Graduate School of Advanced Science and Engineering
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博　士　論　文　概　要
Doctoral Thesis Synopsis

論　文　題　目
Thesis Theme

Multi-dimensional Numerical Study of Molten Corium-Concrete Interaction (MCCI) Mechanism by MPS Method

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This thesis presents a multi-dimensional numerical study on Molten Corium-Concrete Interaction (MCCI) with Moving Particle Semi-implicit (MPS) method and additional originally developed models. The thesis includes validation of the developed MPS method against one-dimensional (1-D), two-dimensional (2-D) and three-dimensional (3-D) MCCI experiments. The complex interactions of influential factors of MCCI has been understood through mechanistic modeling. Discussions on discrepancies of calculated results with experimental results with respect to fundamental physical phenomena have been developed comprehensively for the first time in the history of MCCI research. The developed MPS simulations have shown the mechanism that distinguishes isotropic ablation of limestone concrete and anisotropic ablation of siliceous concrete by oxidic corium.

Chapter 1 states the background, necessity, and objectives of current study. In a hypothetical nuclear reactor severe accident, late containment failure could be caused by long-term melt-through of concrete basemat by core melt or corium discharged from the failed reactor pressure vessel. This scenario is called MCCI. The consequences can be catastrophic since the containment integrity can be threatened and lead to fission products release. Thus, deep understanding of the progression of MCCI is essential to enhance safety and reliability of nuclear power.

Several MCCI experiments have been carried out since 1980s. The early large scale experiments are mostly 1-D MCCI experiments, aiming at studying 1-D ablation behavior of various concrete by oxides or metal, the effect of Zr oxidation, the effect of an overlying water pool, and the aerosol release from the melt. More recent experiments focused more on the 2-D concrete ablation pattern regarding the axial versus lateral ablation ratio and melt coolability of late water injection. In a series of 2-D tests, one of the major findings was that in the tests with siliceous concrete, an anisotropic pattern (lateral ablation more significant than axial ablation) has been observed, while in the tests with limestone concrete, a more isotropic ablation pattern has been observed. However, the mechanism of the isotropic/anisotropic pattern has not yet been well understood.

Several computer codes have been developed, aiming at modeling the physical and chemical phenomena during MCCI and validated against numerous MCCI tests. The difficulty in understanding and predicting MCCI with these past computer codes arises from not only the difficulty in accurate modeling of thermal-hydraulics (heat transfer and convection) and phase change which governs MCCI, but also the difficulty in accurately modeling complex interactions of various influential factors (e.g., chemical reaction heat, formation of slag-film at boundaries, crust formation, dissolution and remelting, relocation of thermally stable aggregates, etc). As the results, the past studies had the following issues:

- Difficulties in understanding discrepancies among simulations or among simulation and experimental results in terms of physical phenomena.
- Good agreement of calculation results with experimental results does not necessarily assure appropriate modeling, because of adjustments of various parameters in the empirical correlations.

Moreover, in these codes, only 1-D or simplified 2-D geometry with average axial and radial ablation depths can be evaluated. Different choices of empirical correlations such as heat transfer correlations at concrete/melt pool side/ bottom have led to discrepancies among predictions of axial/lateral ablation depths among these codes validated against MCCI experiments. These discrepancies indicate the limitations of specific correlations and simplified models based on current knowledge of MCCI, which suggest a necessity to understand MCCI mechanistically and to develop a less empirical correlation dependent method capable of more accurate and multi-dimensional predictions to further improve the reliability of numerical analysis of MCCI.

Considering the importance and necessity mentioned above, a multi-dimensional MCCI code (2-D and 3-D) has been developed based on MPS method. MPS method is a particle method for analyzing incompressible media. As a Lagrangian method, MPS method discretizes the computation domain with particles instead of meshes or grids. The governing equations are also discretized by weight function and particle interaction models. As a result, the advantages of MPS are that it can easily and accurately capture free surface, interface and fluid thermophysical properties, which provide superiority to other methods when simulating important phenomena involving dynamic evolution of solid-liquid boundary such as crust formation/remelting observed in MCCI. Moreover, different geometries of 2-D or 3-D can be established accurately, which facilitate more accurate simulation of ablation profile of MCCI. The above featured advantages of MPS method have been validated against phenomena such as fluid splashing and melt stratification and solidification/melting. There have also been successful validations of MPS method against MCCI tests by other researchers previously. However, the validations were either on only 1-D test or a very small scale MCCI tests with simulant materials. MPS method has never been validated against multi-dimensional MCCI experiments in a comprehensive manner to investigate the mechanism of important phenomenology in MCCI. Hence, this study aims to reveal MCCI mechanism from a more mechanistic and fundamental perspective by multi-dimensional MPS method.

Chapter 2 describes the fundamentals and improvements of MPS method. The additional and originally developed models that are incorporated into MPS code “MPS-SW-MAIN-Ver.2.0” are presented, which include chemical reaction heat, corium viscosity, slag film, crust dissolution models, heat conduction and phase change model. These models have been specially developed for MCCI simulations, especially the former four original ones. Chemical reaction heat model is to consider the chemical heat introduced in melt pool by metal oxidation. Corium viscosity model is to consider temperature dependence of corium viscosity. Slag film model is to consider the heat transfer influence of gas generation from concrete decomposition on corium/concrete interface. Crust dissolution model is to consider the effect of crust dissolution by molten concrete.

Chapter 3 is dedicated to simulations of 1-D MCCI experiments SURC-2 and SURC-4 in order to validate heat conduction, chemical reaction heat and phase change models. 2-D geometry was built to simulate the test sections of SURC-2 and 4 with MPS method. The calculated concrete ablation rate was compared with the experimental measures and the simulation results of CORCON code. The simulation results by MPS agreed well with the experiments, which proved the validity of heat conduction, chemical reaction heat and phase change models. The experimental and MPS results both indicated that Zr oxidation could increase the ablation rate. It also suggested that crust formation/remelting play an important part in MCCI progression, because the crust layer acts a thermal insulation layer between the melt and concrete.

Chapter 4 presents the simulation of 2-D MCCI experiments CCI-2 and CCI-3 in order to validate slag film and crust dissolution models and investigate the isotropic/anisotropic ablation mechanism. MPS simulation successfully distinguished the two different experiments with mechanistic simulation. Moreover, the isotropic/anisotropic ablation mechanism has been indicated through study on different simulation cases based on CCI-2 and 3 with different assumptions. The simulations have indicated that the isotropy/anisotropy mainly depends on the crust formation and natural convection in the melt pool. Aggregates with higher density and thermal conductivity can favor crust formation and consume more power from the melt pool, thus can slightly promote anisotropy. Besides, there exists inherent anisotropy of natural convection in an internally heated pool. On the other hand, gas generation can increase the heat transfer at corium/concrete interface on both basemat and sidewall, thus can facilitate isotropy.

Chapter 5 presents the simulation of 3-D MCCI experiments VULCANO-VB U7 and COMET-L3 in order to further investigate influences of the factors, which are spatially dependent. Simulations of both experiments were carried out with 3-D geometry. Besides the important roles of crust formation, gas generation, and aggregates that play in MCCI progression, MPS simulation results also showed the post-test profiles of both experiments which cannot be obtained accurately by other codes.

Finally, from the simulations carried out by MPS method for 1-D, 2-D and 3-D MCCI experiments, the following isotropic/anisotropic ablation mechanisms have been shown:

- Isotropic ablation mechanism of limestone concrete: The sidewall and basemat crusts lead to isotropy in the boundary heat resistance. Formation of the slag-film at the crust-concrete boundary due to rich gas content of the concrete promotes the boundary heat transfer at the basemat while reduces it at the sidewall. The resultant anisotropy acts in the opposite direction to the anisotropy developed by the temperature stratification of the melt pool, caused by natural convection. As the result, the overall concrete ablation proceeds more or less isotropic
- Anisotropic ablation mechanism of siliceous concrete: Sidewall crust may not be formed due to continuous release of aggregates by concrete ablation. On the other hand, thermally stable aggregates near the corium-basemat boundary act as heat sink and stabilize the basemat crust, leading to substantial anisotropy in the boundary heat resistance, which is the main cause of the anisotropic ablation. The corium pool temperature stratification, developed by natural convection also contributes to the anisotropy.

Chapter 6 summarizes the whole thesis. The MPS method used in this study is able to model the basic thermal-hydraulics and phase change mechanistically. Furthermore, in this study, the MPS method for MCCI simulation has been developed and applied to multi-dimensional MCCI experiments systematically (from 1-D through 3-D) and this approach has succeeded in attaining the following achievements:.

- The complex interactions of influential factors in MCCI has been understood through mechanistic modeling and succeeded in discussing discrepancies of calculated results with experimental results with respect to fundamental physical phenomena.
- By limiting use of empirical models to some of the influential factors and modeling interactions of these influential factors mechanistically, discussions have been successfully developed regarding the mechanism that distinguishes isotropic ablation of limestone concrete and anisotropic ablation of siliceous concrete by oxidic corium.

早稲田大学　博士（工学）　学位申請　研究業績書

(List of research achievements for application of doctorate (Dr. of Engineering), Waseda University)

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(2)Presentations	1. **X. Li**, Y. Oka, R.H. Chen, T. Matsuura, and T. Watanabe. Mechanistic study of melt behavior by MPS method-spreading, melt penetration and MCCI, Int. Workshop on Nuclear Safety and Severe Accident (NUSSA-2014), Sept. 3-5, Chiba, Japan (2014).
	2. **X. Li** and Y. Oka. Mechanistic study of melt behavior by Moving Particle Semi-implicit (MPS) method, 2014 Fall Meeting of the Atomic Energy Society of Japan Sept. 8-10, Kyoto, Japan (2014).
	3. **X. Li**, A. Yamaji, R.H. Chen, T. Matsuura, and T. Watanabe. Mechanistic study of melt behavior in nuclear severe accident by MPS method,「粒子法コードユーザーグループ」第30回会合, 平成26年11月26日, 海上技術安全研究所, 三鷹市, 東京 (2014).
○	4. **X. Li** and Y. Oka. Numerical simulation of MCCI experiments by MPS method – Validation against SURC-2 and 4 experiments, 10th International Topical Meeting on Nuclear Thermal Hydraulics, Operation and Safety (Nuthos-10) Dec. 14-18th, Okinawa, Japan (2014).
○	5. **X. Li** and A. Yamaji. Numerical simulation of anisotropic ablation of siliceous concrete – analysis of CCI-3 MCCI experiment by MPS method, 16th International Topical Meeting on Nuclear Reactor Thermalhydraulics (NURETH-16), August 30-September 4, Hyatt Regency Chicago, USA (2015).