Numerical Analysis of Two-phase Natural Circulation Flow in the Core Catcher Test Facility Using the CUPID Code

Dong Hun Lee[a*], Ik Kyu Park[b], Han Young Yoon[b], Kwang Soon Ha[b], Jae Jun Jeong[a]
[a] *School of Mechanical Enge., Pusan National Univ., Jang-jeon 2-dong, Geumjung-gu, Busan, Korea, 609-735*
[b] *Korea Atomic Energy Research Institute(KAERI), 989-111 Daedeok-daero, Yuseong-gu, Daejeon, Korea, 305-353*
[*] *Corresponding author: dhlee0224@pusan.ac.kr*

1. Introduction

A core catcher system has been developed for the next generation advanced light water reactors to stabilize the molten corium while avoiding molten core concrete interaction in the reactor containment during a hypothetical severe accident [1]. A natural circulation with two-phase flows in the complicated geometry is one of the key processes. Therefore, a multi-dimensional analysis is needed.

A previous study was carried out with a two-dimensional grid of the developing test facility for the core catcher using the CUPID code, which is a three-dimensional thermal-hydraulic code for the simulation of two-phase flows [2]. This paper presents the three-dimensional simulation of this facility using the CUPID code.

2. Mathematical Model

2.1 Governing Equations

To simulate a two-phase flow, CUPID adopts a transient two-fluid, three-field model. The three fields include a continuous liquid, droplets, and a vapor. The governing equations of this model are similar to those of the time-averaged two-fluid model derived by Ishii and Hibiki [3]. The continuity, momentum, and energy equations for the k-field are given by

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla \alpha_k \rho_k \underline{u}_k = \Gamma_k, \quad (1)$$

$$\frac{\partial}{\partial t}\alpha_k\rho_k\underline{u}_k + \nabla\cdot(\alpha_k\rho_k\underline{u}_k\underline{u}_k) = -\alpha_k\nabla P + \alpha_k\mu_k\nabla\underline{u}_k + \alpha_k\rho_k\underline{g} + S_k, \quad (2)$$

$$\frac{\partial(\alpha_k \rho_k e_k)}{\partial t} + \nabla\cdot(\alpha_k \rho_k e_k \underline{u}_k) = -P\frac{\partial \alpha_k}{\partial t} - P\nabla\cdot(\alpha_k \underline{u}_k) + \alpha_k k_{c,k}\nabla T_k + E_k, \quad (3)$$

where α_k, ρ_k, u_k, P, Γ_k, and e_k are the k-field volume fraction, density, velocity, pressure, an interface mass transfer rate, and energy transfer rate, respectively. S_k represents the interfacial momentum transfer due to a mass exchange, a drag force, and non-drag forces. E_k includes the phase change, interfacial heat transfer, wall heat transfer, and volumetric heat source.

For a mathematical closure of the system of equations, constitutive relations and the equation of state are included.

2.2 Physical Model and Correlations

To consider a turbulence effect, the k-ε turbulence model was implemented. The interfacial drag force, interfacial heat transfer, and interfacial area were defined by a local flow regime map. A lift force, a wall lubrication force, and a turbulent dispersion force were implemented as non-drag forces.

In a subcooled boiling flow, the amount of vapor generation is computed by a wall heat flux partitioning model. The heat transfer from the wall consists of the surface quenching, q_q, evaporative heat transfer, q_e, and single-phase convection, q_c [4].

3. Calculations

3.1 Core Catcher Test facility

KAERI has designed the test facility to evaluate the core catcher cooling performance. The geometry of the test facility is shown in Fig. 3. The cooling channel in the core catcher has a gap size of 0.1 m and an angle of inclination of 10 degrees. The total length of the circulation loop from the cooling channel and the downcomer is about 10 m. A water tank with a dimension 1.5 m x 6.4 m is set up on the loop. The thickness of this facility is 30 cm.

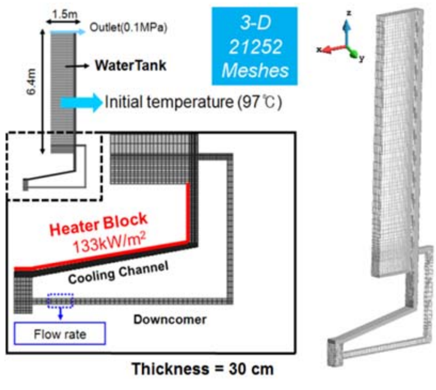


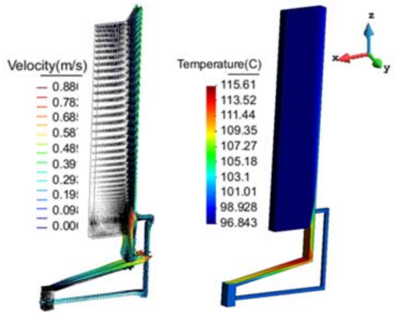
Fig. 1. Calculation domain for the core catcher

The computational mesh is presented in Fig. 1. A computation grid with total 21,252 cells was used for this calculation. Downcomer pipe is modeled as 1m-square channel to maintain structured mesh. The initial liquid temperature and pressure are 97 °C and 0.1 MPa, respectively. The outlet is set to constant pressure boundary of 0.1 MPa. The heater block is installed to simulate a decay heat of the molten corium. The heat flux is set to 0.133 MW/m^2.

3.2 Numerical Analysis

The steady-state velocity vector of the CUPID calculation is shown in Fig. 2 (a). The natural circulation flow from the cooling channel to the downcomer is properly simulated. The mass flux in three-dimensional calculation is less than that of the two-dimensional calculation as presented in Table I. In the two-dimensional calculation, the thickness of all domains is considered as 1 m. But, the three-dimensional calculation considers all domains have varying thickness. So, a flow in the three-dimensional calculation exposed to area changes along thickness direction (y-direction in Fig. 2). Thus, the mass flux is slightly less than that of the two-dimensional result.

The contours of liquid temperature are shown in Fig. 2(b). The temperature distribution in the cooling channel and the downcomer is lower than that of the previous two-dimensional results. In the two-dimensional case, the heated water from the cooling channel is not well mixed with cold water in the water tank. But, three-dimensional results show that a complex flow is formed at the inlet of downcomer and this flow mixes well.



(a) (b)

Fig. 2. Velocity vector (a) and temperature (b)

Table I: Natural circulation flow rate and mass flux in downcomer

	2D	3D
Mass flux (kg/ m^2·s)	223.8	209.5
Flow rate (kg/s)	22.38	2.095

The void fraction is depicted in Fig. 3. The void fraction in the side wall(y-direction) of the cooling channel is higher than that in the center. This distribution results from a wall effect.

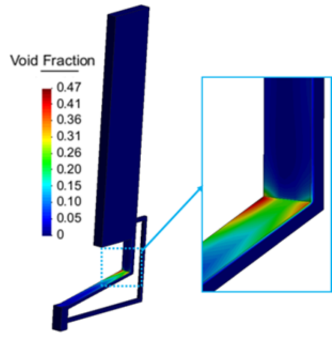


Fig. 3. Void fraction

Parametric study for the downcomer size is presented in Table II. The flow rates considering the change of diameter agree with a theoretical natural circulation flow rate.

Table II: Parametric study for downcomer size

Diameter (mm)	Flow rate (kg/s)
75	1.30
100	2.09
150	4.65

4. Conclusions

In this study, the two-phase flow and natural circulation flow in the core catcher system was analyzed using the CUPID code. The calculation results showed that the CUPID code properly simulates the two-phase flow phenomena in the core catcher. The natural circulation was formed in the cooling channel and downcomer as designed. The parametric study for downcomer size shows CUPID can predict the effect of design parameters.

ACKNOWLEDGEMENTS

This work was supported by Nuclear Research & Development Program of the NRF (National Research Foundation of Korea) grant funded by the Ministry of Education, Science and Technology of the Korean government (Grant code: 2012M2A8A4025647).

REFERENCES

[1] J. H. Song et al., A Core Catcher Design for Advanced Light Water Reactors, Proc. of ICAPP, Nice, France, May 2-5, 2011.
[2] J. J. Jeong et al., The CUPID code Development and Assessment Strategy, Nuclear Engineering and Technology, 42(6), pp.636–655, 2010.
[3] M. Ishii and T. Hibiki, Thermo-Fluid Dynamics of Two-Phase Flow, Springer Inc., New York, p. 217, 2006.
[4] AEA, CFX-4 Solver Manual, UK, 1997.