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Evaluation of Thermal Expansion Reactivity Feedback Effect in Water-moderated Fuel-particle-dispersion System

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1. Introduction

In the last dozen years, criticality safety research on fuel debris in the Fukushima Daiichi Nuclear Power Station has been conducted [1]. One research topic is criticality accident analysis. Such criticality accident analysis contributes to reduction of unnecessary radiation exposure to workers and the public by establishing effective countermeasures based on the estimated consequences of the accidents.

Analysis methods and knowledge for estimating the consequences of criticality accidents, e.g., the released energy by fissions and power profile, have been developed for solution systems, where, historically, most criticality accidents have occurred [2]. There are several codes [3,4] and simplified methods [5,6] for evaluating the consequences of criticality accidents in solution systems. These tools have been enhanced through verification using experimental research [7,8,9] and benchmark analysis [10]. However, the fuel debris is frequently assumed as water-moderated solid fuel systems, specifically fuel-particle-dispersion systems [11,12]. Extremely few cases have been reported related to criticality accident analysis in such systems, and knowledge regarding such analysis is scarce; these facts constitute the background of this study.

Understanding reactivity feedback is essential to estimate the consequences of criticality accidents by analysis. Typically, fuel temperature, radiolysis gas void, and boiling void are crucial reactivity feedback mechanisms. Fukuda et al. clarified that the fuel-temperature-feedback effect dominates the behavior of the first power pulse characterizing the criticality transient in the fuel-particle-dispersion system for prompt supercritical cases [13] because both radiolysis gas and boiling voids occur later than the peak of the first pulse. Thus, first of all, the fuel-temperature-reactivity feedback effect is important for criticality accident analysis in the fuel-particle-dispersion system, i.e., the fuel debris system.

Many materials undergo thermal expansion with their increasing temperature. Uranium dioxide (UO_2), which should also be included in the fuel debris, expands thermally [14]. If the thermal expansion of the fuel is considered in the fuel-particle-dispersion system, the reactivity change might differ from a case where only the Doppler effect is considered for the fuel-temperature feedback as assumed in the existing criticality accident analysis of the fuel debris [11,12]. The difference can be caused by changes in the density and volume-packing fraction of the dispersed fuel particles due to thermal expansion. Furthermore, previous studies have not discussed the effect of the thermal expansion reactivity feedback on the consequence of criticality accidents.

Considering the aforementioned factors, the purpose of this study is to quantitatively clarify the effect of thermal expansion on the consequences of criticality accidents, e.g., energy release, in a water-moderated fuel-particle-dispersion system. Additionally, it discusses whether the thermal expansion phenomena should be included in future analysis. Accordingly, temperature-reactivity-feedback coefficients with and without thermal expansion are calculated for several hypothetical fuel-particle-dispersion systems. Using the coefficients, the released energy and peak power of the first pulse are demonstratively calculated using a simple evaluation method in case of a prompt supercritical transient. The results obtained using multiple coefficients are compared, and the impact of the thermal expansion is discussed.

2. Methods

2.1 Calculation System

Figure 1 shows a calculation system that simulates a hypothetical water-moderated fuel-particle-dispersion system. The fuel particles with a radius of r_0 are gathered into a sphere of radius R_0 with a volume-packing fraction F_0. In the sphere, other volumes than the fuel particles are filled with water. A water reflector with a thickness of 30 cm is set around the sphere.

For simplicity, all fuel material was assumed as UO_2 with enrichment of 3 wt.%. The radius of fuel particles r_0 was determined to be 0.1 cm, which is in the range of the FARO experiment results [15]. For the volume-packing fraction F_0, two values were considered: 0.55, which is close to the value corresponding to the loosest packing, and 0.70, which is close to the value corresponding to the densest packing. The critical radii of sphere R_0 were searched for each volume-packing fraction at a fuel temperature T_0 of 300 K. The density of UO_2 for 300 K was set as 10.96 g/cm^3 [16]. Using the critical systems, the neutron generation time Λ was calculated using the time-dependent tally-based method [17], and the effective delayed neutron fraction β_{eff} was obtained using the k-ratio method [18]. The above-mentioned parameters are listed in Table I.

The calculations in this section were performed using the continuous energy Monte Carlo code MVP3 [19] with the nuclear data library JENDL-4.0 [20]. The total number of histories was 2,000,000 to achieve a standard deviation of the effective multiplication factor of <0.02%.

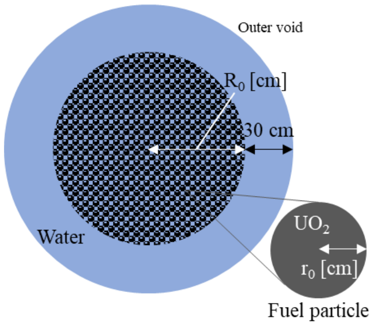

Fig. 1. Water-moderated fuel-particle-dispersion system

Table I: Parameters regarding analysis conditions

	Loose packing	Dense packing
F_0	0.55	0.70
r_0	0.1 cm	0.1 cm
R_0	30.82 cm	57.04 cm
β_{eff}	7.428×10^{-3}	7.833×10^{-3}
Λ	2.505×10^{-5} s	1.646×10^{-5} s

2.2 Thermal Expansion of the UO_2 Particle

According to Martin [14], the recommended linear thermal expansion coefficient Γ [/K] is

$$\Gamma = 9.828 \times 10^{-6} - 6.390 \times 10^{-10}T + 1.330 \times 10^{-12}T^2 - 1.757 \times 10^{-17}T^3 \quad (1a)$$

for 273 K $\leq T \leq$ 923 K, and

$$\Gamma = 1.1833 \times 10^{-5} - 5.013 \times 10^{-9}T + 3.756 \times 10^{-12}T^2 - 6.125 \times 10^{-17}T^3 \quad (1b)$$

for 923 K $\leq T \leq$ 3120 K,

where T represents the temperature [K]. Using Eqns. (1a) and (1b), the thermally expanded fuel particle radius r' at a fuel temperature T' is

$$r' = r_0 + r_0\Gamma(T' - T_0). \quad (2)$$

Because it is challenging to predict a change in the volume-packing fraction F and the radius of the fuel sphere R due to the thermal expansion of the fuel particles, the following two cases are assumed in this study. The total mass of the fuel is conserved before and after thermal expansion in both cases.

■ *R*-conserved case

In this case, while fuel particles have thermal expansion, the radius of the sphere R is conserved instead, the volume-packing fraction F increases. This case estimates a larger moderator/fuel volume ratio decrease. The parameters after the thermal expansion of the fuel particles can be expressed as

$$R' = R_0, \quad (3a)$$
$$F' = {r'^3}/{r_0^3} \cdot F_0, \quad (3b)$$
$$\rho' = {r_0^3}/{r'^3} \cdot \rho_0. \quad (3c)$$

■ *F*-conserved case

This case conserves the volume-packing fraction F, but the radius of the sphere R increases. This case maintains the moderator/fuel volume ratio. The parameters after the thermal expansion of the fuel particles can be expressed as

$$R' = {r'}/{r_0} \cdot R_0, \quad (4a)$$
$$F' = F_0, \quad (4b)$$
$$\rho' = {r_0^3}/{r'^3} \cdot \rho_0. \quad (4c)$$

The evaluation was performed for loose and dense F_0 for the aforementioned two cases.

2.3 Simple Evaluation of the Prompt Supercritical Transient

This study targets a stepwise reactivity-inserted prompt supercritical accident owing to the following reasons: the stepwise reactivity-inserted prompt supercritical accident instantly causes higher energy release and should be addressed more than ramp reactivity-inserted prompt supercritical and delayed critical accidents. The first power pulse was evaluated because its release energy dominates the entire released energy in the targeted cases.

The Nordheim–Fuchs (N–F) model [21] helps evaluate prompt supercritical accidents. The N–F model describes the change in the number of neutrons without the contribution of the delayed neutrons as follows:

$$\frac{dN(t)}{dt} = \frac{\rho(t) - \beta_{eff}}{\Lambda} N(t), \quad (5a)$$
$$\rho(t) = \rho_0 - \alpha\Delta T(t) = \rho_0 - \alpha \cdot {E(t)}/{C}, \quad (5b)$$

where $N(t)$ represents the power density at time t [W/cm^3], $\rho(t)$ represents the reactivity at time t [-], β_{eff} represents the effective delayed neutron fraction [-], Λ represents the neutron generation time, and ρ_0 represents the initial stepwise inserted reactivity [-]. Moreover, α represents the first-order fuel-temperature-reactivity coefficient [/K], ΔT represents the temperature change at time t [K], $E(t)$ represents the released energy density until time t [J/cm^3], and C represents the heat capacity [J/K/cm^3]. Differentiating both sides of Eq. (5b) by t and substituting it into Eq. (5a), we obtain

$$\frac{dN(t)}{dt} = -{C}/{2\alpha\Lambda} \cdot \frac{d}{dt}(\rho(t) - \beta_{eff})^2. \quad (5c)$$

Integrating Eq. (5c) from 0 to the power peak time, we obtain peak power N_p as follows:

$$N_p = \left. C(\rho_0 - \beta_{eff})^2 \middle/ 2\alpha\Lambda \right. . \quad (6)$$

because the reactivity at the power peak time is β_{eff}. Furthermore, the released energy until the power peak time can be easily derived from Eq. (5b). Multiplying it by two, the released energy at the first power pulse E_{pulse} is

$$E_{pulse} = \left. 2C(\rho_0 - \beta_{eff}) \middle/ \alpha \right. . \quad (7)$$

Eqns. (6) and (7) show that N_p and E_{pulse} are inversely proportional to the first-order fuel-temperature-reactivity coefficient α in the N–F model.

3. Results

3.1 Temperature Dependence of Reactivity

Fig. 2 shows the reactivity change depending on the fuel temperature when the initial volume-packing fraction is loose: F_0 = 0.55. The solid line shows the result of the case where thermal expansion is not considered, i.e., only the Doppler effect is included. The other two lines correspond to the *R*- and *F*-conserved cases described in 2.2.

According to Fig. 2, the reactivity monotonically decreases with increasing fuel temperature in all cases. The negative slope of the *R*-conserved case is larger than that of the no thermal expansion case because the moderator/fuel volume ratio decreases owing to the thermal expansion of the fuel particles in the *R*-conserved case. The water-moderated fuel-particle-dispersion system is initially under moderation; thus, the reactivity decreases with decreasing moderator/fuel volume ratio.

Furthermore, the negative slope of the *F*-conserved case is slightly smaller than that of the no thermal expansion case because the thermal expansion increases *R* and reduces the leakage of neutrons.

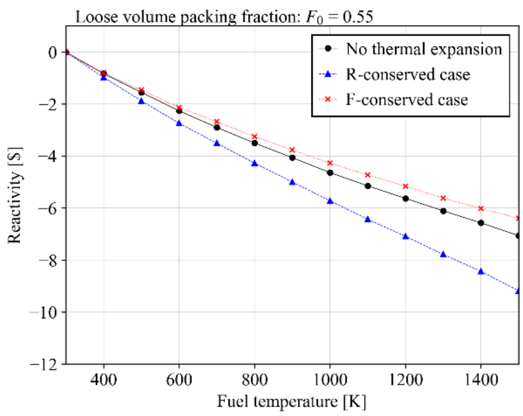

Fig. 2. Dependence of reactivity on fuel temperature (loose packing)

Similarly, Fig. 3 shows the dependence of reactivity on the fuel temperature when the initial volume-packing fraction is dense: F_0 = 0.70. The trend that the reactivity monotonically decreases with increasing temperature and the differences in the negative slopes are the same as in the loose cases.

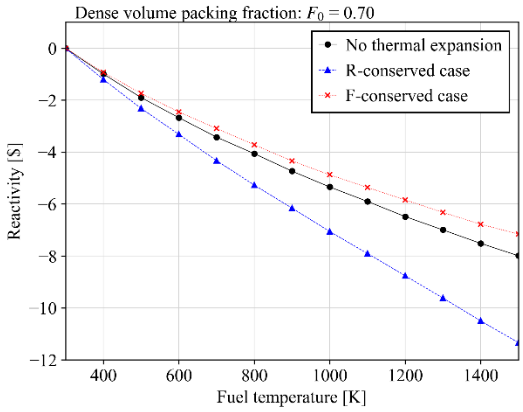

Fig. 3. Dependence of reactivity on fuel temperature (dense packing)

3.2 Peak Power and Released Energy in the First Pulse

The results obtained using Eqns. (6) and (7) are summarized in Tables II and III with the first-order fuel-temperature-reactivity coefficient α. The inserted reactivity was demonstratively determined as 2 \$ (ρ_0/β_{eff} = 2 [\$]). The heat capacity *C* was calculated based on the value for 300 K of the temperature-dependent specific heat capacity [22] as *C* = 2.6 [J/K/cm^3]. α was briefly calculated as

$$\alpha = \left. (\rho(1500\ \mathrm{K}) - \rho(300\ \mathrm{K})) \middle/ (1500 - 300) \right. . \quad (8)$$

Table II shows the result of the loose packing condition. The R-conserved case evaluates N_p and E_{pulse} 23% smaller than those corresponding to the case without the thermal expansion effect. Furthermore, the F-conserved case evaluates the consequences 10% larger. In criticality accident analysis, an underestimation of the consequences must be avoided to ensure conservative countermeasures against criticality accidents. From such a viewpoint, ignoring thermal expansion might be problematic because introducing thermal expansion into the analysis increases the evaluated consequences in the F-conserved case.

However, a difference of 10% is small enough and within the error margin in most criticality accident analyses. However, notably, ignoring thermal expansion might cause the aforementioned errors in situations where evaluators want to obtain the consequence with high accuracy; for example, when they try to obtain the exact amount of exposure and the released radioactive isotopes after an accident.

Table III shows a similar trend of results under the dense packing condition. The R-conserved case evaluates N_p and E_{pulse} 29% smaller, and the F-conserved case 12% larger than the case without the thermal expansion effect.

Based on the abovementioned results and discussion, the following conclusions can be made:

- Evaluators can ignore thermal expansion when they evaluate the peak power and released energy in the first pulse of the prompt supercritical transient in water-moderated solid fuel-dispersion systems, such as fuel debris systems. Only the Doppler effect can be considered when the fuel temperature-feedback coefficient is prepared.

- Notably, ignoring thermal expansion leads to underestimation or overestimation by several tens of percent; thus, evaluators should take care of the error depending on the required accuracy.

Table II: First-order fuel-temperature-reactivity coefficient, peak power, and released energy (loose packing)

	α [/K]	N_p [W/cm^3]	E_{pulse} [J/cm^3]
No thermal expansion	4.4×10^{-5}	6.5×10^4	8.8×10^2
R-conserved	5.7×10^{-5}	5.0×10^4	6.8×10^2
F-conserved	4.0×10^{-5}	7.2×10^4	9.8×10^2

Table III: First-order fuel-temperature-reactivity coefficient, peak power, and released energy (dense packing)

	α [/K]	N_p [W/cm^3]	E_{pulse} [J/cm^3]
No thermal expansion	5.2×10^{-5}	9.3×10^4	7.8×10^2
R-conserved	7.4×10^{-5}	6.5×10^4	5.5×10^2
F-conserved	4.7×10^{-5}	1.0×10^5	8.7×10^2

4. Conclusions

Brief evaluations were performed using the N–F model to quantitatively clarify the effect of thermal expansion on the consequences (the power peak and the released energy of the first pulse) of criticality accidents in the water-moderated fuel-particle-dispersion system. Therefore, temperature-reactivity-feedback coefficients with and without thermal expansion were calculated for several hypothetical water-moderated fuel-particle-dispersion systems. The loose and dense packing was assumed in the analysis. The temperature-reactivity-feedback coefficients and required kinetics parameters were calculated using the Monte Carlo neutron transport method.

The analysis clarified that ignoring thermal expansion can lead to underestimation or overestimation of the consequences by several tens of percent. It is concluded that evaluators can ignore the thermal expansion when they evaluate the consequences of the prompt supercritical transient in water-moderated solid fuel-dispersion systems, such as fuel debris systems. Only the Doppler effect can be considered when the fuel-temperature-feedback coefficient is prepared. However, depending on the required accuracy, the evaluators should take care of the error caused by ignoring thermal expansion.

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