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Experimental study on debris bed characteristics for the sedimentation behavior of solid particles used as simulant debris

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ABSTRACT

Particle bed characteristics are experimentally investigated for the sedimentation and subsequent bed formation of solid particles, related to the coolability aspects in core–disruptive accidents. Presently a series of experiments with gravity driven discharge of solid particles into a quiescent water pool was performed to evaluate bed formation characteristic in the course of particle sedimentation. We evaluated the effects of the crucial factors: nozzle diameter, particle density, particle diameter and nozzle height on four key quantitative parameters of bed shape: mound dimple area, mound dimple volume, repose angle and mound height to illustrate the role of the crucial factors on forming the particle bed shape. The investigated crucial factors exhibit a significant role that diversifies the particle bed formation process. Based on the data obtained in the experimental observations, we developed an empirical correlation to compare the predicted results with the experimental bed heights. The proposed empirical correlation can reasonably demonstrate the general trend of the experimental bed height. This correlation could be useful to assess the particle bed elevation, and to identify the governing parameters.

1. Introduction

The severe damage caused at the Fukushima Daiichi nuclear plant in Japan, resulted from a beyond design-basis magnitude of natural disaster, combining an earthquake and a tsunami on March 11 2011, has raised the rationality of the safety concern in a core disruptive accident (CDA). This disaster provokes the awareness among worldwide public to comprehend the occurrence of severe accidents including the CDAs, even if their probability is extremely low. The Fukushima Daiichi accident revealed the subsequent formation of corium either for an absolute or delayed deficiency of cooling of the reactor core. To ensure the safety margin of the in-vessel retention, assurance of adequate cooling and stabilization of the corium is prerequisite (Park et al., 2013). After such a CDA in a sodium-cooled fast reactor (SFR), melt–sodium contact is expected to lead solidification and fragmentation with small particles (Tentner et al., 2010). As a consequence, in the course of melt relocation, fragmented debris can form debris beds on core-support structure or in the lower plenum of the reactor vessel (Zhang et al., 2008). Such debris bed is formed with particles of different sizes and varying porosity (Harvey et al., 2008). The safe stabilization of the debris bed in a coolable configuration is one of the prime requirements of the in–vessel retention. In this perspective, assessment of the dynamics of molten fuel relocation following such a CDA in SFR is of importance during post–accident material relocation (PAMR) phase. This is because the formation of debris bed and its configuration is a critical issue for the self-sustainable long–term cooling mechanism of the debris bed (Park et al., 2013). Therefore, investigation of debris bed formation characteristic during debris sedimentation on core catcher plate is an important point for cooling considerations and recriticality concern with a view to ensure the safety of the reactor main vessel in CDA (Sudha et al., 2011). The heat transfer phenomena in a coolable configuration of the debris bed have gained much attention in last decades. Lots of theoretical and experimental investigations have focused the related subjects of the debris bed characteristics (Harvey et al., 2008; Yakush and Kudninov, 2009; Weimin et al., 2007). However, among most of those researchers, the shape of debris bed was specified on ad-hoc, e.g., a cylinder (Burger et al., 2006), cone or Gaussian–shaped heap (Yakush et al., 2008), heap–like (Karbojian et al., 2009; Weimin and Truc-Nam, 2010), conical shape (Zhang et al., 2010), homothetic pile (Alvarez and Amblard, 1982). Moreover, previous analysis of debris bed coola-

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Nomenclature

A_{dim}	dimple area [m^2]
d_n	nozzle diameter [m]
d_p	particle diameter [m]
D_c	cylinder diameter [m]
H_b	particle bed height [m]
H_m	mound height [m]
H_e	bed edge height [m]
H_n	nozzle height [m]
J_f	jet factor [−]
V_A	volume of bed mound [m^3]
V_B	volume of bed edge [m^3]
V_{dim}	dimple volume [m^3]
v_i	initial particle velocity [m/s]
v_p	particle velocity [m/s]
v_t	terminal velocity [m/s]
V_p	bulk particle volume [m^3]
μ_f	fluid viscosity [Pa∗s]
ρ_f	fluid density [kg/m^3]
ρ_p	particle density [kg/m^3]
θ_r	repose angle [degree]
ε	porosity [%]
φ	sphericity [−]

Abbreviations

Exp.	experiment
Pred.	predicted

bility in a reactor accident has generally assumed that debris beds are homogeneously and uniformly spread over pool bottom (Weimin et al., 2007). However, to find out the realistic debris bed shape for a particular scenario of melt release, the process of debris bed formation has to be modelled, taking into account the sedimentation process of the debris particles in a CDA. This is because in such a CDA, if the molten core materials relocated from the core cannot be contained in a coolable configuration in the lower plenum, it could eventually make its way to the lower head of the reactor vessel, causing a potential melt through of the reactor vessel (Tentner et al., 2010). Formation of the debris bed in a coolable configuration can potentially ensure the IVR (Tobita, 2013).Therefore, study on such melt–debris relocation and bed formation behaviour is crucial to analyze the debris bed coolability so as to ensure the safety margin of IVR. In this perspective, laboratory scale experiments could be a useful method to mechanistically simulate the debris bed formation process in a reasonably simplified CDA scenario.

In the present study, particle bed characteristics were studied to evaluate the role of particle sedimentation on forming the particle bed shape in terms of four crucial factors: particle diameter d_p, particle density ρ_p, nozzle diameter d_n, and nozzle height H_n. Here particle bed characteristics are investigated in terms of four key quantitative parameters: mound height H_m, mound dimple area A_{dim}, dimple volume V_{dim} and repose angle θ_r of the bed mound to estimate the particle bed shape. The purpose of this work is to understand the basic behaviour of particle sedimentation on bed formation mechanism as a separate effect. One of the prime objectives of the present study is to identify the key parameters for the purpose to comprehend their effects on altering mound shape of the particle bed. Correspondingly, a dimensionless empirical correlation was developed based on the data obtained in the experimental observations to estimate the characteristic particle bed height. After being further authentication at fuel density range, the proposed correlation could be incorporated into advanced fast reactor safety analysis codes for the IVR safety evaluation of SFRs in CDAs.

2. Material and methods

2.1. Experimental apparatus

The diagram of the experimental apparatus used in the particle sedimentation experiment is shown in Fig. 1. In the experiments, solid particles and water simulate the fuel debris and coolant, respectively. The main components of the apparatus are the vessel and the particle injection funnel. The vessel is a cylinder, 375 mm in diameter and 1020 mm in height, made of transparent acrylic. The vessel was filled with water up to a height of 825 mm by pouring water from the top site of the vessel. At the top of the vessel, a particle injection funnel is placed on a separate structural base at 1217 mm height. The diameter of the funnel is 350 mm at the upper end (i.e., wide part) and 53.5 mm at the lower end (i.e., narrow part). The height of the funnel is 405 mm along its axial direction. A 92-mm long nozzle is attached at the lower part of the funnel with keeping its lower end at 720 mm height from the particle collector tray. The tray has an area of 1104 cm^2 and is located at the bottom of the vessel. The lower end of the nozzle was immersed in the water column of the vessel by maintaining water levels 105 mm above the release point of the nozzle. In the experimental runs, a stopper rod with a conical end was inserted into the funnel to plug the release hole, which prevented the solid particles flowing out during filling. However, the consideration of this stopper rod did not affect the initial real particle falling height from the particle release hole of the nozzle to the particle collector plate for the respective experiments. This is because, although initially the small thickness of the conical end of the stopper rod was tied up with the nozzle inlet, but just after its rapid pull out particles pass in the nozzle immediately, and hence particle falling get initiated without any interruption until the complete removal of the remaining portion of the rod. This is because, initially the tied up conical end of the stopper rod with relatively small thickness was pulled out rapidly to initiate the particle falling, and then the remaining portion of the rod was removed gradually. The cylindrical vessel was placed inside an outer rectangular pool of transparent acrylic and the gap between the cylindrical vessel and rectangular pool was filled up by water to reduce the effect of refraction while taking online video camera photography of the experiment events. A rigid structural base was provided at the bottom of the vessel to take care of the "particle tray" and to bear the load of the water column. The entire set–up was supported by a fixed vertical stand to minimize the effect of the mechanical vibration. A front–lighting system was equipped at a suitable vertical height to ensure the image contrast with high quality. To record the whole experimental process of particle sedimentation a digital video camera was employed, which can record tens of frames per second.

2.2. Experimental procedure

A series of particle sedimentation experiments was performed by using solid particles as simulant debris. The present experiments were carried out to investigate the particle bed formation characteristics during particle sedimentation due to its significance on the coolability aspects of the debris bed. Currently, both spher-