Transactions of the Korean Nuclear Society Virtual Spring Meeting
July 9-10, 2020

Methodology Development for 3D Analysis of a Core Catcher Cooling Channel

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1. Introduction

As a cooling strategy for molten corium during a severe accident in a nuclear power plant (NPP), There are in-vessel melt retention (IVR) method to trap and cool the core melt inside the reactor, and ex-Vessel Melt Retention (EVR) method to cool the melt outside the reactor. As far as it is known, IVR can be applied to all accidents in the case of small nuclear power plants below 600 MWe. In the case of larger nuclear power plants above 1000 MWe, an additional accident management strategy is needed to cool the core melt. In the case of EU-APR1400, APR1400 has been proposed that reflects the core catcher in the design in accordance with European enhanced safety standards [1].

In the project of "Development of technology for evaluating the reaction between the outer core melt and the reaction between the core melt and concrete (MCCI)", a 3D analysis methodology is under development for design verification of the core catcher adopted in EU-APR1400 as an accident management strategy for cooling a core melt.

2. Methodology Development

2.1 3D Geometry Modeling of PECS

A core catcher for EU-APR1400 has been designed and named PECS (Passive Ex-Vessel Corium retention and Cooling System). PECS adopts indirect cooling concept and it is composed of a catcher, a cooling channel and a down-comer. Fig. 1 shows the configuration of the core catcher installed in the EU-APR1400 containment.

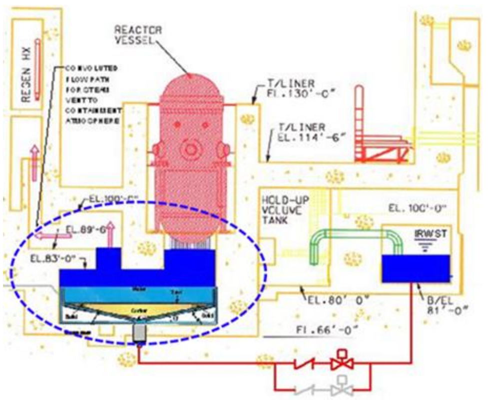

Fig. 1. Schematics of Core-Catcher for EU_APR1400 [2].

It is planned to simulate coolant flow with a full 3-dimensional geometry of PECS for the design verification. So, it was conducted to develop a 3D CAD data of PECS.

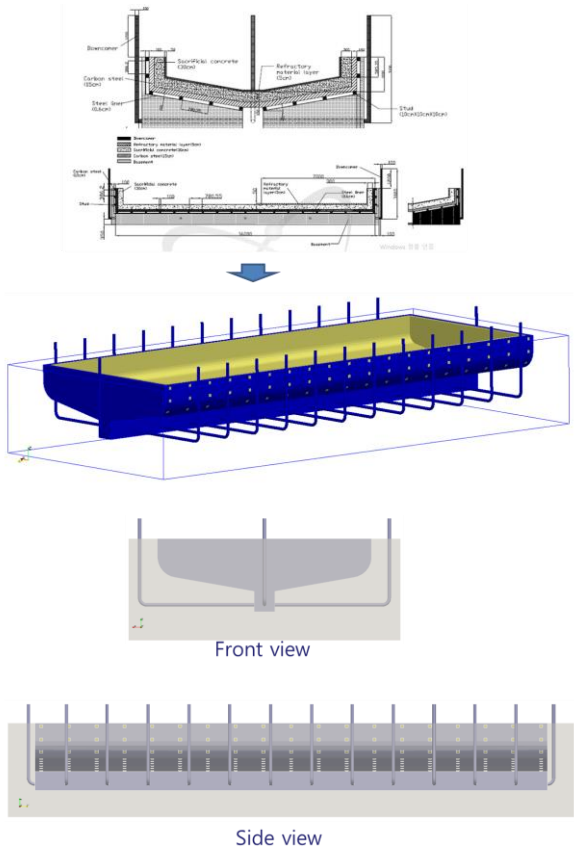

Fig. 2. Visualization of PECS using a 3D CAD data.

2.2 Analytical Method

In order to analyze a boiling heat transfer in the coolant channel of PECS, it is necessary to consider a two-phase flow model considering wall heat transfer and wall boiling heat transfer for liquid flow, and a heat conduction model in structures such as the core catcher body and supports. Generally, two approaches are commonly used. One is based on a commercial CFD package and the other is development from scratch. Here for the development of a methodology for a core catcher performance evaluation, an approach by using an open-source CFD library was chosen. One of the OpenFOAM[3] solvers ChtMultiRegionTwoPhase-EulerFoam with a phase-system library in OpenFOAM was chosen as a basis tool and it is going to be upgraded by adding additional modules especially required for the PECS analysis.

2.3 Application of the Analytical Method to CE-PECS

The analytical method must be verified and validated (V-and-V) before applied to the real core catcher. Here it is expected that the V-and-V will support construction and selection of reliable analysis modules. As an object of analytical methodology, it was applied to a cooling experiment CE-PECS conducted by KAERI for EU-APR1400, which was performed for the purpose of verifying the cooling performance of the core catcher PECS.

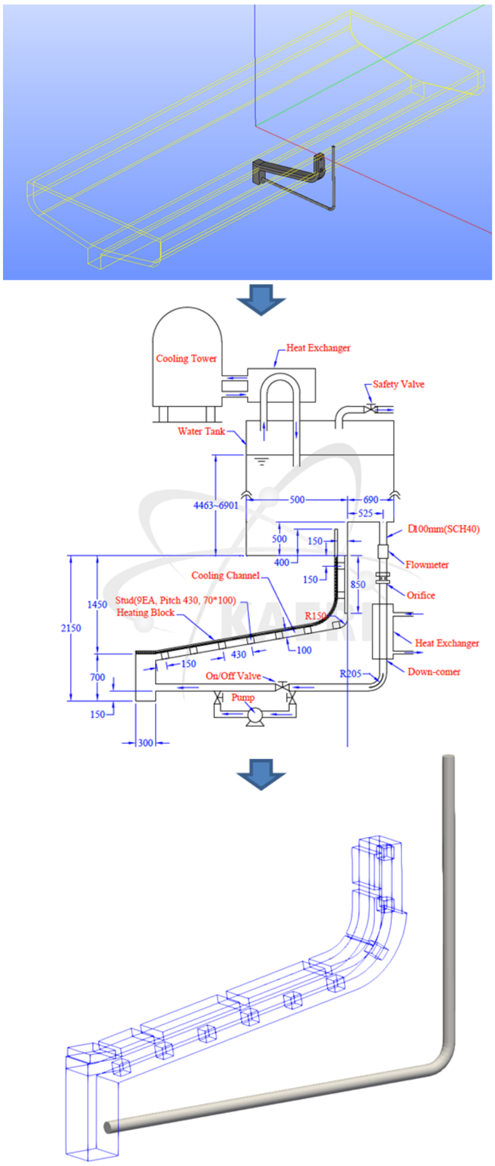

Fig. 3. CE-PECS test facility and geometrical modeling for a validation of the analytical method

Fig. 3 shows the geometrical similarity among PECS, CE-PECS and the geometry model for a preliminary analysis. From the geometrical model, a 3D mesh was constructed.

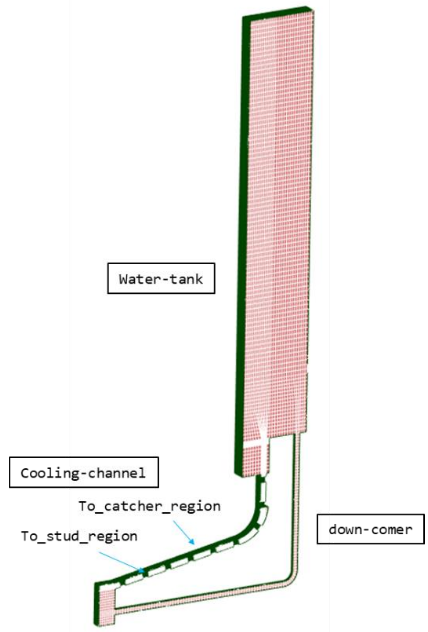

Fig. 4. Mesh system of CE-PECS test facility used for a preliminary analysis.

In order to simulate the flow rate corresponding to a single down-comer part in the actual core catcher, an orifice device was added to the CE-PECS test device.

Since the analysis model for the orifice baffle is not available in the standard OpenFOAM boundary, the existing porousBafflePressure boundary type has been modified to further develop the pressure drop for multi-phase flow.

3. Preliminary Results

The ChtMultiRegionTwoPhaseEulerFoam solver was applied for the analysis of the CE-PECS experiments. In order to implement the heating power of the CE-PECS experiment, it is possible to use a volumetric heat generation or heat flux on the contact surfaces between heat blocks and top surface of the coolant channel. Here only the results from the heat flux method was included.

The current applied heat flux for the preliminary analysis was 125% of the reference condition. In order to apply the corresponding heat flux data to the temperature (T) field, it must be included as a heat flux boundary condition on the external wall of the catcher channel.

It is predictable that bubble sizes are poly-dispersed in the case of a downward-facing flow-boiling such as the current CE-PECS tests. There exist many models for predicting bubble size development, which include constant-sized model, mono-sized models, and polysized models. It is still known that the bubble size models are physically and numerically difficult to implement on real conditions. As a preliminary analysis to support the integration of analytical modules, a constant-sized bubble model was used. The numerical results included in this paper was obtained with a bubble diameter of 1 cm.

The entire analysis was performed up to 1,200s and simulation data sampling was applied at 0.1s intervals to extract monitoring data. The extraction data includes the circulating flow rate and temperature flowing to the precipitation section and the bubble fraction above the cooling channel.

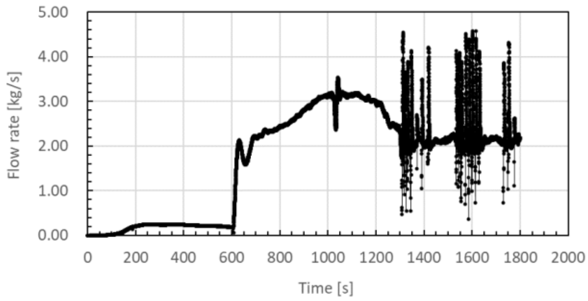

Fig. 4. Temporal flow rate of water flowing through down-comer of CE-PECS.

It is necessary to identify the natural circulation flow formation and extent, which are the most important considerations in the CE-PECS experiment to be analyzed, and is a key confirmation of the analytical model. Fig. 4 shows the mass flow over time from the preliminary analysis. First, it can be seen that the formation of the circulating flow is insufficient for the initial period from about 200 s to 600 s, and the rapid circulating flow occurs after a specific time of 600 s. As the time progressed, the circulating flow rate increased, but after 1200 s, the average flow rate was maintained at the level of 2 kg/s, but it was confirmed that a very large fluctuation occurred. It is expected that these rapid circulating flow up and down fluctuations are from the obscure boundary conditions applied at the top of the pool, where two-phase inlet-outlet boundary condition was applied in the current preliminary analysis

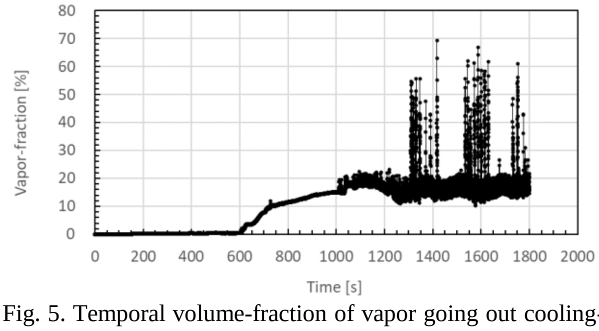

Fig. 5. Temporal volume-fraction of vapor going out cooling-channel of CE-PECS

Fig. 5 shows the area-averaged volume fraction of vapor due to bubble flow in the upper outlet region of the cooling passage.

4. Conclusions

It is underway to develop a methodology for 3D Analysis of a Core Catcher Cooling Channel. The methodology is going to be developed by using OpenFOAM library. As a preliminary analysis to support the selection and integration of analytical modules, one of the CE-PECS tests was simulated. And it was found that the development of the bubble size is one of the major parameters affecting on the prediction of the circulation flow rate.

In this study, it was confirmed that the approach based on the open-source library to develop a methodology for 3D Analysis of a Core Catcher is promising.

ACKNOWLEDGMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korean government (Ministry of Trade, Industry, and Energy) (No. 20193110100090).

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