility of local boiling mode transformation increased. This enhancement explains why the influence pattern of water subcooling in this study was different from those in previous water-droplet mode studies.

3. Injection Pressure The influence of injection pressure on pressure build-up characteristics is shown in [Figure 7: see original paper], with melt temperature of 598 K and injection duration of 1 s, and melt temperature of 623 K with injection durations of 1 s and 2 s. The figure shows that, irrespective of injection duration and melt pool temperature, increasing injection pressure generally leads to enlarged pressure wave in melt pool. Theoretically, the higher the injection pressure, the higher the velocity of the water jet, which implies an increase in the volume of water entering the melt pool per unit time. In addition, increased water jet velocity results in greater momentum, and the penetration effect is significantly enhanced. Consequently, these two factors increase the contact area of water and melt and substantially enhance heat exchange between the two materials, creating more energetic pressure waves in the melt pool.

Furthermore, as injection pressure increased from 0.25 MPa to 0.35 MPa, pressure wave intensity increased at a relatively low rate, whereas the growth rate was considerably higher as injection pressure reached 0.40 MPa. It seems reasonable to conclude that as injection pressure reached a certain level, the momentum of the water jet was sufficiently large to resist the buoyancy force effect of molten LBE. At such injection pressures, pressure plays a dominant role in penetration, allowing the water jet to arrive at deeper regions of the melt pool, which significantly increases the water-melt contact area. Therefore, a significantly more intense pressure wave was observed at this injection pressure level.

4. Injection Duration The influence of injection duration on pressure build-up characteristics under different melt temperatures (from 598 K to 648 K) and injection pressures (0.25 MPa and 0.35 MPa) is shown in [Figure 8: see original paper]. As displayed in the figure, as injection duration increased, the intensity of the pressure wave first increased and then tended to become saturated. This occurred regardless of differences in melt temperature and injection pressure. Referring to previous studies wherein a water lump was delivered into a melt pool [20–23], a consistent influence pattern of water volume was observed.

As indicated by Sibamoto et al. [10, 11], in their visualization experiments, when water was injected into a molten LBE pool, a cavity formed as water evaporated, and water accumulated in the cavity. It is inferred that such a cavity can play a key role in interfering with direct contact between water and the melt pool. Thus, it is rational to conclude that the isolation effect of the cavity may result in saturation of pressure wave intensity.

Although it was not feasible to directly observe whether a cavity formed during the injection process in this study, it is still possible to speculate on cavity existence. Several experimental cases provide evidence of cavity formation. [Figure 9: see original paper] shows the pressure history of the melt pool in one of these cases. As evident, during the pressure build-up process, multiple two-phase pressures were observed and the last one had the greatest peak value, signifying that water interacted "in batches" with melt. It is reasonable to presume that the first few relatively weak two-phase pressures were due to cavity formation, and the last strongest two-phase pressure corresponded to interaction between water accumulated in the cavity and surrounding melt.

However, there is another hypothesis regarding this saturation phenomenon. As mentioned in Sect. II, the interaction vessel was sealed during experiments. As interaction between water and melt begins, steam is generated in the interaction vessel. Based on the pressure history in [Figure 3: see original paper], pressure in the interaction vessel will increase continuously, reducing the difference between injection pressure and in-vessel pressure. For the non-explosion case, pressure in the melt pool increased to approximately 0.17 MPa in 1 s; that is, the injection pressure difference was reduced to approximately 0.18 MPa (initially approximately 0.25 MPa). Although it is not possible to accurately judge when water is injected, considering the experimental conditions of this study, the reduced pressure difference may also be a potential contributing factor to limited pressure wave intensity. As water is injected into melt pool continuously, pressure difference decreases during water-melt interaction, resulting in lower jet velocity, which signifies that less water enters the melt pool per unit time. From the above analysis, the promoting effect of increasing injection duration on injected water volume was limited. Thus, pressure wave intensity in the melt pool revealed a saturation tendency.

5. Nozzle Diameter The influence of nozzle diameter on pressure build-up characteristics under different melt temperatures (573–673 K) and injection durations (1 s and 2 s) is shown in [Figure 10: see original paper]. As depicted in the figure, under relatively lower melt pool temperatures (573–623 K), pressure wave intensities for nozzle diameters of 2 mm and 4 mm at 1 s injection duration along with 2 mm nozzle diameter at 2 s injection duration were limited to a narrow range. Thus, the promotion effect of increasing nozzle diameter on pressure wave intensity was quite limited under such melt pool temperature range. By contrast, with further increase in melt pool temperature, pressure wave intensity was significantly enhanced to several times that of the previous ones. In general, increasing nozzle diameter enhanced pressure wave intensity.

In terms of geometry, doubling the nozzle diameter quadruples the nozzle exit area. However, under the same injection pressure, the outlet velocity of the jet remained unchanged. Therefore, the flow rate of the 4 mm nozzle was four times larger than that of the 2 mm nozzle; that is, a considerably larger volume of water was injected into the melt pool within the same duration. Consequently, it is not difficult to explain the more intensive pressure wave at higher melt-pool temperatures. Based on previous studies [20–23], the saturation phenomenon of pressure wave intensity (as water volume increases) was universally observed regardless of melt-pool temperature; thus, there is another factor that may lead to such an unusual phenomenon at lower melt-pool temperatures. Based on the flow pattern of the water jet in the melt pool observed previously [10, 11], the water jet was initially in the shape of a cylinder under the effect of inertia with its diameter proportional to the nozzle diameter, pushing away surrounding melt and creating a cavity. Then, surrounding melt returned and interacted with the water jet, and heat transfer occurred mainly in the radial direction. In addition, heat transfer from melt to water was relatively less efficient at low melt temperatures, and evaporation and condensation may occur simultaneously in the outer layer of the water jet. Therefore, for a water jet from a nozzle with larger diameter, only a limited quantity of water was involved in water-melt interaction under low melt-pool temperatures despite the larger water volume. In contrast, for high melt-pool temperatures, heat transfer was sufficiently efficient to allow more complete interaction between water and melt. Consequently, pressure wave intensity in experimental groups with larger-diameter nozzles was limited under low melt-pool temperature conditions.

6. Interaction Mechanism In addition to experimental parameters analyzed above, it was found that the interaction mechanism (steam explosion or non-explosion) between water and molten LBE could also influence pressure build-up characteristics. The influence of interaction mechanism on pressure buildup characteristics is shown in [Figure 11: see original paper], where two groups of experimental cases with steam explosion are compared with a higher injection pressure reference group. The figure demonstrates that steam explosion cases generated significantly more intensive pressure waves compared to non-explosion cases under similar experimental conditions.

C. Mechanical Energy Conversion Efficiency

Regardless of interaction mechanism (steam explosion or non-explosion), the thermal energy of water is partially converted into mechanical energy of generated steam and surrounding melt during violent evaporation. Owing to short interaction duration, such release of mechanical energy can cause intensive sloshing motion of the melt pool, posing potential risks to reactor structures. Therefore, it is essential to investigate mechanical energy conversion efficiency during water-melt interactions.

Based on previous studies [20, 34], the total mechanical energy released during interaction can be divided into two parts: compression work of the cover gas (Ec) and kinetic energy of the melt (Ek). Considering the extremely small scale of interaction time, an adiabatic process was assumed for the calculation:

$$E_c = -\int_{V_0}^{V_1} PdV = -\frac{P_1V_1 - P_0V_0}{\gamma - 1} = \frac{P_0V_0}{\gamma - 1}\left[\left(\frac{P_1}{P_0}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

where P0 and P1 are initial and maximum pressures of the cover gas, respectively, V0 and V1 are volumes of cover gas corresponding to P0 and P1, respectively, and γ is the ratio of specific heat of the cover gas. Notably, here (and in the following equations), energy is calculated using maximum pressure in the cover gas region instead of terminal pressure. It is frequently observed in experiments that pressure in the cover gas region reaches its maximum value and then decreases slightly. The most probable reason for this is that part of the steam may be condensed in the relatively low-temperature upper region of the interaction vessel. Therefore, energy would be underestimated if calculated using terminal pressure.

By creating 1D acceleration of the inertial mass, the kinetic energy of the melt can be evaluated as [34, 35]:

$$E_k = \frac{1}{2}m_{pl}V_{pl}^2$$

where mpl denotes total mass of the melt pool.

The thermal energy consumed during water-melt interaction (Ether) can be evaluated by calculating maximum thermal energy absorbable by water:

$$E_{ther} = m_s[c_l(T_{sat} - T_w) + h_{fg} + c_g(T_m - T_{sat})]$$

where cl and cg are specific heats of liquid water and vapor, respectively, hfg is latent heat of water, Tsat, Tw and Tm are temperatures of saturated water, initial water, and melt pool, respectively, and ms is total mass of generated steam, which can be estimated from pressure variation in the cover gas region [20, 22]:

$$m_s = n_sM_s = \frac{M_s}{R}\left(\frac{P_1V_{cg}}{T_1} - \frac{P_0V_{cg}}{T_0}\right) = \frac{(P_1 - P_0)M_sV_{cg}}{RT_0}$$

where ns and Ms are molar quantity and molecular weight of steam, respectively, Vcg is volume of the cover gas region, R is the gas constant (R = 8.314 J/mol/K), and T1 and T0 are cover gas temperatures corresponding to P1 and P0. Under current experimental conditions at the PMCI facility, T1 and T0 are almost identical (as shown in [Figure 3: see original paper] and [Figure 4: see original paper]) due to the relatively small volume of water.

By combining equations (4)–(8), mechanical energy conversion efficiency (TM) and kinetic energy conversion efficiency of the melt (k) during water-melt interaction can be estimated as follows:

$$\eta_{TM} = \frac{E_c + E_k}{E_{ther}}$$

$$\eta_k = \frac{E_k}{E_{ther}}$$

As shown in Figure 12: see original paper, mechanical and kinetic energy conversion efficiencies of the melt in this study were limited within ranges of 2.8–4.1% and 0.013–0.7%, respectively. By observing the orders of magnitude of these conversion efficiencies, it was discovered that mechanical energy release was only an extremely small fraction of total variation in thermal energy. Similarly, kinetic energy of the melt accounted for only a small fraction of total release of mechanical energy, signifying that kinetic energy of the melt was considerably lower than that of the cover gas.

To clarify the effect of water injection mode, conversion efficiency of the water droplet injection mode from a previous study [22] is shown in Figure 12: see original paper as a reference. Through comparison, although the range of mechanical energy conversion efficiency of the present water jet injection mode had a lower upper limit, no significant difference was observed in terms of mechanical energy and kinetic energy conversion efficiencies of the melt for these two water-melt interaction modes.

IV. Concluding Remarks

During an SGTR accident involving an LFR, secondary subcooled pressurized water is injected into the primary melt pool, causing intensive water-melt interactions. Such interactions can result in several complex thermohydraulic phenomena, including flashing of water, sloshing of the melt pool, steam explosion, and vapor bubble transport. Therefore, it is crucial to clarify mechanisms of water-melt interaction to acquire comprehensive understanding of an LFR SGTR accident. In this study, aimed at the first stage of SGTR accident wherein a water jet is injected into the melt pool, several experiments were conducted by injecting pressurized water into a molten LBE pool considering various experimental parameters (melt temperature, water subcooling, injection pressure, injection duration, and nozzle diameter). Through detailed analyses of pressure buildup characteristics in each experimental case, we found the following:

1. Compared with the water-droplet injection mode, transient pressure and temperature variations during water-melt interaction exhibited a consistent pattern. Typically, a two-phase pressure was observed during pressure build-up.

2. Among non-explosion cases under current experimental conditions, increasing injection pressure, melt pool temperature, nozzle diameter, and water subcooling could eventually result in intensified pressure build-up in the melt pool.

3. Only a limited enhancement effect on pressure wave intensity was achieved by increasing injection duration. There may be two possible explanations for this. The generated steam may form a cavity around the jet, which may inhibit direct contact between water and melt. Alternatively, the continually rising pressure in the interaction vessel may decrease the velocity of the water jet.

4. Steam explosion is more likely to occur under certain specific initial water/melt temperature conditions, which could facilitate more intensive pressure build-up in the melt pool. The instantaneous contact interface temperature was the decisive factor for such initial water/melt temperature conditions.

5. Regardless of interaction mode (steam explosion or non-explosion), the calculated mechanical and kinetic energy conversion efficiencies of the melt were relatively small (not exceeding 4.1% and 0.7%, respectively). Further, the range of conversion efficiency was similar to previous water-droplet mode results, although the upper limit of jet-injection mode was slightly lower.

Owing to the invisibility of the interaction process in the PMCI facility, there are still uncertainties underlying the water-melt interaction mechanism, particularly the mechanism of saturated pressure build-up while increasing injection duration. To further contribute to investigation of LFR SGTR accidents, numerical studies that aim to ascertain the interaction mechanism are highly anticipated in the future. Furthermore, following the international trend of using pure lead as primary coolant, similar experiments with molten lead may be initiated to enrich the experimental database and improve the availability of current theoretical explanations.

V. References

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