Multiphase CFD simulation of IVR-ERVC with boiling model and conjugate heat transfer in Ansys Fluent

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1. Introduction

In nuclear power plants, engineered safety functions (ESFs) prevent fuel from melting in accidents. Nevertheless, safety concepts for a molten fuel situation were devised, but they weren't considered significant. Because a severe accident (SA) was too unlikely to happen in a nuclear power plant due to ESFs.

However, in 2011, the Fukushima nuclear disaster occurred. Unfortunately, the SA occurred because of the loss of off-site power. Since then, many kinds of research struggled to devise methods for cooling down without external power.

In the event of a SA, two types of protection strategies are considered; one is Core Catcher and the other is In-Vessel corium Retention through External Reactor Vessel Cooling (IVR-ERVC). Core Catcher is a method that cools down the molten corium. It is assumed that the reactor vessel lost its integrity and the molten corium frees itself from the vessel. It cools down exposed molten corium with a layered cooling structure in that situation. In contrast, IVR-ERVC is a reactor vessel cooling strategy that floods the outer surface of the reactor vessel and keeps cooling with the natural circulation of coolant to avert vessel melting from molten corium.

It involves complex heat transfer mechanisms, and numerical studies regarding them are crucial for improving reactor safety and reducing economic costs.

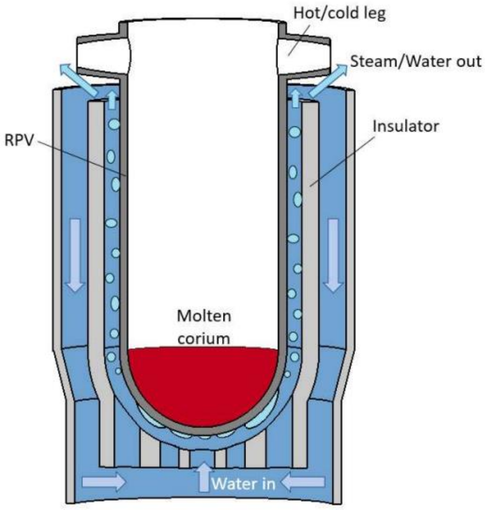


Fig. 1. IVR-ERVC schematic [1]

Several studies have been conducted on IVR-ERVC, such as Park et al. [2], who analyzed the Conjugate Heat Transfer (CHT) between molten corium and the reactor vessel. Another study [3] focused on determining the coolant mass flow rate based on different thermal power. Jung et al. [4] evaluated the heat-flux distribution at the reactor vessel walls in IVR-ERVC. While there have been some studies investigating the phenomena between molten corium and the reactor vessel, there has been relatively little research on the heat transfer between the reactor vessel and coolant.

This study aims to investigate the phase change due to the conduction heat transfer from the reactor vessel in IVR-ERVC through the implementation of a CHT model. For this, implement a CHT model and get data about liquid properties and vessel temperature from it.

Ansys Fluent, a commercial computational fluid dynamics (CFD) program, is used to describe physical phenomena: heat transfer, multi-phase, boiling, and so on. A detailed description of the CHT model between the reactor vessel and coolant in IVR-ERVC is located in the next chapter.

2. Model description

2.1 Geometry

The object of the modeling is an iPOWER and it was made by referring to the master thesis of Hyeon [1]. And proceed with the analysis in axis-symmetric condition. Also, a vessel body is implemented with 230 mm thickness to draw a vessel temperature contour. The value is taken from the thickness of the reactor vessel in APR-1400 [6]. Fig. 2 shows the numerical values used in the modeling.

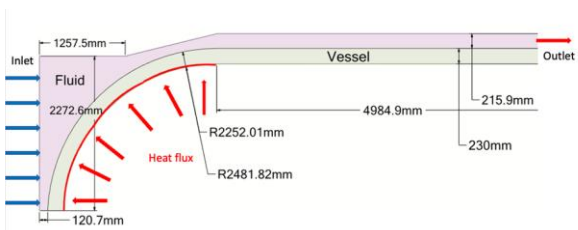


Fig. 2. Model geometry

2.2 Boundary conditions

The boundary conditions used in the model are shown in Table I. Inlet velocity, temperature, outlet pressure, and turbulent model are taken from reference

[1]. The multiphase and boiling models are set by referring to the two-phase flow modeling research [5].

Table I: Boundary conditions

Inlet velocity	0.5201[m/s]
Inlet temperature	368.15[K]
Outlet pressure	101.3[kPa]
Turbulent model	K-epsilon
Multiphase model	Eulerian
Boiling model	RPI

In IVR-ERVC, the heat flux from the molten corium is not uniform belonging to the angle from the vessel; It is shown in Fig 3 [3], so to describe a more realistic heat flux condition in the model, the lower-reactor vessel is divided into four parts to give non-uniform heat flux to the vessel and adapt the MAAP4 results from reference [1]. The detailed values are shown in Table II. And adopted the vessel material which is the same as APR1400's: SA508, Grade 3, Class 1 [4]. Its material properties are not constant but temperature-dependent variables. Therefore, to describe them in Ansys Fluent, the piecewise-polynomial functions were used at thermal conductivity and specific heat. After that, put a User Define Function (UDF) code for density. The graphs of vessel properties were in Fig. 4. The graphs are adopted from the heat flux distribution study in IVR-ERVC [4]

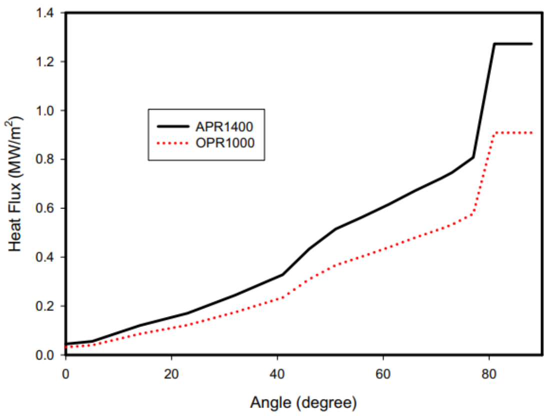
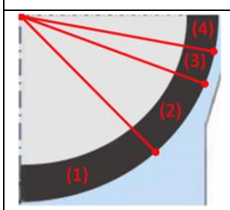


Fig. 3. Heat flux results by the angle from MAAP4 [3]

Table II: Heat flux partition

Zones		Angle (°)	Heat flux (MW/m²)
	1	0.00 ~ 45.68	0.21
	2	45.68 ~ 70.60	0.50
	3	70.60 ~ 79.05	0.68
	4	79.05 ~ 90.00	1.05

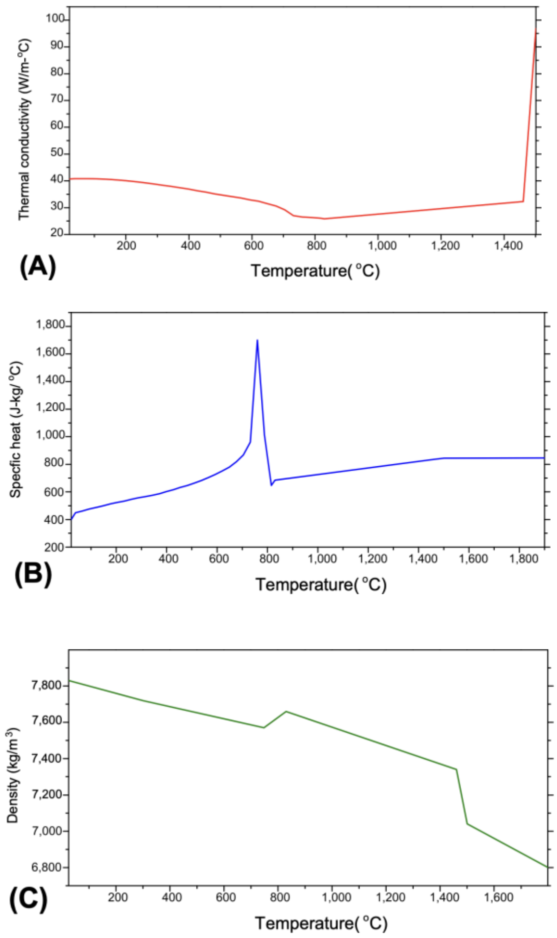


Fig. 4. Thermal properties of SA508: (A) thermal conductivity, (B) Specific heat, (C) Density [4]

2.3 Model description.

In this paper, most of the sub-models adopted refer to the references [1][5]. Firstly, in the turbulent model, k-epsilon is used. The mesh sensitivity is enforced. During this, outlet velocity which is one of the important physical values in IVR-ERVC is checked by increasing the mesh elements and the model adopts medium-mesh elements. The details are shown in Table III. Secondly, the Eulerian model is used to describe multi-phase in the model. However, there is no sensitivity test about it, and the force coefficients: drag, lift, and so on; are taken from the reference [5]. Lastly, the RPI model is adopted to implement the phase- change in the coolant.

Table III: Mesh sensitivity test

Name	Mesh elements	Outlet velocity
Coarse	35322	0.401 [m/s]
Medium	46255	0.425 [m/s]
Fine	74615	0.437 [m/s]

2.4 Convergence determination.

In this study, the convergence of the model is determined by the followings: continuity and the averaged-liquid velocity at the outlet. During the simulation, If the values simultaneously satisfied two conditions, one is that the continuity value is lower than the criteria (10^{-4}) and the other is the almost steady-state liquid velocity at the outlet, it is regarded as convergent. Fig. 5 is the plot used to judge the status of the simulation.

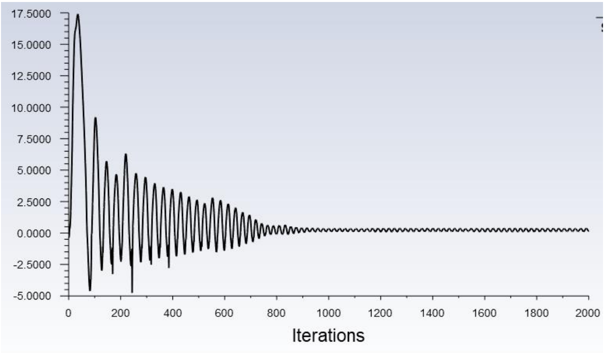


Fig. 5. Average velocity at the outlet[m/s]

3. Results.

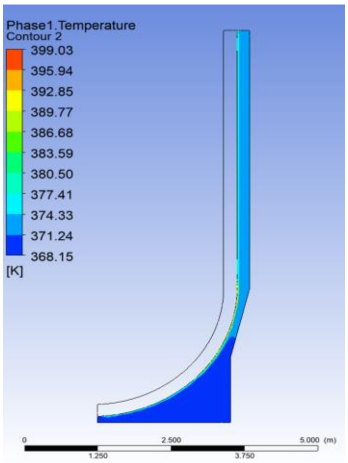


Fig. 6. Liquid temperature\

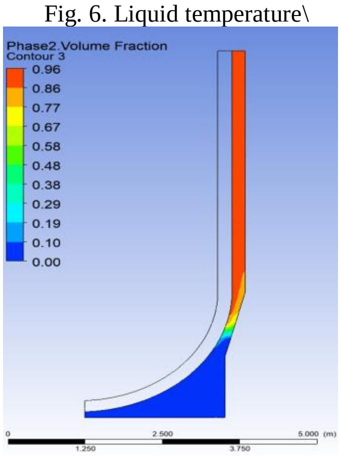


Fig. 7. Void fraction

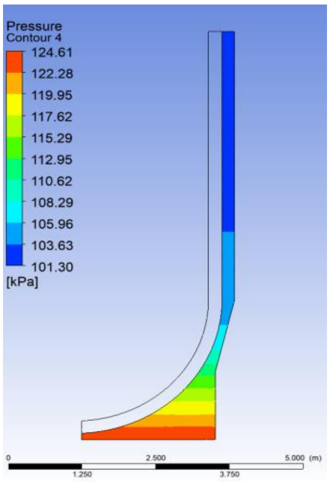


Fig. 8. Liquid pressure

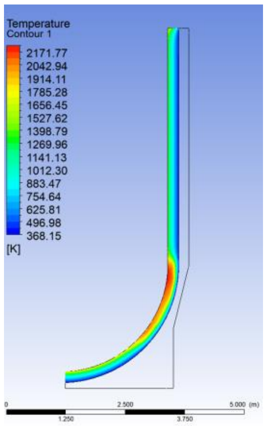


Fig. 9. Vessel temperature

In IVR-ERVC, the cooling mechanism is natural circulation. It is expected that the coolant becomes a vapor phase while it flows along the reactor vessel.

In the model, both CHT and multi-phase are considered. Firstly, the heat flux is not directly given to fluid. Instated give un distributed heat flux to the vessel parts. After that, give heat to the coolant by CHT. Secondly, When the coolant passes the narrow region, the phase change is started. Because at that point, the coolant gets the highest heat flux in a small cross-section. These are shown in Figs 5 and 6. The pressure difference is appeared due to static pressure and it increases the saturated temperature of the coolant. So, the coolant in the lower part of the vessel keeps a liquid phase. These are shown in Figs 6 and 7. The melting point of the vessel is about 1770K [4]. In Fig. 8, the vessel temperature of the outer surface is lower than 1700K. So, it validates that the vessel will retain its integrity in IVR-ERVC.

4. Conclusions

The objective of the study was to investigate phase change due to the interaction between the vessel and coolant with the CHT model in IVR-ERVC. It was implemented by Ansys Fluent to describe complex physical phenomena. It is especially notable that this model simultaneously considered phase change and time-dependent vessel material properties.

In the model, the liquid velocity at the outlet was used to judge convergent. It was not a constant value but it shows a quite small wave at the end of the simulation. So, it is enough to say the model is stable [1]. To validate the accuracy of the model, draw contours with variables: liquid pressure, temperature, void fraction, and vessel temperature. As a result, it predicted not only fluid properties but also the vessel temperature as reasonable. Also, it showed that IVR-ERVC could prevent the vessel from melting in a severe accident.

ACKNOWLEDGEMENT

This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (2106022).

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