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Development and analysis of a regime map for predicting debris bed formation behavior

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ABSTRACT

Studies on debris bed formation behavior are important for the improved evaluation of core relocation and debris bed coolability that might be encountered in a Core Disruptive Accident (CDA) of Sodium-cooled Fast Reactors (SFR). To clarify the characteristics of flow regimes underlying this behavior, a series of simulated experiments is being performed at the Sun Yat-sen University in China by discharging various solid particles into Two-Dimensional (2D) water pools. Based on the preliminary experimental analyses, it has been recognized that, due to the different interaction mechanisms observed between solid particles and water pool, four kinds of flow regimes, termed respectively as the particle-suspension regime, the pool-convection dominant regime, the transitional regime and the particle-inertial dominant regime, were identifiable. In this work, owing to a much enlarged experimental database, a regime map is developed to describe the regime transition and final bed geometry formed by considering the competitive role between the particle-inertial and water-convection during the particle accumulation process. It is found that a respective agreement on the regime transition between experiments and the regime-map predictions could be obtained given current range of conditions including much difference in particle size (0.125–8 mm), particle density (beads of glass, alumina, zirconia, steel and lead), particle release pipe diameter (∼30 mm) and water depth (∼60 cm). With further improvements, the developed regime map (base map) will be tested under more realistic reactor conditions (e.g. irregularly-shaped particles or larger-scale dimensions) and is expectable to benefit the design of in-vessel core catcher as well as the verifications and improvement of future SFR severe accident analysis codes in China.

1. Introduction

In a postulated Core Disruptive Accident (CDA) of Sodium-cooled Fast Reactors (SFR), possibly as a consequence of rapid quenching and fragmentation of core materials, a multiphase flow system can form that could be composed of a mixture of liquid sodium, molten fuel, molten structure, refrozen fuel, solid fuel pellets, fission gas, fuel vapor, and other materials (Tentner et al., 2010). A deposition of this system will lead to the formation of debris beds over the core-support structure and/or in the lower inlet plenum of the reactor vessel, as depicted in Fig. 1 (Zhang et al., 2010, 2011).

To prevent the penetration of the reactor vessel by molten fuel, and distribute molten fuel or core debris formed in a CDA into non-critical configurations, in-vessel retention devices (e.g. the core catcher) are used in some SFR designs (Tentner et al., 2010; Waltar and Reynolds, 1981). Although the detailed structure of the core catcher (e.g. single-layer or multi-layer) might be different depending on the reactor-type in different countries (Nakai et al., 2010; Ren, 2015; Vasilyev et al., 2013), it is expected that during a hypothetical CDA, after being quenched and fragmented into fuel debris in the lower plenum region, discharged molten fuel should be accumulated on the layers of the in-vessel core catcher (Tentner et al., 2010). To stably remove the decay heat generated from the debris bed on the core catcher, thus, the size, retention capability and structure of the catcher should be carefully designed.

Unfortunately, over the past decades, although extensive studies on debris bed hydrodynamics and heat transfer were performed (Cheng et al., 2011a), most of them generally assumed that the upper surface of debris bed is level. Noting the importance of debris-bed geometry (e.g. height) in the heat removal capability, by assuming that a conically-shaped debris bed might be initially formed, in recent years Cheng et al. (2011a,b; 2013a,b,c; 2014a,b) performed several series of experiments on the so-called debris bed self-leveling behavior (see Fig. 2). Overall, as illustrated in

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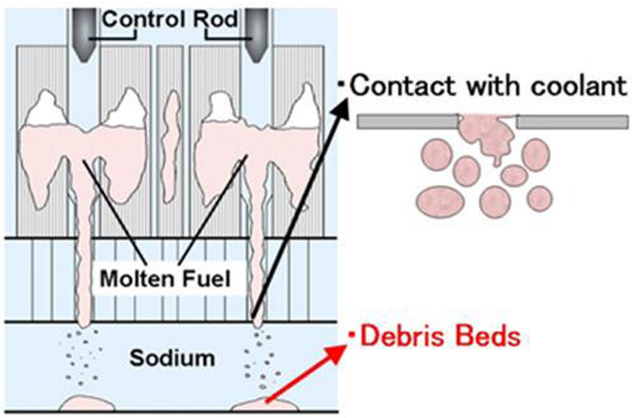

Fig. 1. Debris bed formation.

Fig. 3, their experiments can be generally divided into two categories, namely the macroscopic leveling experiments and microscopic flow-regime investigations. Due to the nontransparency of particle beds, the macroscopic leveling experiments were mainly conducted with the purpose to clarify the overall characteristics of leveling (Cheng et al., 2011b, 2013b,c, 2014a,b), namely the role of experimental parameters (such as particle properties and bubbling rate) on the leveling onset and evolution. As for the microscopic flow-regime series (Cheng et al., 2011a, 2013a), which also consists of several well-organized tests performed at various bubbling conditions (as shown in Fig. 3), was specifically carried out to ascertain the flow characteristics within particle beds, thus providing convincible visual evidence (esp. bubble-particle interaction) for supporting the overall understandings. It has been well confirmed that by combining the knowledge from flow-regime investigations the observed overall leveling characteristics can be understood more effectively (Cheng et al., 2013a).

In order to ascertain what geometries the debris bed will form initially during CDAs, currently a series of simulated experiments on the so-called debris bed formation behavior is being conducted by discharging various solid particles into Two-Dimensional (2D) water pools at the Sun Yat-sen University in China (Cheng et al., 2016). To achieve a comprehensive understanding, various experimental parameters including much difference in particle size (0.125–8 mm), particle density (glass, alumina, zirconia, steel and lead), particle shape (spherical and non-spherical), water depth (0–60 cm), particle release pipe diameter (10–30 mm), particle release height (110–130 cm) as well as the gap thickness of water tanks (30–60 mm), were taken. Based on the preliminary parametric analyses (Cheng et al., 2016; Lin et al., 2017), it is recognized 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-inertial dominant regime, were identifiable. Owing to a much enlarged experimental database, in this work by using dimensional analysis technique, a regime map is proposed with the aim to predict the regime transition and final bed geometry formed. Detailed conditions of our performed experiments, which support the regime-map development, are described in Section 2, while in Section 3, after a briefing of the experimental results, a judge index, which plays the decisive role in regime-map development, is suggested by considering the competitive interaction between particle inertial and water convection. Finally, in Section 4, the development and validity of our regime map is presented. Knowledge and evidence from our work will be utilized for the improved design of in-vessel core catcher as well as verifications and improvement of computer models developed in future SFR severe accident analysis codes in China.

2. Experimental conditions

Fig. 4(a) depicts the schematic diagram of the whole experimental system used for our debris bed formation experiments, while Fig. 4(b) further shows a detailed view of the main apparatus. To facilitate the visual observation and quantitative measurement, two-dimensional (2D) viewing tanks made of transparent acrylic resin with the dimensions of 1000 mm in height, 700 mm in width and 30–60 mm in gap thickness were utilized. Water, which was poured into the tank from the top of the viewing tank, is employed to simulate the coolant. Before the commencement of each experimental run, water-depth was adjusted to target values. At the bottom of the viewing tank, a drain valve (not depicted in Fig. 4) allowing water and solid particles to drain out of the tank after experiments is designed.

To simulate the fuel debris, five kinds of solid particles (namely glass, alumina, zirconia, steel and lead) with different sizes and shapes were used, the properties of which are listed in Table 1. It is believed that such a range of physical properties (for example, the particle size and density) might be possibly broad to cover the entire range of physical properties of actual debris generated during CDAs of a typical SFR (e.g. mean debris size of several hundreds of microns and a maximum density of fuel (MOX) pellets up to about 11 g/cm^3) (Cheng et al., 2013a; IAEA, 2006).

Before the start of each experimental run, a fixed volume (10L) of solid particles is carefully weighed and loaded into the particle release device which is actually a conical funnel made of stainless steel. To avoid the potential dispersion of solid particles out of the water tank during their free-falling, cylindrical pipes with appropriate lengths and adjustable inner diameters (10–30 mm) were connected at the bottom of the particle release device. By pulling the plug upwards with a string, particles initially accumulated in the funnel will be released and fall into the water tank due to the gravity. The whole experimental process is recorded by a video camera which can record tens of frames per second (fps). To obtain a high-quality recording, for most cases back-lighting was applied

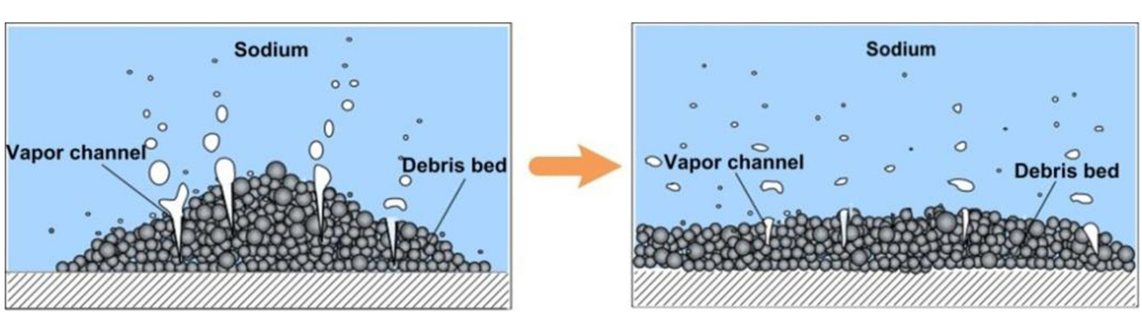

Fig. 2. Schematic view of debris bed self-leveling behavior.