

Validation of CUPID-RV Subchannel-Scale Analysis against OECD/NEA RBHT Phase I Benchmark Reflood Test Matrix

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1. Introduction

This study aims to perform a capability for multi-dimensional two-phase thermal hydraulics of the emergency core cooling procedure during the reflood phase of a Large Break Loss-of-Coolant Accident (LBLOCA) — a design-basis accident in Pressurized Water Reactors (PWRs) — at the subchannel scale.

For simulating reflood phase, Rod Bundle Heat Transfer (RBHT) experiments [1] were conducted in the 2010s under the auspices of the United States Nuclear Regulatory Commission (USNRC) and Pennsylvania State University (PSU) to validate detailed physical phenomena. In this study, a numerical analysis of RBHT reflood simulation was performed using CUPID-RV, a thermal-hydraulic analysis code developed by the Korea Atomic Energy Research Institute (KAERI).

CUPID-RV is a component-scale code optimized for reactor vessel (RV) analysis; it solves the three-dimensional, two-fluid, transient, three-field governing equations on an unstructured mesh, enabling the rigorous simulation of complex two-phase flow and heat transfer within the reactor core during the reflood transient. [2,3]

2. Background and Results

This section describes the numerical framework and validation results of the proposed study. It first addresses the inherent numerical stiffness encountered in reflood simulations, followed by the governing equations and empirical correlations implemented in CUPID-RV. The simulation results for the reflood transient are presented and discussed in terms of Peak Cladding Temperature (PCT) and Quench Front.

2.1. Physical and numerical framework

2.1.1. Theoretical background

Jin [4] emphasized that the coupling between macroscale cladding temperatures and microscale interfacial phenomena — such as droplet breakup at spacer grids and interfacial drag — is paramount for high-fidelity modeling. This necessitates a comprehensive approach to reflood simulation that bridges the gap between macroscopic thermal-hydraulic behavior and microscopic interfacial dynamics.

Furthermore, the reflood and re-wetting process involves physical mechanisms that are fundamentally distinct and more complex than those in the standard transition of boiling regimes. During the re-wetting phase, the collapse of the stable vapor film at the Leidenfrost point triggers an instantaneous transition from film boiling to nucleate boiling. According to the classical definition of the heat transfer coefficient, $h = q''/(T_w - T_{sat})$, as the wall temperature T_w rapidly approaches the saturation temperature T_{sat} , the denominator approaches zero while the heat flux q'' surges due to direct liquid-wall contact. This physical singularity results in a discontinuous expansion of the interfacial heat transfer coefficient (IHTC), often by several orders of magnitude. [1,5]. Such abrupt changes in IHTC and associated interfacial drag induce extreme numerical stiffness within the non-equilibrium three-field governing equations.

Consequently, these intricate dynamics — characterized by the rapid cooling of a preheated dry surface and the subsequent collapse of the vapor film — distinguish the reflood from steady-state boiling behaviors, which typically involve the evolution from nucleate boiling to film boiling and Departure from Nucleate Boiling (DNB) phenomena. This underscores the necessity of a multi-scale modeling approach to accurately capture the recovery of cooling effectiveness and ensure numerical stability during the reflood phase.

2.1.2. Governing equations

The CUPID code adopts a transient three-field model to simulate the non-equilibrium thermal-hydraulic behaviors of two-phase flows. [3] The model independently resolves three distinct fields: vapor, continuous liquid, and droplets. Separate conservation equations for mass, momentum, and energy are formulated for each field, coupled through interfacial exchange terms. The mass conservation for a representative field k is given by:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla \cdot (\alpha_k \rho_k \mathbf{u}_k) = \Omega_k$$

Where Ω_k accounts for the net interfacial mass transfer. For the liquid and droplet fields, Ω_k incorporates phase change and the mechanical exchange

of mass through entrainment and deposition. The momentum conservation equation is defined as:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k u_k) + \nabla \cdot (\alpha_k \rho_k u_k u_k) = -\alpha_k \nabla P + \nabla \cdot [\alpha_k (\mu_l + \mu_t) \nabla u_k] + \alpha_k \rho_k g + M_k$$

The total momentum transfer, M_k , consists of contributions from phase change, drag force, non-drag forces, and virtual mass force. The energy conservation for the vapor and liquid fields is expressed as:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k e_k) + \nabla \cdot (\alpha_k \rho_k e_k u_k) = -P \frac{\partial \alpha_k}{\partial t} - P \nabla \cdot (\alpha_k u_k) + Q_{ik} + q_{wk}$$

Where Q_{ik} and q_{wk} denote the interfacial and wall heat transfer, respectively.

2.2. Reflood Heat Transfer Analysis

For the reflood analysis, we used a total of 11 experiments from the OECD/NEA RBHT (Rod Bundle Heat Transfer) Phase I Benchmark Open Test Matrix. [6] The benchmark was conducted using the existing RBHT facility at the Pennsylvania State University (PSU) to generate new, high-quality reflood experimental data and evaluate the predictive capabilities and limitations of thermal-hydraulic codes through comparative assessment. It covers a wide range of experimental conditions, including oscillating, stepped, high, and low reflood velocities, as well as various subcooling temperatures. The detailed experimental conditions are summarized in Table I. In Table I, the reflood rates are denoted as C for constant, V for variable stepped, and O for oscillatory with a 4 seconds period. Reflood water subcooling refers to the difference between the saturation temperature and the coolant temperature. Bundle power refers to the total heat generation rate of all 45 heated rods. For comparison with the experimental data, the cladding wall temperature, quench front location, quench time, and steam temperature near the peak temperature locations (2.69 m and 2.89 m) were examined to evaluate errors in PCT, quenching performance, and other thermal-hydraulic behaviors.

The RBHT 7x7 rod bundle consists of 45 heated rods and 4 unheated rods, enclosed by a rectangular 90.2 mm housing wall. The outer diameter of the heated rods is approximately 9.5 mm. In this study, only the 45 heated rods were modeled as two-dimensional heat structures to focus on the heat generation and PCT behaviors. This modeling assumption provides a slightly conservative estimation of the cladding wall temperature by excluding the heat sink effect of the unheated rods.

To model the fluid domain at the subchannel scale, a mesh was generated using the SALOME platform. The cross-section is discretized into 64 (8×8) subchannels categorized into three types: interior (36), edge (24), and corner (4). Axially, the domain is uniformly divided into

61 computational nodes, resulting in a total of 3,904 cells for the 3D thermal-hydraulic analysis.

The cross-sectional layout of the rod bundle is shown in Fig. 1. As shown in Fig. 1., the inner and outer rods are distinguished in blue and white, respectively. Unlike system thermal hydraulic codes that use a single lumped channel, subchannel analysis can capture the radial gradients of thermal hydraulic parameters. Therefore, it is essential to distinguish between the inner and outer rods to accurately simulate the local differences in quench front progression and PCT. Thermocouple channel 238 ($l=2.69\text{m}$) data was used for the cladding wall temperature comparison. While conventional system code evaluations rely on comparing bulk predictions with single thermocouple measurements (e.g., Ch. 238 at 2.69 m), subchannel analysis allow direct extraction of individual rod temperatures. This enable a location-specific comparison between numerical results and corresponding experimental data. Thermocouple channel 238 corresponds to location C4 on the rod bundle, which is marked in red in Fig. 2.

The cladding wall temperatures are plotted for three representative rod groups: the total 45 rods (red), 25 inner rods (blue), and the C4 rod (green). The cladding wall temperature comparisons for representative high and low reflood velocity cases are presented in Figs. 3 and 4, while the corresponding quench front progressions are shown in Figs. 5 and 6. The quench front is defined as the moving boundary at which film boiling collapses and direct liquid-wall rewetting occurs on the heated cladding surface. In this analysis, the quench front is defined based on the rate of temperature change criterion from the NUREG report, $dT_{wall}/dt < -11.1\text{K/s}$. [1] For the high reflood velocity case (Test 9014), the PCT occurrence time is slightly delayed compared to the experiment, and the PCT is overpredicted (Fig. 3). Conversely, the quench front advances faster than in the experiment at all axial locations, indicating earlier precursory cooling and faster coolant progression (Fig. 5).

For low reflood velocity case (Test 9021), the temperature decline trend of the inner rod average wall temperatures shows the closest agreement with the experiment data (Fig. 4). However, the quench front propagation indicates that no distinct quenching occurs in the upper 1/4 section of the heated length (Fig. 6). The overestimated precursory cooling in the Dispersed Flow Film Boiling (DFFB) regime drives both the earlier quench front propagation in high-velocity cases and the smoother temperature drop at upper axial elevations in low-velocity cases.

Table I: Open test matrix conditions of RBHT Phase I Benchmark experiment. [6]

Experiment Number	Reflood Rate (cm/s)	Reflood Water Subcooling (K)	Bundle Power (kW)
9005	5, C	10	144
9011	8, 5, 3, 1.2, V	25	144
9012	2.5±2.5, O	10	144
9014	15, C	80	252

9015	15, C	10	252
9021	2.5, C	10	144
9026	2.5, C	80	144
9027	2.5, C	30	144
9029	2.54, C	47	222, decay
9037	5, C	10	144
9043	0.5, C	2.8	35

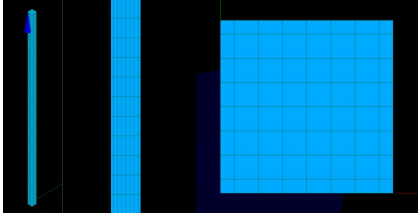


Fig. 1. Computational mesh structure for the RBHT reflood analysis.

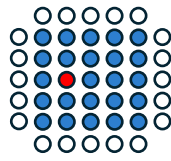


Fig. 2. The cross-sectional view of the heated rod bundle - inner rods (Blue), outer rods (White), single rod C4 (Red).

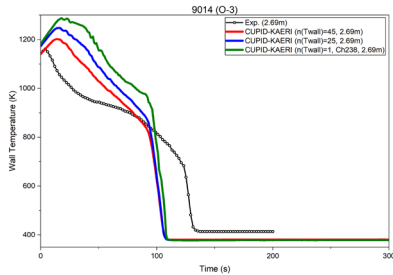


Fig. 3. Comparison of cladding wall temperature transients over time for the high reflood velocity case (15 cm/s), RBHT Test 9014.

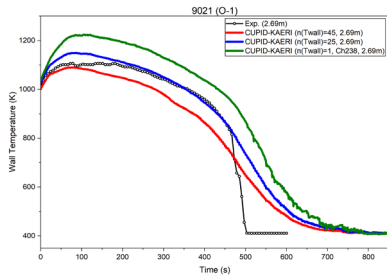


Fig. 4. Comparison of cladding wall temperature transients over time for the low reflood velocity case (2.5 cm/s), RBHT Test 9021.

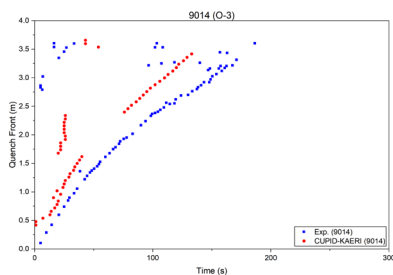


Fig. 5. Comparison of quench front elevation over time for the

high reflood velocity case (15 cm/s), RBHT Test 9014.

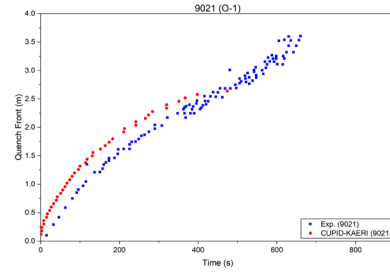


Fig. 6. Comparison of quench front elevation over time for the low reflood velocity case (2.5 cm/s), RBHT Test 9021.

3. Conclusions

The verification of the multi-physics thermal-hydraulic code CUPID-RV for subchannel reflood analysis was achieved using 11 experiments from the open test matrix of the RBHT Phase I Benchmark data. The reflood analysis results from CUPID-RV demonstrate that the code can produce predictions compliant with nuclear safety standards. The code successfully captures the key reflood phenomena and cooling trends across most axial locations, demonstrating its physical validity. To further improve the code capability, addressing the overestimation of precursory cooling in the DFFB regime remains a key challenge, as it directly governs quench front behavior and surface rewetting mechanisms.

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