Neutronics and Heat Transfer Coupled Time-Dependent Analysis Framework for Complex Fuel Element Loaded Fuel Assembly

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1. Introduction

From several recent studies [1]–[3], an advanced fuel design called centrally-shielded burnable absorber (CSBA) has been applied to various light water reactor designs in regard of soluble-boron-free design. The primary purpose of the rather complex fuel design is to reduce the excessive reactivity during the cycle to minimize the concentration of soluble boron in the coolant. From the reduced reactivity swing over the operation, the temperature coefficient would become further negative, resulting enhanced intrinsic safety and chance of passive autonomous operation.

The burnable absorber (BA) loaded fuel pellet cannot be numerically handled as same as the conventional fuel pellet since the BA significantly deforms the intra-pin power distribution. Therefore, we previously proposed to tally detailed power distribution using unstructured mesh-grid [4], allowing additional computation overhead. However, it may become unaffordable in time-dependent simulations, so we proposed an approximated strategy. In the subsequent section, numerical schemes used in this analysis framework is introduced followed by investigation of possible error incurred from the simplification.

2. Methods and Results

2.1 Dynamic Monte Carlo

The dynamic Monte Carlo (DMC) scheme for the time-dependent Monte Carlo simulation is well established and explained in Sjenitzer's previous studies [5], [6]. In this section, we list a few important features of the DMC which are essential to achieve a stable and reliable result. The DMC simulates the particle directly in the time-domain considering the flight time. The flight time of the particle is calculated by dividing the sampled distance with the particle's speed. When the cumulative flight time exceeds the time-step boundary, the particle is stored for the next time-step. To reduce the variance caused from particle generation branching during the simulation, the DMC adopted the branchless method which adjust particle weights instead of starting a new branch at a fission event.

One of the most important feature of the DMC method is the forced decay, as it reduces variance caused from the precursor uncertainty. In the forced decay strategy, each alive precursor produces a neutron in every time step, unlike a precursor produces neutron only once in reality. The weight of the emitted neutron from the forced decay (w_d) is adjusted as follows to prevent a biased result:

$$w_d = w_C \Delta t \sum_i f d_i \lambda_i e^{-\lambda_i (t-t_0)} \tag{1}$$

Meanwhile, the precursor weight (w_C) is also adjusted after each time step:

$$\begin{aligned} w_C' &= w_C \frac{w_{surv}}{w_{n,av}} \quad \text{if } \xi < \frac{w_{n,av}}{w_{surv}} \\ w_C' &= 0 \qquad\qquad \text{else} \end{aligned} \tag{2}$$

where,

$$\begin{aligned} w_{n,av} &= \frac{w_C}{\Delta t} \int_{t_1}^{t_1+\Delta t} \Delta t \sum_i f d_i \lambda_i e^{-\lambda_i (t-t_0)} dt \\ &= w_C \sum_i f d_i \lambda_i e^{\lambda_i t_0} \left(e^{-\lambda_i t_1} - e^{-\lambda_i (t_1+\Delta t)} \right) \end{aligned} \tag{3}$$

To control the population of particles to be simulated, the combing technique [7] is used. The combing technique preserves the total weight of the particle bank, but resample a limited number of particles based on their weight. The technique can be applied for both time sources and precursors to maintain reasonable computation time regardless of an external reactivity insertion.

2.2. Time-Dependent Finite Element Heat Transfer

The time-dependent conduction equation includes an additional time derivative term.

$$k \nabla^2 T(\vec{r},t) + Q(\vec{r},t) = \rho c \frac{\partial T(\vec{r},t)}{\partial t} \tag{4}$$

Eq. (4) can be simplified into a system of linear equations:

$$[C]\{\dot{T}\} + \left([K_c] + [K_h]\right)\{T\} = \{R_q\} + \{\mathrm{R}_h\} \tag{5}$$

where, $[C]$ denotes the heat capacitance matrix. To solve the equation in the time-domain, an implicit time-step discretization is used:

$$[C]\frac{\{T^{(i+1)}-T^{(i)}\}}{\delta t}+([K_c]+[K_h])\{T^{(i+1)}\}=\{R_q\}+\{R_h\} \quad (6)$$

Finally, the nodal temperature vector at each time step can be evaluated from the following recurrence relation.

$$([C']+[K_c]+[K_h])\{T^{(i+1)}\}=\{R_q\}+\{R_h\}+[C']T^{(i)} \quad (7)$$

where, $[C']=[C]/\delta t$.

2.3. Simplified Method for Transient Coupled Analysis

In this section, an approximated time-dependent neutronics and heat transfer coupled analysis framework is described. Before describing the proposed method, it is worth to review our previous studies, as the method has been inspired from a study on steady-state coupled multi-physics analysis [4]. In the steady-state analysis, we investigated an effect of guide-thimble (GT) neighboring fuel rods. Using unstructured mesh-grid tally, a detailed power distribution was measured for a CSBA pellet next to the GT, the confirmed highly skewed power distribution to the GT (Figure 1). However, the corresponding temperature distribution was rather symmetric, as the peak thermal power was generated around the perimeter of the pellet and easily transferred to the coolant.

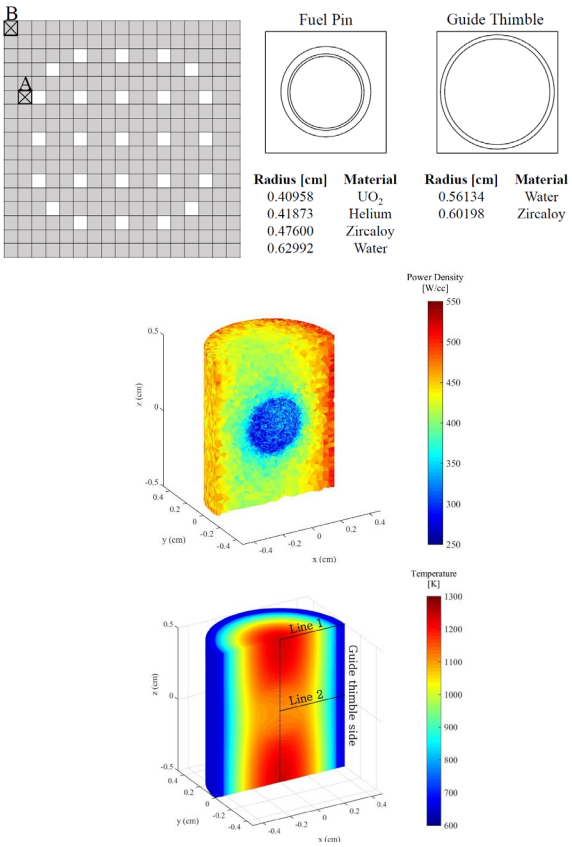

Figure 1. Power distribution of a pellet near GT and temperature.

Based on this observation, we may imagine an approximated approach for simulating the coupled analysis in a reactor transient. Instead of tallying detailed power distribution for every fuel rods in every time step, which is computationally exhaustive, we may compute pin-wise power distribution from the transient Monte Carlo simulation and apply a symmetric intra-pin power shape from all-reflective pin cell calculation for the heat transfer calculation. However, the difference due to the simplified approach is needed to be quantified to assure that its impact on temperature is minor.

To investigate the impact of symmetric power assumption, we devised two step-up reactivity insertion scenarios. In both cases, two normalized CSBA power distributions were used; a symmetric power pin from all-reflective pin cell calculation and a skewed power pin due to GT neighboring effect. The power distributions are illustrated in Figure 2. The two scenarios are power step-up ($P = 2P_0$) and power step-down ($P = 0.5P_0$) transients. The heat transfer calculation conditions are described in Table I.

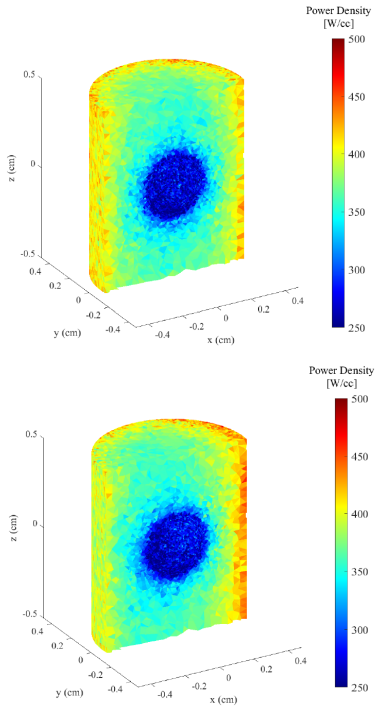

Figure 2. Normalized power distributions of CSBA pellet (symmetric and skewed).

Table I. Heat transfer calculation conditions

Simulated time duration	5 sec
Time step size	0.01 sec
Initial specific power density of UO_2	37 W/gU
Number of nodal points	48,218
Number of tetrahedrons	284,695

The power step-up and down simulation results are shown in Figure 4. In Figure 4, each figure illustrates the temperature difference between the symmetric and the skewed power distribution at a time that the difference is maximum. (t = 5 sec for the step-up and t = 0 for step-down) From the result, the maximum difference was around or less than 10 K and we may consider it as minor error, compared to more than 60 K difference with homogeneous power assumption [4]. Therefore, we can safely assume the CSBA intra-pin power distribution as symmetric without incurring a significant error in temperature. Since the computation burden for tallying detailed power in each time-step is reduced, a more accurate power distribution like Figure 3 would be used.

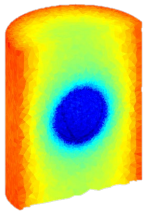

Figure 3. CSBA power distribution shape from all reflective pin-cell calculation.

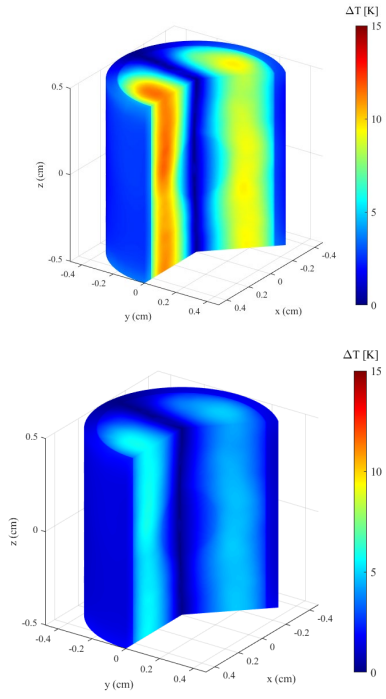

Figure 4. Temperature difference between symmetric and skewed power in ramp-up (up, t = 5 sec) and in ramp-down (down, t = 0 sec).

The proposed time-dependent neutronics and heat transfer coupled calculation framework is as follows: 1. Time-dependent pin-wise power distribution is acquired from DMC simulation, 2. Intra-pin power distribution is reconstructed using power shape calculated from all-reflective pin-cell calculation and the DMC pin-power distribution, 3. The corresponding intra-pin temperature is calculated based on the detailed power. In the subsequent feedback calculation, point-wise temperature is used to adjust the cross-section in a tracking framework of the Woodcock delta-tracking algorithm. An example of problem of interest is as follows: a CSBA loaded assembly is initially fully loaded with full control rods (CRs), and some of the CRs are instantly ejected. In Figure 5, a pin-power distribution from DMC simulation is illustrated.

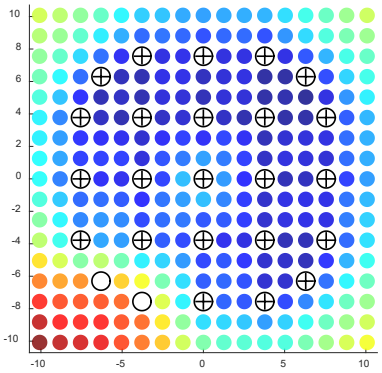

Figure 5. Snapshot of pin-power distribution in a CR ejection transient.

3. Summary and Conclusions

In this study, we proposed a simplified approach for time-dependent coupled analysis for complex fuel element. From this preliminary investigation, we quantified temperature error caused from the approximation, and we found it minor. Using the DMC algorithm and time-dependent FEM heat transfer module implemented in the iMC code, the framework is considered adequate for short transient calculations for complex fuel loaded reactors.

In a subsequent study, we will demonstrate various multi-physics capabilities of the iMC code for complex fuel elements. Followed by proper optimization, the iMC code will present a complete time-dependent multi-physics platform for the analysis of complex fuel elements' performance studies.

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