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An experimental investigation on flow-regime characteristics in debris bed formation behavior using gas-injection

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ABSTRACT

Studies on debris bed formation behavior are important for the improved evaluation of Core Disruptive Accident (CDA) of Sodium-cooled Fast Reactors (SFR). To clarify the flow-regime characteristics underlying this behavior, in recent years a series of simulated experiments was performed at the Sun Yat-sen University by discharging various solid particles into Two-Dimensional (2D) water pools. 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, are identifiable. In this work, aimed at providing some evidence for understanding the effect of coolant boiling on the regime transition, a number of new experiments are performed by percolating nitrogen gas uniformly through the water pool during the particle sedimentation. It is recognized that, possibly caused by the enhanced pool convection as well as the weakened role of particle inertia, increasing the gas velocity are confirmable to have an evident impact on the regime transition. On the other hand, even for the cases without regime transition, the gas flow injected is also verifiable to have a great influence on the particle-bed properties (e.g. specific geometric angles), regardless what regime it is. Knowledge and evidence from our work might be utilized for future development of a general model directly applicable for reactor safety analyses as well as the verifications of SFR severe accident analysis codes in China.

1. Introduction

During the material relocation phase of a hypothetical Core Disruptive Accident (CDA) of a Sodium-cooled Fast Reactor (SFR), molten core materials may relocate through some potential paths because of their gravity-driven discharge into the sodium plenum. These settle to form debris beds over the core-support structure and/or in the lower inlet plenum of the reactor vessel (Tentner et al., 2010; Zhang et al., 2011), as depicted in Fig. 1. Sufficient cooling of the formed debris beds as well as their neutronically subcritical configuration is necessary for In-Vessel Retention (IVR) of degraded core materials.

To prevent the penetration of the reactor vessel by molten fuel, and distribute the 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; Vasilyev et al., 2013; Ren, 2015), it is expected that during a postulated 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 (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, although over the past decades 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 the past years several series of experiments on the debris bed self-leveling behavior (see Fig. 2) were performed by Cheng et al. under the collaboration framework between the Japan Atomic Energy Agency (JAEA) and Kyushu University in Japan (Cheng et al., 2011a,b, 2013b,c, 2014a,b). Overall, their experiments can be divided into two categories, namely the macroscopic leveling experiments and microscopic flow-regime investigations (Cheng

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Nomenclature

D_{pipe}	diameter of particle release pipe [mm]
d_{p}	particle size [mm]
H_{ps}	height of particles suspended [cm]
H_{w}	water depth [cm]
I	regime judge index [–]
K_{b}	empirical constant in base model [–]
K_{s}	correction factor representing the effect of sodium boiling [–]
L, W	length and width of water pool [mm]
Q_{g}	gas flow rate [L/min]
V_{p}	average particle release rate [m/s]
V_0	a critical velocity defined to invoke the pool convection [m/s]
V_{T}	particle terminal velocity [m/s]
Greek letters	
ρ_{p}	particle density [kg/m^3]
ρ_{w}	water density [kg/m^3]
μ_{w}	water viscosity [Pa·s]
σ_{w}	water surface tension [N/m]

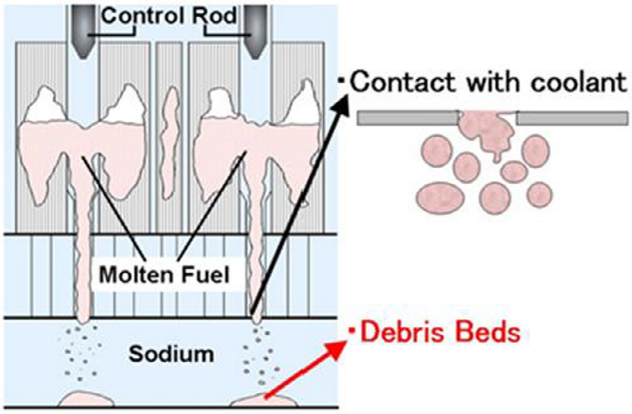

Fig. 1. Debris bed formation.

et al., 2013b, 2014a). 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, 2013a,c, 2014a), 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, 2013b), which also consists of several well-organized tests performed at various bubbling conditions, 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., 2013b).

In order to ascertain what geometries the debris bed will form initially during CDAs, recently several series of experiments on the so-called debris bed formation behavior have been initiated at the Sun Yat-sen University in China (see Fig. 3). Although in the past a few studies regarding the particle sedimentation behavior were conducted by some investigators from the macroscopic aspect (e.g. average bed height) (Shamsuzzaman et al., 2013), 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. 3, our researches, including both experimental study and predictive-model development, mainly contain two steps: Step 1-Understanding the mechanisms of flow regimes and performing modeling studies for various parameters 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-dimensional (3D) conditions. In our recent publication (Lin et al., 2017), a series of simulated experiments was performed by discharging various solid particles into two-dimensional water pools. To achieve a comprehensive understanding, various parameters such as particle size (0.125–8 mm), particle density (beads of glass, alumina, zirconia, steel and lead), water depth (0–80 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), have been taken (Lin et al., 2017). Based on the experimental observations and parametric analyses, 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-inertia dominant regime, were identifiable.

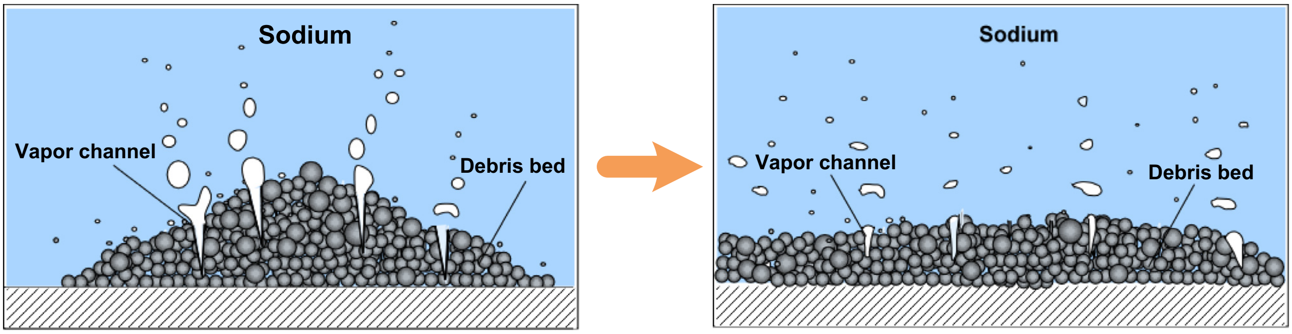

Fig. 2. Schematic view of debris bed self-leveling behavior.

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