

Fuel lattice design in a boiling water reactor using a knowledge-based automation system



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HIGHLIGHTS

- An automation system was developed for the fuel lattice radial design of BWRs.
- An enrichment group peaking equalizing method is applied to optimize the design.
- Several heuristic rules and restrictions are incorporated to facilitate the design.
- The CPU time for the system to design a 10x10 lattice was less than 1.2 h.
- The beginning-of-life LPF was improved from 1.319 to 1.272 for one of the cases.

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ABSTRACT

A knowledge-based fuel lattice design automation system for BWRs is developed and applied to the design of 10×10 fuel lattices. The knowledge implemented in this fuel lattice design automation system includes the determination of gadolinium fuel pin location, the determination of fuel pin enrichment and enrichment distribution. The optimization process starts by determining the gadolinium distribution based on the pin power distribution of a flat enrichment lattice and some heuristic rules. Next, a pin power distribution flattening and an enrichment grouping process are introduced to determine the enrichment of each fuel pin enrichment type and the initial enrichment distribution of a fuel lattice design. Finally, enrichment group peaking equalizing processes are performed to achieve lower lattice peaking. Several fuel lattice design constraints are also incorporated in the automation system such that the system can accomplish a design which meets the requirements of practical use. Depending on the axial position of the lattice, a different method is applied in the design of the fuel lattice. Two typical fuel lattices with U^{235} enrichment of 4.471% and 4.386% were taken as references. Application of the method demonstrates that improved lattice designs can be achieved through the enrichment grouping and the enrichment group peaking equalizing method. It takes about 11 min and 1 h 11 min of CPU time for the automation system to accomplish two design cases on an HP-8000 workstation, including the execution of CASMO-4 lattice code. The results obtained with the application of the implemented system show the potential of the proposed methodology in the fuel lattice design automation for BWRs.

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1. Introduction

The BWR (Boiling Water Reactor) fuel lattice design includes the determination of several parameters, such as the fuel pellet enrichment, the number of fuel pellet enrichment, the enrichment distribution, the gadolinium weight percent, the number of

gadolinium fuel pin, and the gadolinium distribution. The complexity of fuel lattice design not only comes from the many degrees of freedom but also derives from the coupling with the core design. As a fuel lattice will reside in a core for many cycles, the fuel lattice design will be even more complex if the multi-cycle performance is considered. In the design process, several iterations between the fuel lattice design and the core loading pattern design are performed, and the fuel lattice design may be adjusted according to the feedback of core parameters, such as MFLCPR (Maximum Fraction Limiting Critical Power Ratio), MFLPD (Maximum Fraction

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Limiting Power Density), etc. For a fixed core loading pattern and control rod pattern, it is possible to correlate the core design parameters to the fuel lattice design parameters. A fuel lattice with better lattice design parameters is expected to have better core design parameters. For example, a fresh fuel bundle with a lower local peaking factor (LPF) at its bottom portion is expected to have a better MFLPD performance in the core loading pattern design. Therefore, in this study, LPF is the optimization target for the fuel lattice located at the lower portion of a fuel bundle. On the other hand, F-eff, which is the weighted sum of the power fractions of a fuel pin and its neighboring fuel pins, is the optimization target for the fuel lattice located at the upper portion of the fuel bundle. In order to reduce the complexity, an existing reload core loading pattern is used to evaluate the performance of the fuel lattice design. In this study, the fuel pin power distribution and the burnup status of a fuel lattice are obtained using CASMO-4 (Rhodes and Smith, 2007); whereas, the core performance parameters, such as MFLPD and MFLCPR, are calculated using SIMULATE-3 (Covington, 2007).

Several kinds of optimization techniques have been used to solve this complex space-composition combinatorial problem, including the tabu search (Francois et al., 2003), the tabu search method and fuzzy logic (Martín-Del-Campo et al., 2007a), the genetic algorithms and knowledge (Martín-Del-Campo et al., 2007b), the path re-linking (Castillo et al., 2011), the ant-colony (Montes et al., 2011), and the hybrid method of greedy search and neural network (Ortiz-Servin et al., 2010), etc. Most of them apply the heuristic rules to increase the efficiency of the optimization process, and two heuristic rules are commonly used. The first one is that the four corner fuel pins should have the lowest enrichment in the fuel lattice, and the other one is that the gadolinium fuel pin is not allowed to exist in the periphery of a fuel lattice.

Cuevas et al. (2002) used a modified linear programming technique to optimize the enrichment distribution in a typical LWR (Light Water Reactor) assembly, and the optimization process is initiated from flattening the enrichment distribution until a target maximum local power peaking factor is achieved. The optimal locations and values for a reduced number of fuel rod enrichment groups are obtained for an inputted target maximum local power peaking factor by applying the sensitivity to change techniques.

Lin and Lin (2012) developed an automatic procedure based on a particle swarm optimization (PSO) algorithm and a local search with some heuristic rules to simplify the search for the radial enrichment and gadolinium distribution of BWR fuel lattices. Lin and Lin consider a different object function for the different axial zone in their study. The minimization of LPF and F-eff has to be taken care of separately, because the minimization of LPF doesn't mean the minimization of F-eff. The MFLPD of a core is sensitive to the design of fresh fuel lattices located at a lower portion of a fuel bundle, and therefore, the minimization of LPF should be considered for these fuel lattices. The MFLCPR of a core is mostly sensitive to the design of fuel lattices located at a near top portion of a fuel bundle, and hence, the minimization of F-eff should be considered for these fuel lattices.

As burnable poison is commonly used in the BWR fuel lattice to suppress K_{inf} at the beginning of life (BOL), the distribution of gadolinium has to be addressed. In this study, the first step of the automation process is to determine the gadolinium distribution, using a specified gadolinium concentration and number of gadolinium fuel pin as a design constraint. Several heuristic rules are incorporated in the automation system to facilitate the determination of gadolinium distribution.

The enrichment selection for each fuel pin enrichment type and the enrichment distribution are another issue to be solved by a nuclear engineer in designing a fuel lattice. In this study, the enrichment of each fuel pin enrichment type is a variable to be

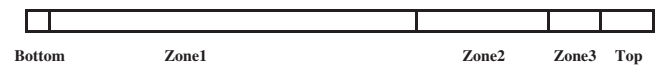


Fig. 1. Fuel assembly axial zoning.

determined in the design, not a value specified before carrying out the automation process. Usually, the engineer has to spend a lot of time to go through a trial and error process, to find the best fuel pin enrichment distribution, with the enrichment of each pin location selected from a specified set of enrichments. In this study, a different approach is presented to facilitate the lattice design tasks. The enrichment of each fuel pin enrichment type is determined by using a process that flatten the pin power or F-eff distribution to obtain an ideal enrichment distribution, and a process that divides the ideal enrichment distribution into several enrichment groups. This method eliminates the need to determine the enrichment for each fuel pin enrichment type prior to executing the fuel lattice design automation process, and also reduces the time spent in searching for the best fuel pin enrichment distribution. Following the determination of fuel pin enrichment, the enrichment group peaking equalizing process, which gradually reduces the difference between the highest and the lowest enrichment group peaking, is performed to reduce the lattice peaking factors such as LPF and F-eff. A fuel lattice design with the improved lattice peaking can be obtained if the distribution of enrichment group peaking is equalized.

Due to the voiding of moderator, a BWR fuel assembly is characterized by its several different axial lattice zones with varying enrichment from the bottom zone to the top zone. Currently, the 10×10 fuel assemblies used in the BWR4 and BWR6 nuclear power plant in Taiwan contain five zones in the axial direction, as shown in Fig. 1. To better utilize the neutron moderation, zone 1, which generates most of the energy during the cycle, is designed to have a higher enrichment than the rest of lattice zones. As for the upper portion of the fuel assembly, the neutron moderation is inferior and the fuel utilization is not so efficient because of a larger void fraction there. Therefore, the enrichments at zone 2 and zone 3 are lower than that at zone 1. Zone 2, playing an important role in the cold shutdown margin value, is usually designed with the highest gadolinium concentration. As the transition boiling often occurs near the top of a fuel assembly, zone 3 is designed to have a minimized F-eff, which affects the critical power of a fuel assembly.

2. Concepts and knowledge for the fuel lattice design automation

The basic concept of designing a BWR fuel lattice is to emplace the enrichment based on the degree of neutron moderation effect at each fuel pin location. It is expected that a lower enrichment is emplaced at a fuel pin location with a better moderation effect and a higher enrichment is emplaced at a fuel pin location with a poorer moderation effect. The ideal design is that each fuel pin in a fuel lattice has its own unique enrichment depending on the degree of neutron moderation effect at the pin location. In such ideal condition, it is possible to design a fuel lattice with LPF equal to 1.0 if no gadolinium is used and the 5% enrichment upper limit is not considered. Due to the manufacturing complexity, there is a limit on the number of fuel pin enrichment type used in a fuel lattice design, and thus will result in the enrichment at each fuel pin location to deviate from its enrichment in the ideal design and increase LPF. It is important to properly determine the enrichment for each fuel pin enrichment type and select the enrichment type of each fuel pin location appropriately such that LPF can be minimized.

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