Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

Validation of MAAP 5.06 API model with MARS/KS and numerical 2-fluid model

Yongju Cho[a], Daehyung Lee[a], Chungwon Seo[a]*
[a]KEPCO-E&C, Nuclear Technology Research Dept, 269 Hyeoksin-ro, Gimcheon-si, 39660
[*]Corresponding author: cyongju93@kepco-enc.com

***Keywords : MAAP 5.06, MARS/KS2,0, Severe Accident, Validation**

1. Introduction

Following the Fukushima nuclear accident, global nuclear industry regulations have increasingly emphasized the importance of robust severe accident mitigation capabilities According to guidelines established for European nuclear operators, dedicated severe accident mitigation systems must be designed to be physically and functionally separate from conventional safety systems intended for design-basis accident scenarios. For high-power reactors, which may not sufficiently demonstrate cooling capability through reactor cavity flooding systems or in-vessel retention (IVR) alone, additional specialized molten core cooling facilities must be implemented [1].

The core catcher represents a crucial severe accident mitigation technology specifically engineered to safely cool molten core material that is released into the reactor cavity following reactor vessel failure. By effectively cooling and stabilizing the molten core, the core catcher maintains the structural integrity of the reactor containment building, thereby preventing severe consequences such as basement melt-through (BMT) incidents [2]. The efficacy and reliability of core catcher designs have made them highly favored within the European nuclear market, influencing the integration of core catcher technology into the Advanced Power Reactor (APR) series specifically developed for export to European markets.

Initial development of the EU-APR1400 reactor previously included basic core catcher designs and preliminary experimental studies. However, these experiments utilized two-dimensional slice test facilities that were unable to accurately represent critical phenomena such as three-dimensional flow distribution, flow instability, and comprehensive cooling performance [3]. Consequently, further optimization of core catcher designs is necessary to effectively resolve potential licensing issues, reduce validation requirements, and minimize associated costs. Additionally, targeted experimental analyses are required to thoroughly evaluate localized flow instabilities and their impacts on cooling performance under realistic three-dimensional geometric conditions.

In response to these challenges, this research introduces a newly developed Application Programming Interface (API) integrated with the MAAP5 severe accident analysis code. This API enables flexible and comprehensive modeling of diverse heat flux distributions within the molten core catcher cooling channels, addressing existing uncertainties in heat transfer modeling [4]. The study also presents comparative analyses between simulations obtained through the new API, MARS/KS2.0 code, and a simplified one-dimensional homogeneous-equilibrium model.

2. Code model description

2.1 MAAP Core catcher model

The cooling channels in the core catcher are inclined at a 10-degree angle horizontally to facilitate efficient cooling water inflow from below. The effectiveness of core catcher cooling channel design depends significantly on the volumetric heat generation within the core catcher and the resulting heat flux distribution along these cooling channels. Due to the absence of established data specifically detailing heat flux distributions within these inclined cooling channels, assumptions based on analogous geometries, such as reactor lower head configurations, have been employed. The following assumptions were considered to estimate heat flux distributions for core catcher design:

I The base of the core catcher is represented as a gently curved surface to approximate realistic heat flux distribution.

II Given the lack of empirical heat flux data for gently curved pools, available data from hemispherical pool geometries have been adopted. This implies that the heat flux distribution assumed will likely exceed actual conditions due to the steeper inclination angle in real core catcher designs.

Based on experimental findings, Theofanous and Liu (1995)[5] proposed a heat flux distribution model specifically for hemispherical molten pools, detailed below.

$$\left[\frac{N_{dn}(\theta)}{\overline{N_{dn}}}\right]_{sph} = \begin{cases} 0.1 + 1.08\left(\frac{\theta}{\emptyset}\right) - 4.5\left(\frac{\theta}{\emptyset}\right)^2 + 8.6\left(\frac{\theta}{\emptyset}\right)^3 & ; 0 \le \left(\frac{\theta}{\emptyset}\right) \le 0.6 \\ 0.41 + 0.35\left(\frac{\theta}{\emptyset}\right) + \left(\frac{\theta}{\emptyset}\right)^2 & ; 0.6 \le \left(\frac{\theta}{\emptyset}\right) \le 1.0 \end{cases} \quad (1)$$

In this equation, $N_{dn}(\theta)$ represents the local heat transfer coefficient at an angular position θ measured from the central axis of the reactor vessel, while $\overline{N_{dn}}$ indicates the corresponding downward heat transfer Nusselt number. Additionally, the angle ∅ is defined as the angular position of the molten core pool surface inside the reactor vessel.

To accurately determine local heat flux distributions using correlation equations developed for gently curved molten pools equivalent to core catcher conditions, it is essential to first calculate the average heat flux. For this purpose, the correlation proposed by Jahn and Reineke (1974)[6] for gently curved molten pools is utilized as follows:

$$\overline{N_{dn}} = 0.54 Ra^{0.18}\left(\frac{y_p}{R}\right)^2 \quad (2)$$

Here, the dimensionless Rayleigh number (Ra) is defined by:

$$Ra = \frac{g\beta R^5 Q}{\kappa\alpha\upsilon} \quad (3)$$

In the above expression, the parameters g,β,R,Q,k,a,ν have clear physical implications regarding convective heat transfer in molten core pools. If the molten pool depth (y_p) within the core catcher exceeds the depth of its inclined bottom surface (H), the height parameter should be substituted by y_p . Consequently, the correlation equation proposed by Steinbrenner and Reineke (1978) is employed to evaluate the average lateral heat flux distribution, which is expressed as:

$$Nu_{side} = 0.85 {Ra_H}^{0.19} \quad (4)$$

where H represents the lateral height of the molten pool within the core catcher, while all other variables maintain the same definitions as previously described [7].

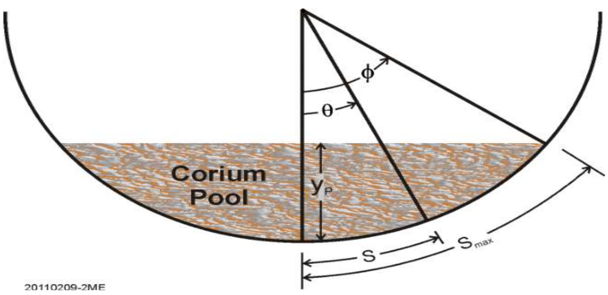

Fig. 1 Definition of spherical segment pools[4]

2.2 MAAP API model

The MAAP severe accident analysis code supports the execution of user-defined code segments during runtime through an Application Programming Interface (API). This capability is implemented by integrating an external Dynamic Link Library (DLL), which contains the customized user code. The external DLL is loaded into MAAP via specific commands included in the MAAP input deck, particularly within the designated DLL LOAD block required by MAAP's internal subroutine, ExternCall. The MAAP executable processes this DLL LOAD block, which specifies external subroutines callable during runtime, and executes these external calls as needed. Interaction between the external DLL and MAAP occurs through the MAAPInterface.dll library, facilitating the exchange of variable data. A simplified diagram illustrating the logic flow of the ExternCall operation within the MAAP code is presented in Fig. 4.

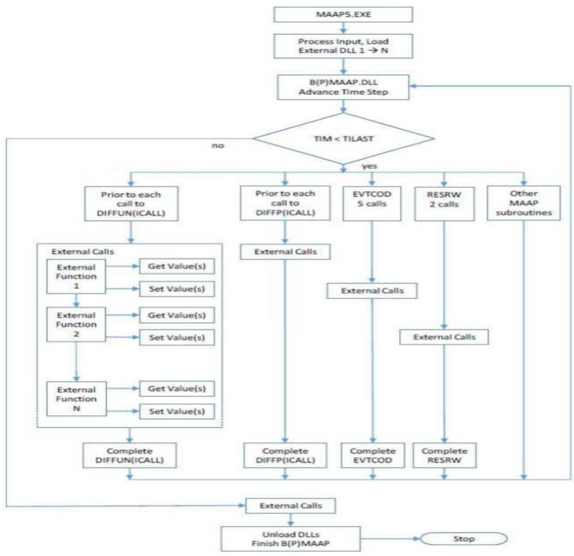

Fig. 2 Code flow diagram depicting the locations in MAAP [10]

2.3 Numerical Solution of 2-flow model, One-dimensional Conservation Equations

The governing equations presented describe mass, momentum, and energy conservation principles for steady-state, one-dimensional two-phase flow systems, typically encountered in heated channels involving boiling or condensation processes. The mass conservation equation accounts for changes in the density and equilibrium quality, influencing the axial pressure and quality gradients within the flow channel. The momentum equation relates the axial pressure gradient to gravitational forces and frictional resistance, highlighting the effects of wall shear stress and gravitational acceleration. Meanwhile, the energy conservation equation addresses the balance of enthalpy changes, latent heat, pressure variations, and the heat flux from channel walls, incorporating terms related to frictional energy dissipation. These equations can be represented compactly in matrix form, simplifying numerical analysis and facilitating computational modeling [9].

$$\rho_h \frac{\partial j}{\partial z} + j\frac{f(x_{eq})}{\rho_g^2}\rho_h^2\frac{d\rho_g}{dP}\left(\frac{dP}{dz}\right) + j\left(\frac{1}{\rho_L}-\frac{1}{\rho_g}\right)\rho_h^2\frac{df(x_{eq})}{dx_{eq}}\left(\frac{dx_{eq}}{dz}\right) = 0 \tag{4}$$

$$\rho_h\, j\frac{\partial j}{\partial z} + \frac{\partial P}{\partial z} = -\rho_h\, g\, \sin\theta - \frac{4\tau_w}{D} \tag{5}$$

$$\rho_h h_{fg} j\frac{dx_{eq}}{dz} + \left\{\rho_h j\left[(1-x_{eq})\frac{\partial h_f}{\partial P} + x_{eq}\frac{\partial h_g}{\partial P}\right] - j\right\}\frac{dP}{dz} = \frac{4q_w''}{D} + \frac{4j\tau_w}{D} \tag{6}$$

write this as a matrix,

$$\begin{bmatrix} \rho_s & j\left(\frac{1}{\rho_L}-\frac{1}{\rho_g}\right)\rho_h^2\frac{df(x_{eq})}{dx_{eq}} & j\frac{f(x_{eq})}{\rho_g^2}\rho_h^2\frac{d\rho_g}{dP}\left(\frac{dP}{dz}\right) \\ \rho_s\, \mathrm{j} & 0 & 1 \\ 0 & \rho_h h_{fg} j & \rho_h j\left[(1-x_{eq})\frac{\partial h_f}{\partial P} + x_{eq}\frac{\partial h_g}{\partial P}\right] - \mathrm{j} \end{bmatrix} \frac{\mathrm{d}}{\mathrm{dz}}\begin{bmatrix} 0 \\ x_{eq} \\ \mathrm{P} \end{bmatrix} = \begin{bmatrix} 0 \\ -\rho_h\, g\, \sin\theta - \frac{4\tau_w}{D} \\ \frac{4q_w''}{D} + \frac{4j\tau_w}{D} \end{bmatrix} \tag{7}$$

3. Methods and Node Schematic

A specialized API has been developed within MAAP to enable a simplified representation of the core catcher. To validate this simplified model, flow analyses will be conducted using both MARS/KS 2.0 and a Python-based two-flow model (Numerical Solution of the Two-Flow Model, One-Dimensional Conservation Equations). The results obtained from these approaches will subsequently be compared against those produced by the MAAP API.

Fig.3 is schematic which illustrates an inclined cooling channel subdivided into ten discrete nodes, each designed to capture local variations in thermal-hydraulic behavior along the channel's 2-meter length. The entire channel is tilted at a 10° angle, allowing coolant to flow from the lower inlet node to the upper outlet node. Each of the ten nodes has a cross-sectional area of 0.2 m², providing a uniform basis for tracking changes in fluid and heat transfer properties.

At the inlet, the pressure is set to 1.8×10^5 Pa, the mass flow rate of liquid coolant is 3.73 kg/s, and the fluid enters at a temperature of 370.15 K. The pipe diameter is 0.1 m, which influences the flow velocity and pressure drop characteristics. A heat source of 463,300 W is uniformly applied along the channel's top boundary, supplying a significant thermal load for the coolant to absorb as it travels through each node.

By dividing the channel into multiple nodes, the model can more accurately capture local phenomena, such as potential boiling onset, two-phase flow development, or changes in flow regimes along the inclined geometry. The 10° slope further emphasizes the role of gravity in driving the coolant upward, affecting both flow distribution and heat transfer performance. In practical analyses, such detailed nodal modeling supports a deeper understanding of temperature distributions, pressure gradients, and overall heat removal efficiency within the channel.

Table. 1 Parameters for numerical Solution of 2-flow model

Main Parameter	Value
ρ_f	960.52kg/ kg/m^3
ρ_g	1.022 kg/m^3
U_g	0.49459 m/s
U_f	0.49459 m/s
C_d(drag coefficient)	0.44
τ_w(wall shear stress)	4.383

Because each node is treated as a smaller control volume, it becomes possible to evaluate how local conditions (e.g., fluid velocity, quality, and enthalpy) evolve step-by-step along the channel. This finer resolution is especially valuable in scenarios involving high heat fluxes or substantial thermal gradients. Ultimately, the nodal approach provides more accurate insights into system behavior, aiding in the design and safety assessment of inclined cooling channels within nuclear or other thermal engineering applications.

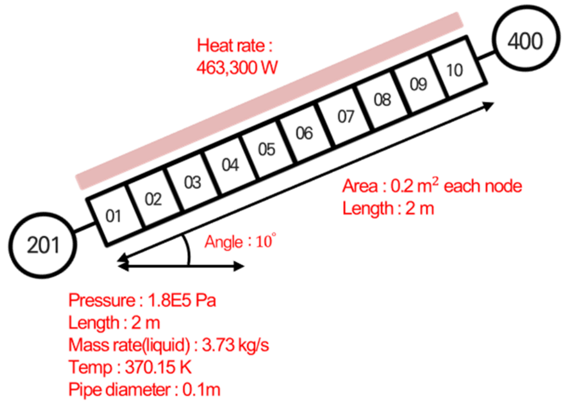

Fig. 3 Node schematic with MAAP and MARS/KS

4. Conclusion

The results obtained by simulating the conditions shown in Fig. 3 using MAAP and MARS/KS 2.0 were compared. The key parameters for fluid analysis, namely void fraction and enthalpy, were verified through the calculated results. MARS/KS 2.0 includes a steady-state feature that automatically terminates the calculation once the fluid reaches a steady state; this termination point was subsequently used as the reference condition for comparison with the MAAP 5.06 API results. The steady state in the MARS/KS calculation was reached at 34.75 seconds. At the first boundary node, the pressure and mass flow rate from both codes were found to be consistent, as illustrated in Fig. 4 and Fig. 5.

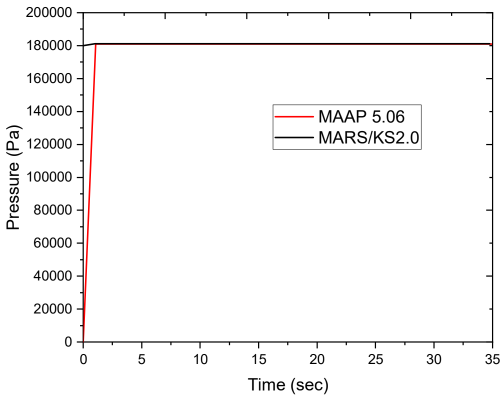

Fig. 4 Initial condition of pressure

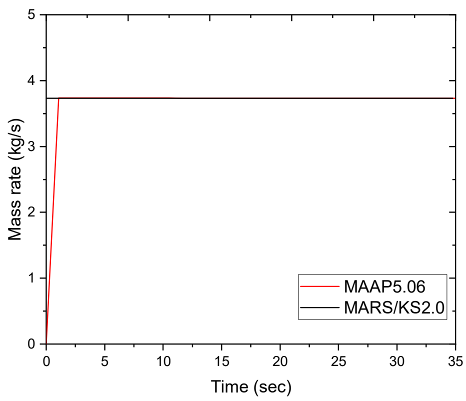

Fig. 5 Initial condition of mass rate

Fig. 6 and Fig. 7 show the distributions of void fraction and enthalpy at each node obtained by MARS/KS 2.0, MAAP 5.06, and a numerical solution based on one-dimensional conservation equations (hereafter referred to as 2FM), under steady-state conditions. Void fraction and enthalpy are critical parameters in two-phase flow because they significantly influence pressure drop, heat transfer, and phase-to-phase flow regime transitions. Therefore, these parameters can serve as indicators to evaluate fluid behavior variations due to heat input within a pipe. As illustrated in Fig. 6, the void fraction results from all three approaches exhibit an increasing trend along the node positions; however, noticeable discrepancies exist among the computed results of each code. Such differences arise primarily due to the application of different phase separation models and correlations predicting slip phenomena between gas and liquid phases. Consequently, despite identical boundary and initial conditions, the differences in these models and correlations lead to varying predictions of relative velocity and volumetric distributions between the phases, which ultimately cause variations in void fraction and enthalpy distributions across nodes.

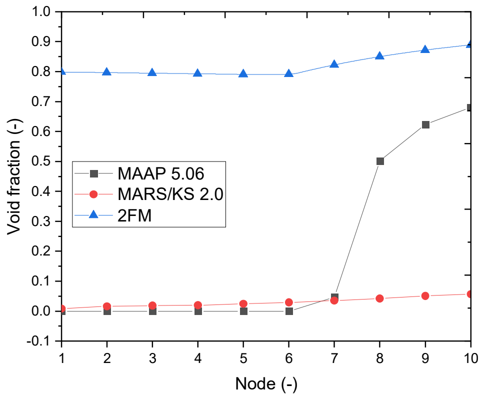

Fig. 6 Results from each code and numerical calculation - Void fraction

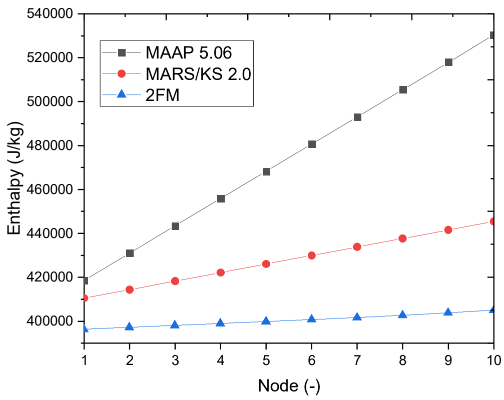

Fig. 7 Results from each code and numerical calculation – Enthalpy

REFERENCES

[1] Nuclear Energy Agency (NEA). Status Report on Ex-Vessel Core Melt Coolability and Core Catcher Development, OECD-NEA.
[2] Nuclear Regulatory Commission (NRC). Severe Accident Management Guidelines, NUREG-1793.
[3] Korea Atomic Energy Research Institute (KAERI). Core Catcher Development Project Reports, Internal Technical Reports.
[4] Electric Power Research Institute (EPRI). Modular Accident Analysis Program (MAAP5) Manual.
[5] Theofanous, T. G., and Liu, C. (1995). "Heat flux distribution in hemispherical pools under severe accident conditions," Nuclear Engineering and Design.
[6] Jahn, M., and Reineke, H. H., 1974, “Free Convection Heat Transfer With Internal Heat Sources, Calculations and Measurements,” Proc. of the 5th Intl. Heat Transfer Conf., Tokyo, Japan, Paper NC2.8.

[7] Steinbrenner, V. and Reineke, H. H., 1978, "Turbulent Buoyancy Convection Heat Transfer with Internal Heat Sources," Proc. 6th Int'l Heat Transfer Conf., Toronto, Canada (August 7-11).
[8] Dae-Hyung Lee, et al. "Development of an API for Modifying the Core Catcher Heat Transfer Model in the Severe Nuclear Accident Analysis Code MAAP5", KSME February 8, 2024
[9] Ghiaasiaan, S.M. (2007). Two-Phase Flow, Boiling and Condensation in Conventional and Miniature Systems. Cambridge University Press, pp. 191–197.

ACKNOWLEDGEMENT

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (N2o. 20217810100040)