Annals of Nuclear Energy 120 (2018) 593–603

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

A new experimental investigation on local fuel-coolant interaction in a molten pool

Ting Zhang, Songbai Cheng *, Ting Zhu, Chuiyi Meng, Xu'an Li

Sino-French Institute of Nuclear Engineering & Technology, Sun Yat-Sen University, Tang-Jia-Wan, Zhuhai City, Guangdong Province 519-082, PR China

ARTICLE INFO

Article history:
Received 7 May 2018
Received in revised form 13 June 2018
Accepted 15 June 2018

Keywords:
Sodium-cooled fast reactor
Core disruptive accident
Molten pool
Fuel-coolant interaction
Pressure characteristics

ABSTRACT

Studies on local fuel-coolant interaction in a molten pool are important for the improved evaluation of severe accidents that might be encountered for sodium-cooled fast reactors. To clarify the characteristics of this interaction, several years ago a series of simulated experiments was conducted at the Japan Atomic Energy Agency (JAEA) by delivering a given quantity of water into a molten pool formed with a low-melting-point alloy. In this work, motivated by acquiring more reliable database and knowledge, an improved experimental system has been developed recently at the Sun Yat-sen University. Experimental results from various conditions including much difference in water volume, melt temperature, water subcooling, initial water-lump shape along with melt depth, are discussed. It is found that the water volume, melt temperature, initial water-lump shape and melt depth are observable to have remarkable impact on the pressure-buildup characteristics while the role of water subcooling is less prominent. The observed consistent influence of water volume, melt temperature and water subcooling, as compared to previous studies at JAEA, indicates that despite the existence of some uncertainties, the statistical results recognized at JAEA might be overall valid. Owing to much enriched evidence, the present analyses suggest that the most probable reason leading to the limited pressurization as water volume increases for a given melt and water temperature, should be primarily due to the isolation effect of vapor bubbles at the melt-water interface.

1. Introduction

The disaster in March 2011 at the Fukushima Dai-Ichi nuclear power plant in Japan makes many people realize that severe accidents, including Core Disruptive Accidents (CDAs), might occur, even if their probability is extremely low (Cheng et al., 2013). From the analyses of CDAs for Sodium-cooled Fast Reactors (SFRs), 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) (Maschek et al., 1992; Theofanous and Bell, 1986; Tobita et al., 1999; Yamano et al., 2009). It is expectable that for such a pool, a local power excursion or pressure buildup could possibly disturb the pool by pushing the liquid fuel away from core center toward the peripheries, and then the gravity impels it back to the core center (Cheng et al., 2018). The inward pool sloshing motion is likely to cause 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 (e.g. at the failure of control rod guide tubes) (Kayser et al., 1998), local Fuel-Coolant Interaction (FCI) in the fuel pool is regarded as one of the various initiators that could lead to the above compactive sloshing motion (Maschek et al., 1992). To benefit the evaluation of accident progression during a CDA, it is therefore of crucial importance to understand the mechanisms underlying local FCIs and resultant sloshing motion.

It is instructive to note that, over the past decades, although extensive studies (e.g. CCM (Spencer et al., 1994), KROTOS (Huhtiniemi et al., 1999), FARO (Magallon, 2006) and TROI (Kim et al., 2010)), with an emphasis on ascertaining the mechanisms of steam explosion and debris bed formation in a FCI, have been performed, most of them were conducted in a Fuel-Injection (FI) mode, namely by injecting or pouring melt into a coolant pool, while the knowledge and data gained from a Coolant-Injection (CI) mode, have not been accumulated sufficiently. Park et al. (1998) and Sibamoto et al. (2002) are the few representative authors that independently performed their investigations in a CI mode within various situations (such as energetic and non-energetic conditions). In their studies, valuable information and

* Corresponding author.
E-mail address: chengsb3@mail.sysu.edu.cn (S. Cheng).

https://doi.org/10.1016/j.anucene.2018.06.031
0306-4549/

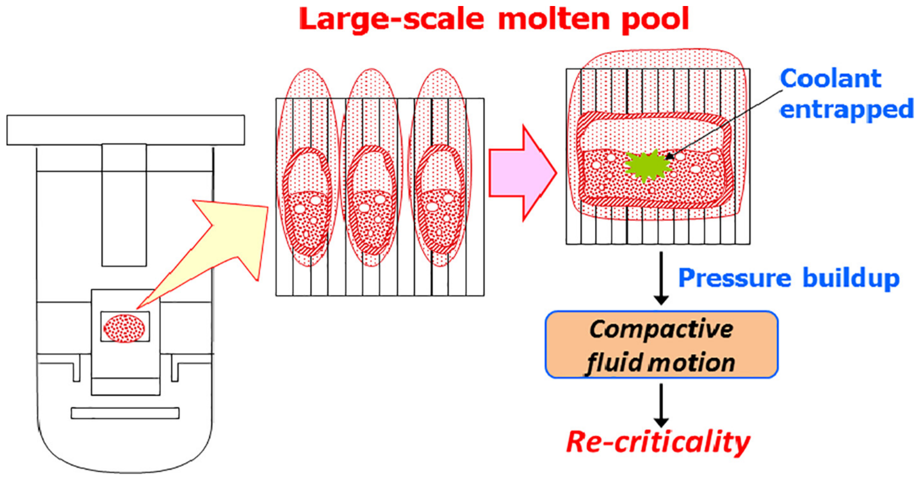

Fig. 1. Large-scale molten pool formed during transition phase.

data on the jet penetration behavior (e.g. penetration velocity, depth and cavity characteristics) were collected, while the knowledge and data gained on the pressure-buildup characteristics during local FCIs, especially in a scenario where a certain amount of liquid coolant is entrapped within a larger melt pool, is still limited, despite their crucial importance for accident progression evaluation.

To clarify the characteristics of molten fuel pool at various disturbances, in the past several series of studies, including specifically-designed in-pile and out-of-pile experiments as well as numerical simulations (Tobita et al., 2006; Yamano et al., 2009), have been performed at the Japan Atomic Energy Agency (JAEA). Among those studies, to understand the pressure-buildup characteristics during local FCIs, in recent years a series of simulated experiments was conducted by Cheng et al. (2014) through delivering a given quantity of water into a molten pool formed with a low-melting-point alloy. In addition to experiments, 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). However, through those analyses, much of limitations and uncertainties of their experimentation (esp. the existence of random initial shape of water lump) were recognized. It has been confirmed that such uncertainties would not only impair the reliability of experimental findings but also make it difficult to perform accurate quantitative comparisons between experiments and numerical calculations (Cheng et al., 2014, 2015).

On the other hand, it should be noted that, aimed to ascertain the mechanisms of pool sloshing behavior at various situations, a systematic research program, including both experimental study and empirical-model development, has been initiated at the Sun Yat-sen University (SYSU) in China (Cheng et al., 2018). The research program is divided into three steps: Step 1-understanding the mechanisms and performing modeling studies for pool sloshing behavior in an idealized pure water pool within Two-Dimensional (2D) conditions; Step 2- further conducting 2D sloshing investigations under various complicated and realistic conditions (e.g. in a scenario with solid particles, rod structure or high-density liquid); and Step 3-validating of the 2D experimental results at larger-scale Three-Dimensions (3D) and developing predictive models that may be directly applicable for reactor safety analyses. For the Step-1, recently a series of simulated experiments was successfully performed by injecting nitrogen gas into a 2D rectangular pure water pool through a nozzle positioned at the center of pool bottom (Cheng et al., 2018). Based on the experimental observation and quantitative data obtained, much of knowledge regarding the sloshing characteristics in a pure water pool has been accumulated (Cheng et al., 2018). To support the subsequent investigations at more realistic conditions, it is therefore evident that a more reliable and accurate understanding on local FCIs, one of its initiators as mentioned above, is pressingly needed.

Focusing on those aspects, a new experimental facility, called PMCI (Pressure-buildup characteristics in Melt-Coolant Interaction), has been developed at the Sun Yat-sen University. Compared to the original one at JAEA, the known experimental limitations and uncertainties are mitigated as much as possible. To achieve more comprehensive understanding, in addition to previous parameters (e.g. water volume, melt temperature and water subcooling), in this work new experimental parameters such as the initial water-lump shape and melt depth are specifically investigated. In Section 2, after a briefing of the original facility and procedures (esp. its limitations and uncertainties) used at JAEA, the improved design of our new system at SYSU is presented, while the obtained results from the new facility as well as their interpretations are discussed in detail in Section 3. Knowledge and fundamental data from our work will be utilized for the future analyses and verifications of heat-transfer models developed in SFR severe accident analysis codes in China.

2. Experimental details

2.1. Original experimental facility and procedures at JAEA

Fig. 2 shows the schematic view of the original experimental facility developed at JAEA. It is clearly seen that, most of the apparatuses are contained in an outer vessel which provides protection from FCI events occurring in an interaction vessel located in it.

The interaction vessel is a rigid cylindrical stainless steel vessel of 140 mm in inner diameter. Several thermocouples, dynamic pressure transducers and strain gauges are installed at different positions (see Fig. 2). For all experimental runs, a low-melting-point alloy (60% Bi, 20% Sn and 20% In by weight), with its density and melting point of around 8500 kg/m^3 and 352 K, respectively, is utilized for simulating the fuel material. Before depositing on the bottom of the interaction vessel, the mass of the alloy blocks is well weighed so that the molten pool, formed later by heating the alloy blocks, can keep target heights.