Transactions of the Korean Nuclear Society Virtual Autumn Meeting
October 21-22, 2021

Uncertainty of Cladding Contact on Fuel behavior during LOCA Environments

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1. Introduction

Zirconium alloy cladded fuel rods in a given hot assembly can be deformed excessively and come into contact each other during a loss-of-coolant accident (LOCA) in light water reactors. This contact phenomenon is clearly observed at the past LOCA experimental programs conducted from late 70's to early 80's such as REBEKA, MRBT, PHEBUS, and so on [1,2]. Cladding contact can affect the heat transfer from fuel to coolant by a convective and also a conductive heat transfer.

In a safety point of view, cladding contact phenomenon has not been highlighted because peak cladding temperature (PCT) during LOCA was not observed in this highly deformed region. The lower cladding temperature in this region is due to the lower gap conductance caused by the formation of larger gap between cladding and fuel pellet. However, it is expected that fuel performance behaves differently when fuel relocation occurs in the deformed region. Due to the outward relocation of fragmented and pulverized fuel pellet, gap conductance will be increased greatly. Heat source in a deformed cladding region will be increased also through the axial relocation.

From this point of view authors have established two cladding contact models [3]. Preliminary analysis with these models shows the potential for cladding temperature rise due to cladding contact. In this paper, the impact of cladding contact has been evaluated by uncertainty quantification. FAMILY computer code is used for fuel performance analysis [4].

2. Cladding contact model

Fig.1 shows developed two cladding contact models [3]. Contact model ① is an ideal deformation model, which means the surrounding fuel rods deform exactly the same way with the center rod. The initial cladding contact with surrounding rods occurs when cladding hoop strain reaches 39.3 % (based on cladding mid plane), and complete contact expected as 78.6 % strain attained in a 16x16 PLUS7 fuel assembly. Complete contact means complete blockage. But, this is too conservative to be used. Thereby maximum contact area fraction (CAF) was limited to 62 % based on the experimental observation results [3].

Contact model ② was developed based on the experimental results. The data are obtained from MRBT, PHEBUS and REBEKA test results. Because the analysis uses low-resolution photos, some errors are expected. Nevertheless, it shows that cladding contact starts at about 20 % hoop strain and increases with further straining. The following CAF correlation is developed with a linear relationship assumption.

$$CAF(hs) = 0 \qquad (hs < 0.2)$$
$$CAF(hs) = -0.04 + 0.575 \times hs \qquad (hs \geq 0.2) \quad (1)$$

CAF = contact area fraction (unitless)
hs = hoop strain of cladding (unitless)
σ (standard deviation) = 0.135

Cladding contact showed relatively strong influences on the peak cladding temperature (PCT). Fig. 2 shows PCT evolution during LOCA. When the contact model ① was used, the reflood PCT increased by 67 K compared to the relocation case. As the cladding contact model ② was used, the reflood PCT increased by 24 K. In this study, contact model ② was used for the uncertainty quantification because it is a realistic and established based on the experimental observation.

3. Analysis Details

3.1 Heat transfer assumption

Regarding the heat transfer in the contacted cladding area, following two assumptions were made. 1) Heat transfer in the contacted cladding area is not assumed. 2) The circumferential cladding temperature is assumed to be uniform despite of cladding contact.

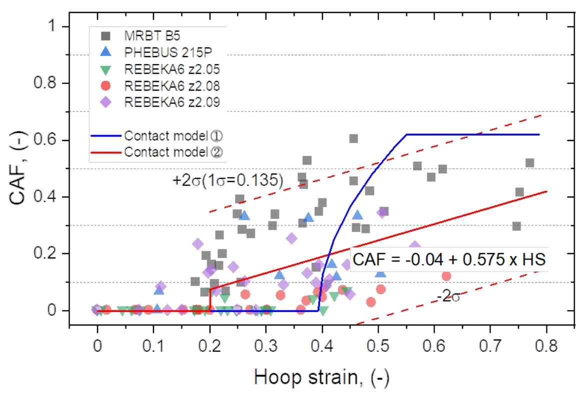

Fig. 1. Developed cladding contact area fraction (CAF) model as a function of cladding hoop strain (HS) [3].

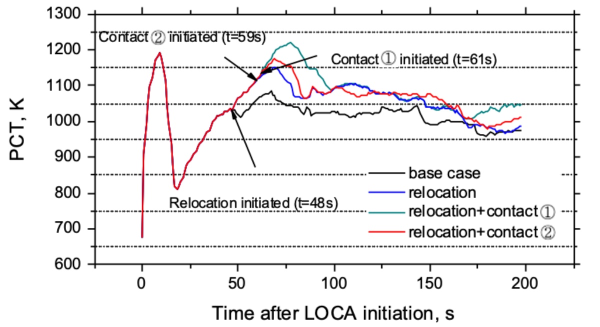

Fig. 2. PCT evolution during LOCA in APR1400 after factorization of cladding contact model with fuel relocation [3].

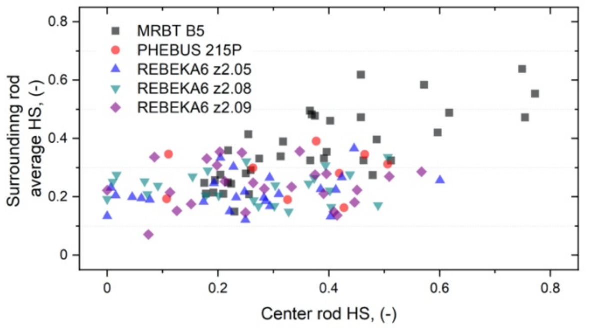

Fig. 3. Hoop strain (HS) data between center rod and surrounding rods (average).

Assumption 1) is partly justified that the convective heat transfer is very limited because water or steam coolant almost can't pass through this area. Conductive heat transfer will be possible if cladding temperatures between analyzing hot rod and surrounding rods are different. Under the fuel relocation condition, cladding temperature will be affected by the hoop strain of cladding. Thus distribution of hoop strain within a deformed fuel bundle during LOCA is important to the conductive heat transfer. Fig. 3 shows the relationship between hoop strain of center rod and surrounding rods. These data also obtained from MRBT, PHEBUS and REBEKA bundle test results [1,2]. It clearly shows that the hoop strain of surrounding rods increases with the center rod to a similar level. This means the cladding temperature between center rod and surrounding rods will not be much different. Therefore, in this study we do not consider the conductive heat transfer. However, as larger amounts of scatter are existed, these effects need to be confirmed with further studies. For the implementation of heat transfer in the contacted area, heat transfer coefficient (HTC) in the contact node is reduced linearly in accordance with the contact fraction. Regarding assumption 2), this will introduce somewhat less conservative result on the PCT perspective.

3.2 LOCA modeling

LOCA safety analysis has been performed in APR1400 PWR plant with 16x16 ZIRLO cladding fuel. Design parameters of fuel rod, operating conditions, and base irradiation power history are obtained from Ref. [5]. Transient fuel behaviors for a LOCA period are analyzed by FAMILY computer code. FAMILY is an integrated computer code between FRAPTRAN and MARS-KS [4]. Reactor core is divided into one hot channel and one average channel, and single fuel rod is allocated in the hot channel. Core is axially divided into 40 evenly spaced nodes. Analyzed fuel burnup is 30 MWd/kgU (rod average) and maximum peak fuel power of 14.5 kW/ft is assumed before accident initiation. In the LOCA analysis following model and assumptions are used.

- Burnup dependent packing fraction model developed by KINS is used for the simulation of fuel relocation [6].

$$PF(bu) = 0.68 + 8.58\times10^{-4} \times bu \qquad (2)$$

PF = packing fraction (unitless)
bu = segment average fuel burnup (MWd/kgU)
σ (standard deviation) = 0.0483
Burnup range = 0~90 MWd/kgU

- Maximum cladding hoop strain limit is set to 78.6 %. If cladding strain reaches this limit, axial propagation of deformation is assumed.
- FRACAS cladding deformation model and strain based NUREG-0630 cladding burst criterion are used.

3.3 Uncertainty analysis

For the fuel performance evaluation during LOCA, a best-estimate plus uncertainty quantification (BEPU) methodology has been used. Many uncertainty parameters related to the fuel and thermal-hydraulics (TH) are taken into account. Details on these parameters can be founded in authors' previous work [7]. In this study, cladding contact model ②, described in Fig.1 and packing fraction model described in section 3.2 are added as additional uncertainty parameters. Uncertainty on these parameters are set as $\pm2\sigma$ with uniform probability density function. Uncertainty analysis has been done at fuel burnup of 30 MWd/kgU. Effects of cladding contact are investigated with and without fuel relocation. Thereby, following 4 different sets of 124 inputs for running of FRAPCON and FAMILY are prepared; (1) without cladding contact and relocation, (2) with cladding contact but without relocation, (3) without cladding contact but with relocation and (4) with cladding contact and relocation.

4. Results

The impact of cladding contact is investigated with and without fuel relocation. Fig. 4 shows the results of 124 PCT evolutions during LOCA without fuel relocation. As can be seen in Fig. 4, effects of cladding contact on the PCT evolution are very limited. In the base case, the blowdown and reflood PCT are evaluated at 1190.5 K and 1084.7 K, respectively, and they do not change after the cladding contact model is activated. Without cladding contact, the third highest PCT in the blowdown and reflood periods are 1299.6 K and 1173.1 K, respectively. With cladding contact model, the third highest PCT in the blowdown and reflood periods are evaluated at 1299.6 K and 1176.0 K, respectively. The blowdown PCT is the same, and the difference between reflood PCT is also very small, less than 3 K. This means if we consider the error due to the time step difference during numerical analysis, the impact of cladding contact is almost nothing.

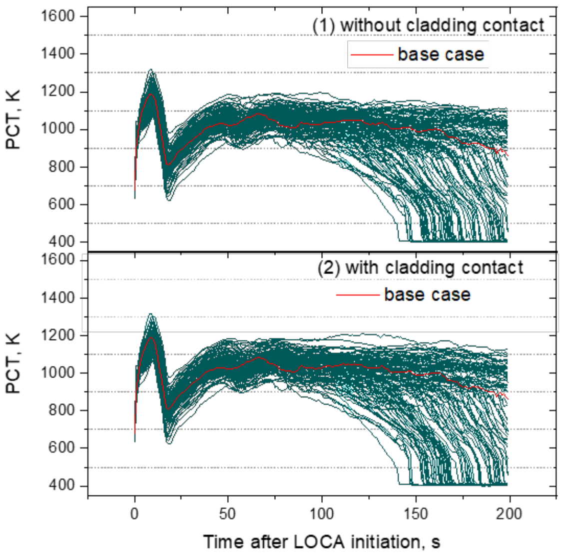

Fig. 4. PCT evolutions with and without cladding contact. Fuel relocation is not considered. Fuel burnup is 30 MWd/kgU.

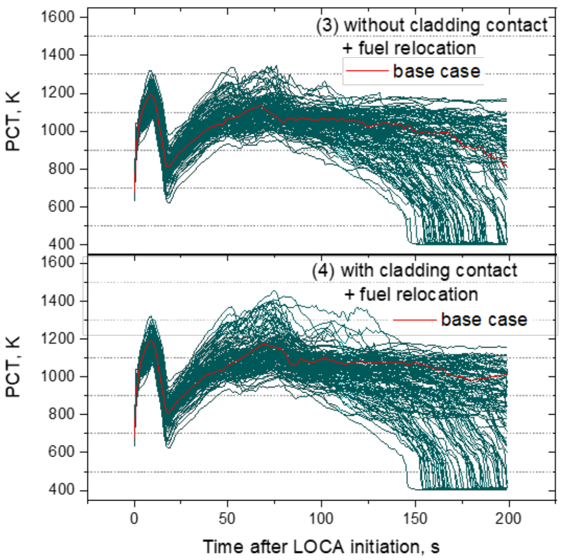

Fig. 5. PCT evolutions with and without cladding contact. Fuel relocation is considered. Fuel burnup is 30 MWd/kgU.

Meanwhile, as the fuel relocation is involved, cladding contact shows relatively strong impacts, especially reflood period. Fig. 5 shows the results of 124 PCT evolutions during LOCA. In the base case, the reflood PCT is evaluated at 1151.5 K, but changes to 1170.0 K as the cladding contact model is activated. Without cladding contact, the third highest PCT in the blowdown and reflood periods are 1299.6 K and 1338.7 K, respectively. Comparing with the analysis results in Fig. 4, it can be seen that the fuel relocation can induce 165.6 K higher reflood PCT. In this circumstance, as cladding contact is considered additionally, the third highest reflood PCT is increased to 1404.7 K. This implies the cladding contact can induce about 66 K higher reflood PCT. Analyzed results are summarized in Table 1.

Table 1. Summary of PCT in 124 SRS runs

	$PCT_{Blowdown}$, K	$PCT_{Reflood}$, K	Δ[1]
Third highest			
(1)	1299.6	1173.1	-
(2)	1299.6	1176.0	2.9
(3)	1299.6	1338.7	165.6
(4)	1299.6	1404.7	231.6
Base case			
(1)	1190.5	1084.7	-
(2)	1190.5	1084.7	0
(3)	1190.5	1151.5	66.8
(4)	1190.5	1170.0	85.3

[1] Difference of reflood PCT compared to case (1)

5. Summary

The impact of cladding contact on fuel performance during the LOCA period was assessed by uncertainty quantification. Following results can be drawn preliminary.

- If fuel relocation is not taken into account, the effects of cladding contact on peak cladding temperature during LOCA is very limited.
- If fuel relocation is considered, cladding contact can induce relatively strong influence on the reflood PCT. In this study, these two models induced about 231.6 K reflood PCT rise. Specifically, cladding contact and fuel relocation induced about 66 K and 165.6 K PCT rise, respectively.

In this study, the importance of fuel relocation and cladding contact for the reflood PCT behavior was confirmed. Therefore, more detailed studies such as detailed model establishment and development of analysis methodology should be conducted.

ACKNOWLEGEMENT

The preparation of this paper was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KOFONS), granted financial resource from the Nuclear Safety and Security Commission (NSSC), Republic of Korea (No. 1805004-0118-SB110).

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