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A two-dimensional experimental investigation on the sloshing behavior in a water pool

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ABSTRACT

Studies on the pool sloshing behavior are important for the improved evaluation of energetic potential of a large whole-core-scale molten fuel pool that might be formed during a Core Disruptive Accident (CDA) of Sodium-cooled Fast Reactors (SFR). Motivated to understand the characteristics of this behavior, in this study a series of simulated experiments was conducted by injecting nitrogen gas into a Two-Dimensional (2D) rectangular water pool through a nozzle positioned at the center of pool bottom. To achieve a comprehensive understanding, experimental parameters, including nitrogen gas pressure (~4.2 bar), initial water depth (~60 cm), gas injection duration (0.06–0.1 s) along with the nozzle size (10–50 mm), were varied. Through detailed analyses, it is found that under current range of conditions, all the experimental parameters employed are confirmable to have remarkable impact on the sloshing characteristics (e.g. maximum elevation of water level at the pool center and peripheries). The performed analyses also suggest that possibly due to a diminished residence time of the injected-gas in the pool, a limited sloshing intensity is observable as the gas-injection pressure increases. Evidence and fundamental data from our work will be utilized for the empirical-model development as well as the analyses and verifications of future SFR severe accident analysis codes in China.

1. Introduction

The disaster in March 2011 at the Fukushima Dai-Ichi nuclear power plant in Japan makes many people to realize that severe accidents might occur, even if their probability is extremely low (Cheng et al., 2013, 2014a). From the analyses of severe accidents for Sodium-cooled Fast Reactors (SFR) (Maschek et al., 1992; Theofanous and Bell, 1986; Tobita et al., 1999; Yamano et al., 2009), it is believed that by assuming pessimistic conditions (e.g. minimal fuel discharge from the core), the accident might proceed into a transition phase where a large whole-core-scale molten fuel pool containing sufficient fuel to exceed prompt criticality by fuel compaction might be formed (see Fig. 1) (Suzuki et al., 2012, 2014). It is expectable that for such a pool, a local power excursion or pressure buildup could disturb the pool by pushing the liquid fuel away from the pool center toward the pool peripheries, and then the gravity impels it back toward the core center (as depicted in Fig. 2). This so-called centralized pool sloshing behavior would possibly lead to energetic nuclear power excursions by fuel accumulation (Maschek et al., 1992).

Since during the molten-pool enlargement there is the possibility that a certain amount of liquid coolant would be entrapped within the pool at the failure of control rod guide tubes, local Fuel-Coolant Interaction (FCI) in the fuel pool is regarded as one of the various initiators that could lead to the pressure buildup and sequential sloshing motion (Maschek et al., 1992). In our previous study (Cheng et al., 2014b), to clarify the characteristics of pressure buildup during local FCIs, a series of simulated experiments was conducted by delivering a given quantity of water into a molten pool which is formed by a low-melting-point alloy. In addition to experimental analyses, motivated to acquire more visual evidence for enhanced understanding on this interaction, numerical calculations using SIMMER-III, an advanced fast reactor safety analysis code, were also conducted (Cheng et al., 2015). Through those analyses, much of knowledge and experimental database regarding local FCIs have been accumulated; therefore in this study our intention is switched to elucidating the characteristics of the pool sloshing behavior that follows the local FCI.

Noting the importance of pool sloshing behavior in the evaluation of reactor accident progression, over the past decades, a few pioneering studies related to this subject have been performed, generally in Two-Dimensional (2D) or axially symmetrical conditions (Maschek et al., 1992; Morita et al., 2014). Maschek et al. (1992) conducted a series of dam-break experiments by releasing

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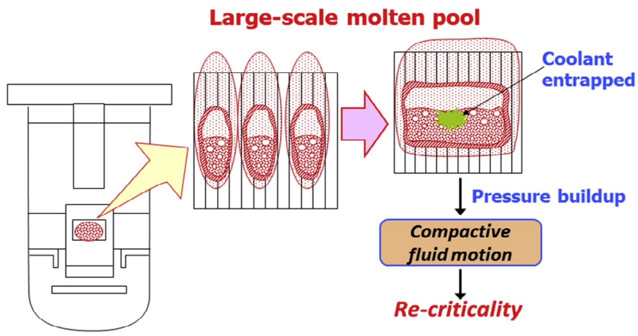

Fig. 1. Large-scale molten pool formed during transition phase.

water from a small cylindrical Plexiglas container to a larger outer vessel. During their experiments, various parameters such as diameters and heights of the central water column and the water depth in the outer cylindrical vessel have been taken. Although some essential features of the sloshing process (e.g. pileup of the liquid fuel at the walls and gravity-driven inward sloshing) can be captured by their experiments, it is noticeable that their experimental conditions are still quite far from the actual reactor accident scenario in which as described-above, the outward sloshing motion is triggered by a rapid vapor generation and expansion around the pool center. Recently, a further study on the augmenting and mitigation effect of hydraulic disturbances on sloshing behavior was carried out by Morita et al. (2014) through injecting nitrogen gas into a steady symmetrical sloshing motion at timing different from the sloshing period. However, as indicated above, since the target of current study is concentrated on the mechanism of sloshing motion following a local FCI, therefore compared to the overlaying effect of different hydraulic disturbances, we have more interest on the sloshing behavior which is triggered by a single pressure event at various parametric conditions.

Focusing on this aspect, in this study a series of simulated experiments was conducted by injecting nitrogen gas into a two-dimensional rectangular water pool through a nozzle positioned at the center of pool bottom. To achieve a comprehensive understanding, different experimental parameters, including nitrogen gas pressure (~4.2 bar), initial water depth (~60 cm), gas injection duration (0.06–0.1 s) along with the nozzle size (10–50 mm), were employed. The experimental apparatus and procedures involved are described in Section 2, while the obtained results and their interpretations are discussed in detail in Section 3. Knowledge and fundamental data from our work will be utilized for the empirical-model studies as well as the analyses and verifications of future SFR severe accident analysis codes in China.

2. Experimental apparatus and procedures

Fig. 3 depicts the schematic diagram of the whole experimental system used in current sloshing experiment. To facilitate the visual observation and video recording of fluid motion, a narrow rectangular viewing tank made of methyl methacrylate with the effective dimensions of 1000 mm in height, 1000 mm in width and 60 mm in gap thickness, was utilized. Purified water, which was poured into the tank from the top of the viewing tank, is used to simulate the molten fuel. Before the commencement of each experimental run, the initial water depth was adjusted carefully to target values.

Nitrogen gas is employed to simulate the vapor generated from local FCIs. At the center of pool bottom, a circular nozzle, with adjustable inner diameters, was designed for allowing the gas phase to be injected into the viewing tank. Under the viewing tank, a gas container is equipped to contain the gas delivered from nitrogen gas vessel. Before any gas injection, the gas pressure in the gas container was measured and controlled at specific values. The volume of gas container is large enough to ensure that the gas pressure is constant throughout the injection.

For each experimental run, nitrogen gas was injected into the pool only once with certain injection duration. The current value of injection duration is set to be 0.06–0.1 s, which corresponds to the duration of vapor expansion caused by local FCIs as observed in our earlier studies (Cheng et al., 2014b, 2015). To accurately control the gas injection, a high-accuracy magnetic valve is installed between the gas container and circular nozzle.

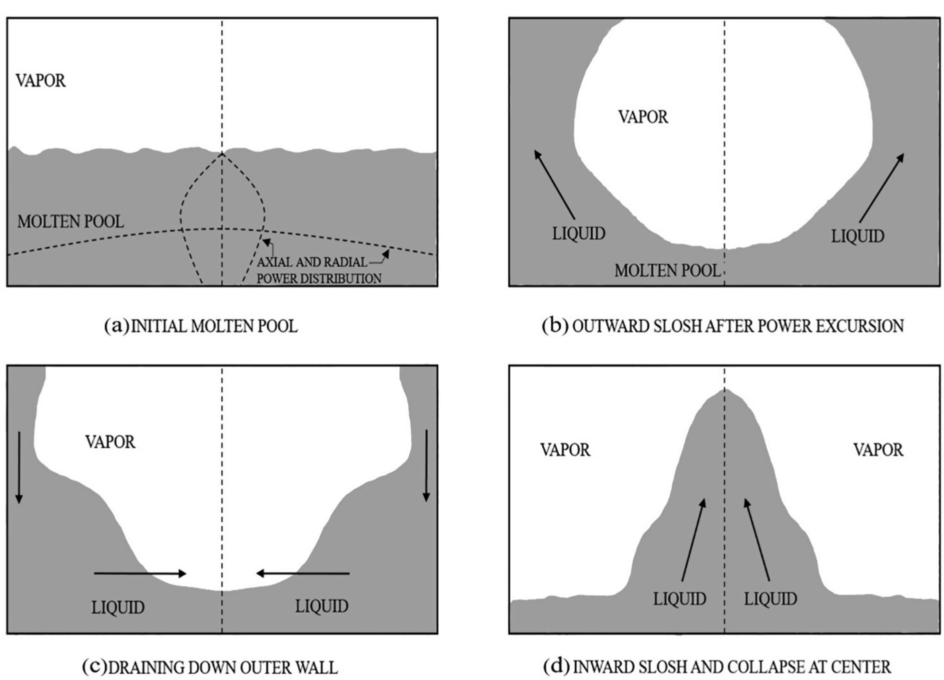

Fig. 2. Schematic view of centralized pool sloshing behavior (Maschek et al., 1992).