Three-Dimensional Analysis of Containment Vessel Behavior for i-SMR Using MARS-KS and MULTID Component

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1. Introduction

Nowadays, several passive safety systems are under development for the Innovative Small Modular Reactor (i-SMR). [1] One of the developed safety systems is the Passive Containment Cooling System (PCCS), as shown in Figure 1. This PCCS replaces the traditional active Containment Spray System (CSS) used in conventional nuclear power plants and therefore allows for passive containment cooling and pressurize decrease during any loss-of-coolant accident (LOCA) event.

PCCS heat removal performance is determined by the heat transfer inside HX tube based on the single-phase natural circulation, and outside tube heat transfer driven mainly by a steam condensation.

The condensation on the outside of PCCS HX tube is affected by a complex steam flow field inside the CV. To predict the PCCS HX performance well, it is necessary to understand this behavior precisely.

In this study, based on the i-SMR conceptual diagram, the CV is modeled by a MULTID component and EDV-LOCA scenario simulated using MARS-KS to reflect the three-dimensional phenomena occurring inside CV.

Results of this research study and new insight obtained from the three-dimensional CV modelling approach are presented in this paper.

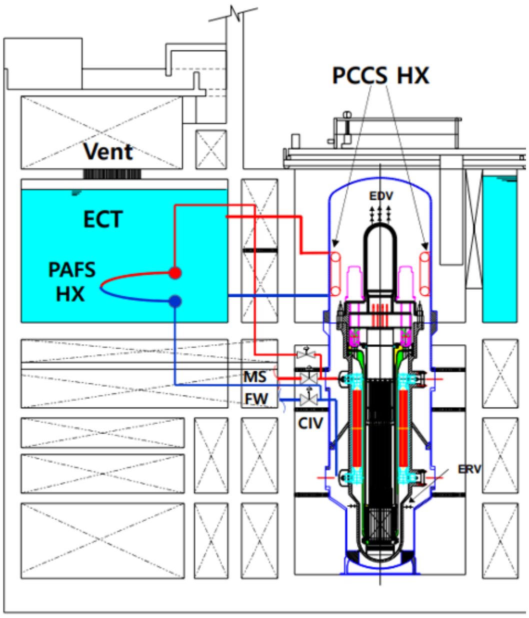

Fig. 1. Conceptual design of i-SMR including PCCS

2. Methods and Results

2.1 MARS-KS Model of i-SMR

For research purpose, a prototypic i-SMR input model for MARS-KS had been developed by Jeon et al. [2]. This model includes major components of the primary and secondary systems, containment vessel (CV), as well as safety systems, including the PCCS.

2.2 Three-Dimensional CV Modelling Using MULTID

In the original MARS-KS model of i-SMR, the CV is modeled simply as two PIPE components with 9 axial nodes, connected by a multiple junction component to allow for cross-flow and circulation inside the CV.

However, due to the rapid behavior and complex three-dimensional phenomena occurring within the CV during EDV-LOCA, a comprehensive CV model with more detailed structure is essential. The detailed model can provide realistic insights in the overall CV behavior, including accurate simulation of the multi-dimensional two-phase flow and condensation on the PCCS HX. For this purpose, the simple PIPE model of CV is replaced by a MULTID component to evaluate the complex flow field inside the CV.

Conceptual diagram of the new modelling approach of CV using MULTID is depicted in the Figure 2.

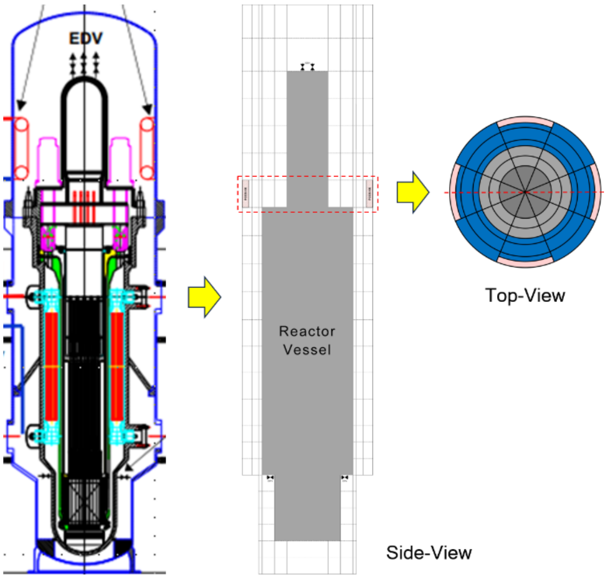

Fig. 2. Three-dimensional model of CV using MULTID

The MULTID component can be utilized by a three-dimensional array of volumes that are cross-connected with internal junctions. The volume modelling can be done either in Cartesian (x, y, z) or cylindrical (r, Θ, z) geometry. [3] Due to the nature of the actual CV shape, cylindrical geometry was chosen and 6 nodes in radial, 8 nodes in azimuthal and 24 in axial direction applied to roughly reflect the actual CV dimensions. All of the related heat structures were modified accordingly, to simulate the effect of CV and RV walls, as well as heat structures of the PCCS HX, including their respective axial locations and connections.

In general, using the MULTID component is rather difficult and restrictions arise to the user when using this component. For example, since all the volumes of the MULTID component must be placed within the same hydrodynamic system, and every volume must be connected at least by one junction, dead volumes representing the RV and outer cylinder at the CV bottom are cross-connected and separated from other CV volumes by closed junctions. This approach was chosen since the number of nodes in each direction is fixed and cannot be changed along any of the axes.

2.3 Simulation of EDV-LOCA

In this study, the EDV-LOCA scenario was simulated, where one of the Emergency Depressurization Valves (EDVs), placed at the top part of the RV, is fully opened during nominal operation and releases high-pressure and high-temperature steam directly into the CV. This steam is condensed on PCCS HX, which allows CV cooldown and consequent pressure decrease. Condensated steam can flow down into the bottom part of the CV and the CV water level increases as the accident progresses. This is shown in Figure 3, where void fraction of the MULTID component is plotted in a side-view of the CV for several time sequences of EDV-LOCA. After a certain level is reached, water can re-enter the RV through Emergency Recirculation Valves (ERVs), which are located above the reactor core and connect RV with CV.

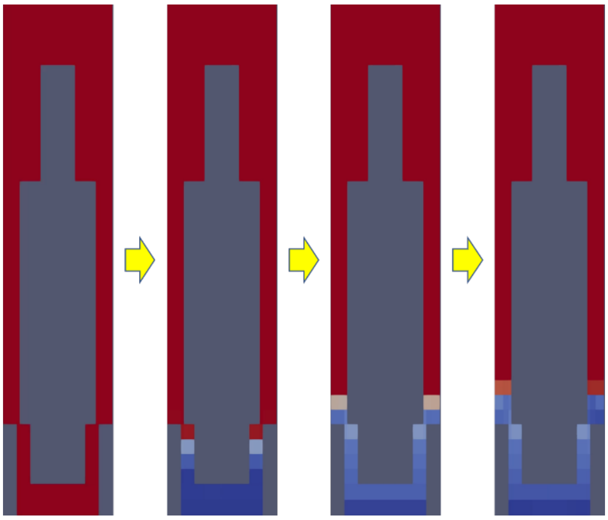

Fig. 3. Water level increase in the CV during EDV-LOCA

Since the purpose of this study is to evaluate the behavior inside the CV rather than overall accident progression, and also considering the simulation time of such complex model, the EDV-LOCA scenario was simulated for 1 hour. During this initial time of the accident, the cooling (condensation) effect of the PCCS HX in the CV is the most significant, since the high-pressure and high-temperature steam is released from the RV into CV and rapid two-phase flow is present.

2.4 Insights of the Three-Dimensional Modelling

The following insights have been achieved through the multidimensional modelling of CV during EDV-LOCA.

Firstly, after the accident is initiated, all other ECCS valves (EDVs and ERVs) are assumed to open. In the initial stage of the EDV-LOCA, due to a high-pressure difference between RV and CV, primary coolant is also discharged from the RV into CV through the ERVs. Due to a high temperature of the coolant and low pressure in the CV, flashing occurs as the coolant enters the CV.

Secondly, there is a multi-dimensional circulation of steam inside the CV. On the side, where PCCS HXs are located and condensation occurs, the condensate and some portion of the steam flow downwards. However, on the other side, where no PCCS HXs are placed, steam flows in an opposite direction. This behavior is shown using a vapor velocity vector field in the Figure 4. Such a dynamic three-dimensional behavior would not be possible to calculate in detail with the simplified CV modeled using a 1D PIPE component.

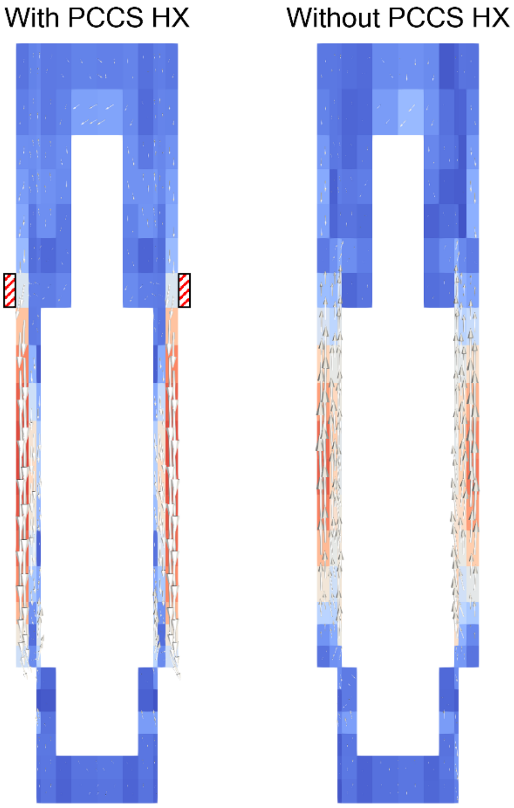

Fig. 4. Vapor velocity in the CV during EDV-LOCA

3. Conclusions

In this paper, EDV-LOCA scenario of the conceptual i-SMR model was simulated using MARS-KS. The CV was modeled using a MULTID component to reflect the dynamic two-phase flow inside the containment vessel and to get an insight into this three-dimensional behavior during the simulated accident.

Although the i-SMR input model is currently under development and will require further improvements in the future, including reflection of the design information and parameters, the results of this research study show a clear behavior of the multidimensional flow occurring inside the CV during EDV-LOCA, where PCCS plays a crucial role in the accident mitigation.

Acknowledgement

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