Flow Blockage Modeling and Its Impact on LOCA Safety Assessed by FAMILY Code

Joosuk Lee[a*], Taewan Kim[b], Young Seok Bang[a]
[a]*Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yusong-gu, Daejeon, 305-338, Korea*
[b]*Incheon National University, 119 Academy-ro, Yeonsu-gu, Incheon, Korea*
[*]*Corresponding author: jslee2@kins.re.kr*

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1. Introduction

Zirconium alloy fuel cladding has the potential to undergo deformation and rupture during a large break loss-of-coolant accident (LBLOCA) in a typical nuclear power plant [1]. Such occurrences can impact fuel performance during LOCA due to changes in fuel geometry and heat source arrangement. As fuel cladding deformation occurs, there can be alterations in hydraulic volumes through the blockage process, leading to changes in the amount of coolant flowing through the fuel assembly. From a fuel pellet perspective, there exists a chance that fragmented and cracked fuel pellets might be relocated axially and radially within the deformed cladding [2]. This pellet relocation can modify the distribution of local heat sources.

Simultaneously, there's a potential for highly deformed claddings within a fuel assembly to come into contact with each other. This cladding contact has been observed in previous LOCA experimental programs such as REBEKA, MRBT, and PHEBUS [1,3]. The contact between claddings could potentially impact the heat transfer from the cladding to the coolant.

Traditionally, the current licensing methodology for LOCA, as developed by utilities and also audit methodologies, does not extensively account for these phenomena [4]. This is primarily because the thermal-hydraulic system codes utilized, such as RELAP and MARS-KS, possess limitations when it comes to accurately simulating these blockage processes.

Recently, KINS has been actively developing the FAMILY computer code, an integrated tool combining the thermal-hydraulic MARS-KS and the fuel performance FRAPTRAN code [5-7]. The FAMILY code has been updated to model these blockage phenomena. In this paper, we introduce the developed models for blockage analysis and preliminarily evaluate their effects on fuel performance during LOCA in APR1400 reactor.

2. Models for Blockage Analysis

2.1 Hydraulic volume change and form loss

The thermal-hydraulic volume change in FAMILY is formulated by incorporating the concept of porosity (γ), which is treated as a variable responsive to cladding deformation. The parameter γ is integrated into the governing equations for mass, energy, and momentum (2 fields 6 equations). The definition of γ is as follows:

$$\gamma = 1.0 - \frac{L}{V}\left[\pi\left(r_{clad}^2 - r_{clad,o}^2\right)\right] \tag{2-1}$$

Where L and V stand for the axial length and initial volume at the deformed node, respectively, while r_{clad} and $r_{clad,o}$ represent the deformed and initial radius of the fuel cladding. Verification of the volume change model can be found in reference [8].
Additionally, the analysis considers the form loss attributed to fuel cladding deformation. FAMILY employs a form loss correlation, represented as follows, which is applied in this analysis:

$$[K_E, K_C]^T=[(1-B)^{2.0}, 0.45(1-B)]^T \tag{2-2}$$

Here, K means the loss coefficient, with subscripts E and C denoting expansion and contraction, respectively. The variable B represents the ratio of the flow area in comparison to the original undeformed state. This coefficient is incorporated as an additional factor specifically for node with the highest deformed cladding.

2.2 Cladding contact

Contact between deformed fuel claddings within a fuel assembly is a plausible scenario. Authors have previously developed a model for contact area fraction (*CAF*) based on empirical observations from MRBT, PHEBUS, and REBEKA bundle test results [9]. The developed model is depicted in Fig. 1. The *CAF* is defined by the following expressions:

$$\begin{aligned} &CAF = 0 && (hs < 0.2) \\ &CAF = -0.04 + 0.575 \times hs && (hs \geq 0.2) \end{aligned} \tag{2-3}$$

Here, *CAF* denotes the contact area fraction (dimensionless), and *hs* represents the hoop strain of the cladding (dimensionless). The standard deviation (σ) of the model is 0.135.

2.3 Fuel relocation

A slightly adjusted fuel relocation model, developed by Quantum Technology (QT), is employed in this analysis [10]. Authors have additionally developed

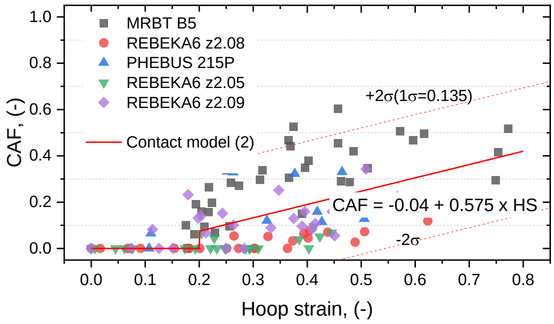

Fig. 1. Contact area fraction (*CAF*) as a function of cladding hoop strain (*hs*) [9].

the packing fraction for fine fragments [11], which is used to estimate the packing fraction when combined with coarse fragments. The developed model for the packing fraction of fine fragments is as follows.

$$x_s = 1.0 - [1.0 - (4.979 \times 10^{-9}(BU)^{4.427}/D_{PO})]^2 \qquad (2\text{-}4)$$

Here, x_s represents the mass fraction of small fragments, *BU* means the pellet average fuel burnup (MWd/kgU), and D_{po} corresponds to the pellet diameter under cold conditions (mm). The standard deviation of the packing fraction model is 0.041.

3. Modeling for LOCA Analysis

A LBLOCA safety analysis was conducted on the 16x16 PLUS7 fuel with ZIRLO cladding in the APR1400 reactor. The initial conditions of the fuel rods prior to the accident were determined using the FRAPCON4.0P1 fuel performance code [12]. The transient behaviors of the fuel during the LOCA were investigated using the FAMILY code [5], incorporating the blockage models outlined in section 2. For the LOCA assessment, the APR1400 reactor core was partitioned into a hot channel and an average channel. Within the hot channel, a single hot fuel rod was allocated and divided into 40 evenly spaced axial nodes.

The blockage models are primarily calculated on the cladding strain of the hot rod. However, the average strain of fuel claddings in the coplanar hot channel must be lower than that of the hot rod, due to the deformation randomness and lower fuel power, etc. In this study, it is assumed that the average coplanar cladding strain in a fuel assembly is approximately 0.612 times that of the hot rod. This value is drawn from experimental observations including MRBT, PHEBUS, and REBEKA outcomes. The average strain is then employed to assess parameters such as porosity (γ), form loss ($K_{E,C}$), and the flow area ratio (*B*).

In the calculation of the equivalent hydraulic diameter (D_e) for the hot rod subchannel, the cladding contact fraction, as defined in equation (2-3), is subtracted from the wetted perimeter calculation.

Regarding cladding contact, it's assumed that no heat transfer occurs in the contacted area. This assumption is partly based on the fact that convective heat transfer is greatly restricted due to minimal coolant passage through this region. While conductive heat transfer between contacted fuel rods is possible, but this analysis disregards it due to the limited capability of the FAMILY code. To implement this heat transfer assumption, the heat transfer coefficient at the contacted cladding node is linearly reduced in accordance with the contact fraction.

The LOCA analysis was conducted at a fuel burnup of 30 MWd/kgU, as this burnup yields the most significant effects from a fuel relocation perspective [11]. The local peak fuel power prior to the accident initiation was set at 14.1 kW/ft. Limitations on cladding deformation due to adjacent fuel rod contact were enforced. When the cladding hoop strain at a particular axial node reached 78.6 % (based on the cladding's mid plane), plastic deformation at the node ceased and the deformation propagated axially. The cladding burst evaluation has conducted to the strain-based NUREG-0630 fast ramp burst criterion [13]. The Carthcart-Pawel oxidation model was employed to quantify the equivalent cladding reacted (CP-ECR) [14].

An uncertainty analysis encompassing fuel and thermal-hydraulic uncertainties was also undertaken. Detailed uncertainty parameter descriptions are available in reference [15]. Specifically, the uncertainties of packing fraction and contact area fraction were considered also. A non-parametric statistical approach was used to quantify the uncertainties in peak cladding temperature (PCT) and ECR. Employing a simple random sampling method, 124 inputs were generated for subsequent calculations.

4. Fuel Performance

4.1 Verification

The verification of blockage models within the FAMILY code was carried out through a postulated increase in cladding strain during a null transient condition in APR1400 before LOCA. Specifically, the cladding strain was linearly increased from 0 to 0.7 over a period of 50 seconds at the axial midpoint of the fuel rod (#21 node among 40), maintaining this strain until 100 seconds. Fig. 2 illustrates the evolution of the prescribed cladding strain (ε_θ) and the resulting alterations in equivalent diameter (D_e), porosity (γ), flow area ratio (*B*), and form loss ($K_{E,C}$).

In the depicted graph, the D_e steadily decreases from 0.0125 m to 0.00125 m. A slight uptick in D_e at around 11.2 seconds is attributed to the reduction in wetted perimeter due to the initiation of cladding contact, as evidenced in Fig. 2(c).

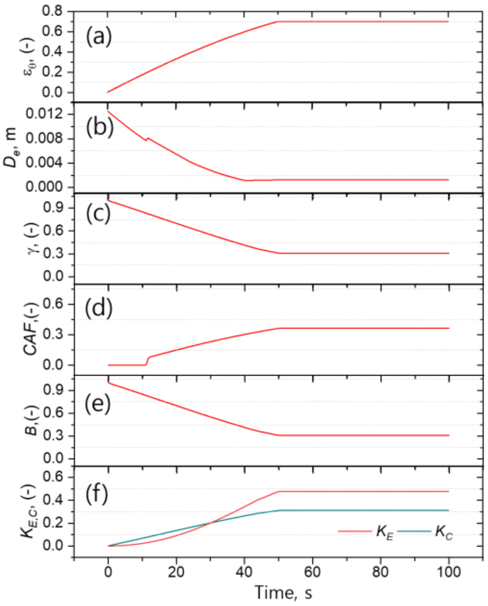

Fig. 2. Evolution of (a) cladding hoop strain (ε_θ), (b) equivalent hydraulic diameter (D_e), (c) porosity (γ), (d) contact area fraction (CAF), (e) flow area ratio (B), (f) form loss coefficient of expansion (K_E) and contraction (K_C)

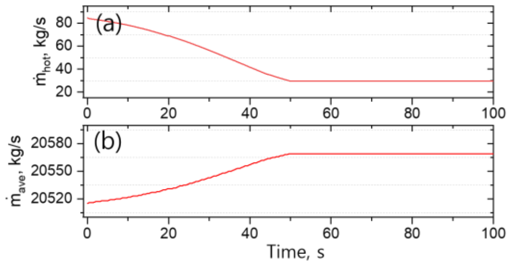

Fig. 3. Change of mass flow rate at (a) hot channel ($\dot{m}_{hot}$) and (b) average channel ($\dot{m}_{ave}$)

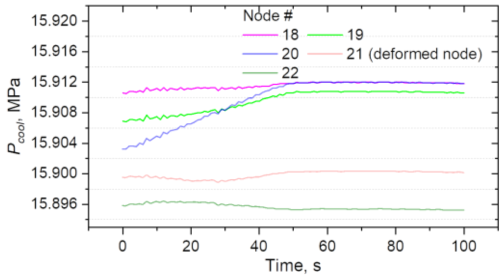

Fig. 4. Change of hot channel coolant pressure (P_{cool}) at around deforming fuel node (#21)

The γ also experiences a decline, changing from 1.0 to 0.309. Similarly, B undergoes a corresponding reduction, from 1.0 to 0.309, the same as the behavior of γ. K_E and K_C increases from 0 to 0.478 and from 0 to 0.311, respectively. The evaluation of γ, B, K_E, and K_C is based in the average coplanar cladding strain within the hot channel.

Fig. 3 illustrates the alterations in mass flow rate within a hot channel ($\dot{m}_{hot}$) and an average channel ($\dot{m}_{ave}$). The mass flow rate within the deformed hot channel experiences a reduction from 84.7 kg/s to 29.5 kg/s. However, this decrease is offset within the average channel to maintain a constant total mass flow rate. Fig. 4 presents the changes in coolant pressure. A minor increase in coolant pressure (0.004~0.009 MPa) is observed at the front of the deformed node (#19, #20), while the pressure changes at the deformed node (#21) is minimal. Based on these analyses, it can be concluded that the blockage models in the FAMILY code appear to perform adequately.

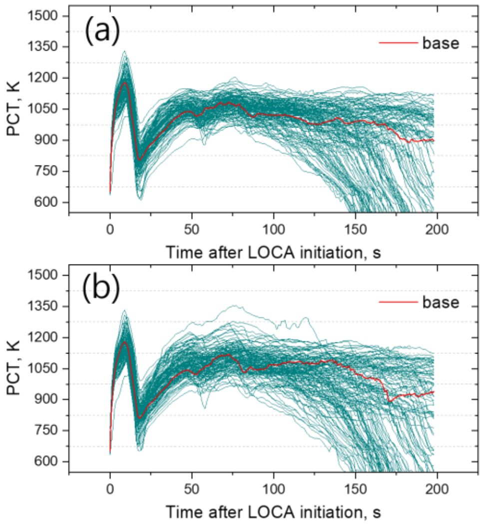

Fig. 5. Evolution of 124 PCT curves during LOCA, evaluated with (a) no blockage models and (b) blockage models

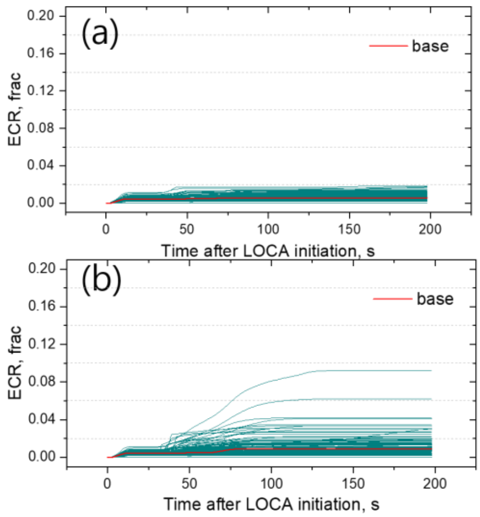

Fig. 6. Evolution of 124 CP-ECR curves during LOCA, evaluated with (a) no blockage models and (b) blockage models

4.2 Fuel performance during LOCA

Fig. 5 displays the evolution of peak cladding temperature (PCT) during the LOCA. In cases where the blockage models are excluded—as illustrated in Fig. 5(a)—the base case values for blowdown and reflood

PCT are 1178.1 K and 1083.3 K, respectively. Among the 124 evaluated cases, the third-highest blowdown and reflood PCT values are 1297.4 K and 1174.3 K, respectively.

When the blockage models are incorporated, as shown in Fig. 5(b), the base case blowdown and reflood PCT values are measured at 1178.5 K and 1118.6 K, respectively. The third-highest blowdown and reflood PCT values are 1298.5 K and 1269.9 K. These outcomes show the notable impact of blockage models, particularly in terms of the third-highest reflood PCT, with an increase of 95.6 K. Moving to Fig. 6, it presents the evolution of equivalent cladding reacted (CP-ECR) during the LOCA period. In cases where blockage models are not considered, as illustrated in Fig. 6(a), the base case CP-ECR is 0.005. Among the 124 evaluated cases, the highest ECR observed is 0.018. Meanwhile, as the blockage models are included, depicted in Fig. 6(b), the base case CP-ECR is 0.009, and the highest value reaches 0.092. These results emphasize that blockage models can also lead to a strong increase in CP-ECR.

5. Summary

Blockage models in a fuel assembly have been developed and successfully integrated into the FAMILY computer code. These models have been utilized to perform preliminary LBLOCA analyses, yielding the following findings:

A set of blockage models, encompassing thermal-hydraulic volume change, form loss, cladding contact, and fuel relocation with cladding deformation, has been successfully developed, integrated, and verified in the FAMILY code.

The factorization of these blockage models has led to pronounced impacts on fuel performance during the LOCA. Particularly, notable increases have been observed in reflood peak cladding temperature (PCT) and equivalent cladding reacted (ECR).

This study shows the significant influence of blockage models on fuel performance metrics. Further refinement of models and more comprehensive analyses might be necessary to get an understanding of these effects

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