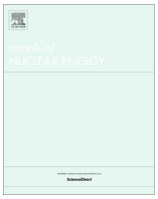
Annals of Nuclear Energy 75 (2015) 20–25

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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



Technical Note

The effect of coolant quantity on local fuel–coolant interactions in a molten pool

Songbai Cheng *, Ken-ichi Matsuba, Mikio Isozaki, Kenji Kamiyama, Tohru Suzuki, Yoshiharu Tobita

Advanced Fast Reactor Cycle System Research and Development Center, Japan Atomic Energy Agency (JAEA), 4002 Narita, Oarai, Ibaraki 311-1393, Japan

ARTICLE INFO

Article history:
Received 28 March 2014
Received in revised form 22 July 2014
Accepted 25 July 2014

Keywords:
Sodium-cooled fast reactor
Severe accident
Local fuel–coolant interaction
Molten pool
Pressure-buildup
Mechanical energy

ABSTRACT

Studies on local fuel–coolant interactions (FCI) in a molten pool are important for severe accident analyses of sodium-cooled fast reactors (SFRs). Motivated by providing some evidence for understanding this interaction, in this study several experimental tests, with comparatively larger difference in coolant volumes, were conducted by delivering a given quantity of water into a simulated molten fuel pool (formed with a low-melting-point alloy). Interaction characteristics including the pressure-buildup as well as mechanical energy release and its conversion efficiency are evaluated and compared. It is found that as water quantity increases, a limited pressure-buildup and the resultant mechanical energy release are observable. The performed analyses also suggest that only a part of water is probably vaporized during local FCIs and responsible for the pressurization and mechanical energy release, especially for those cases with much larger water volumes.

1. Introduction

In the severe accidents analyses for sodium-cooled fast reactors, it has been recognized 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 pool containing sufficient fuel to exceed prompt criticality by fuel compaction might be formed (Maschek et al., 1992; Theofanous and Bell, 1986; Tobita et al., 1999; Yamano et al., 2009). Possibly, during the pool enlargement a certain amount of liquid coolant might be entrapped within the pool; therefore, local fuel–coolant interaction (FCI) in the fuel pool is regarded as one of the various initiators that could lead to such compactive fluid motions (Maschek et al., 1992).

Unfortunately, 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)) have been conducted with an emphasis on ascertaining the mechanisms of steam explosion and debris bed formation in a FCI, most of them were performed in a fuel-injection (FI) mode, namely by injecting or pouring melt into a coolant pool, while for the coolant-injection (CI) mode, though some investigations with their focus on steam explosions exist in the field of volcanology (Röder et al., 1999; Zimanowski et al., 1995), much less can be found relevant to reactor safety analyses, especially in a scenario where a certain amount of liquid coolant is entrapped within a melt pool. 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 conditions. In their studies, valuable information and data on the jet penetration behavior (e.g. penetration velocity, depth and cavity characteristics) were collected, while the knowledge on the pressure-buildup by FCIs is comparatively sparse, despite of their crucial importance for accident progression evaluation. On the other hand, although some limited information regarding the pressure-buildup is available from performed projects such as MFTF and CORRECT (Berthoud et al., 1994), their experimental purpose and scenario (e.g. inflow/pouring of coolant into a melt pool) are quite different from our local FCI conditions. Therefore, it might be judged that the existing knowledge and data regarding pressure-buildup from local FCIs especially in a CI-mode are still quite insufficient.

To clarify the characteristics of molten fuel pool at various disturbances, in the past years several series of studies, including specifically-designed in-pile and out-of-pile experiments as well as numerical simulations (Yamano et al., 2009), have been initiated at the Japan Atomic Energy Agency. The current study, being one of them, is aimed to provide some knowledge for understanding the mechanism underlying the local FCIs in a molten fuel pool. For this purpose, several tests were conducted by delivering a given quantity of water into a simulated molten fuel pool. Evidence and data from this work will be also utilized for analyses and

---

* Corresponding author.
E-mail address: cheng.songbai@jaea.go.jp (S. Cheng).

http://dx.doi.org/10.1016/j.anucene.2014.07.042

verifications of some heat-transfer models developed in SIMMER-III, an advanced fast reactor safety analysis code (Tobita et al., 2006; Yamano et al., 2009), which is believed to be a unique simulation code currently in the world for event progression analyses in a whole-core-scale (Yamano et al., 2009).

2. Experimental facility and test condition

The representative experimental facility is shown in Fig. 1, while the instrumentations are further described in Table 1. It is evident 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. 1). For all experimental runs, a low-melting-point alloy (Bi 60%–Sn 20%–In 20%), 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 a target height of around 140 mm.

Water is used as simulant material for coolant. The combination of water and the above-mentioned low-melting-point alloy has been elaborately selected after comprehensive evaluation in cost, operation easiness as well as the capability for simulating the typical heat exchange mode between molten fuel and sodium in reactor core disruptive accident (CDA) conditions (Kamiyama et al., 2013; Kondo et al., 1995). Water, with its volume carefully measured, is loaded into a glass flask connected to the bottom end of the drive rod. Currently, two sizes of flask (50 or 100 ml) can be utilized depending on the corresponding water volume required in a specific run.

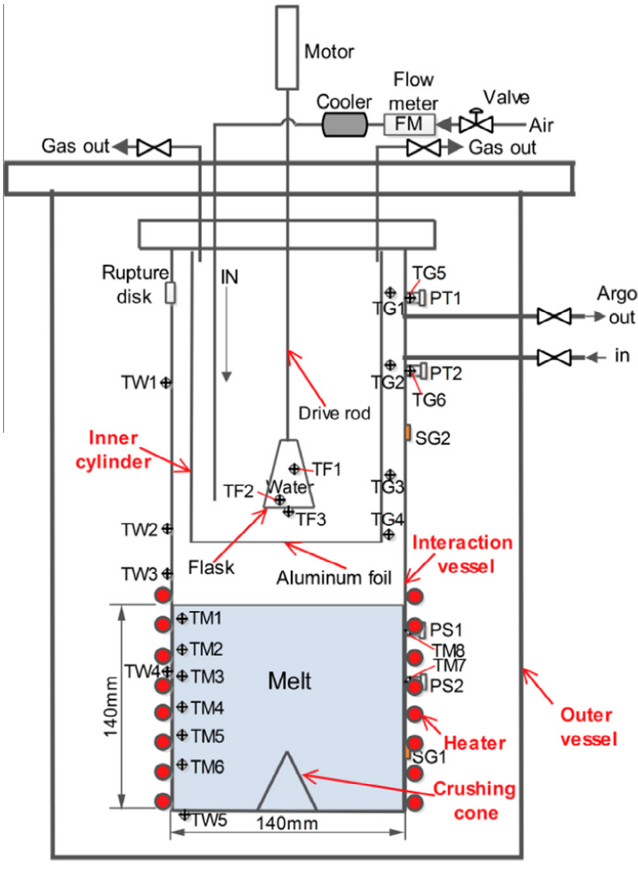


Fig. 1. Representative experimental facility.

An electric heater, wrapped around the external wall of the interaction vessel, is used to heat the alloy and water. Since the temperature of liquid water (<373 K) is generally rather lower than the temperature of melt (as will be shown later in Table 2), to avoid the heat convection within the interaction vessel (thereby ensuring the water temperature not to rise too rapidly), an inner cylinder, with it s bottom covered by a thin aluminum foil, is equipped through hanging from the top of the interaction vessel. It should be also pointed out that in such a way, the heating-up of the melt becomes much promoted simultaneously. Another advantage of employing such a design is that the thin aluminum foil, though plays an effective role in preventing the heat convection between the melt and water regions, is quite susceptible to being pierced through by the drive rod, thereby leading to a neglectable interference on the water-delivering. During the heating, as illustrated in Fig. 1, air and argon flows, are kept delivering separately, to achieve a more accurate control of water temperature and prevent the oxidation of the alloy, respectively.

After the temperature of water and melt reaches target values, through operating the motor the flask is transported downwards (with a speed of 250 mm/s) and ruptured by a crushing cone pre-positioned on the bottom of the interaction vessel. Fig. 2 shows the rupture process of a preliminary test, from which it can be seen that the flask can be thoroughly destroyed. Therefore, the confining role of the flask, if any, is expectable to be remarkably reduced during FCIs.

It is instructive to note that, over the past decades, extensive knowledge and findings on CDAs have been accumulated, in response to the increase in experimental evidence and upgrading of computer codes (Yamano et al., 2009). For instance, it becomes gradually clear that the potential of forming a stable vapor film at the fuel–sodium interface during CDAs should not be much higher (Kamiyama et al., 2013; Kondo et al., 1995). For this reason, here our attention is confined solely on the non-film boiling conditions and the primary interest is to ascertain whether under such a heat-exchange mode a limited pressurization is maintainable, even if the water mass delivered into the pool is remarkably increased. In addition, as aforementioned, another objective of this study is to acquire experimental data and evidence for the analyses and verifications of the SIMMER-III code, it is therefore also necessary to judge which parameters are of the prior importance. Here, it should be evoked that in our earlier FI-mode FCI investigation (Kondo et al., 1995), which is performed by injecting the same kind of molten alloy into a water pool, a large palette of experimental data under various melt and coolant temperature conditions has been accumulated. On the other hand, the well-developed SIMMER-III code, during its extensive applications in the past, to some extent has proven itself to be comparatively applicable to reproduce the much highly transient multiphase flow problems (Morita et al., 1999). Thus, to further benefit its verifications efficiently, it is natural that for the current CI-mode local FCI investigations, our prior attention should be focused on the remaining parameters that have not been employed so far, e.g. the coolant–fuel mass ratio. Evidently, compared to the widely-used inflow/pouring method in FCI investigations (Berthoud et al., 1994; Huhtiniemi et al., 1999; Kim et al., 2010; Magallon, 2006; Park et al., 1998; Röder et al., 1999; Sibamoto et al., 2002; Spencer et al., 1994; Zimanowski et al., 1995), the developed method in this work ensures that water, with both its volume and temperature well controllable, can be easily delivered into a specific site of the pool to achieve local interactions (depending on where the crushing cone is placed). Table 2 lists the detailed conditions of each experimental run performed. The initial pressure is