論 文 の 内 容 の 要 旨

Study on corium behavior in BWR lower plenum by the improvement of DCA module in SAMPSON

（SAMPSONのDCAモジュール改善によるBWR下部プレナムにおける炉心溶融物挙動に関する研究）

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This thesis presents the study on penetration tube effects on corium behavior in BWR lower plenum by the improved Debris Coolability Analysis (DCA) module in SAMPSON (2013). The thesis includes improvement of heat transfer between molten pool and RPV wall model, development of one-dimension (1-D) jet breakup model, and implementation of penetration tube melt model. The corium behavior in BWR lower plenum has been understood through improved DCA module. The effects of control rod guide tubes (CRGTs) on jet breakup process have been clarified through an original jet breakup experiment. The failure mechanism of BWR lower plenum has been investigated by implementation of penetration tube melt model.

Chapter 1 states the background, necessity, and objectives of current study. As the last in-vessel barrier in nuclear reactor, the integrity of the Reactor Pressure Vessel (RPV) is important. In a hypothetical nuclear reactor severe accident, the failure of reactor pressure vessel (RPV) lower head could cause a direct attack on the containment basement, and further containment failure could lead to fission product release to the environment. Corium behavior in reactor lower plenum has vital effects on the integrity of RPV. Thus, deep understanding of the progression of corium behavior in lower plenum is essential to enhance safety and reliability of nuclear power.
Most of severe accident experiments were used to point out the significant events and clarify the specific phenomena in detail. It is difficult to clarify different phenomena in full-range of a severe accident scenario by experiments. Integrated experiments used to simulate different severe accident conditions and using radioactive nuclides are difficulty and costly. Thus, it is necessary to have a code for the whole-plant severe accident analysis. Currently, MELCOR and MAAP are widely used in severe accident analysis. These two codes mainly use lumped parameter method, empirical correlations, and user tuning parameters. These two codes have the capability of evaluation of severe accident measurement and sensitivity analysis of PRA Level2 studies.

From the perspective of mechanistic modeling, the United States Nuclear Regulatory Commission (USNRC) has developed RELAP/SCDAP for the analysis of severe accident events in the reactor vessel and CONTAIN for the events inside the containment. They adopted simplified models. Due to the complexity of severe accident phenomena, these mechanistic codes still could not obtain a sufficient understanding of these phenomena.

Considering the importance and necessity mentioned above, SAMPSON has been developed based on fundamental physical principles, theoretical-based equations and mechanistic models. The features of SAMPSON are very fewer user tuning parameters, high-speed simulation on the parallel processing of computers, multi-dimensional mechanistic models and consideration of various events in a hypothetical severe accident. Moreover, SAMPSON can be used to simulate a wide range of scenarios covering from the normal operation to the hypothetical severe accident events. As a result, the advantages of SAMPSON have been validated against phenomena in DCA module such as natural convection, fluid spreading and solidification.

However, the original DCA module in SAMPSON was more suitable for pressurized water reactor (PWR). Therefore, the original DCA module have never been considered jet breakup process and the penetration tubes in BWR lower plenum. Hence, this study aims to study corium behavior in BWR lower plenum from a more mechanistic and fundamental perspective by the improved DCA module.

Chapter 2 describes how heat transfer between molten pool and RPV wall model has been improved. Validation work needs to be conducted before using DCA module to analyze corium behavior in BWR lower plenum. The crust growth model has been implemented into DCA module and heat transfer between molten pool and RPV wall model has been improved. The improved and modified DCA module has been validated against LIVE-L4 test. Compared to simulation results of original DCA module, the improved DCA module could predict the LIVE-L4 test process reasonably by comparing molten pool average temperature, crust growth rate and heat flux along vessel wall, which indicated that the heat transfer model in the improved DCA module could be used to evaluate the heat transfer more accurately for the real condition in BWR lower plenum.

Chapter 3 shows how jet breakup model has been incorporated into DCA module and validation work against FARO-L8 test. Based on Kelvin-Helmholtz instability and Rayleigh-Taylor instability, a 1-D jet breakup model has been implemented into DCA module. Both 1-D jet breakup model and the Institute of Applied Energy (IAE) proposed jet breakup model have been used to simulate FARO-L8 test. By comparing the jet breakup fraction, departure droplets' diameter, vessel pressure and water swell, the implemented 1-D jet breakup model could be proved as a proper tool to simulate such phenomena. This indicated that the developed 1-D jet breakup model could be capable to simulate jet breakup process accurately and could be extrapolated to simulate jet breakup process in reactor case.

Chapter 4 presents the detailed jet breakup experiment that used to confirm whether the implemented jet breakup model is suitable for BWR. Since the implemented jet breakup model is based on PWR, the effects of CRGTs on jet breakup process need to be considered for BWR. In order to identify the effects of CRGTs on the jet breakup behavior, a molten material (U-alloy) breakup experiment considering CRGTs in a BWR lower plenum has been conducted under isothermal boundary conditions. The experiment results showed that CRGTs could prevent the jet breakup process and this prevention ability depends on pitch/diameter (P/D) ratio. Relative breakup fraction has been proposed to evaluate the jet breakup process in BWR lower plenum. The experiments also indicated that CRGTs had almost no effect on the fragmentation droplet diameter. Based on the current jet breakup experiment results, the implemented 1-D jet breakup model has been modified for BWR.

Chapter 5 presents the molten pool test simulation after the implementation of penetration tube melt model. Besides the effects of CRGTs on the jet breakup process, the CRGTs and Instrument Guide tubes (IGTs) could also act as the heat sink for molten pool in BWR lower plenum. The penetration tube melt model has been developed and incorporated into DCA module. By assuming no corium leakage from failed CRGTs or IGTs, the improved DCA module has been used to evaluate BWR lower plenum failure mechanism. The simulation results indicated that penetration tubes could fail earlier than RPV wall, which needs to be considered in the evaluation of BWR severe accident management.

Chapter 6 summarizes the whole thesis. The improved DCA module used in this study is able to simulate the corium behavior in BWR lower plenum. Furthermore, in this study, the penetration tube effects on the corium behavior have been investigated. This approach has succeeded in attaining the following achievements:

- The DCA module has been modified for BWR lower plenum analysis. The heat transfer model between molten pool and RPV wall has been improved and validated against LIVE-L4 test. The 1-D jet breakup model has been implemented into DCA module and validated with FARO-L8 test. After implementation of penetration tube melt model, molten pool simulation has been conducted to study penetration tube effects on corium behavior and BWR lower plenum failure mechanism.

- The effects of penetration tubes on corium behavior have been clarified. During corium falling process, jet breakup process could happen. How CRGTs could affect jet breakup behavior has been investigated and relative breakup fraction has been proposed to evaluate jet breakup fraction in BWR. After falling process ends and corium pool forms in the BWR lower plenum, a simulation test has been conducted. In BWR lower plenum, penetration tubes could fail earlier than RPV wall, which has to be considered in severe accident management.