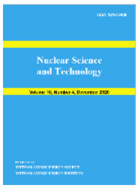
Nucl. Sci. and Tech., Vol.10, No. 4 (2020), pp. 08-15

Nuclear Science and Technology

Journal homepage: https://jnst.vn/index.php/nst



Verification of a real-time interactive transient simulator for Dalat Nuclear Research Reactor

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Abstract: A PC-based real-time interactive transient simulator of Dalat Nuclear Research Reactor (DNRR), namely DalatSim, based on the best-estimate thermal-hydraulic code RELAP5/MOD3.3 has been currently building at Center for Nuclear Technologies (CNT). This paper presents the study on developing the physics core, control module, and human-machine interface (HMI) of DalatSim. The nodalization of DNRR used for DalatSim was based on the reported numerical model in the Safety Analysis Report (SAR) in 2012. DalatSim can simulate operational procedures and several hypothetical transient accidents of DNRR. A curve of real operational power of DNRR was used to compare with calculation power results from DalatSim to verify its capability. The verification results are presented and discussed.

Keywords: *Simulator, Dalat Nuclear Research Reactor, RELAP5/MOD3.3, physics core, human-machine interface.*

I. INTRODUCTION

Nuclear reactor simulation systems play an important role in operator training, research on safety analysis, thermal-hydraulic, automatic control, and protection system design. In addition to full scope simulators describing the entire real systems, basic principle simulators have also been designed and developed for educational purposes. These simulators, which can operate on personal computers, provide efficient tools for learning fundamental physical processes, the basic operation of complex systems, and the general operating procedures of various nuclear reactor types [1]. Numerous scientific, educational and training organizations in the world have developed basic principle simulators for nuclear research reactor studies. Ricardo Pinto de Carvalho and José Rubens Maiorino built a simulation system for Brazil's IEA-R1 nuclear research reactor in 2006, which allows simulation in real-time of start-up, power maneuver, and shutdown [2]. The Korea Atomic Energy Research Institute (KAERI) developed a real-time simulation system for High-flux Advanced Neutron Application Reactor (HANARO) in Korea and Jordan Research and Training Reactor (JRTR) in Jordan for operator training in 2014 [3]. They also studied to construct a web-based nuclear reactor simulator using the best-estimate nuclear system analysis code RELAP5 as the core program and LabVIEW for the real-time interactive interface in 2007 [4]. Moreover, the Dalton Nuclear Institute at the University of Manchester, UK provided a simple nuclear reactor simulator on their website allowing

https://doi.org/10.53747/jnst.v10i4.10
Received 28 October 2020, accepted 17 December 2020

students and internet users to access, familiarize, and understand nuclear reactor operation [5].

In Vietnam, there are many activities of learning and utilizing nuclear reactor simulators. These simulators, however, are mainly for nuclear power plants and supplied from other countries. The applications of the real-time OPR 1000 core simulator and the VVER-1200 nuclear power plant simulator installed at Dalat University and Nuclear Training Center (VINATOM), respectively, are such examples. The development of a simulation system for DNRR is an essential task to support the operational training and educating students from universities. Furthermore, it also helps to preserve valuable knowledge and experience gained from research and operating activities on DNRR.

The research to build the first real-time transient simulator for DNRR in Vietnam is being performed at CNT. This simulator is expected to simulate operational procedures in normal condition and several hypothetical transient accidents of DNRR. The next section presents the methodology used to develop the simulator. The computational capability of the simulator was verified with actual operational power data of DNRR. The verification results are also presented and discussed.

II. SIMULATOR DEVELOPMENT

The real-time interactive transient simulator for DNRR (in short DalatSim) consists of two main modules: a physics core module and a driver module. The modules exchange necessary data together to build a complete simulation program. Figure 1 displays their functions and data transfer.

- The physics core module solves necessary neutron kinetics and thermal-hydraulic problems for each time step required by the driver module for both steady-state and transient processes of DNRR. It provides the required parameters for the driver module for control and display functions of DalatSim.
- The driver module is responsible for controlling the execution of DalatSim and comprises two main modules: a control module, and a human-machine interface (HMI) module. The control module simulates the reactor control and protection system of DNRR. The HMI module includes graphical interfaces that help users to interact with DalatSim. Besides, an auxiliary “realism” module is required to prepare and process input data for the physics core, retrieve and display the calculation data from the physics core module to the HMI module in real-time, simulate the actual three monitoring channels of DNRR, etc.

The application of Hypertext Transfer Protocol (HTTP) [6] was used to exchange calculation parameters between the physics core and the driver module. The driver module, as a client, sends requests for necessary control or display parameters to the physics core. The physics core, as a server, will return the required calculated parameters for further simulation performance.

The physics core, control, and HMI modules are described in more detail in the next subsections.

A. Physics core module

The physics core was built based on RELAP5/MOD3.3 code. RELAP5 is a best-estimate thermal-hydraulic system analysis code used extensively as the engine in many real-time reactor simulators [4, 7-9]. The code validation of thermal-hydraulic and core dynamic characteristics of DNRR was confirmed by comparing the analytical results with the experimental data [10].

However, necessary work was implemented to investigate computational characteristics and capability of the code to develop our physics core module. Although RELAP5 is a very good tool for reactor simulation, some features need to be modified and enhanced to meet the design requirements of a simulation system.

Firstly, RELAP5/MOD3.3 code does not have the capability of real-time simulation. The transient calculation control subroutine (tran) of the code was customized to ensure this feature. Secondly, users basically can not interact with the code in real-time besides preparing input files, running the code, and analyzing its printed output files. It is impractical to prepare input files to describe all operational states of DNRR. Therefore, an interface written in C++ language was designed and coupled with RELAP5/MOD3.3 which was written in FORTRAN77 language to solve this problem (Figure 1). This interface was able to directly access the memory of RELAP5/MOD3.3, retrieve and change all calculation variables. Data transfer from the physics core to other modules of DalatSim would be easier with this coupling method.

The nodalization of DNRR was based on the reported numerical model in the Safety Analysis Report of DNRR in 2012 [11]. The reactor core was divided into two channels: hot channel and average channel. The hot channel represents the hottest channel in the core corresponding to a cooling channel with maximum heat flux. The average channel represents the rest of the cooling channels. Each channel was modeled as three fuel element plates and four coolant flow gaps according to the design of VVR-M2 fuel assembly. The piping of the primary cooling system and reactor pool was divided into volumes with similar dynamic characteristics.

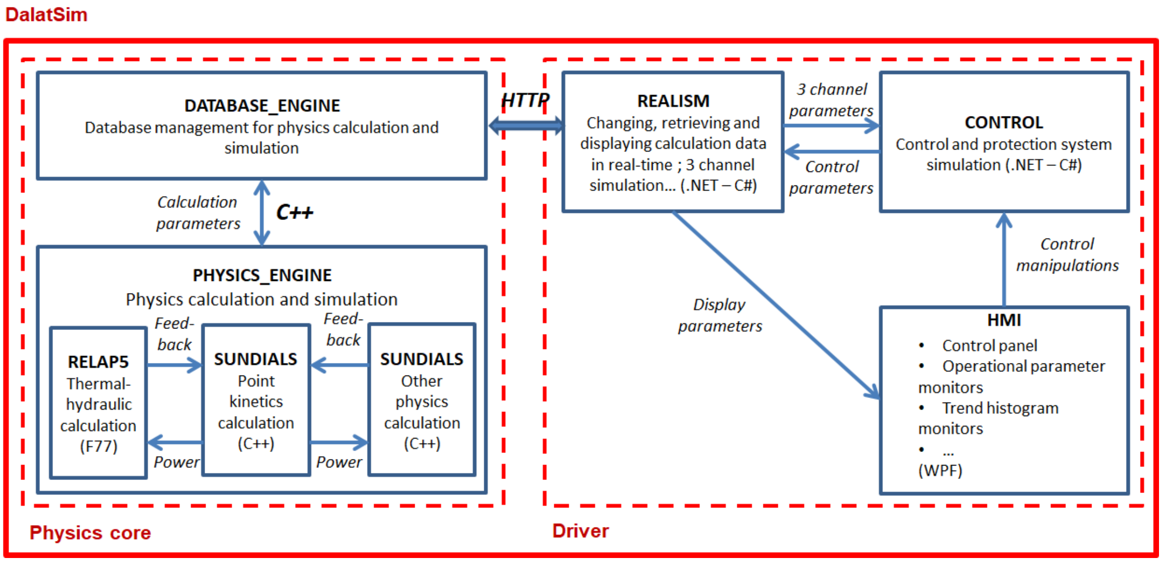

Fig. 1. Design diagram of the real-time transient simulator for DNRR (DalatSim)

Finally, a bug occurs inside the embedded point reactor kinetics module of RELAP5/MOD3.3 resulting in nonphysical reactor power curves when applying small calculation time steps [12]. To solve that problem, the embedded module was replaced with SUNDIALS solver [13]. It has been verified with benchmarks and proven to produce up to nine-decimal-place accurate results [14]. The coupled code, so-called

RELAP/SUNDIALS, not only helped us to prevent the bug but also enhanced the calculation accuracy of the physics core.

B. Control module

Instead of using the limited “control variable” and “trip” card features of RELAP5/MOD3.3 code, the control module of DalatSim was built with many flexible capabilities. This module processes all the required control and protection logic of DNRR during the simulations. The module was designed based on the logic circuit of the actual reactor control and protection system of DNRR. It was written in C# language using object-oriented programming with .NET Core technology, a new open source and cross-platform framework from Microsoft [15].

For simulation of control rods, i.e. shim rods, safety rods, and automatic regulating rod, a linear interpolation method was used to calculate insertion reactivity based on the current position of each control rod in the reactor core. An excess reactivity lookup table for DNRR’s core configuration on December 28, 2011 was used as known data points. Another linear interpolation was also applied to the module for feedback reactivity calculation due to the Xenon poisoning effect. Calculation and experimental data of reactivity compensation of Xenon poisoning effect was used for the interpolation. In terms of reactor protection features, the control module can simulate the generation of warning and emergency signals of reactor overpower, fast period, or abnormal technological parameters in accordance with safety system settings of DNRR.

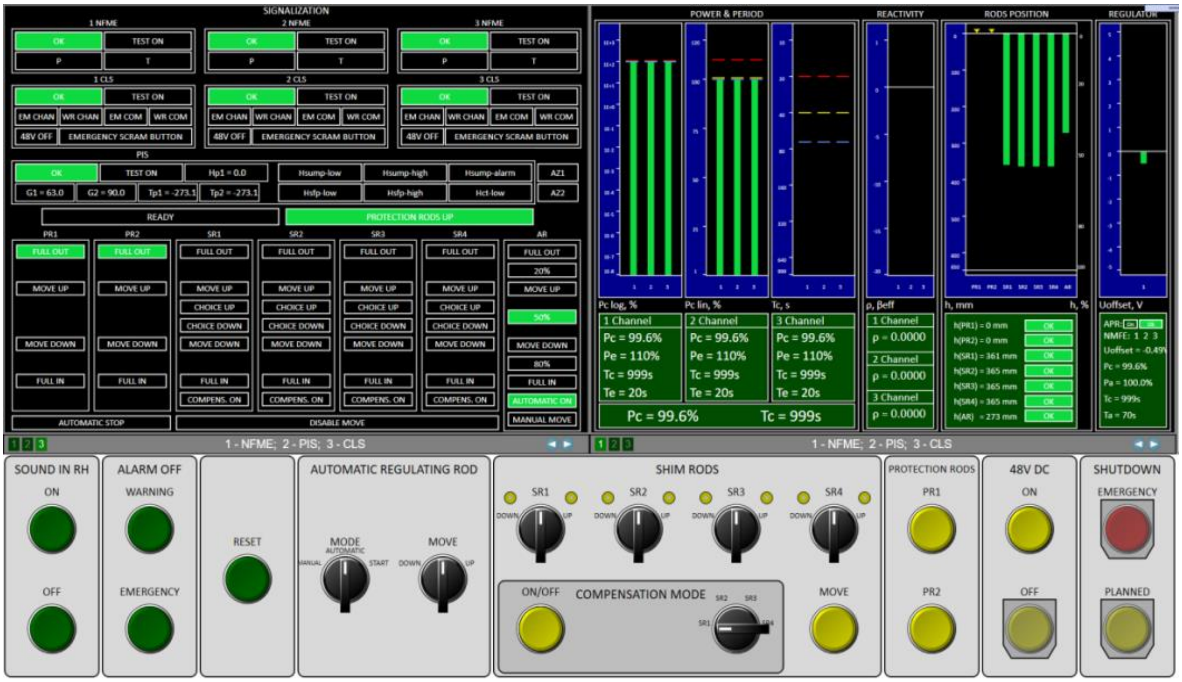

Fig. 2. The control panel and two parameter monitors of HMI module

C. HMI module

- Windows Presentation Foundation (WPF), which is a powerful Microsoft's user interface framework, was chosen to develop the HMI due to its flexible graphical programming features [16]. This technology has not been ever used to construct front ends for nuclear reactor simulators in the world. The HMI was designed to be as identical as possible to the real control panel of DNRR. All design formats and functions of each component were retained on the HMI for fidelity. Figure 2 displays a portion of the module. The module consists of several submodules as follows:

- A control panel section allows users to perform operation actions such as reactor start-up, maneuvering control rods as well as reactor shutdown when accidents occur (Figure 2);

- Three parameter monitors display important operational, technological parameters and status of signals of the reactor control and protection system (Figure 2);

- A panel of threshold setting for operative change of set points of emergency and warning protection by power; preset values of power and period for automatic control;

- A monitor displays trend histograms of important operational parameters for further analysis purposes;

- A monitor allows users to select and launch normal operational and accident scenarios exercises;

- A monitor for user manual.

III. SIMULATOR VERIFICATION

To assess the capability of DalatSim, the verification was performed by simulating a start-up process of DNRR. The start-up process includes changing the reactor from subcritical to critical state; raising the reactor power to required levels of 0.5%, 50%, 80%, and finally 100% of nominal power (500 kW). All operations during the simulation were carried out according to the start-up procedure for DNRR as follows [17]:

- Withdrawing two safety rods in sequence to the top of the reactor core;

- Setting the automatic control values of power and period to 0.5% and 70 seconds, respectively;

- Changing the reactor from a deeply subcritical to the critical state by withdrawing shim rods;

- Raising reactor power to the power level of 0.5% using manual mode of automatic regulating rod;

- Maintaining reactor power at the power level of 0.5% using automatic mode of automatic regulating rod;

- Raising reactor power to the power level of 50% by the steps below.

  - Setting the set points of emergency power to 10% higher than the required power level;

  - Setting the automatic control values of power to the required power level;

  - Controlling automatic regulating rod in manual mode to raise reactor power to the required power level so that reactor period is not lower than 70 seconds;

  - Maintaining reactor power at the required power level using automatic mode of automatic regulating rod.

- Waiting for the reactor to work for 5 minutes at the power level of 50%;

- Raising reactor power to the power level of 80% by performing similar steps above;

- Waiting for the reactor to work for 10 minutes at the power level of 80%;

- Raising reactor power to the power level of 100% by performing similar steps above.

The calculational power result given from DalatSim was compared with a set of operational data of reactor power for a real start-up process of DNRR. The operational data was extracted from a module called archiving, diagnostic, and recording (ADR) equipment of the reactor control and protection system of DNRR. The start-up process of interest lasted 3290 seconds, started from 8:00:10 A.M to 9:00:00 A.M on June 10, 2019.

IV. RESULTS AND DISCUSSION

The comparison between calculational reactor power results obtained from DalatSim and operational data for the start-up process is presented and discussed in this section. Table I shows differences in the time to acquire each required power level. Table II presents the waiting duration at the power level of 50%, 80% of nominal power. Figure 3 illustrates the curves of reactor power from the simulation and operational data.

The time to reach each required power level and the waiting duration at power levels of 50%, 80% of nominal power depend on the operator's experience. In reality, the operator operated the reactor with higher reactor period for safety purpose that results in longer time to reach the power levels as shown in Figure 3. In our simulation, the simulator was manipulated with lower reactor period but still higher than 70 seconds, which obeys the start-up procedure for DNRR.

Figure 3 also shows that the reactor power curves are not exactly the same but their shapes are similar. That demonstrates the real-time simulation of a start-up process of DNRR can be achieved with DalatSim. The simulator can automatically maintain the reactor power at each required power level as expected as illustrated clearly in Figure 3.

Table I. The time (in second) to acquire required power levels

Power level	0.5%	50%	80%	100%
Simulation result (s)	1400	1800	2160	2820
Operational data (s)	1610	2165	2590	3036

Table II. The waiting duration (in second) at required power levels

Power level	50%	80%
Simulation result (s)	300	600
Operational data (s)	333	371

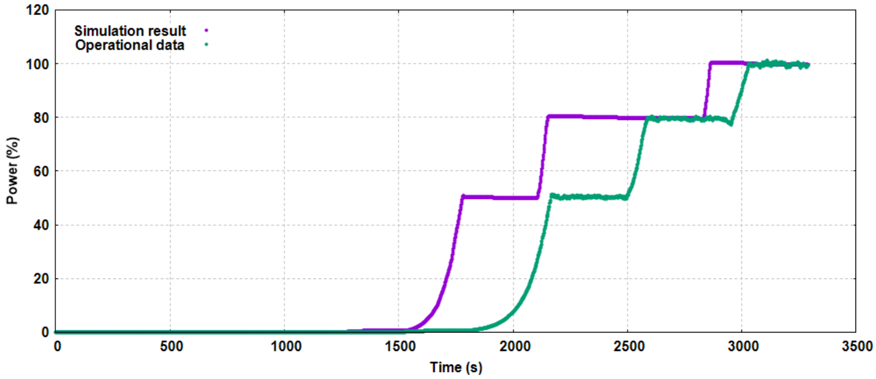

Fig. 3. The comparison between simulation result and operational data

V. CONCLUSIONS

The verification result shows that the computational capability of DalatSim can meet the requirement of real-time transient simulation of DNRR. The verification also demonstrates DalatSim can be a suitable tool to effectively support the operator training and nuclear education for trainees from VINATOM subsidiary units as well as local university students. Moreover, the research to build this simulator is an active contribution to the development of nuclear research reactor modeling and simulation capabilities in Vietnam in the future.

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ACKNOWLEDGMENT

This research has been performed within the framework of a project encoded “DTCB. 03/18/TTHN”. The authors express their thanks to the Ministry of Science and Technology of Vietnam (MOST) for the financial support and CNT for assisting us to carry out this research. We are grateful to the collaborative researchers and operators in the Dalat Nuclear Research Institute (DNRI) for their useful help.

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