Experimental Measurement and Monte Carlo Calculation for Moderator Temperature Coefficient in CROCUS Reactor

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1. Introduction

It is widely known that moderator temperature coefficient (MTC) plays an important role in the safety analysis for reactor operation. As a collaborative research in the frame work of young researcher exchange program between Korea and Switzerland, an experimental campaign for MTC measurements are performed in the zero-power research reactor CROCUS with two different methods. As MTC can also be numerically estimated by Monte Carlo perturbation calculation, this collaborative work is a good opportunity to validate the capability of perturbation calculation in McCARD, a Monte Carlo code developed in Seoul National University. In this research, the MTC of CROCUS reactor at 18 ~ 22 ℃ is numerically estimated by McCARD, then it is compared with the results from experimental measurements.

2. Experiments for MTC Measurement in CROCUS

CROCUS is an experimental zero power reactor in École Polytechnique Fédérale de Lausanne (EPFL), Switzerland. It is a uranium-fueled and water-moderated reactor, controlled by changing water level or by B_4C control rods. In this research, two different methods are adopted for MTC measurement. The first one is measurement of critical water level and reactivity worth of water level, referring to the past experiments at TCA in Japan [1]. The second one is measurement of reactivity changes during heating or cooling using inverse point kinetics [2]. To cover both methods at the same time, the experiments are designed and performed as follows

At first, the temperature of reactor is set to 18 ℃ and critical water level at 18 ℃ is found. Then positive period measurement is conducted with raising water level by 2 mm or 4 mm from critical level to measure the reactivity worth of water level. After finishing period measurement and returning to critical state, the water in reactor is heated up with fixed water level for an hour until it reaches to 22 ℃. The power in reactor drops during the heating since CROCUS has negative MTC. The power and temperature are recorded simultaneously during the heat up period. When the moderator temperature reaches to 22 ℃, water level is raised to find the new critical level. Then positive period measurement at 22 ℃ is repeated just like that at 18 ℃. After returning to critical state again, the reactor is cooled down to 18 ℃ with fixed water level, letting power increase at this time. All positive period measurements are conducted at the power range from 10 W to 20 W. The power changes during heating and cooling range from 0.3 W to 20 W.

3. Methods and Results

In the experimental measurement part, only one measurement method with critical water level and positivity period method is presented at this time, because the research with the other method is ongoing. The experimental results are compared with the numerical results from McCARD perturbation calculation. The measurement and calculation results for MTC of CROCUS with brief descriptions are as follows.

3.1 Measurement of critical water level and reactivity worth of water level

This method refers to MTC measurement experiment at TCA in Japan. Unlike other experiments [3,4] using shim rods, the reactivity worth is measured by changing water level in this approach. It starts with an idea that the temperature coefficient can be expressed in terms of difference of critical water level by temperature, $\Delta \mathrm{H}_{\mathrm{crit}}/\Delta \mathrm{T}$, and reactivity worth of water level $\Delta\rho/\Delta \mathrm{H}$ as follows.

$$\frac{\partial\rho}{\partial \mathrm{T}} \approx \frac{\Delta\rho}{\Delta \mathrm{H}}\frac{\Delta \mathrm{H}}{\Delta \mathrm{H}_{\mathrm{crit}}}\frac{\Delta \mathrm{H}_{\mathrm{crit}}}{\Delta \mathrm{T}} \tag{1}$$

The reactivity worth of water level, $\Delta\rho/\Delta \mathrm{H}$, is measured by asymptotic period method in this experiment. The water level is raised slightly above from critical and the increasing reactor power is recorded from fission chamber detector. Then inverse reactor period, ω, is obtained from fitting the time dependent reactor power to exponential function, $\mathrm{A}\cdot \mathrm{e}^{\omega t}$. The fitting is done with removing delayed transition period.

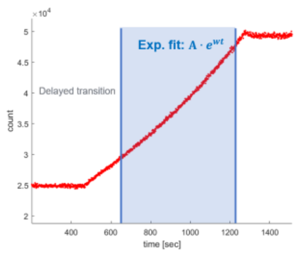

Fig. 1. Exponential fitting for the asymptotic period

The reactivity can be calculated by Inhour equation from the measured inverse reactor period, ω, as follows,

$$\Delta\rho = \omega\Lambda + \sum_i \frac{\omega\beta_i}{\omega + \lambda_i} \quad (2)$$

where Λ is the neutron generation time [sec], λ_i is the decay constant in precursor's group [sec^{-1}], and β_i is the effective delayed neutron fraction in each precursor group. The kinetics parameters here, Λ, β_i, can be obtained from McCARD calculation.

The Table I shows the measured inverse periods from the experiments in CROCUS and corresponding reactivities in cent ($\Delta\rho/\beta$) from Inhour equation. The uncertainties in Table I are calculated from error propagation of ω and β_i. The uncertainties in water level measurement are assumed as 0.1 mm, propagated to those in reactivity worth of water level, $\Delta\rho/\Delta\mathrm{H}$. The averaged value of reactivity worth of water level, $\Delta\rho/\Delta\mathrm{H}$, for all experimental data is 0.492 ± 0.011 [cent / mm]

Table I: Inversed period and reactivity from experiments

	$\Delta\boldsymbol{H}$ [mm]	ω [s^{-1}]	$\Delta\rho$ [cent]	$\Delta\rho/\Delta\boldsymbol{H}$ [cent / mm]
1a	2	9.97E-04	1.020±0.034	0.510±0.031
1a'	2	9.94E-04	1.017±0.034	0.508±0.031
1b	2	9.72E-04	0.995±0.033	0.498±0.030
1b'	2	9.73E-04	0.996±0.033	0.498±0.030
2a	2	8.39E-04	0.862±0.029	0.431±0.026
2a'	2	8.40E-04	0.864±0.029	0.432±0.026
2b	2	8.57E-04	0.881±0.029	0.440±0.026
2b'	2	9.97E-04	1.020±0.034	0.510±0.031
3a	4	2.04E-03	2.024±0.067	0.506±0.021
3a'	4	2.05E-03	2.032±0.067	0.508±0.021
3b	4	2.01E-03	1.992±0.066	0.498±0.021
3b'	4	2.00E-03	1.986±0.065	0.497±0.021
3c	4	2.14E-03	2.108±0.069	0.527±0.022
3c'	4	2.13E-03	2.107±0.069	0.527±0.022
4a	4	2.04E-03	2.017±0.066	0.504±0.021
4a'	4	2.01E-03	1.995±0.066	0.499±0.021
4b	4	2.09E-03	2.070±0.068	0.517±0.021
4b'	4	2.09E-03	2.064±0.068	0.516±0.021
		Avg.		**0.492 ±0.011**

The Table II shows the measured critical water level at 18 ℃ and 22 ℃. The water level measurement is done by spillway indicator. The uncertainty in water level measurement is also assumed as 0.1 mm. The critical water levels are measured as 952.0 mm at 18 ℃ and 956.0 mm at 22 ℃, respectively, in all experiments. Thus, the difference of critical water level per 1 ℃ of temperature is measured as 0.998 ± 0.036 [mm / ℃]

MTC can be obtained by Eq. (1) with combining the two measurement results, the difference of critical water level and reactivity worth of water level. The calculated MTC is -0.490 ± 0.011 [cent / ℃], or -3.622 ± 0.117 [pcm / ℃].

Table II: Critical water level at 18 ℃ and 22 ℃

	T [℃]	**H_{crit} [mm]**	**$\Delta H_{crit}/\Delta T$ [mm/℃]**
1a	18.01±0.02	952.0±0.1	0.998±0.036
1b	22.02±0.02	956.0±0.1	
2a	18.01±0.02	952.0±0.1	0.998±0.036
2b	22.02±0.02	956.0±0.1	
3a	18.01±0.02	952.0±0.1	0.995±0.036
3b	22.03±0.02	956.0±0.1	
4a	22.01±0.02	952.0±0.1	0.998±0.036
4b	18.00±0.02	956.0±0.1	
		Avg.	**0.997±0.018**

3.2. McCARD perturbation calculation

The numerical estimation for MTC in CROCUS is performed using McCARD. It is conducted by Monte Carlo Adjoin Weighted Perturbation (MC AWP) calculation in McCARD [5]. The water level and reactor temperature in the McCARD modeling are set to 952.0 mm and 18 ℃, respectively. The numerical results are shown in Table III. It should be noted that the perturbation effect by TSL thermal scattering library is not listed in Table III, but it seems to be negligible from preliminary observation (0.200±0.207 pcm / ℃). The uncertainties suggested in the Table III does not include those of nuclear data, instead they are purely induced by statistical uncertainties in Monte Carlo simulation.

Table III: Numerical results for MTC measurement by McCARD perturbation calculation

Perturbation source	**Isotope**	**MTC by MC AWP [pcm / ℃]**
Density	^{1}H	-2.264±0.045
	^{16}O	-0.679±0.010
Cross section	^{1}H	-0.003±0.000
	^{16}O	-0.787±0.000
All		-3.736±0.046

3.3. Comparison of experiment and calculation results

Table IV shows a brief summary for MTC measurement by comparison of experimental measurements and numerical results by McCARD.

Table ΙV: Summary of MTC measurement

	MTC [cent / ℃]	**MTC [pcm / ℃]**
Experiment	-0.490±0.117	-3.622±0.117
McCARD	0.506±0.003	-3.736±0.046

4. Conclusion

This research covers the measurement of moderator temperature coefficient in CROCUS reactor and the comparison of the experimental results to numerical calculations by Monte Carlo code, McCARD. The results from experimental measurement the numerical estimation of MTC in CROCUS agrees well within statistical error. This measurement data will be good resource to develop and validate the perturbation calculation in Monte Carlo codes.

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