Multiphase Modeling of Debris Particles in Nuclear Severe Accidents

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1. Introduction

In severe accident scenarios involving core melt progression (DEC-B conditions), molten corium may relocate and interact with surrounding coolant, leading to rapid fragmentation and the formation of particulate debris [1]. Historical accident analyses have shown that such debris can accumulate in the lower head of the reactor pressure vessel (RPV) or ex-vessel cavity, forming porous debris beds whose configuration strongly affects long-term coolability and accident progression [2].

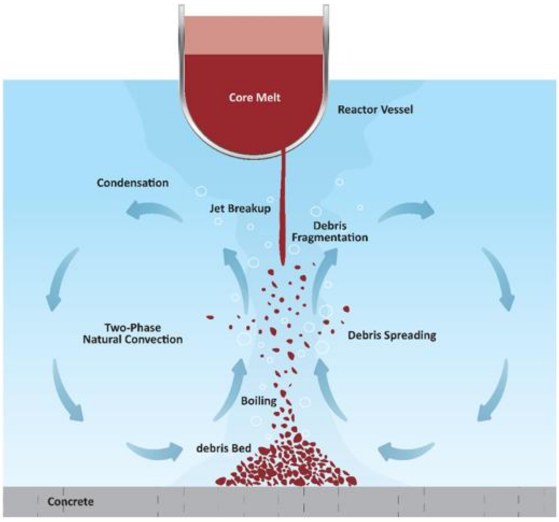

Fig. 1. Phenomena on the late phase of severe accident in a nuclear reactor. [3]

The behavior of nuclear fuel debris during the late phase of a severe accident is inherently a three-phase (gas–liquid–solid) phenomenon. Vapor generation, natural circulation, and particle relocation occur simultaneously within and above the porous debris structure [3]. Experimental and numerical studies have demonstrated that particle spreading, self-leveling, and sedimentation mechanisms significantly influence debris bed geometry and dryout characteristics [4]. Since debris bed coolability is strongly dependent on bed height, porosity, and particle distribution, accurate prediction of debris relocation and formation behavior is essential for safety evaluation [5].

From a computational perspective, severe accident analysis has traditionally relied on system-level codes employing lumped-parameter or coarse Eulerian formulations, such as MAAP and MELCOR [6]. While computationally efficient for regulatory assessments, these approaches depend on empirical correlations and simplified representations of multiphase flow. To improve mechanistic fidelity, continuum-based two-fluid models have been developed for debris bed cooling and spreading analysis [6]. However, the discrete nature of solid particles and inter-particle collision dynamics are not fully resolved in such formulations [1]. Recently, coupled CFD-DEM and particle-based Lagrangian approaches (e.g., SPH-DEM, MPS-DEM) have been introduced to explicitly resolve particle–particle and fluid–particle interactions under multiphase conditions [7]. These methods enable more detailed simulation of debris bed formation and dynamic relocation behavior, particularly under complex three-phase flow environments [3]. The increasing modeling fidelity reflects the need to reduce epistemic uncertainty in debris behavior prediction under extreme, poorly accessible accident conditions.

This paper reviews the evolution of computational methodologies for modeling nuclear fuel debris during severe accidents, ranging from lumped-parameter approaches to continuum models and emerging discrete particle-based techniques. Each methodology has inherent strengths and limitations in terms of computational efficiency and physical fidelity. Accordingly, a comparative perspective is necessary to understand their respective roles in severe accident analysis. Future research directions toward high-fidelity multiphase simulations are discussed in Section 4.

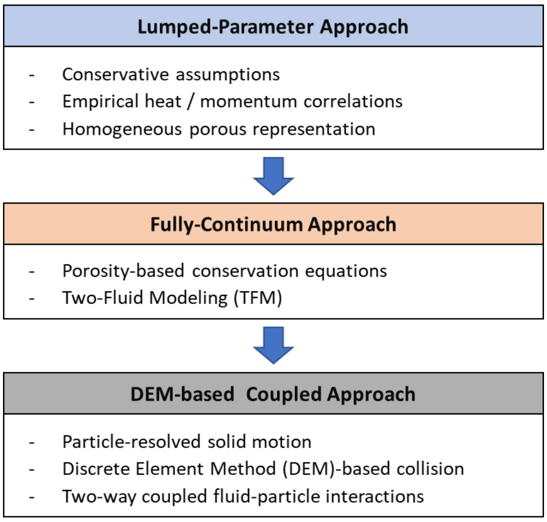

Fig. 2. Evolution of Modeling Approaches for Debris Behavior

2. Traditional Approaches for Debris Modeling

The behavior of nuclear fuel debris during severe accidents is governed by complex three-phase interactions among solid particles, liquid coolant, and generated vapor. Nevertheless, due to the difficulty of directly resolving such particulate multiphase systems at reactor scale, debris modeling has traditionally relied on simplified approaches based on lumped-parameter correlations and continuum representations.

2.1. Lumped-Parameter Approaches

Early assessments of debris bed behavior and coolability were primarily conducted using system-level severe accident codes and empirical models. System codes such as MAAP and MELCOR have long served, and continue to serve, as the backbone of integral severe accident analysis [6]. These codes simulate core degradation, melt relocation, and ex-vessel phenomena within a plant-scale framework and remain indispensable for regulatory and probabilistic safety assessments.

In the evaluation of debris bed cooling performance, the debris layer is typically treated as a homogeneous porous medium with prescribed geometry, porosity, and representative particle size. Conservative assumptions are often introduced regarding debris bed shape, cooling mechanisms, and void fraction. Based on these assumptions, key safety parameters such as dryout heat flux (DHF) at the top surface of the debris bed and debris heat removal rate (DHRR) are calculated using empirical correlations derived from separate-effect experiments [5].

In this framework, pressure drop across the porous layer and convective heat transfer between phases are evaluated through various correlation-based formulations [5]. While such approaches enable practical and computationally efficient assessment of debris coolability within system codes, their predictive capability is constrained by experimentally validated conditions. When applied beyond the range of available data, uncertainties increase significantly. Considering that severe accidents involve extreme conditions that cannot be fully reproduced experimentally, reliance on empirical correlations may introduce additional epistemic uncertainties in debris behavior prediction.

Despite these limitations, lumped-parameter approaches will continue to play a central role in severe accident analysis due to their robustness, computational efficiency, and integration within system-level frameworks. In this context, advances in high-fidelity and particle-resolved simulations can provide mechanistic insight beyond experimental limitations and ultimately contribute to refining and strengthening the empirical correlations embedded in system-level codes.

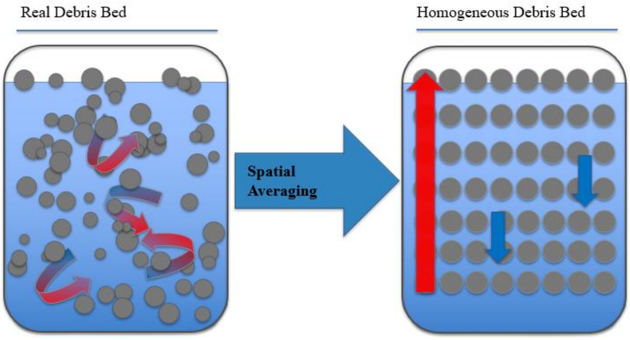

Fig. 3. Schematic illustration of spatial averaging in lumped-parameter debris bed modeling.

2.2. Continuum-Based Two-Fluid Modeling

To overcome the limitations of purely empirical models, mechanistic continuum approaches have been developed to represent debris beds within a two-fluid (liquid–gas) Eulerian framework. In such models, the debris bed is treated as a porous medium embedded in a multiphase flow domain, and governing conservation equations are solved for each phase.

For example, DPCOOL formulates pool and debris regions using two-fluid equations combined with porous media models to evaluate debris bed cooling behavior [6]. Similarly, DECOSIM applies mechanistic modeling of two-phase flow and particle spreading phenomena in debris beds [5]. In fast reactor safety research, multi-fluid models have also been coupled with debris transport formulations to simulate self-leveling and spreading processes [8].

Compared with lumped-parameter approaches, continuum models allow improved representation of vapor generation, interfacial friction, and large-scale natural circulation within debris beds. However, solid particles are still not treated as discrete entities. Inter-particle collisions, granular rearrangement, and localized heterogeneity are not explicitly resolved [1]. As a result, continuum formulations provide enhanced mechanistic fidelity but remain limited in capturing the detailed dynamics of debris bed formation and transient particle relocation.

Despite these improvements, continuum formulations are fundamentally limited in resolving particle-scale interactions such as inter-particle collisions, granular rearrangement, and local heterogeneity. These limitations become particularly critical when debris bed formation and transient relocation behavior are strongly governed by discrete particle dynamics. To overcome these challenges, discrete particle-based modeling approaches have been developed, as discussed in the following section.

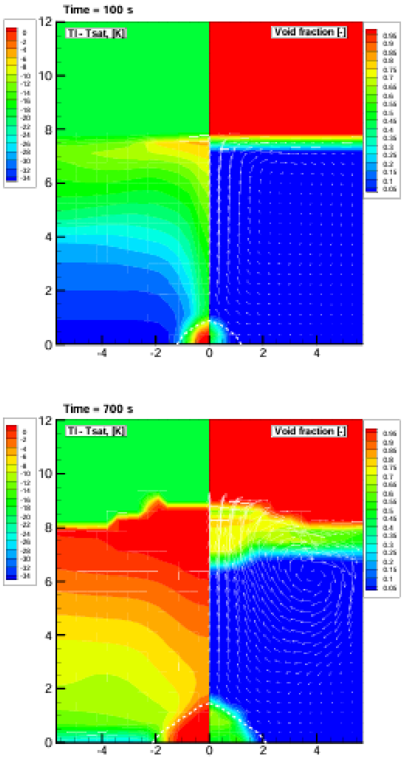

Fig. 4. Formation of debris bed in a pool with initial subcooling 20 K [5]

3. Discrete Modeling of Solid Debris

3.1. TFM–DEM Coupling Approach

One of the earliest strategies for incorporating particle-scale physics into multiphase severe accident analysis has been the coupling of DEM with continuum two-fluid models (TFM). In this framework, the liquid and gas phases are described using Eulerian multi-fluid equations, while solid debris particles are treated as discrete entities through DEM.

Such approaches have been applied to simulate debris bed formation and self-leveling behavior in sodium-cooled fast reactor scenarios [8]. The DEM accounts for particle–particle and particle–wall collisions, while the surrounding multiphase flow field is computed using TFM formulations. Momentum exchange between phases is modeled through two-way coupling, enabling improved representation of sedimentation and spreading processes compared with purely continuum models.

Although TFM–DEM coupling significantly enhances the description of granular dynamics, the fluid phases are still resolved on a continuum grid, and the coupling between fluid cells and particles is generally treated in an unresolved manner. That is, the fluid flow around individual particles is not spatially resolved; instead, averaged interaction forces are imposed at the cell scale. Consequently, local interfacial phenomena and small-scale three-phase interactions remain approximated.

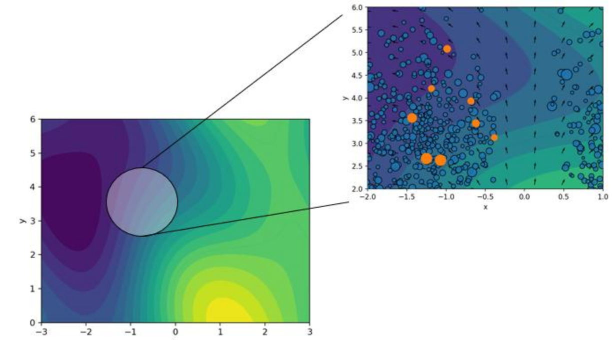

Fig. 5. Conceptual representation of multiscale TFM–DEM coupling.
The continuum-scale flow field (left) is described using an Euler–Euler formulation, whereas individual particles are resolved at the discrete level (right).

3.2. Particle-Based CFD–DEM Approaches

In late-phase severe accidents, three-phase flow characteristics become particularly important. Vapor generation due to decay heat leads to sharp and dynamic gas–liquid interfaces, while debris particles undergo transient relocation within the multiphase environment. Under such conditions, spatial resolution of the liquid–gas interface can be essential for accurately capturing debris relocation and spreading behavior.

To address this need, particle-based Lagrangian CFD methods, such as Smoothed Particle Hydrodynamics (SPH) and Moving Particle Semi-implicit (MPS), have been coupled with DEM. For example, SPH–DEM frameworks have been developed to simulate three-phase hydrodynamic interactions between gas–liquid flow and solid particles [3]. Similarly, MPS–DEM approaches have been applied to investigate debris bed formation dynamics under severe accident conditions [1].

These fully Lagrangian formulations allow direct treatment of highly deformable interfaces without relying on interface-capturing schemes and are particularly advantageous for modeling complex three-phase particulate flows. GPU-based acceleration has further improved their computational feasibility for large-scale simulations [3].

However, despite the particle-based nature of both fluid and solid phases, most existing implementations still adopt unresolved coupling between fluid particles and debris particles. Because reactor-scale severe accidents involve an enormous number of debris particles, resolving the fluid field around each particle remains computationally prohibitive. As a result, spatial overlap between phases is allowed at the coupling level, and interaction forces are evaluated based on averaged models rather than fully resolved fluid–particle interfaces. Therefore, while discrete modeling approaches represent a significant advancement over traditional formulations, challenges remain in achieving fully resolved, first-principle simulations of debris behavior under realistic severe accident conditions.

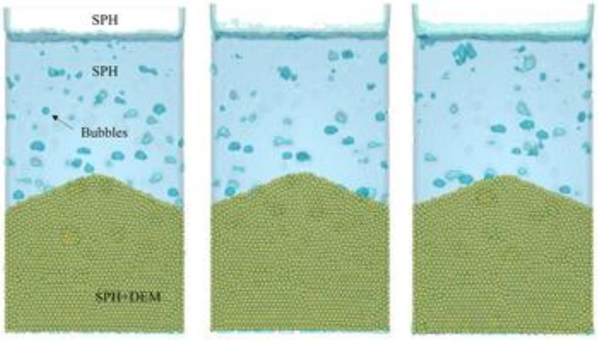

Fig. 6. SPH-DEM simulation results [3]

4. Future Directions in Modeling of Debris

4.1. Advancement of Physical Modeling

Current discrete modeling studies have mainly focused on hydrodynamic interactions between debris particles and surrounding multiphase flow [1][3], and have achieved a relatively high level of fidelity in predicting particle motion, collision, and spreading behavior. However, thermal effects are often simplified or neglected, while severe accidents are characterized by extremely high temperatures, intense decay heat generation, dynamic phase change, and transient boiling phenomena.

Experimental and mechanistic studies have shown that debris bed coolability depends strongly on vapor generation, interfacial heat transfer, and dryout behavior [5]. Furthermore, melt fragmentation, quenching, possible remelting, and reflooding processes may occur sequentially or simultaneously during accident progression. These processes involve tightly coupled thermo-hydrodynamic interactions.

These phenomena also involve strong phase change and large volumetric expansion, which remain difficult to fully resolve within current high-fidelity simulation frameworks. Therefore, further development and validation of models capable of capturing these processes are required.

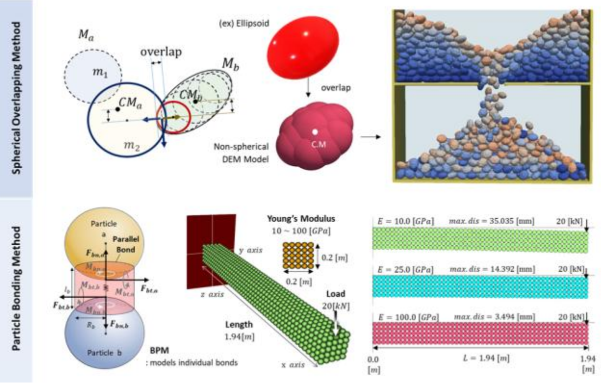

Fig. 7. Schematic of Non-Spherical Particle Modeling in DEM Using Overlapping and Bonding Methods

In severe accident scenarios, debris particles exhibit non-spherical geometries. Approximating such particles as spheres may lead to non-conservative predictions, particularly in terms of packing structure, flow resistance, and interfacial interactions. As illustrated in Fig. 7, non-spherical particles can be represented in DEM using approaches such as overlapping spheres or bonding models. Since particle shape directly influences hydrodynamic behavior and interaction forces, it is necessary to develop a methodology for coupling these DEM-based representations with CFD frameworks.

Therefore, future high-fidelity simulations should incorporate heat transfer, phase change, and thermochemical interactions within discrete particle frameworks. Coupling DEM-based debris motion with thermal energy conservation, boiling models, and potentially resolidification or remelting mechanisms will be essential to represent late-phase severe accident phenomena more realistically.

4.2. Advances in Computational Capability

Historically, one of the primary constraints on detailed debris modeling has been computational cost. Reactor-scale severe accidents involve an enormous number of debris particles, making fully resolved particle-scale simulation impractical using conventional CPU-based methods.

Recent developments in GPU-based parallel computing have substantially improved the scalability of Lagrangian particle methods. GPU acceleration has demonstrated strong performance gains for SPH–DEM coupled solvers, particularly in simulations involving large numbers of Lagrangian nodes [3]. These advances suggest that engineering-scale three-phase particulate simulations are becoming increasingly feasible.

However, as discussed in Section 3, most current implementations still rely on unresolved coupling between fluid and debris particles. Interaction forces are computed using averaged models, and the fluid field around individual debris particles is not spatially resolved. Achieving fully resolved fluid–particle interaction, in which the liquid–gas interface and local flow structures around each particle are explicitly captured, remains a major computational challenge.

With continued improvements in parallel architectures, memory capacity, and algorithmic efficiency, it is foreseeable that first-principle-based, fully resolved multiphase simulations may become attainable for larger domains. Such capability would significantly reduce dependence on empirical correlations and could eventually provide a complementary numerical platform to experimental programs in severe accident research.

Therefore, the development and application of CFD–DEM coupling models require extensive validation efforts, as unresolved coupling approaches inherently depend on empirical or semi-empirical correlations. Ensuring model robustness across a wide range of thermohydraulic conditions is essential for the reliable application of such models and remains a key challenge for future research.

5. Conclusion

The modeling of nuclear fuel debris during severe accidents has evolved from lumped-parameter and correlation-based approaches to continuum two-fluid formulations and, more recently, to discrete particle-based methods. This evolution reflects the increasing need to reduce epistemic uncertainty in debris behavior prediction under extreme and experimentally inaccessible accident conditions. System-level severe accident codes remain indispensable for integral plant analysis and regulatory assessment; however, their reliance on empirical assumptions limits detailed mechanistic prediction of debris spreading, granular dynamics, and complex three-phase interactions.

Discrete modeling approaches, including TFM–DEM and particle-based CFD–DEM frameworks, provide enhanced capability to represent particle motion and multiphase interactions. With continued advances in thermal modeling and computational capability, high-fidelity multiphase simulations are expected to play an increasingly important complementary role in severe accident analysis, supporting the refinement and extension of empirical correlations embedded within traditional system-code methodologies.

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