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An experimental study on local fuel–coolant interactions by delivering water into a simulated molten fuel pool

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HIGHLIGHTS

- We investigate local fuel–coolant interaction within a simulated molten fuel pool.
- Characteristics of pressure buildup and mechanical energy release analyzed.
- Significant effect of water volume, melt temperature and water release site observed.
- Non-remarkable impact of water subcooling recognized.
- Limited pressurization and mechanical energy generation confirmable.

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ABSTRACT

Analyses of severe accidents for sodium-cooled fast reactors have indicated that there is the possibility that the accident could 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. Local fuel–coolant interaction (FCI) in the pool is regarded as one of the probable initiators that could lead to such compactive fluid motions. To clarify the mechanisms underlying this interaction, in this study a series of experiments was conducted by delivering a given quantity of water into a simulated molten fuel pool (formed with a low-melting-point alloy). Based on the experimental data obtained from a variety of conditions, interaction characteristics including the pressure-buildup as well as resultant mechanical energy release and its conversion efficiency, is checked and compared. From the analyses, it is confirmed that under our experimental conditions the water volume, melt temperature and water release position are observable to have remarkable impact on the interaction, while the role of water subcooling seems to be less prominent. The analyses also suggest that the pressurization and resultant mechanical energy release during local FCIs should be intrinsically limited, due to an observed suppressing role caused by the increasing of coolant volume entrapped within the pool as well as the transition of boiling mode. The evidence and fundamental data from this work will be utilized for future analyses and improved verifications of computer models developed in advanced fast reactor safety analysis codes.

1. Introduction

From the analyses of severe accidents for sodium-cooled fast reactors (Maschek et al., 1992; Theofanous and Bell, 1986; Tobita et al., 1999; Yamano et al., 2009), it has been realized 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 (see Fig. 1) (Suzuki et al., 2012, 2014). Since during the 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 such compactive fluid motions (Maschek et al., 1992). To benefit the evaluation of accident progression (esp. for the energetic events caused by fuel compaction), it is therefore of crucial importance to clarify the mechanisms underlying such interaction.

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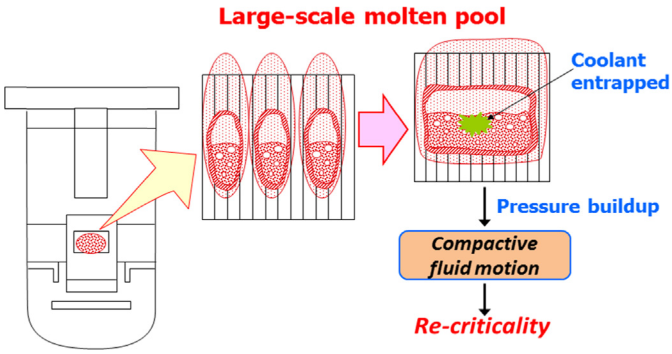

Fig. 1. Large-scale molten pool formed during transition phase.

Unfortunately, it is instructive to note that, although in the past decades 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 conducted, most of them were performed 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, especially in a scenario where a certain amount of liquid coolant is entrapped within a large 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 (such as energetic and non-energetic 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 and resultant mechanical energy release by local FCIs in the pool is still limited, despite of their crucial importance for evaluating the impact on accident progression.

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 (JAEA). The current study, being one of them, is aimed to ascertain the mechanisms underlying the local fuel–coolant interactions in the molten fuel pool. For this purpose, a series of experiments was performed by delivering a given quantity of water into a simulated molten fuel pool (formed with a low-melting-point alloy). Although in an earlier publication (Cheng et al., 2013), the experimental design as well as preliminary results of several typical runs has been presented, it is believed that more discussions are still indispensable because the previous analyses are restricted to a rather narrow range of water quantities (less than 40 cm^3) at unvaried melt and water temperature conditions (namely around 673 K and 330 K, respectively).

Motivated to provide a more reliable and systematical understanding on the characteristics of local FCIs in the molten fuel pool, in this paper further analyses are performed based on a much larger

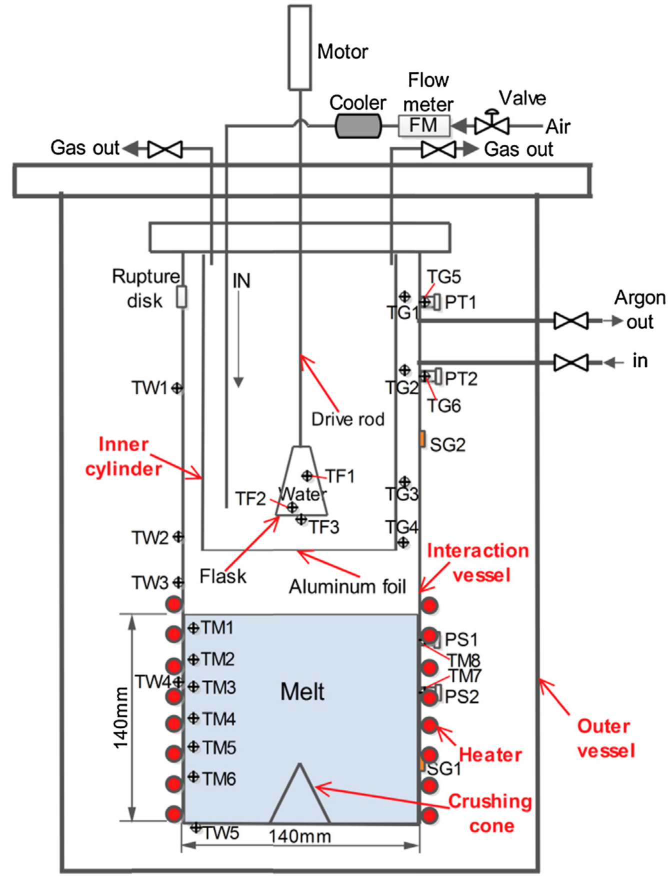

Fig. 2. Representative experimental facility.

experimental database covering various conditions, including difference in water volume (up to around 96 cm^3), melt temperature (472–818 K), water subcooling (~43 K) as well as water release position (pool surface or bottom). The experimental apparatus and procedures are described briefly in Section 2, while the obtained results and their interpretations are discussed in detail in Section 3.

2. Experimental apparatus and procedures

Fig. 2 shows the representative experimental facility, while the relevant instrumentations are further described in Table 1. It can be 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. A video camera (not depicted in Fig. 2), capable of recording tens of frames per second, is used to record the motion of the drive rod (connected to a motor for delivering water) as well as possible vessel vibrations due to the pressure events generated during FCIs.

The interaction vessel is a rigid cylindrical stainless steel vessel of 140 mm in inner diameter. Several thermocouples, dynamic

Table 1
Measurement parameters and their descriptions.

Parameters	Sensing location	Sensor description	
Temperature	Melt	TM1–8	Thermocouple (1.6 mm, 1 kHz)
	External wall	TW1–5	Thermocouple (3.2 mm, 1 kHz)
	Cover gas	TG1–6	Thermocouple (1.6 mm, 1 kHz)
	Water/flask	TF1–3	Thermocouple (1.0 mm, 1 kHz)
Pressure	Melt	PS1–2	High-temperature pressure sensor (24 kHz, <873 K)(PS1: <10 MPa; PS2: <20 MPa)
	Cover gas	PT1–2	Semiconductor-type (24 kHz, <1.7 MPa)
Strain	Interaction vessel	SG1–2	High temperature strain gauge (24 kHz, <1073 K)