

STUDY ON SELF-LEVELING BEHAVIOR OF MIXED SOLID PARTICLES FOR REACTOR SAFETY ANALYSIS

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論 文 名 : STUDY ON SELF-LEVELING BEHAVIOR OF MIXED SOLID PARTICLES FOR REACTOR SAFETY ANALYSIS

(原子炉安全解析のための混合固体粒子のセルフレベルリング挙動に関する研究)

区 分 : 甲

論 文 内 容 の 要 旨

During a postulated core-disruptive accident of sodium-cooled fast reactors (SFRs), after molten core materials are discharged into the lower plenum of the reactor vessel, they may be quenched and fragmented rapidly because of melt-coolant interactions. The deposition of fragments will lead to the formation of debris beds over the core-support structure and/or in the lower plenum. The debris bed, however, could be leveled-off due to coolant boiling that is caused by the fuel decay heat. This phenomenon, which is termed self-leveling behavior, is of essential importance for neutronic characteristics and heat-removal capability from debris beds because the cooling and recriticality depend strongly on the thickness or the height of the debris bed. To investigate self-leveling behaviors, experimental studies have been performed using simulant materials of solid particles, and empirical models have been proposed to predict the bed height change during self-leveling processes in particle beds under various conditions. However, the obtained experimental knowledge and proposed model have been limited to homogeneous particles, although actual fragmented core debris are mixtures of fuel and stainless-steel particles with different sizes. Therefore, further investigations are necessary to understand the self-leveling phenomena in inhomogeneous particles beds, that is multi-size and multi-density mixed particles beds.

In this study, a series of experiments using simulant debris materials of mixed solid particles with different properties was performed to develop an extensive experimental database for self-leveling processes in cylindrical beds. Based on the experimental results, a new empirical correlation was developed to predict the bed height change during the self-leveling process for both homogeneous and mixed particle beds. The applicability of the empirical model was validated by comparing the prediction results with the experimental data. In addition, a hybrid numerical simulation method, which couples a 3D multi-fluid model with the discrete element method (DEM), was validated to demonstrate its applicability to the self-leveling behaviors of mixed solid particles in a cylindrical bed.

The present thesis is divided into five chapters.

Chapter 1 introduces the background and objective of this study. Overviews of nuclear energy development, nuclear fuel cycle and the role of fast reactors were described with emphasis on safety characteristics of fast reactors as well as severe accidents and safety measures.

Chapter 2 gives a detailed description of the experiments using a gas injection method performed to examine the self-leveling behavior and the characteristics of debris beds. Spherical and/or non-spherical particles of alumina, zirconia, zinc, stainless steel, copper and their mixtures were used as debris simulants.

We employed various binary mixtures with different-density particles of equal size, the same-density particles of different sizes and/or sphericity. Variations in bed mound height during the self-leveling process over time were measured for different gas-injection velocities. In general, there is a common trend that when the volume fraction of heavier/larger or more uneven particles (smaller sphericity) develops, the particle mixtures become more difficult to level off. In addition, it was found that the self-leveling behavior also depends on the bed diameter and the particle volume because the gas-velocity profile changes before the gas flows into the cone-shaped mound of the bed that affects particle motion. These fundamental characteristics observed in the experiments give us valuable knowledge on general understanding of self-leveling behavior of mixed particles with different properties.

Chapter 3 presents the development of the new empirical model using a dimensional analysis technique to correlate the experimental data on the transient bed height during self-leveling process under various experimental conditions. Based on the experimental knowledge obtained in this study, a new model was formulated for the overall bed height, which is the height measured from the bed bottom to the top mound of the bed, instead of the bed height or inclination angle of the cone-shaped mound as used in the previous studies. This model represents the effects of mixed particle properties and predicts the experimental data reasonably well for a wide range of experimental conditions. The average relative root-mean-square error between the predictions and the experimental values is 3.1% with a maximum error of 8.0% for 62 experimental cases including 19 cases with spherical particles, 12 with non-spherical particles and 31 with binary-mixed particles. The developed model is expected to be useful for the development and validation of physical models used in computational tools for safety analysis of SFRs.

Chapter 4 describes a validation study of the 3D hybrid numerical simulation method for the self-leveling behaviors in cylindrical beds. The simulations were performed for some typical experimental cases using alumina and stainless-steel particles as well as their mixtures at various gas injection flow rates. The effects of friction between particles on the simulation results were investigated by sensitivity analysis in detail. A reasonable agreement between simulation results and corresponding experimental data demonstrates the potential applicability of the present method to the simulation of the self-leveling behaviors in cylindrical beds for mixed particles. The present hybrid method is expected to be a prospective computational tool for analysis of safety issues related to solid particle debris bed in SFRs.

Chapter 5 draws conclusions of this thesis. Future works are also discussed. The present study preliminarily established an extensive experimental database on the self-leveling behavior of mixed solid particle beds. An empirical model was formulated to predict the behavior of binary-mixed particle beds consistently. These extensive experimental and empirical results are necessary to develop and validate physical models used by computer codes that simulate the self-leveling phenomena under reactor accident conditions. Although further investigations would be necessary to expand the current experimental conditions and applicable ranges of the empirical model, it is expected that this study will be helpful to understand the fundamental characteristics of self-leveling behavior for reactor safety analysis.