Development of On-Line HANARO Core Tracking Tool Using McCARD

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1. Introduction

Entering the 21st century, due to the development of technologies such as communication technology, big data analysis and Internet of Things (IoT), attempts have been made to move objects in physical space into virtual space. The first advent of the term, digital twin was in the presentation made by M. Grieves in 2003 [1]. The concept of DT proposed to include three parts: physical product, virtual product, and their connection.

In the nuclear industry, the nuclear power plant which includes a lot of physical components such as reactor core and thermal-hydraulics systems correspond to the physical products. On the other side, computational codes for analyzing each corresponding field like neutronics and thermal hydraulics correspond to the virtual products. In this study, the connection between physical and virtual products in the field of neutronics is proposed and tested as a reactor core tracking tool.

The physical product to be tested in this study is the HANARO (High-flux Advanced Nuclear Application Reactor) research reactor, which is developed in KAERI (Korea Atomic Energy Research Institute). The reactor states in a timely manner are represented by a historical dataset in the ANSIM (Advanced Nuclear Safety Information Management) database [2].

The virtual part is conducted by McCARD code, which is designed for the neutron and photon transport calculation [3]. Although the computational cost is more expensive compared to deterministic approaches, the Monte Carlo (MC) approach is adopted in this study due to its flexibility in geometry treatment and capability for continuous energy treatment, which means it can mimic the physical world more realistic.

The connection between physical and virtual parts is shown through a visualization tool called McView, which is developed by Seoul National University (SNU) to visualize the McCARD input files. The McView is a user interface and McCARD serves as a neutronics engine.

In this study, the reactor core of HANARO in the 104th operation cycle was tracked on-line and the signal of fission chamber detector and the McCARD tally were compared as verification results.

2. Architecture of Core Tracking Tool

In this section, some of the techniques used to connect between ANSIM database and McCARD engine are described. The schematic diagram of the HANARO core tracking tool is depicted in Fig. 1. The architecture of the reactor core tracking tool is divided into three parts: 1) User interface, 2) Data import from ANSIM database, and 3) Socket communication with the McCARD server.

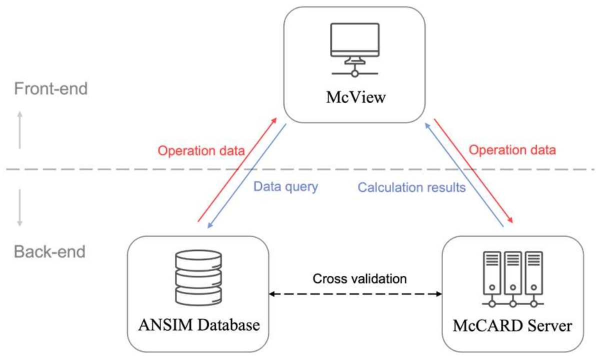

Fig. 1. Schematic diagram of the HANARO core tracking tool

2.1 User Interface

The McCARD input file visualization tool, McView, is a front-end of the system and the HANARO core tracking tool is implemented in the McView. Fig. 2. is user interface of the HANARO core tracking tool and it contains:

1. Setting control of the operation cycle,
2. Operation data from ANSIM database, and
3. Results from McCARD calculation

The setting control of the starting and end point of operation cycle is shown in upper left side (section 1). The operation data from ANSIM database including thermal power and control rod positions are represented in the middle of left side (section 2). The calculation summary including reactivity and peaking factor are shown in the middle of screen (section 3). The results from McCARD calculation, including reactivity and detector flux, are shown in the left lower side chart control (section 4) and the power distribution of the HANARO core is visualized in the right side (section 5).

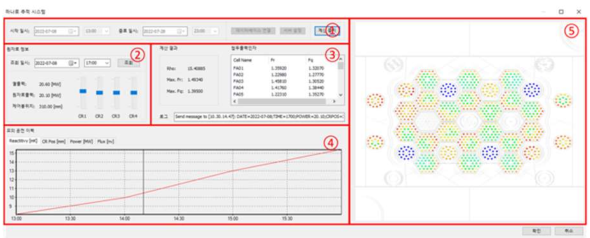

Fig. 2. User-interface of the HANARO core tracking tool

2.2 Data Import from ANSIM Database

As McView is developed with Microsoft Foundation Class (MFC), it can use Windows' standard application programming interface (API) called Open Database Connectivity (ODBC) [4]. ODBC allows McView to access ANSIM database that uses Oracle Database Management System (DBMS).

The required data is the reactor power and control rod position at a specific time and these data are recorded in the ANSIM database manually by operators through Operator Workstation (OWS) [5]. OWS is included in the HANARO control system and the configuration of that is shown in Fig. 3.

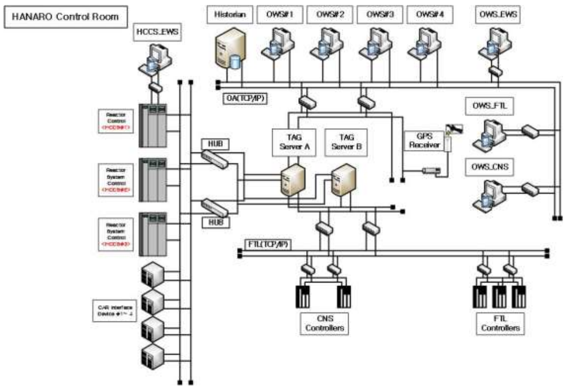

Fig. 3. Configuration of HANARO control system

These recorded operation data is transmitted to the McCARD server through the McView for burn-up calculation.

2.3 Socket Communication with McCARD Server

With the operation data from ANSIM database, the virtual reactor is simulated by McCARD code on a server. In this architecture, McView and McCARD act like client and server, and the data is transmitted by socket communication. The computation scheme via socket communication operates in the following order:

1. Client (McView) sends a message containing the operation data to the server, and the server generates a modified input file reflecting the received reactivity and control rod position.
2. Server orders the McCARD to perform burn-up calculation and sends a message containing the calculated results to the client.
3. Client visualizes the results and imports next step operation data from the database.
4. Repeat 1 to 3 until the operation cycle ends.

The flow chart of the operation cycle tracking burn-up calculation is described in Fig. 4.

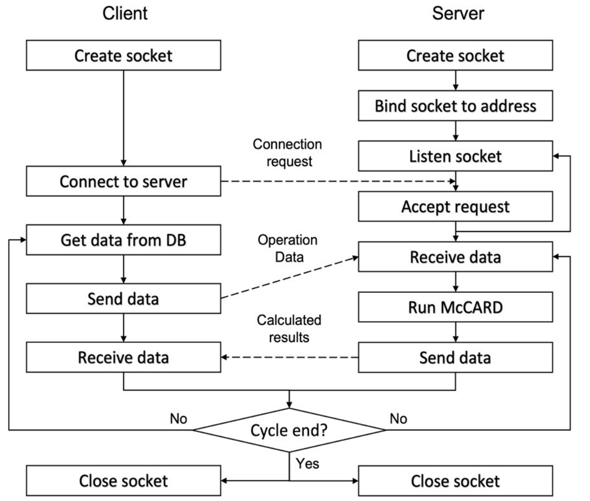

Fig. 4. Flow chart of the operation cycle tracking burn-up calculation via socket communication

3. Methodology

3.1 Measurement and Estimation of Neutron Flux

HANARO has three fission chamber type out-core detectors. These detectors measure the neutron flux by converting an electric signal into a neutron flux with a certain sensitivity value. The electric signals in mA units are recorded in ANSIM database. These out-core detectors are modeled in the McCARD input for HANARO as depicted in Fig. 5.

According to the HANARO neutron detector specifications, the thermal neutron sensitivity of the detector assembly is 9.0×10^{-1} *Amps/nv* [6]. By dividing the electric signal by the thermal neutron sensitivity, the measured value of thermal neutron flux can be obtained.

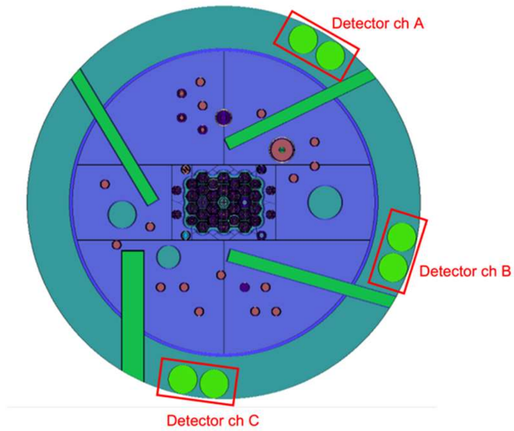

Fig. 5. HANARO core model with out-core detectors

The McCARD code generates flux conversion factor, which has the physical means the number of fission neutrons in current generation [7]. The conversion factor is calculated by

$$(\,Conv.\,Factor) = \frac{Q}{\kappa \cdot \sum_{i=1}^{m} \Sigma_f^i \phi_i V_i} \qquad \text{(Eq. 1)}$$

The tallies calculated by burn-up calculation are normalized by the number of fission sources and the cell volume. By multiplying the conversion factor, the tallies are unnormalized and converted into realistic values corresponding to the reactor power.

In this study, the measured neutron flux from detector signal and the estimated neutron flux by McCARD burn-up calculation are compared as verification results.

3.2 On-line Burn-up Calculation

As mentioned in section 2.3., the McCARD burn-up calculation is performed according to the operation data. The operation data is recorded every hour by the reactor operator and these data are transmitted to the calculation server. The server modifies the initial input file reflecting control rod positions and reactor power. The control rod positions, and reactor power is set to the average value during the time interval (1 hour). The material composition for each unit cell after a single burn-up calculation is stored in a file (STD file), and this file is read from the next burn-up calculation. Fig. 6. describes the schematic diagram of on-line burn-up calculation.

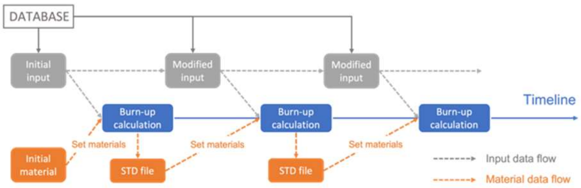

Fig. 6. Schematic diagram of on-line burn-up calculation

4. Calculation Results

The capability of the HANARO core tracking is tested by on-line real data following burn-up calculations. For remaining criticality, the operator periodically withdraws control rod during operation due to the depletion of material. In this section, the reactivity insertion ($\Delta k/k$) and the flux level at the detector position are presented as results. If the value cannot be retrieved from the database during online calculations, the previous value is used in calculations.

4.1 k_{eff} Prediction Accuracy

Fig. 6. is a graph of control rod positions and reactivity insertion. As shown in the graph, one can see that the criticality remains inside ±750 pcm (blue region in Fig. 7.) while the control rods are withdrawn. It is because the fuel undergoes depletion during operation.

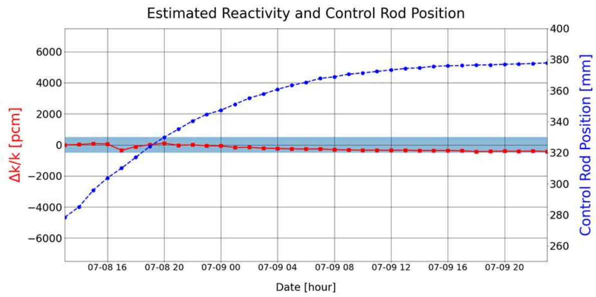

Fig. 7. Graph of control rod positions and reactivity

4.2 Neutron Flux Prediction

Because of the large sensitivity of flux according to the radial position on both measurement and calculation, the measured and estimated flux are normalized by initial value and the trends of the values are compared. Fig. 8. is a graph of estimated neutron flux and detector signal. The error bar of the estimated flux level represents 95% confidence interval.

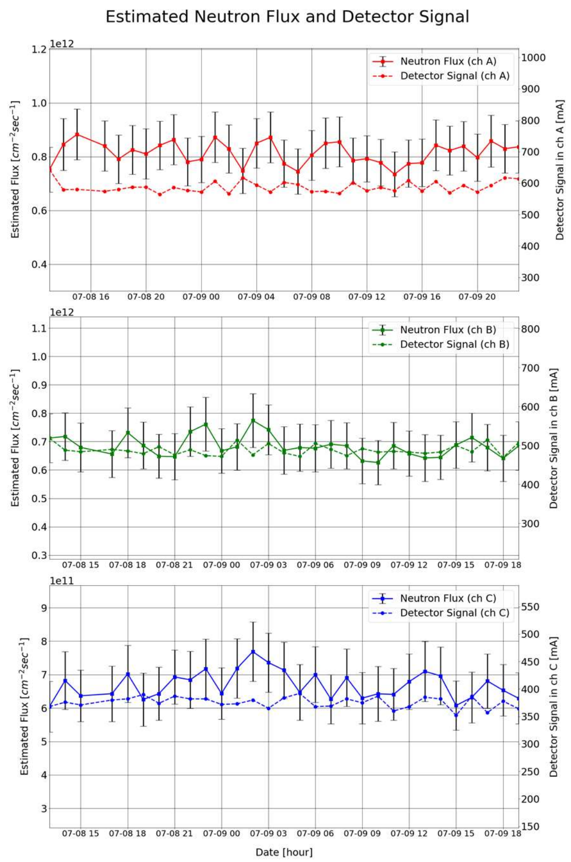

Fig. 8. graph of estimated neutron flux and detector signal

One can see that the estimated and measured neutron flux level remains constantly in all three detectors.

5. Conclusion

In this study, the HANARO core tracking tool is developed, and it performs on-line core tracking based on ANSIM – McView – McCARD system. The core tracking capability of this tool is validated by reactivity following and comparison between measurement and estimation of neutron flux.

As a preliminary study on the nuclear digital twin, this study suggests a possibility for on-line core tracking from neutronics perspective. For the ultimate nuclear digital twin system, the multi-physics analysis such as thermal hydraulics and system analysis should be included.

REFERENCES

[1] M. Grieves, "Digital Twin: Manufacturing Excellence through Virtual Factory Replication," White paper, 2014.
[2] J.M. Sohn et al, "Development of Advanced Nuclear Safety Information Management (ANSIM) System", KNS Spring Meeting, Korea Nuclear Society, Jeju, Korea, May 17-18, 2012.
[3] H.J. Shim, B.S. Han, J.S. Jung, H.J. Park, and C.H. Kim, "McCARD: Monte Carlo Code for Advanced Reactor Design and Analysis", Nuclear Engineering and Technology, vol. 44, no. 2, pp. 128-138, 2000.
[4] Andy Shum, "Open Database Connectivity Development of the Context Interchange System", Massachusetts Institute of Technology EECS Master Engineering Thesis, Cambridge, MA, February 1997.
[5] H.S. Jung et al, "Improvement of the HANARO Control and Monitoring System", KNS Autumn Meeting, Korea Nuclear Society, Gyeongju, Korea, November 2-3, 2006.
[6] S.G. Doo, Y.S. Choe, M.W. Lee, and H.K. Kim, "Replacement of HANARO Neutron Detector", HANARO Measurement Division, Korea Atomic Energy Research Institute (KAERI), 2013.
[7] S.J. Hwang, Y.I. Kim, H.J. Shim, and C.G. Seo, "Nuclear Heating Analysis for HANARO Cold Neutron Source by McCARD Burnup Calculations", KNS Virtual Spring Meeting, Korea Nuclear Society, May 13-14, 2021.