Sedimentation and Bed Formation Behaviors of Core Debris in Severe Accidents of Sodium-Cooled Fast Reactors

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論 文 名　：Sedimentation and Bed Formation Behaviors of Core Debris in Severe Accidents of Sodium-Cooled Fast Reactors
（ナトリウム冷却高速炉の過酷事故における炉心デブリの堆積及びベッド形成挙動）

論　文　の　要　約

During the material relocation phase of core-disruptive accidents (CDAs) in sodium-cooled fast reactors (SFRs), the sedimentation of core materials fragmented in the lower plenum region leading to formation of a debris bed is crucial in regard to in-vessel retention (IVR) and safety concerns. This is because the height and shape of the formed beds may influence both the cooling of the bed from the decay heat in the fuel and the neutronic characteristics. To investigate debris sedimentation and bed formation behaviors, experimental studies have been performed using simulant materials of solid particles, and an empirical model has been proposed to predict the bed height under various conditions of particle sedimentation. However, obtained experimental knowledge and developed model applicability are limited only to homogeneous particles used in the experiments, although core debris could be mixtures of fuel and stainless-steel particles with size distribution. Hence, a comprehensive study is required to understand characteristics of debris sedimentation and bed formation behaviors under a wide range of conditions in CDAs of SFRs.

In this study, a series of experiments using simulant debris materials of mixed solid particles with different properties was performed to investigate the characteristics of debris sedimentation and bed formation behaviors. Based on the experimental results, a new empirical correlation was developed to predict the bed height for both homogeneous and mixed particles. An empirical model was also proposed to predict bed formation modes of convex and concave shapes of the bed mound. In addition, a hybrid numerical simulation method, which couples a 3D multi-fluid model with the discrete element method, was validated to demonstrate its applicability to the particle sedimentation and bed formation behaviors.

The whole thesis is organized into five chapters.

Chapter 1 introduces the contextual and the objective of this study. The development of nuclear power including Generation IV systems was described with emphasize of distinctive features of liquid-metal cooled reactors (LMRs) and the essence of the safety analysis of CDAs in LMRs. Lastly, the scope and outline of the present study are presented.

Chapter 2 gives a description of the particle sedimentation experiments performed under gravity-driven discharge of solid alumina, zirconia and stainless-steel particles through a nozzle into a quiescent cylindrical water pool. As previously observed in the beds of homogeneous particles, mixed particles also formed concave-shaped beds depending on nozzle diameter and

the particle size. We investigated the effect of the particle density and size on particle sedimentation and bed formation. In general, homogenous particles with smaller densities and larger sizes tend to form relatively higher mounds, whereas for mixed particles, bed porosity, which depends on the mixing ratio of particles of different sizes, and the average particle density are also crucial factors in bed formation. These fundamental characteristics observed in the experiments give us valuable knowledge on general understanding of bed formation behavior of mixed particles with different properties.

Chapter 3 presents the development of new empirical models using a dimensional analysis technique to represent characteristics of bed formation behavior for both mixed and homogeneous particles. The form of the developed correlation for the bed height was confirmed by performing a detailed analysis of the effect of the current experimental parameters. The correlation represents the effects of mixed particle properties reasonably and predicts the experimental data for the particles ranging from 1.0 to 6.0 mm in diameter and from 3,720 to 8,050 kg/m^3 in density with the coefficient of determination of 0.97. In addition, an empirical model was proposed to correlate the dimple area at the mound top of a concave-shaped bed. This model also enables us to predict modes of bed formation characterized by convex and concave shapes of the bed mound. The developed empirical models are expected to be useful for the development and validation of physical models used by computational tools for safety analysis of SFRs.

Chapter 4 describes a validation study of the 3D hybrid numerical simulation method for particle sedimentation and bed formation behaviors. The simulations were performed for the whole transient processes including discharge of solid particles into the water pool, particle sedimentation in the pool and bed formation on the bottom of the pool in the particle sedimentation experiments. The simulation results not only reproduced the fundamental characteristics observed in the experiment, but also indicated quantitative agreements with measured heterogeneous behaviors of particle distribution in the beds as well as bed shapes for binary mixtures of particles. The present simulations demonstrate practical applicability of the hybrid method to the particle sedimentation and bed formation behaviors of mixed particles.

Chapter 5 draws conclusions of the present works. The current investigation was accomplished with a view to clarify the particle bed formation mechanism so as to categorize the leading essential aspects on the sedimentation progression. This basic experimental database of particle sedimentation phenomena has a worth to be developed as the baseline to validate and progress the pertinent models and approaches of fast reactor safety analysis codes. Therefore, the existing research has a potential solicitation opportunity to substantiate the IVR safety approach, as an ultimate safety objective of SFRs. Although additional studies would be necessary by outspreading the variety of present experimental limitations, it is expected that the present study will contribute to understand the fundamental behaviors of core-debris sedimentation and bed formation in CDAs of SFRs.