Sensitivity Analysis of Material Property Correlations in FRAPCON and FRAPTRAN with Cladding Material Change

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1. Introduction

There is a trend to develop a new fuel cladding with a high burn-up capability at home and abroad for efficiently operating nuclear power plants. In order to deal with the needs of nuclear industries, Korea Institute of Nuclear Safety (KINS) has conducted a research project to examine the safety of a new type of cladding material under normal and postulated accident conditions. Although no fuel claddings (> 60,000 KWd/kgU) have been licensed in South Korea, a major candidate is HANA-6 as a fuel cladding having the high burn-up performance. According the background, the research project has studied various aspects of HANA-6 cladding in a viewpoint of the nuclear safety.

One of the purposes in the research project is to verify the integrity of HANA-6 cladding under any circumstances. For achieving the goal, physical models or material property correlations are firstly identified as replacing the current cladding with HANA-6 and the models and correlations changed have been determined in the previous study [1]. Then, it is numerically validated to use the models and correlations because of the cladding change.

The objective of this study is to analyze effects of the physical models and material property correlations of HANA-6 cladding chosen in the previous study [1] on the fuel integrity under steady-state and transient conditions. To achieve this, the models and correlations substituted are applied in FRAPCON and FRAPTRAN, and numerical studies conducted about the safety of the fuel having HANA-6 cladding under the normal and accident conditions using the codes.

2. Previous Study

Specific evaluations for each of the pre-identified models and material property correlations from FRAPCON and FRAPTRAN codes [2-4] with cladding change application by primary researches are conducted based on in-depth expert panel discussion and using proper references including experimental data for HANA-6 cladding [1]. Total 12 out of 18 models and material properties correlation are re-identified as the critical items needs clear modifications for HANA-6 cladding application of FRAPCON and FRAPTRAN codes [1]. Among 12 models and material properties from previous study, cladding density, thermal conductivity, oxide thermal conductivity and radial-direction thermal expansion (See, Table 1) need sensitivity studies to confirm the effect of cladding material change.

Table 1. Status of confirmed material property correlations from FRAPCON and FRAPTRAN codes which need sensitivity studies [1]

No.	Models or Material Property correlations	Confirm	Note
1	Cladding density	No	Sensitivity
2	Cladding thermal conductivity	Yes	Sensitivity Data
3	Cladding oxide thermal conductivity	No	Sensitivity
4	Cladding thermal expansion	Yes	R-direction Sensitivity

3. Sensitivity Analysis

The present study computationally investigates the effects of the material property correlations stated in the previous section on the fuel integrity. Numerical codes for simulating the steady-state and transient condition are FRAPCON 4.0P1 and FRAPTRAN 2.0P1, respectively. The inputs of FRRAPCON and FRAPTRAN codes are based on Halden IFA-650.5 test.

3.1 Halden IFA-650.5 Test

In 2006, Halden IFA-650.5 test was carried out to examine behaviors of a test rod under loss of coolant accident (LOCA) conditions [5]. The test rod was cut from a PWR fuel rod in a commercial reactor and the cladding material was Zircaloy-4 base duplex [5].

3.2 Calculation results

To implement the correlations able to simulate the characteristics of HANA-6 cladding, related subroutines in the FRAPCON and FRAPTRAN are modified. Input decks are prepared employing the irradiation conditions, the designs of test rod, and the steady-state and transient conditions in Halden IFA-650.5. The temperature of the fuel centerline, surface, and cladding inside surface in the simulation results are chosen to compare to the default case using FRAPCON and FRAPTRAN codes.

3.2.1. Cladding density

The density of cladding in FRAPCON and FRAPTRAN is defined by ZircTD as a constant value. Although the density is dependent on the cladding temperature, the default is 6.52 kg/m^3 regardless of the temperature. According to the reference [6], the density of HANA-6 cladding varies from 6.552 to 6.418 kg/m^3 within from 20 to 1200°C. Therefore, ZircTD in FRAPCON and FRAPTRAN are changed as 6.552 and 6.418 kg/m^3. Code simulations with the steady-state and transient conditions are then run.

As compared to the default case having the cladding density of 6.52 kg/m^3, the simulation results of two cases (6.552 and 6.418 kg/m^3) show no differences. The reason of the calculation results in the steady-state is that the thermal analysis scheme in FRAPCON is unrelated time ($\partial T/\partial t = 0$). Thus, the temperature of the fuel centerline and surface, and cladding inside temperature of the two cases in FRAPCON have no differences in comparison with the default case. When it comes to the transient, the variations of the cladding density in the two cases (+0.032 and -0.102 kg/m^3) are too small to make no differences compared to the default case.

3.2.2. Cladding thermal conductivity

The cladding thermal conductivity in FRAPCON and FRAPTRAN codes is defined in CTHCON as a function of cladding temperature. The standard deviation (σk) is 1.01 W/m·K [4]. Fig. 1 indicates the comparison of the cladding thermal conductivity in FRAPCON and FRAPTRAN codes and the experimental data for HANA-6 cladding. The comparison shows that overall trend is similar but the uncertainty band of the cladding thermal conductivity in FRAPCON and FRAPTRAN codes is not able to cover the HANA-6 and also a discrepancy is observed near 1,073 K.

To confirm the effect on the cladding material change, the function of the cladding thermal conductivity in FRAPCON and FRAPTRAN codes is changed to HAHA-6. Since the HANA-6 thermal conductivity is greater than that of CTHCON in FRAPCON and FRAPTRAN codes, the calculation results for cladding inner temperature are reversed (See, Fig. 2). Because of the difference of the cladding inside temperature (about 4.4 K), the fuel centerline and surface temperature also differ about 8 K and 4.4 K respectively.

Unlike the calculation results using FRAPCON, it is not confirmed to the effect of the change in the thermal conductivity in LOCA analysis using FRAPTRAN. Because the cladding temperature distribution is small, the change of the thermal conductivity doesn't affect the calculation of the cladding temperature. Therefore, it is preliminary concluded that an additional analysis for a different accident like a rod ejection accident should be needed to determine the effect of cladding material change. Although the effect on change in the thermal conductivity at the high temperature region is confirmed, the HANA-6 thermal conductivity should be changed according to calculation results using FRAPCON. The difference of the thermal conductivity between CTHCON and HANA-6 at low temperature region (below 1,073 K) is smaller than that at the high temperature region (See, Fig. 1) but the fuel and cladding inside temperature were changed. Therefore, the model for HANA-6 cladding should be needed in FRAPCON and FRAPTRAN codes.

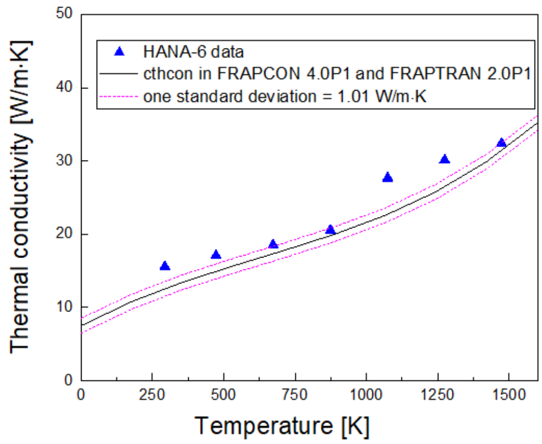

Fig. 1. Comparison of the HANA-6 thermal conductivity with CTHCON in FRAPCON and FRAPTRAN codes

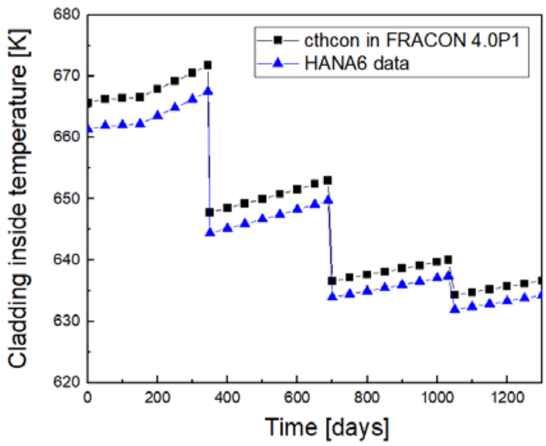

Fig. 2. Comparison of the calculation results using FRAPCON

3.2.3. Cladding oxide thermal conductivity

The cladding oxide thermal conductivity in FRAPCON and FRAPTRAN is defined by ZOTCON as a function of the cladding temperature. Although a new cladding material, HANA-6 is Zircaloy based alloy and it is assumed that the chemical composition of the cladding oxide generated on the outside of the fuel rod is totally equal to other Zircaloy based material like ZIRLO. Due to the fact, it is not able to define the correlation of the cladding oxide thermal conductivity in HANA-6. Instead, the present study conducts numerical calculations in FRAPCON and FRAPTRAN with ZOTCON having the deviation of ±10% already known by the reference [4].

In comparison to the default case, the simulation results under the steady-state and transient conditions show ±3 ~ 4 K and up to ±0.01 K, respectively. The direction of heat transfer at the fuel rod is radial, and the thickness of the cladding oxide is decades of micrometer. According to the facts, it is considered that computational results make some differences and the results in the steady-sate are larger than the transient because the simulation time of the stead-state is much longer than the transient.

3.2.4. Cladding radial direction thermal expansion

The cladding axial and radial direction thermal expansion in FRAPCON and FRAPTRAN codes are defined in CTHEXP as a function of cladding temperature. Unlike other material properties, the uncertainty of the axial and radial direction thermal expansion has not been quantified [4].

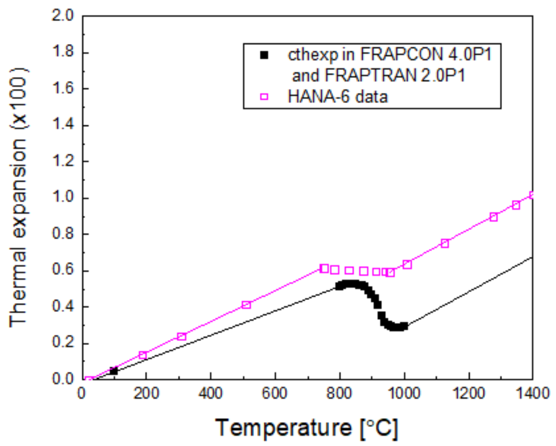

Fig. 3. Comparison of the HANA-6 radial direction thermal expansion with CTHEXP in FRAPCON and FRAPTRAN

Fig. 3 indicates the comparison of the radial direction thermal expansion in FRAPCON and FRAPTRAN codes with experimental data for HANA-6 cladding. It shows that the difference of the radial direction thermal expansion is greater at high temperature range (beyond 1,000 ℃).

To confirm the effect on the cladding material change, the function of the cladding radial direction thermal expansion in FRAPCON and FRAPTRAN codes is changed to HANA-6. Fig. 4 shows that the maximum difference of the fuel centerline and surface temperature is about 20 K and 11 K respectively. It is concluded that increase of the radial direction thermal expansion for cladding induces the decrease of the heat transfer between fuel and cladding because the fuel-cladding gap increases.

Unlike the calculation results using FRAPCON, the results in LOCA using FRAPTRAN are same as the case of cladding thermal conductivity.

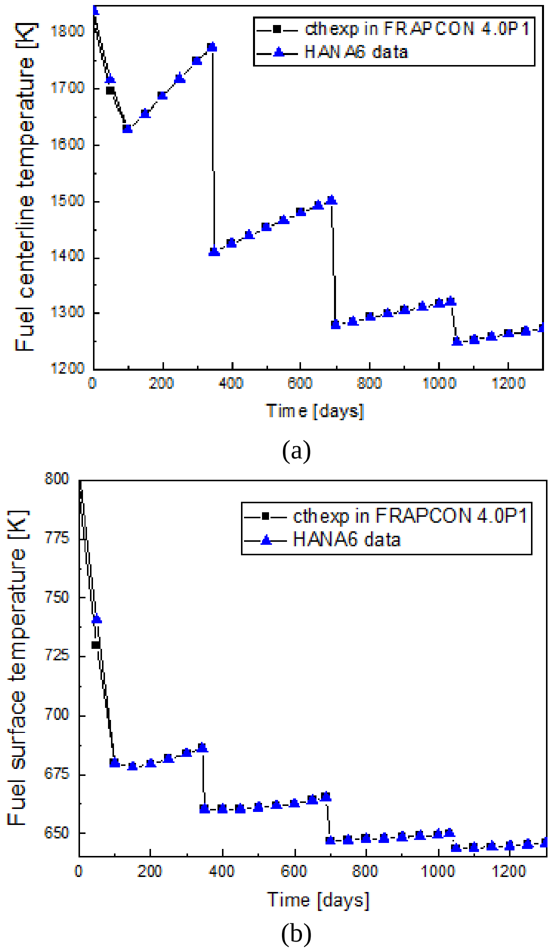

Fig. 4. Comparison of the calculation results using FRAPCON – (a) Fuel centerline temperature; (b) Fuel surface temperature

In FRAPTRAN, the ballooning model, BALON2 is used to calculate the localized, non-uniform straining of the cladding if the cladding effective plastic strain is greater than the cladding instability strain [3]. Because the thermal expansion of the cladding is not used in the calculation of ballooning in BALON2 model, it is not able to confirm the effect of the cladding radial direction thermal expansion change. Based on the calculation results using FRAPCON, it is concluded that the cladding radial direction thermal expansion is one of the properties to affect the fuel temperature, therefore, the model for HANA-6 cladding should be needed in FRAPCON and FRAPTRAN codes.

4. Conclusions

This study conducts sensitivity analysis of material property correlations in FRAPCON and FRAPTRAN with cladding material change. When it comes to the case of the cladding thermal conductivity and radial direction thermal expansion in FRAPCON, there are certain trends to have some differences between the original code and modified code by using HANA-6. Thus, the correlations of HANA-6 should be applied in FRAPCON and FRAPTRAN. However, it is difficult to analyze the effects of the two correlations on the temperature of the fuel centerline, surface, and cladding inside surface in case of FRAPTRAN. Therefore, the results of the two correlations during the transient such as a rod ejection accident will be investigated in the further study.

In the other two cases, the effect of the density in HANA-6 is shown to make no differences in FRAPCON and FRAPTRAN. Although the case of the cladding oxide thermal conductivity in FRAPCON and FRAPTRAN finds some differences, the case is not based on the characteristics of HANA-6 but the inherent feature of the material correlation (the deviation band of $\pm$10%). So, the change of the correlation for the cladding oxide thermal conductivity in FRAPCON and FRAPTRAN will be concluded in the further study.

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