

# Study on Particle-based Simulations of Multiphase Flows with Heat and Mass Transfer for Reactor Safety Analysis

Aprianti, Nur Asiah

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氏 名 : ヌル アシア アプリアンティ

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(原子炉安全解析のための熱及び質量移行を伴う多相流の粒子法シミュレーションに関する研究)

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### 論 文 内 容 の 要 旨

Core disruptive accidents (CDAs) have been one of the major safety concerns in sodium-cooled fast reactors (SFRs). To clarify thermal-hydraulics behaviors of multiphase flows involved in CDAs, not only in-pile and out-of-pile experiments but also computational simulations have been conducted extensively. They have accomplished certain successful results in assessing the SFR safety. However, meanwhile computational fluid dynamic (CFD) simulations using conventional Eulerian mesh methods revealed their limitation in representing essential characteristics of multiphase flows, namely interface phenomena between two different phases. On the other hand, a fully Lagrangian CFD technique, i.e. the particle-based simulation methods, does not need to generate computational grids. Construction of interphases is also unnecessary because each moving numerical particle represents each phase with specific physical properties. Therefore, the present study employed the particle-based simulation using the finite volume particle (FVP) method, to directly simulate multicomponent, multiphase flows without empirical models such as flow regime map and heat transfer correlations.

In this study, two series of particle-based simulations were performed to clarify thermal-hydraulic behaviors involved in particular experiments relevant to CDA phenomena in SFRs. One of the simulations was dedicated to the analysis of the EAGLE in-pile ID1 test performed by Japan Atomic Energy Agency (JAEA) to demonstrate early fuel discharge from a fuel subassembly with an inner duct structure (FAIDUS). One of the key behaviors observed in the ID1 test is the duct wall failure caused under high heat-flux conditions. The other was the simulation of a series of fundamental experiments for melt freezing behavior in a narrow flow channel. These experiments using simulant melts were conducted in order to investigate characteristics of melt penetration and solidification in a channel that is similar to a reactor pin bundle. The whole thesis is divided into five chapters.

Chapter 1 introduces the background and the objective of the present study. Overviews of nuclear energy and nuclear reactor safety are described. The particle-based simulations and their applications to nuclear engineering are also reviewed briefly.

Chapter 2 describes fundamental models and methods of the particle-based simulation including the FVP method, governing equations and their solution algorithm, and treatment of boundary conditions. Some key physical models are also presented for numerical simulations of multicomponent, multiphase flows with heat and mass transfer.

Chapter 3 presents the particle-based simulations to analyze a set of heat transfer processes after the formation of fuel ( $\text{UO}_2$ )/steel mixture pool in the EAGLE ID1 test. In this 2D simulations, extended heat and mass transfer models were introduced to represent key thermal hydraulic behaviors involved in local thermal attack of the pool mixture to the duct wall, fuel crust formation on the wall surface and so on. Mechanisms of effective heat transfer from the molten pool to the duct wall were clarified through parametric simulations on material distribution in the molten pool after its formation. The present analysis indicates that effective pool-to-duct wall heat transfer is caused by local contact of molten steel with high thermal conductivity to the duct wall. As a result, the duct wall is exposed by large thermal load with heat flux more than  $10 \text{ MW/m}^2$ , which is attributed to nuclear heat in the fuel. In addition, although the molten fuel can freeze on the duct wall surface as crust, it would not deteriorate the pool-to-duct wall heat transfer largely due to its local and discrete formation. The present results ensure phenomenological understanding of the duct wall failure leading to early fuel discharge from FAIDUS by the simulations without empirical models.

In Chapter 4, the fundamental experiments for melt freezing behavior in a pin bundle were analyzed by the particle-based simulations to understand local meso-scale freezing and penetration behavior of melt flowing into narrow channel geometry. The 3D calculations were performed to simulate the injection of molten Bi-Sn-In alloy and its mixture with solid bronze particles into a seven-pin bundle made of stainless steel. The simulation results were compared with the observed characteristics of melt penetration and freezing, which are represented by penetration length as well as geometrical shape of the frozen melt forming blockage in the flow channel. The observed penetration and freezing characteristics were reasonably reproduced in the cases of not only molten metal, but also its mixture with solid particles. In the case of mixed melt, a certain amount of mixture separated from the bulk melt flow without adhesion on the pin surface. It was found that this melt separation reduces the penetration length due to the fact that the pure melt can readily freeze onto pin surfaces but particles cannot. The present simulations clarify local melt freezing behaviors such as blockage formation due to melt adhesion on pin surface and their difference between pure and mixed melts.

Chapter 5 draws a conclusion of this thesis. For future extensive works, several directions were also suggested.