

Development and Verification of a Representative-Channel Thermal-Hydraulic Analysis Code Using Three-Dimensional Core Power Distribution

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1. Introduction

The reactor protection system is a key system that detects abnormal conditions and initiates protective actions, such as reactor trip, before core thermal safety limits are exceeded. For an independently developed reactor intended for overseas export, reliance on the protection logic or design and analysis framework of an existing foreign reactor may lead to disputes over technology licensing and intellectual property. It is therefore necessary to establish an analysis framework capable of independently deriving protection variables, setpoints, and actuation logic that reflect the reactor's specific neutronic and thermal-hydraulic characteristics.

Development of protection logic requires quantifying the relationship between measurable quantities, including power, flow rate, pressure, and temperature, and the actual thermal margin within the core. The minimum departure from nucleate boiling ratio (MDNBR) depends not only on total power but also on assembly-wise and axial power distributions; therefore, core-average quantities alone are insufficient to identify the limiting channel and axial location. A dedicated calculation tool is also required to evaluate the thermal margin of numerous three-dimensional power distributions rapidly and consistently for protection-system design.

In this study, a representative-channel thermal-hydraulic analysis code was developed in MATLAB to calculate MDNBR, PCT, and PFT from a three-dimensional core power distribution comprising 26 axial nodes and a 19×19 lateral grid. The 241 fuel assemblies were represented by 482 channels corresponding to average and hot fuel rods, and flow redistribution under a common pressure-drop condition was coupled with coolant and fuel-rod thermal analyses. Numerical consistency was assessed through power, mass, and energy conservation and radial-mesh convergence, while the limiting hot channel at the minimum-MDNBR condition was

modeled in MARS-KS to benchmark coolant and wall temperatures and MDNBR.

2. Development of the Representative-Channel Thermal-Hydraulic Analysis Code

2.1 Three-dimensional power mapping and channel representation

The developed code uses a three-dimensional core power distribution consisting of 26 axial nodes and a 19×19 lateral grid as input. After removing the zero-power padding at the outer boundary, nodal powers for 241 fuel assemblies were extracted from the 17×17 region. Each assembly was divided into an average channel representing 235 average fuel rods and a hot channel representing one hot fuel rod, resulting in 482 parallel channels. The power $Q_{a,i}$ assigned to axial node i of assembly a was distributed using the hot-pin factor F_{hot} as given in Eqs. (1) and (2).

$$P_{a,i}^{avg} = \frac{Q_{a,i}}{N^{avg} + N^{hot}F_{hot}} \quad (Eq. 1)$$

$$P_{a,i}^{hot} = F_{hot}P_{a,i}^{avg} \quad (Eq. 2)$$

where $N^{avg} = 235$, $N^{hot} = 1$, $F_{hot} = 1.1$. This decomposition preserves both the assembly power and the total core power.

2.2 Hydraulic and heat transfer models

The total core flow rate and core inlet temperature were fixed at 20,900 kg/s and 290.6 °C, respectively. The flow rate in each representative channel was iteratively calculated to satisfy both total mass conservation and a common pressure-drop condition.

$$\sum_{k=1}^{482} N_k \dot{m}_k = \dot{m}_{core}, \quad \Delta P_1 = \Delta P_2 = \dots = \Delta P_{482} \quad (Eq. 3)$$

The channel pressure drop comprised frictional, inlet/outlet form-loss, and gravitational-head components, and the friction factor was calculated using the Colebrook correlation. The coolant temperature was obtained by first calculating enthalpy from the cumulative heat input, as given in Eq. (4), and then converting the enthalpy to temperature.

$$h_i = h_{i-1} + \frac{Q_i}{\dot{m}} \quad (Eq. 4)$$

where $Q_i, h_i, \dot{m}$ denote the heat transferred to the i th node, enthalpy, and mass flow rate, respectively, for a given channel. In each axial cell, the steady-state radial heat-conduction equation for the fuel-gap-cladding system was solved using the finite-difference method. The fuel and cladding were discretized into 10 and 5 radial nodes, respectively, and their properties were updated with temperature. The Dittus-Boelter correlation [1], Bergles-Rohsenow criterion [2], and Jens-Lottes correlation [3] were applied for single-phase forced convection, onset of nucleate boiling, and post-ONB heat transfer, respectively. Axial heat conduction and cross-flow were neglected.

In the nucleate-boiling region, the heat-transfer coefficient can be derived from the Jens-Lottes correlation in Eq. (5), as shown in Eq. (6). Because it is proportional to the fourth power of wall superheat, strong feedback between wall temperature and the heat-transfer coefficient can cause oscillations during iterative convergence of the temperature field. To improve numerical stability, the larger of the Dittus-Boelter and Jens-Lottes coefficients was selected and relaxed according to Eq. (7). Based on a sensitivity analysis of the relaxation factor of $\alpha = 0.02$ was used in this study.

$$T_w - T_{sat} = 25 \left(\frac{q''_{JL}}{10^6} \right)^{\frac{1}{4}} \exp \left(-\frac{P}{6.2} \right) \quad (Eq. 5)$$

$$h_{Jens} = \frac{10^6}{25^4} \exp \left(\frac{4P}{6.2} \right) \frac{(T_w - T_{sat})^4}{T_w - T_b} \quad (Eq. 6)$$

$$h^{n+1} = \exp[\alpha \times \ln h_{target}^n + (1 - \alpha) \ln h^n] \quad (Eq. 7)$$

2.3 Thermal-margin evaluation

The equilibrium quality at each axial location was calculated from coolant enthalpy. The critical heat flux was evaluated using the 2006 CHF lookup table [4], with pressure, mass flux, and equilibrium quality as inputs, together with a hydraulic-diameter correction. The local DNBR and core minimum DNBR were

defined as follows.

$$DNBR_{i,k} = \frac{q''_{CHF,i,k}}{q''_{actual,i,k}},$$

$$MDNBR = \min_{i,k} (DNBR_{i,k}) \quad (Eq. 8)$$

For each three-dimensional power-distribution case, the code reports MDNBR, PCT, and PFT, together with the corresponding assembly, channel, and axial elevation.

3. Verification and Results

3.1 Conservation and mesh convergence

To assess the numerical consistency of the code, power-mapping, mass-conservation, and energy-conservation errors were evaluated for all 1,728 power distributions. As shown in Table 1, the errors were at the level of numerical precision, confirming the numerical consistency of the calculation.

Table 1. Maximum conservation errors for all power-distribution cases

Verification quantity	Maximum error over all cases
Input-to-channel power mapping error [%]	2.218e-13
Mass conservation error [%]	2.490e-13
Energy conservation error [%]	1.741e-13

Radial-mesh sensitivity was evaluated for the three power distributions with the lowest MDNBR. As shown in Table 2, MDNBR, PCT, and their limiting channels remained unchanged for all three cases, while PFT showed no significant discrepancy. The radial temperature distributions in Fig. 1 were also nearly identical; therefore, considering computational cost, 10 fuel nodes and 5 cladding nodes were used in the subsequent calculations.

Table 2. Radial mesh-sensitivity results for three lowest MDNBR cases

Mesh (fuel/cladding)	MDNBR	Channel_ MDNBR	PCT (°C)	Channel_ PCT	PFT (°C)	Channel_ PFT
Current(10/5)	3.03821180	328	346.509762	275	1928.140319	328
Refined(20/10)	3.03821180	328	346.509762	275	1926.398238	328
Fine(40/20)	3.03821180	328	346.509762	275	1926.331370	328

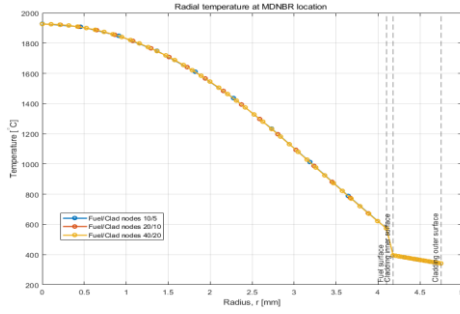


Fig. 1. Radial temperature distributions at the MDNBR location for different radial meshes.

3.2 Benchmark of the limiting hot channel against MARS-KS

The three power-distribution cases with the lowest MDNBR were selected to compare the coolant and CHF calculations in the limiting hot channel. In all three cases, MDNBR occurred in Channel 328. The 26-node axial heat-flux distribution, flow area, hydraulic diameter, inlet conditions, and mass flow rate of this channel were modeled in MARS-KS [5]. Instead of explicitly modeling the fuel, MARS-KS used a heat structure to transfer the nodal heat fluxes to the coolant, and the resulting coolant enthalpy, coolant temperature, and wall temperature were compared with the MATLAB results.

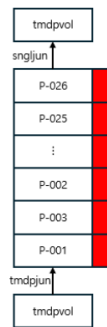


Fig. 2. MARS-KS nodalization of the limiting hot channel

The coolant and wall temperature profiles for one case are shown in Fig. 3. Across the three cases, the mean absolute errors in coolant and wall temperatures were about 0.409°C and 1.900°C, respectively.

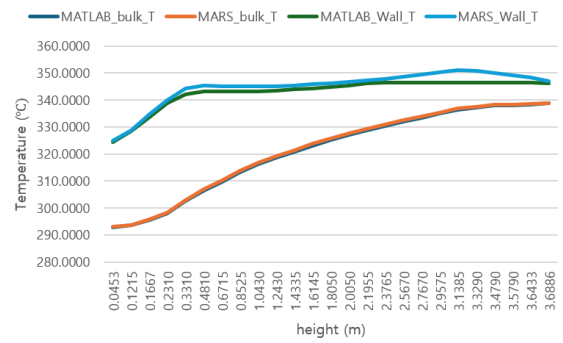


Fig. 3. Comparison of axial coolant and wall temperature profiles between MATLAB and MARS-KS for one case

To eliminate differences in the CHF models, the pressure, mass flux, and quality calculated by MARS-KS were applied to the same CHF lookup table used in MATLAB. As shown in Table 3, the MDNBR values from MARS-KS and MATLAB differed by approximately 0.65% for all three cases, while both codes identified the same limiting axial location at $z = 0.481$ m.

Table 3. Comparison of MDNBR between MATLAB and MARS-KS using the common CHF lookup-table

Case	MATLAB MDNBR	MARS-KS MDNBR	Relative Difference [%]	Limiting Location [m]
1	3.038212	3.057946	+0.650	0.481
2	3.038334	3.058062	+0.649	0.481
3	3.038561	3.058298	+0.650	0.481

In terms of computational cost, the developed MATLAB code required 1,916.4 s of wall-clock time to analyze all 1,728 three-dimensional power-distribution cases, corresponding to approximately 1.11 s per case. For reference, the MARS-KS single-channel calculations required an average wall-clock time of 1.03 s per case.

However, because the MARS-KS comparison was limited to a single limiting channel, verification of flow redistribution among the representative channels was outside the scope of this comparison.

4. Summary and Conclusions

In this study, a MATLAB-based representative-channel thermal-hydraulic analysis code was developed to rapidly calculate fuel-pin-level MDNBR using a three-dimensional core power distribution consisting of 26 axial nodes and a 19×19 lateral grid. The 241 fuel assemblies were represented by 482 channels corresponding to average and hot fuel rods, and channel flow rates were distributed to satisfy the

fixed total core flow rate and common pressure-drop condition. The code also coupled energy conservation, radial heat conduction through the fuel-gap-cladding system, onset of nucleate boiling, and critical heat flux calculations to identify the limiting channel and axial location for MDNBR.

The maximum power-mapping, mass-conservation, and heat-balance errors for all 1,728 power distributions were $2.218 \times 10^{-13}\%$, $2.490 \times 10^{-13}\%$, $1.741 \times 10^{-13}\%$, respectively. Radial-mesh sensitivity showed that MDNBR, PCT, and their limiting channels remained unchanged as the mesh was refined from 10/5 to 40/20, while the maximum PFT change was limited to approximately 1.81 °C. In addition, MARS-KS modeling of the limiting hot channels for the three lowest-MDNBR power distributions produced MDNBR values within approximately 0.65% of the MATLAB results and predicted the same limiting location. The developed code can therefore rapidly evaluate thermal margin for a range of three-dimensional core power distributions and can serve as a fundamental analysis tool for reducing dependence on intellectual property associated with existing protection-system algorithms. Future work will improve the thermal-hydraulic models and accumulate results for diverse power distributions, providing training data for an artificial-intelligence model that rapidly predicts MDNBR from power distributions.

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