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Using a combination of weighting factor method and imperialist competitive algorithm to improve speed and enhance process of reloading pattern optimization of VVER-1000 reactors in transient cycles

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HIGHLIGHTS

- This article was an attempt to optimize reloading pattern of Bushehr VVER-1000 reactor.
- A combination of weighting factor method and the imperialist competitive algorithm was used.
- The speed of optimization and desirability of the proposed pattern increased considerably.
- To evaluate arrangements, a coupling of WIMSD5-B, CITATION-LDI2 and WERL codes was used.
- Results reflected the considerable superiority of the proposed method over direct optimization.

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ABSTRACT

In this research, an innovative solution is described which can be used with a combination of the new imperialist competitive algorithm and the weighting factor method to improve speed and increase globality of search in reloading pattern optimization of VVER-1000 reactors in transient cycles and even obtain more desirable results than conventional direct method. In this regard, to reduce the scope of the assumed searchable arrangements, first using the weighting factor method and based on values of these coefficients in each of the 16 types of loadable fuel assemblies in the second cycle, the fuel assemblies were classified in more limited groups. In consequence, the types of fuel assemblies were reduced from 16 to 6 and consequently the number of possible arrangements was reduced considerably. Afterwards, in the first phase of optimization the imperialist competitive algorithm was used to propose an optimum reloading pattern with 6 groups. In the second phase, the algorithm was reused for finding desirable placement of the subset assemblies of each group in the optimum arrangement obtained from the previous phase, and thus the retransformation of the optimum arrangement takes place from the virtual 6-group mode to the real mode with 16 fuel types. In this research, the optimization process was conducted in two states. In the first state, it was tried to obtain an arrangement with the maximum effective multiplication factor and the smallest maximum power peaking factor. In the second state, the objective of optimization was to obtain a reloading pattern with the most flattened thermal power distribution. Using the method proposed in this paper, the optimum arrangement was obtained almost 2.5 times quicker than the conventional direct method. In addition, optimality of the arrangements obtained from this method was higher than the conventional direct method and even the pattern proposed by Russian contractors. However, it is worth mentioning that the method proposed in this research is not solely limited to the imperialist competitive algorithm and it is possible to use other meta-heuristic smart algorithms with the proposed solution. Finally, to calculate the objective parameters more precisely during evaluation of arrangements and examine their desirability during an operational cycle length, a computational thermo-neutronic coupling was designed using the WIMSD5-B and CITATION-LDI2 codes in the neutronic section and the WERL code in the thermohydraulic part.

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1. Introduction

So far, different optimization methods such as the genetic algorithm (Mohseni et al., 2008; Rahmani et al., 2013b), neural networks (Fadaei and Setayeshi, 2008), particle-swarm optimization (Khoshahval et al., 2010), Artificial Bee Colony (Safarzadeh et al., 2011), Cellular automata (Fadaei and Setayeshi, 2009a; Fadaei et al., 2009b), etc. have been used for reloading pattern optimization of Bushehr's VVER-1000 reactor. However, in most of such investigations, optimization takes place either in the first or equilibrium cycles, which have lower fuel diversity than transient cycles.

In this research, the imperialist competitive algorithm (Atashpaz-Gargari and Lucas, 2007; Ardalan et al., 2015; Hosseini and Abdullah, 2014) was for the first time used to optimize reloading patterns of nuclear reactors. This algorithm was originally innovated by Atashpaz and Lucas, and it is based on conventional imperialistic strategies. In addition, by assigning weighting coefficients to each assembly and classifying the assemblies accordingly, an innovative solution was designed, which considerably improved the globality and speed of the search process.

As this paper aimed to achieve a method for the reloading pattern optimization of VVER-1000 reactors in transient cycles, first, the fuel compositions were calculated for each remaining assembly from the first cycle. To this end, a computational program was designed and the coupling of the WIMDD5-B (Roth et al., 1997) and CITATION-LDI2 (Fowler et al., 1999) codes was used in its neutronic component. Moreover, in order to consider the effects of temperature feedbacks a thermohydraulic computational program (WERL code) was also designed (Rahmani, 2013c). Finally, by coupling of neutronic and thermohydraulic components a thermo-neutronic computational chain was formed. The computational chain could be used to estimate the fuel composition of the fuel assemblies remaining from the previous cycle, calculate the objective parameters of probable arrangements and conduct a thermo-neutronic analysis of the optimum reloading pattern for the second operational cycle.

Optimization calculations were carried out in two modes. In the first state, it was tried to obtain an arrangement with the maximum effective multiplication factor and the safe maximum power peaking factor. In the second state, optimization was conducted to obtain an arrangement with the flattest distribution of radial power peaking factor.

2. General Introduction to the main characteristics of the Bushsher VVER-1000 reactor

The Bushehr's VVER-1000 reactor falls into the category of pressurized light water reactors. The core of this reactor is composed of 163 hexahedral fuel assemblies. Ten groups of control rod assemblies are used to control and maintain the reactor's safety.

In the second operational cycle, 16 types of fuel assemblies are used including 12 types that remain from the first cycle (109 fuel assemblies). Chromium diboride has been used as a burnable absorber in three of the 16 types of assemblies. Table 1 describes the main characteristics and working conditions of the BUSHEHR VVER-1000 reactor (Atomenergoproekt, 2003a,b).

Table 1
The technical characteristics of VVER-1000(V-446) reactor.

Reactor nominal thermal power, MW	3000
Coolant heating in the reactor, °C	30
Number of loops, pieces	4
Flow area of the core, m^2	4.14
Maximum allowable radial power peaking factor	1.44
Fuel assembly geometry	Hexahedral prism
Fuel height in the cold state, m	3.53
Fuel	Pellets UO_2
Absorbing material	$B_4C + (Dy_2O_3TiO_2)$
Pitch between fuel assemblies, m	0.236
Pitch between the fuel rods, m	12.75×10^{-3}

Fig. 1 also outlines the general layout of the core of Bushehr's VVER-1000 reactor and the arrangement of the fuel assemblies in the first operational cycle (Atomenergoproekt, 2003a). Fig. 2 also shows the arrangement of control rods in cycle 2 (Atomenergoproekt, 2003a).

3. Burnup calculation process

Because the purpose of this study is to describe the process of the optimum reloading pattern proposition in the second cycle of Bushehr's VVER-1000 reactor, burnup calculations should be conducted to determine the fuel compositions of the reused fuel assemblies. Therefore, a coupling of neutronic and thermo-hydraulic calculations was used (Rahmani et al., 2013a). To do this, the physical group constants of the fuel assemblies and reflectors were calculated using the WIMSD5-B code.

Furthermore, to obtain the time-dependent changes in the fuel composition and calculate the rate of burnup in each fuel assembly, the computational capabilities of the WIMSD5-B code were utilized. By inserting the physical group constants obtained from the WIMSD5-B code into the input file of the CITATION-LDI2 code and also defining the geometry of the reactor core, the effective multiplication factor and the three-dimensional distribution of the reactor's thermal power were calculated (Rahmani et al., 2013a).

In this study, a thermo-hydraulic software was designed using the Enveloped Pin method (Rahmani et al., 2013a,b). Furthermore, the Dittus-Boelter (Todreas and Kazimi, 1993), Ross-Stoute (Todreas and Kazimi, 1993; Rahmani and Rahgoshay, 2011) and Lee-Kesler (Sontag and Borgnakke, 1997) models were used in the calculations of the heat transfer coefficient of coolant, gap conductance coefficient and gap pressure, respectively.

In addition, to estimate the concentration of the released gaseous fission products into the gap space of fuel, the Weisman model (Weisman et al., 1969) was used.

By using the results of the thermo-hydraulic calculations, the temperature and density of the fuel, clad and coolant elements (in each fuel assembly) were applied to the neutronic calculations and thus, a continuous sequence of neutronic and thermo-hydraulic calculations was created. Fig. 3 provides a schematic description of the applied computational flowchart.

After studying the depletion rate of fuel assemblies used in the first cycle and considering safety constraints, it was found out that it was not possible to use type 1.6% fuel assemblies and the 54 assemblies had to be replaced with fresh fuels in the second cycle. Table 2 illustrates the type, quantity and burn-up rate of loadable fuel assemblies in the second cycle.

4. Utilizing a combination of weighting factor method and imperialist competitive algorithm for reloading pattern optimization

In this research, to reduce the types of fuel assemblies applicable to reloading of VVER-1000 reactor in the second cycle, the weighting factor method was used to classify assemblies with similar effective multiplication factors into more limited groups. Since the number of variables is also reduced as a result, the search process was speeded up and more importantly the globality of search increases in the optimization algorithm. Hence, using the imperialist competitive algorithm in the first phase, the reactor reloading pattern is optimized based on the limited fuel groups.