Development of an Aerosol Migration Model for Source Term Evaluation in Reactor Severe Accidents

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論 文 名　: Development of an Aerosol Migration Model for Source Term Evaluation in Reactor Severe Accidents
(原子炉過酷事故時のソースターム評価のためのエアロゾル移行モデルの開発)

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論　文　内　容　の　要　旨

In a core disruptive accident (CDA) of a sodium-cooled fast reactor (SFR), the interaction between molten core materials and coolant sodium rapidly vaporizes a large amount of coolant, forming a large scale, multi-component, multi-phase bubble in the sodium pool, called a CDA bubble. This bubble subsequently rises in the sodium pool with repeated expansion and compression, eventually carrying a portion of fission products released from the core through the sodium pool to the cover gas within a few hundred milliseconds (commonly referred to as instantaneous source terms). At present, there are several multi-component, multi-phase, multi-physic codes developed specifically for detailed simulation of CDA sequences, such as the fast reactor safety analysis code SIMMER-III, but they lack the physical models needed to evaluate instantaneous source terms. Therefore, in order to reasonably evaluate and understand the instantaneous source term, it is necessary to develop a dedicated analysis and evaluation tool that tightly integrates the transport behavior of the radioactive aerosols with the dynamics of the CDA bubble.

In this study, a simplified model was developed to elucidate the dynamics of the CDA bubble in the sodium pool and the associated transport of radioactive aerosols. First, a one-dimensional CDA bubble model was developed to provide a reliable pathway for aerosol migration. In addition, an aerosol migration model was developed for incorporation into this CDA bubble model. Each of these models was validated by analyzing existing experiments. Finally, the developed model was applied to calculate cesium migration under certain CDA conditions and its behavior was evaluated.

The thesis consists of five chapters.

Chapter 1 introduces the background and objective of this study. Perspectives on the development of nuclear energy, the prospect for Generation IV reactor systems and SFRs, and the importance of severe accident research for SFRs are presented. The progress of research on CDA sequences and source term is also outlined. Finally, the objectives and outline of the study are presented.

Chapter 2 describes the details of the developed one-dimensional, two-phase, multi-component (fuel/steel/sodium) CDA bubble model and its validation based on experimental data. The model simulates the rise of a bubble in the sodium pool and the change in interface height of the cover gas due to the compression and expansion as a vertical one-dimensional motion, and also considers radial expansion and contraction of the bubble. Possible heat and mass transfer paths among all components in the bubble and cover gas were modeled, including coolant entrainment based on the second instability (Kelvin-Helmholtz and Raleigh-Taylor) at the bubble interface and the Raleigh-Taylor instability at the cover gas interface. Finally, the validity of the model for two-phase large-scale bubble expansion behavior was demonstrated using experimental data from the OMEGA test conducted at Purdue University.

In Chapter 3 the aerosol migration model developed for incorporation into the developed CDA bubble model and the validation of this model through analysis of experiments are described. The model assumed that all aerosols move radially and tangentially inside the bubble, and employed an aerosol scavenging model analogous to precipitation washout. Finally, the model was validated using data from experiments conducted at Karlsruhe Institute of Technology, called FAUST-2B, in which simulated radioactive material (source material) was transported by a high-pressure large-scale bubble in a sodium pool. In comparison with two sets of experiments with different types of source materials, particulate strontium oxide and liquid cesium, both the calculated bubble dynamics and the amount of source material transported with the bubble to the cover gas are in good agreement with the experimental results. The results demonstrate the reliability of the aerosol migration model as well as the CDA bubble model that integrates it. This validation identified the two most important mechanisms with respect to source material absorption during the movement of the large scale bubble with source material. These are: inertial impaction between sodium droplets entrained into the bubble and aerosols, and the escape of aerosols from the bubble interface.

Chapter 4 presents the migration behavior of cesium under reactor conditions obtained by applying the developed model to the CDA conditions of the Indian pool-type sodium-cooled fast reactor PFBR. First, under the assumption that all components are immiscible as in the SIMMER-III code, cesium migration behavior was calculated using the discharge conditions of core materials provided by the SIMMER-III calculation. The model results for bubble dynamics and the behavior of each component inside the bubble are generally consistent with the SIMMER-III code calculation. It is shown that a small part of the cesium discharged from the core is absorbed by the sodium pool, while the majority migrates into the cover gas in the form of vapor. Next, taking into account the extremely strong mutual solubility of cesium and sodium, which are both alkaline metals, the cesium migration behavior was evaluated assuming that the cesium condensed on sodium droplets in the bubble is instantly scavenged into the sodium droplets. As a result, compared to the immiscible condition, the amount of cesium vapor transported to the cover gas clearly decreases when cesium and sodium are miscible, while the amount of cesium in the cover gas in the form of mixed droplets of sodium and cesium increases significantly. This application shows that the developed model is useful for quantitative analysis of the detailed migration behavior of cesium associated with a CDA bubble in a sodium pool.

Chapter 5 draws a conclusion of the thesis and indicates some future works.