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An experimental study on debris bed formation behavior at bottom-heated boiling condition

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ABSTRACT

Motivated to further understand the effect of sodium boiling on the debris bed formation behavior that might be encountered during a core disruptive accident of sodium-cooled fast reactors, in this work a series of new experiments has been performed under the bottom-heated boiling condition. It is found that the four kinds of flow regimes (namely the particle-suspension regime, the pool-convection dominant regime, the transitional regime and the particle-inertia dominant regime), as observed from previous non-bubbling experiments, can be generally reproduced under current boiling condition, despite the existence of some local differences. Although a similar influence of particle properties (size, density and shape) on the regime transition is observable, the regime boundary is confirmed to be changed due to the steam bubbles generated from boiling. Even for the experimental cases without regime transition, the generated bubbling is verified to have an evident impact on the bed characteristic quantities during the debris bed formation process. As for the experimental parameter of water depth, different from previous non-boiling experiments, in this work for a given heating power, a non-monotonous effect is found to exist, due to the much diminished bubbling rate at rather higher water depths. To be comparable with previous experiments using gas-injection, based on energy conservation a quantity of effective bubbling rate is suggested. By using this quantity, the validity of gas-injection to simulate sodium boiling is justified, thereby providing us enhanced confidence for future studies over a much larger range of gas velocities.

1. Introduction

The evaluation of severe accidents is one of the key issues of R&D activities for advanced reactor systems in general, and for Sodium-cooled Fast Reactor (SFR) in particular, because such extremely unlikely accidents constitute the major risk to the public associated with potential radioactive releases from the nuclear power plant (Tentner et al., 2010). Over the past decades, extensive knowledge and findings on the Core Disruptive Accidents (CDAs) of SFR have been accumulated, in response to the increase in experimental evidence, theoretical modeling as well as the upgrading of computer codes (Suzuki et al., 2014; Yamano et al., 2009). It becomes gradually recognized that, during the material relocation phase of a hypothetical CDA of SFR, molten core materials, because of their gravity-driven discharge, may relocate through some potential paths (e.g. the control rod guide tube) into the sodium plenum. The melt-sodium contact is expectable to result in solidification and fragmentation with small particles, and settle to form debris beds over the core-support structure and/or in the lower inlet plenum of the reactor vessel, as depicted in Fig. 1 (Cheng et al., 2014a,b; Tentner et al., 2010). The safe stabilization of the formed debris bed in a coolable configuration is one of the prime requirements to achieve In-Vessel Retention (IVR) (Cheng et al., 2018b; Shamsuzzaman et al., 2018).

To prevent the melt-through of the reactor vessel by molten core materials and thus enhance the safety margin of IVR, in-vessel retention devices such as the core catcher are equipped in some SFR designs (Suzuki et al., 2014; Tentner et al., 2010; Vasilyev et al., 2013). Despite much difference in detailed structure of the core catcher (e.g. single-layer or multi-layer) (Suzuki et al., 2014; Tentner et al., 2010; Vasilyev et al., 2013), it is expected that during the material relocation phase of CDA, after being quenched and fragmented into fuel debris in the lower plenum region, fuel debris should be accumulated on the layers of the in-vessel core catcher (Suzuki et al., 2014; Tentner et al., 2010). To effectively remove the decay heat from the debris beds on the core catcher, thus, the size, retention capability and structure of the catcher should be carefully designed.

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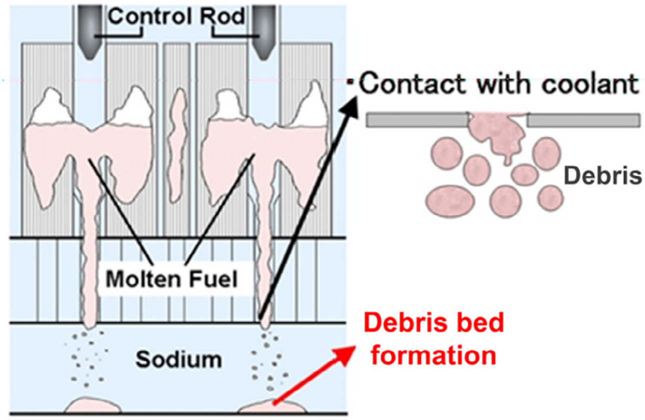

Fig. 1. Debris bed formation.

It is well known that the debris-bed coolability is affected by many key factors such as its power density, particle size, bed thickness and porosity (Suzuki et al., 2014). Aside from these factors, recently the bed geometrical shape (e.g. cylindrical or conical) has been also experimentally verified to play a crucial role (Takasuo, 2016). Unfortunately, over the past decades, although extensive studies on the debris bed hydrodynamics and heat transfer were performed, most of them generally assumed that the upper surface of debris bed is level (Cheng et al., 2013, 2014a,b). Noticing the potential importance of debris-bed geometry in the heat removal capability, by assuming that a quasi-conical debris bed might be formed initially, in the past years several series of experiments on the so-called debris bed self-leveling behavior were performed by Cheng et al. (2011, 2013, 2014a,b) under the collaboration framework between the Japan Atomic Energy Agency (JAEA) and Kyushu University in Japan. Through those studies, much of knowledge and evidence regarding the debris-bed self-leveling behavior, including both overall leveling characteristics (e.g. the role of experimental parameters on the leveling onset and evolution) and the microscopic bubble-particle interactions, were well collected (Cheng et al., 2011, 2013, 2014a,b), which provides us significant support to the followed computer-model development and code verifications (Tagami et al, 2018). Aside from our past studies, here it is worthwhile supplementing that at the same period, in the field of light water reactors, Basso et al. (2014) and Konovalenko et al. (2012) also performed some experimental and analytical studies for the particulate debris spreading phenomenon. They obtained many experimental data on spreading of particle beds in a water pool induced by gas injection from the bottom of the bed.

To find out what realistic geometries the debris bed will form initially during CDAs, a systematic research program, called FRBG-DBF (Flow Regime and Bed Geometry in Debris Bed Formation behavior), has been initiated at the Sun Yat-sen University in China (see Fig. 2). Although currently a few studies regarding the particle sedimentation behavior are being conducted by other investigators from the macroscopic aspect (e.g. with a focus on the average bed height) (Shamsuzzaman et al., 2018), the information regarding the flow-regime characteristics (i.e. in a microscopic level) is still quite scarce, despite their crucial importance for understanding the mechanisms underlying this behavior. As shown in Fig. 2, our FRBG-DBF program, including both experimental study and predictive-model development, mainly contains two steps: Step 1-Understanding the mechanisms of flow regimes and performing modeling studies for various situations within Two-dimensional (2D) conditions; and Step 2-Validating the 2D experimental results and developing a general model (or regime map) directly applicable for reactor safety analyses at larger-scale Three-dimensions (3D). For the Step-1 study, in recent years a large number of simulated experiments were performed by discharging various spherical and non-spherical solid particles into two-dimensional water pools (Cheng et al., 2018a; Lin et al., 2017). Based on the experimental observation, it is found that, due to the different interaction mechanisms between solid particles and water pool, four kinds of regimes, termed respectively as the particle-suspension regime, the pool-convection dominant regime, the transitional regime and the particle-inertia dominant regime, could be identified (Lin et al., 2017). In addition to qualitative observation, detailed quantitative parametrical analyses have been also performed and suggest that the particle size, particle density, particle shape, water depth along with the particle release pipe diameter can have remarkable impact on the regime transition, while the role of particle release height and the gap thickness of 2D water tanks (e.g. from 30 to 60 mm) over our present range seems to be insignificant (Cheng et al., 2018a; Lin et al., 2017). Further, aimed at checking whether the sodium boiling caused by the decay heat from the accumulated debris bed can have some influence on the regime transition (see Fig. 2), a series of experiments has been even performed by percolating nitrogen gas uniformly through the bottom of water pool during the particle sedimentation (Cheng et al., 2018b). Through preliminary analyses, it is recognized that possibly caused by the enhanced pool convection as well as the weakened role of particle inertia, increasing the gas flow rate is verified to have an evident impact on the regime transition and final bed geometry formed (Cheng et al., 2018b). However, it should be pointed out that during an actual reactor accident, as indicated above, instead of gas-injection, the vapor bubbles are generated from sodium boiling. Therefore, there is a pressing need to check whether the above findings regarding the gas phase can be reproduced at the boiling environment. In addition, in order to provide more comprehensive confirmation of the results obtained from previous non-bubbling experiments (Cheng et al., 2018a; Lin et al., 2017), it is further believed that instead of just bubbling rate (namely the gas flow rate at gas-injection condition), various other parameters, especially the particle density, shape and water depth that have not been analyzed at the gas-injection condition, should be also examined sufficiently under the boiling condition.

On the other hand, as for the predictive-model development, some progress has been also achieved. For instance, based on the evidence and database from the 2D basic experiments (see Fig. 2), by using dimensional analysis technique, an empirical model (base model) has been successfully developed to predict the regime transition and final bed geometry formed (Cheng et al., 2017). By coupling the knowledge from experiments using non-spherical particles, the predictive capability of our base model was even extended to cover the particle-shape influence (Cheng et al., 2018a), as a result stimulating us to accelerate our modeling at other more realistic accident conditions (e.g. sodium boiling). Since compared to the boiling method, a gas phase can be adjusted and controlled more easily using the gas-injection method (Cheng et al., 2013, 2014b), especially for comparatively larger gas velocities, it is therefore natural to determine that the much enlarged experimental database, which will be used for modeling the sodium-boiling effect, should be accumulated using the gas-injection method. However, prior to that, validity of the gas-injection method to simulate the sodium boiling should be sufficiently checked, in order to guarantee the data reliability and applicability for future modeling.

Focusing on the above aspects, in this work a series of new experiments using the conventional bottom-heated boiling to generate bubbling is performed at the Sun Yat-sen University. To achieve comprehensive understanding, a variety of conditions including