EVALUATION OF THE REACTIVITY FEEDBACK IN A LIQUID METAL-COOLED FAST REACTOR

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Since the evaluation of the temperature changes and the coolant void reactivity in a nuclear reactor are among the most important reactivity effects for the safe operation of the reactor during normal operation as well as in accident conditions, this study aims to present a comparative analysis of the simulation results and the experimental data obtained for the temperature coefficient and the void reactivity during CEFR (China Experimental Fast Reactor) start-up test. The neutronic calculations have been performed for the detailed 3D model of the CEFR core using the Monte Carlo code MCNP6.2 along with the ENDF/B-VIII.0 nuclear data library.

Keywords: temperature reactivity, coolant void reactivity, liquid metal-cooled reactor, Monte Carlo

1. Introduction

In recent years, the interest in advanced nuclear reactor technology led to an increased need for advanced computing tools for modeling and simulation, as well as the validation of existing computational codes [1]. The feedback reactivity coefficients are among the most important parameters for assessing the inherent safety of a nuclear reactor. Therefore, in order to ensure the safety of the reactor, it is important to obtain negative values for the temperature reactivity and the coolant void reactivity [2], [3].

In 2018, a coordinated research project (CRP) was launched by IAEA based on the China Experimental Fast Reactor (CEFR) start-up tests [4]. The objective of this benchmark is to improve the capabilities in the simulation, design and neutronic analysis of fast reactors based on the large amount of experimental data acquired during CEFR operation.

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The CEFR [5] is a sodium fast reactor with a thermal power of 65MW_{th} (20MW_e), located at the China Institute of Atomic Energy (CIAE), near Beijing. It is a pool-type reactor that can accommodate two types of fuel: uranium oxide (UO_2) and uranium-plutonium mixed oxide (PuO_2).

2. Model description

For this study, the considered core configuration (see Fig. 1) includes:

- 79 fuel assemblies fueled with 64.4 wt% enriched UO_2;
- 8 control assemblies that are divided into three types: 2 regulating assemblies, 3 shim assemblies, and 3 safety assemblies. All control assemblies have the same geometry, but different boron carbide (B_4C) contents (the regulating rods contains natural abundance ^{10}B, while the shim and safety rods have 92.0 a% enriched ^{10}B);
- a neutron source containing 0.43 mg of ^{252}Cf loaded in the center of the active core;
- 394 stainless steel assemblies with two different geometries are divided into four categories: 2 Type I, 37 Type II, 132 Type II and 223 Type IV.
- 230 boron shielding assemblies having the same geometry as SS Type I and II but containing B_4C with natural abundance ^{10}B.

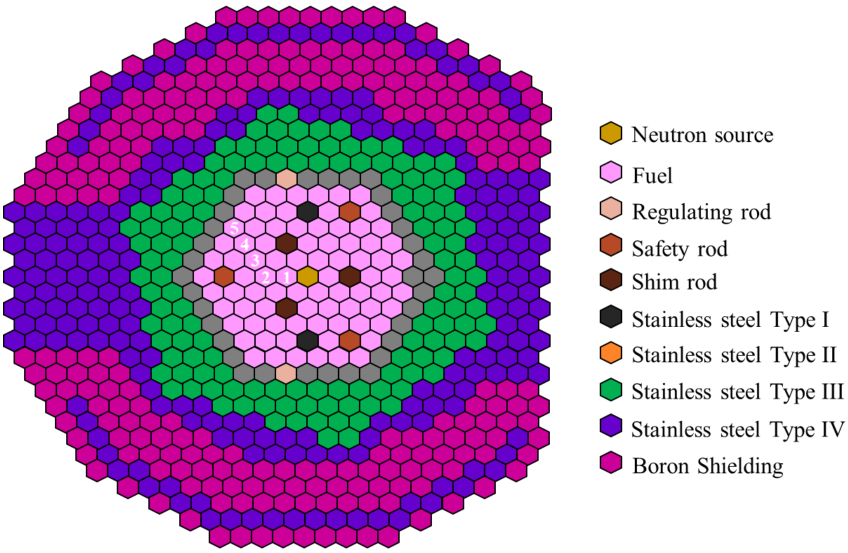

Fig. 1. CEFR radial core layout.

The 3D modeling of the reactor core was performed using the Monte Carlo code: MCNP [6] Version 6.2, along with the ENDF/B-VIII.0 [7] nuclear data library provided by SCK, which is a partner in the CRP project. To save computational time, with a standard deviation of keff results between 5 and 6 pcm, simulations were carried out using 5×10^5 source neutrons per cycle with 100 inactive and 300 active cycles.

The MCNP model is based on the description provided in the CRP technical specifications [8]. Each assembly is individually modeled, only a few regions of the active core, considered less relevant for simulations, have been omitted. For example, the spacer wire mass was integrated into the clad, the spring of the fuel assembly was modeled as a cylinder, the nozzle section of all assemblies and the supporting plug of the fuel rod were ignored.

3. Results and discussions

3.1. Temperature reactivity

The experimental measurements of the temperature effect in the CEFR reactor included 10 data measurement sets: five steps of temperature increasing (from 250 ℃ to 300 ℃) and five steps of temperature decreasing (from 300 ℃ to 250 ℃). The temperature was considered to be uniform in the whole active core. Even if from the neutronic point of view, the difference between the increasing and the decreasing process is not relevant, it could become significant for the experiment due to the measurement uncertainty.

It should be noted that the Doppler effect, the thermal expansion, and the density changes of each material were considered for each simulation.

Three different methods were used to simulate the temperature reactivity coefficient:

- *Method 1* - considering the control rod positions fixed outside the core;
- *Method 2* - using the control rod positions according to the experiment, and performing control rod reactivity correction based on the integral rod worth;
- *Method 3* - introducing a third step, besides the experimental measurements to calculate the control rod movement reactivity.

The temperature coefficient was obtained as a linear fitting of the reactivity change at various temperature steps as shown in Fig. 2.

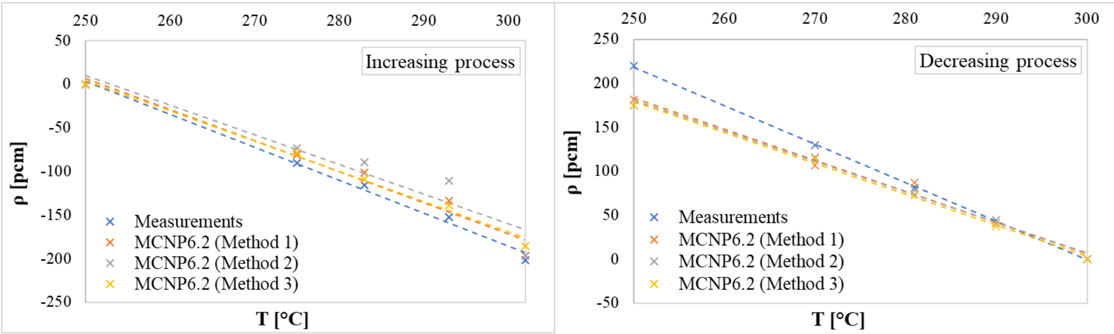

Fig. 2. The temperature reactivity for increasing and decreasing process.

The temperature reactivity coefficients obtained through simulations, as well as the experimental ones [9], for both the increasing and decreasing processes, respectively, are provided in Table 1.

Table 1

Temperature coefficients for increasing process and decreasing process.

Temperature, °C	α (Std. dev.), pcm/°C			
	Measurements	Method 1	Method 2	Method 3
Increasing process (from 250°C to 302°C)	-3.76((±0.50)	-3.57 (±0.29)	-3.40 (±0.86)	-3.48 (±0.28)
Decreasing process (from 300°C to 250°C)	-4.38((±0.57)	-3.55 (±0.29)	-3.46 (±0.84)	-3.51 (±0.28)

3.2. Coolant void reactivity

The sodium void reactivity was determined experimentally by replacing a fuel assembly (the locations in the active core of the changed fuel assemblies are given in Fig 1) with a special vacuum-sealed designed assembly. A total of five different locations were measured during operation at cold state (while the sodium temperature was about 250 °C).

Two different methods were used to determine the coolant void reactivity effect:

- *Method 1* - considering the control rod positions fixed outside the core;
- *Method 2* - using the control rod positions according to the experiment, and introducing a third step to calculate the control rod reactivity change with movement;

The comparison between the MCNP6.2 simulation results and the experimental data [10] regarding the coolant void reactivity in CEFR is provided in Fig. 3.

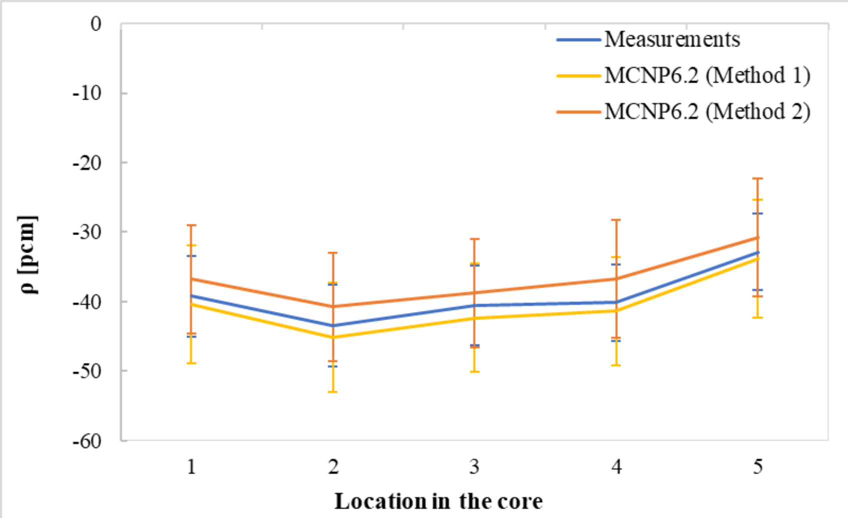

Fig. 3. Coolant void reactivity.

6. Conclusions

In this paper, the CEFR core was modeled using the MCNP6.2 code, and it presents the simulation results compared to the experimental data obtained from the following experiments performed during the CEFR reactor start-up tests: temperature reactivity and sodium void reactivity.

In order to simulate the temperature reactivity coefficients, three different approaches were used. For all three methods, a slight underestimation of the experimental data was observed for the temperature increasing process, but a more pronounced discrepancy was obtained for the decreasing process.

The void reactivity results were obtained using two different approaches. In both cases, the sodium void reactivity for the selected location in the CEFR core is negative and in agreement with the experimental data. It is noteworthy that all the simulation results fall within the standard deviation of the experimental measurements.

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