PC BASED RESEARCH REACTOR SIMULATOR

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ABSTRACT

A real time research reactor simulator was developed at the Jožef Stefan Institute. It's primary goal is to help educate students and future reactor operators, especially in countries with limited or no access to a research reactor. The RR simulator simulates time behaviour of reactor power, fuel temperature and reactivity by using the 6 group point kinetics equation. It features temperature feedback mechanisms as well as Xe poisoning. It has 6 modes of operation (manual, pulse, automatic, 3 patterns reactivity insertions – step, sine, saw tooth) and is very flexible, as practically all physical parameters can be adjusted. Its main advantages compared to other simulators are; high degree of flexibility, user friendliness, robustness, high speed, support for many platforms.

1. Introduction

Research nuclear reactors are among others commonly used for education and training of nuclear power plant (NPP) personnel, research reactor (RR) operators, students of physics, nuclear engineering and similar [1-4]. However not all countries and educational institutions have direct access to research reactors. Hence they should either host at one of the existing research reactors or use simulators. There are several NPP simulators available in the market, from PC based to full scope, however there are only few research reactor simulators. The world's first PC based TRIGA research reactor simulator is developed by the Microsimtech company [6]. It is intended for education of reactor principles on the concept of delayed neutron effect, multiplication factor, criticality, control by rods and boron concentration, feedback on fuel (Doppler) and moderator temperatures, Xenon and Samarium poisoning. Another type or research reactor simulator is a simulator featuring console for moving the control rods and small display for reactor data display developed by the Czech Technical University. Their disadvantage is relatively low degree of flexibility in the sense of adjusting simulators parameters, such as delayed neutron fraction, mean neutron generation time, control rod worth curves, control rod insertion velocity, various modes of operation, etc. In other words, they serve well as a tool to get familiar with reactor operation and behaviour but with less attention to reactor physics. Hence it was decided at the Jozef Stefan Institute (JSI) in Ljubljana, Slovenia to develop a research reactor simulator focusing on reactor physics. Our goal is to develop PC based low power ($P < 1$ MW) research reactor simulator for countries/institutions with no or limited access to real RR. In countries with easy access to RR it can be used for class-room presentation of RR experiments prior to the real reactor. The requirement was, it should be robust, fast, flexible and user friendly.

The JSI operates a 250 kW TRIGA research reactor, which was used as a starting point and for validation purposes. However, due to above mentioned flexibility, the simulator is general and can be applied to other RRs as well

The paper is structured as follows; in section 2 the physics of simulator together with validation of models is presented, section 3 describes simulator features and section 3 present the simulator and implementation.

2. RR simulator physics

2.1 Time behaviour

The simulator essentially simulates time behaviour of reactor power, fuel temperature and reactivity and uses inserted reactivity by control rods as input parameter. Time behaviour of reactor power is calculated by using the 6 group point kinetics equation. These are solved by Fourth stage Runge-Kutta integration in a 1 ms time step. All physical parameters such as delayed neutron fraction, mean neutron generation time, decay constants and fractions of delayed neutron precursors can be easily changed by the user.

2.2 Temperature feedback effects

The TRIGA reactor can operate in three power regimes based on the effect of temperature feedback on reactivity:

- **Neutron source regime** - Power is lower than 10 mW and the neutron population is determined by neutron source intensity.
- **Low power** – below point of adding heat. Population of neutrons that are produced by fission is much greater than the one produced by the neutron source, but the power is too low to measurably heat up the moderator.
- **High power** -The reactor dynamics is dominated by thermal feedback effects on reactivity.

At high power the reactivity is reduced due to negative temperature reactivity coefficient, α_T. Currently the α_T is fixed and relates to fuel temperature only, however in the future versions of the simulator, it will be adjustable. Moreover it could be temperature dependent. The temperature effect on reactivity is described by

$$\rho(T) = \rho_0 - \alpha_T T$$

The relation between the power of the reactor and temperature of the fuel is calculated by two models, one used for normal power operation, i.e. up to 1 MW and one for pulse mode operation.

In pulse mode operation the adiabatic model is used for calculating the fuel temperature and can be described by

$$T_f\ (t_0 + \Delta t) = T_f(t_0) + \Delta t \frac{P(t_0)}{C_f}$$

where $T_f(t_0)$ is temperature of the fuel at time $t = t_0$,

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Δt = time interval

$P(t_0)$ = reactor power at time $t = t_0$

C_f = heat capacity of the fuel

At normal operation the temperature of the fuel depends on the power of the reactor, fuel design and mode of cooling (natural convection or forced cooling). As these relations are very complex and depend on many variables, it was decided to use the relation that corresponds to the standard TRIGA fuel elements and is used in TRIGA core design tool TRIGLAW [8]. The temperature of the TRIGA fuel cooled by natural convection at steady state conditions as a function of fuel element power can be described as

$$T_{s,f} = a_1 P_{el} + a_2 P_{el}^2 + a_3 P_{el}^3 + T_{s,water}$$

where $T_{s,fuel}$ is stationary temperature of the fuel, P_{el} is power of a fuel element, $T_{s,water}$ is stationary temperature of water surrounding the fuel element, and a_i (i=1,2,3) are empirically obtained coefficients. Using this model the dependence of stationary temperature on reactor power in stationary conditions is consistent with reactor behaviour in the range from 0 W to 300 kW, but the transitions dynamics are not correctly simulated. In reality, the fuel temperature does not reach the steady state immediately, but only after the power generated by fission becomes equal to the power that leaves the system by heat removal (mainly conduction). This effect can be simulated by introduction of an asymptotic approach to the stationary temperature $T_{s,fuel}$ using

$$T_f\ (t_0 + \Delta t) = \Delta t C\ \left(T_f(t_0) - T_{s,f}(t_0)\right)$$

where C is a constant obtained by fitting the above equation to experimental values.

2.3 Xenon poisoning

Xenon poisoning was modelled by solving the differential equations describing ^{135}I and ^{135}Xe concentrations and then calculating the effect of ^{135}Xe on reactivity by

$$\Delta\rho_{Xe} = -\frac{\sigma_a^{Xe} X(t)}{\Sigma_a}$$

where X(t) is Xenon concentration [8]. Combined effect of fuel temperature and xenon on reactivity is calculated as

$$\rho(T) = \rho_0 - \alpha_T T\ - \Delta\rho_{Xe}$$

2.4 Physics validation

Efforts were made to validate the simulator against experiments or other software. Firstly we validated modelling of point kinetics equations by using the digital reactivity meter - DRM [10]. The digital reactivity meter was sampling the neutron flux signal from the simulator and the calculated reactivity was compared with the input reactivity to the simulator. Comparison of inserted and DMR calculated reactivity for step reactivity change is presented in Figure 1. It can be seen that that in stationary conditions the difference is lower than 10^{-9}. During the transient the

differences are larges mainly due to different sampling time of the simulator and DMR. The latter has sampling time of 1.43 s.

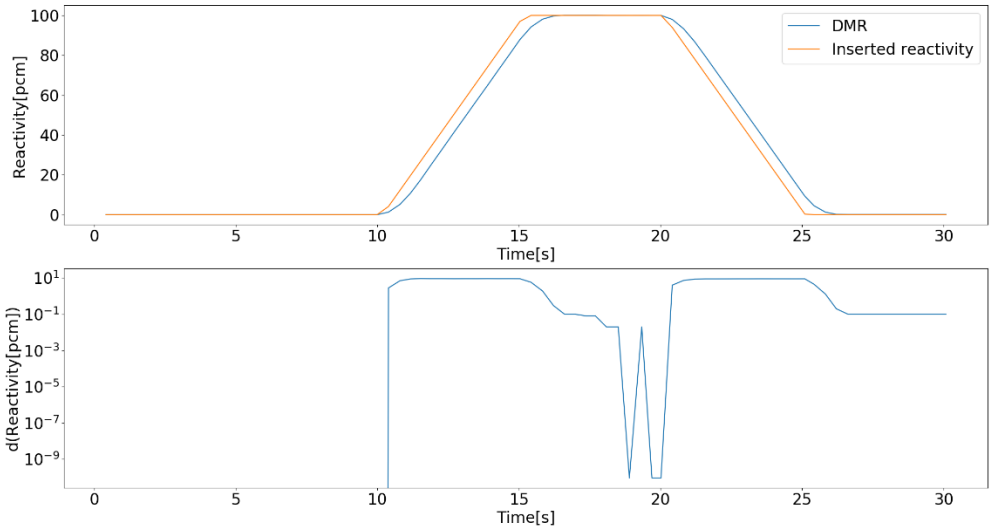

Figure 1: Comparison of input reactivity and reactivity calculated by DRM (above) and the difference between them (below).

The operation in pulse mode was tested by comparing the full width at half maximum (FHWM) and maximum values of the reactor power time dependence during a pulse. A comparisons of the maximum power reached during a pulse at given reactivity calculated by the simulator to the one reached during experiments is presented in *Figure 2*. Relatively good agreement is observed indicating that the simulator describes well the pulse mode operation.

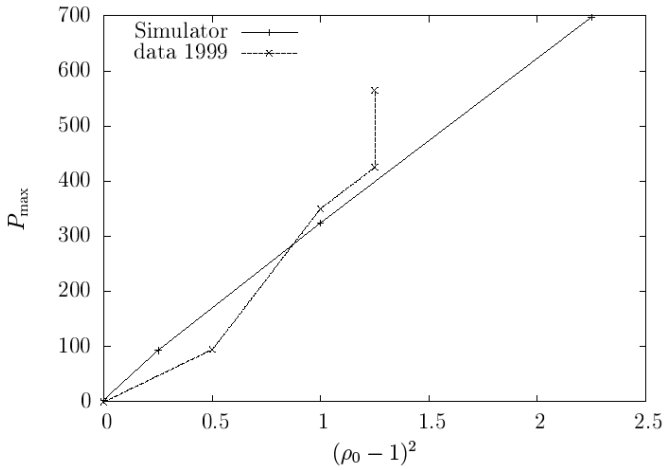

Figure 2: Comparison of maximum power achieved during simulated pulses with experimental data.

3. RR simulator implementation

The simulator is written in C++ and uses a modified version of the Nanogui [7] library to draw the graphical user interface (GUI) and simulation results. The modifications include performance improvements needed to draw the simulation results in real time with a frame rate higher than 30fps and introduction of new graphical elements not available in the original Nanogui library. NanoGUI is a minimalistic cross-platform widget library for OpenGL 3.x or higher. High performance and low RAM usage was achieved also by implementing fixed-length-element circular buffer.

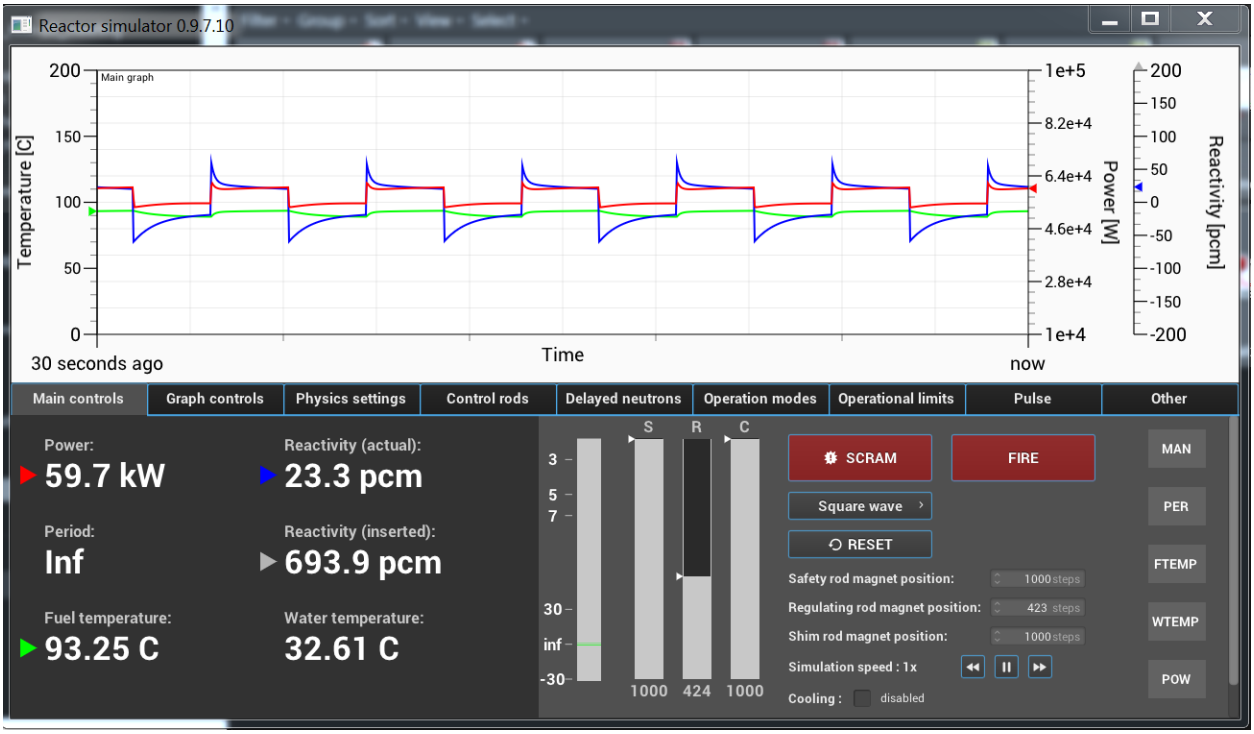

Figure 3: Graphical user interface of the research reactor simulator.

Its main advantages with respect to the RR simulator are the following: it is open source (no need for paying expensive license fees), it is general and can be applied to any platform (Windows, Macos, Android,etc.), the interface does not pose significant load on the processor allowing the user to run the simulator at 1000 the speed of real time and to make on the fly changes of any of the parameters in the simulation.

4. RR simulator features

The research reactor simulator has several unique features, which are presented in this section. The upper part of the GUI is devote to the graph presenting reactor power (P), fuel temperature (T) and reactivity (ρ) versus time. The user can change the display size, time interval as well as range of T and ρ. The power range is adjusted automatically so power level of the reactor is always displayed.

Below the graph window, there are several tabs allowing the user to operate the reactor and change various parameters and settings; main window, graph controls, physics settings, control rods, delayed neutrons, operation modes, operational limits, pulse mode and other.

The main control window contains numerical values of power, period, fuel and water temperature as well as inserted and actual reactivity. In addition to this the control rod positions and reactor period are displayed graphically. There are three control rods (CR) that can be moved individually, safety (S), regulating (R) and compensating (C). The user can change the position of the control rods by arrow keys (rod letter + ↓ or ↑) or by setting (typing in) the desired position. Control rods can be moved simultaneously or individually. In addition integral rod worth as well as the shape of differential CR worth can be adjusted for each of the CRs. Rod velocity and number of steps can also be adjusted. Rod worth curves can be exported as an ASCII text file.

The RR simulator features five modes of operation:

- **Manual** – in this mode the user can move all control rods individually
- **Square wave** – the inserted reactivity has the shape of a square wave. Magnitude, period and shape of a square wave can be adjusted
- **Sine wave** – the inserted reactivity has the shape of a sine function. Magnitude, period and shape of a square wave can be adjusted
- **Saw tooth** – the inserted reactivity has the shape of a saw tooth function. Magnitude, period and shape of a saw tooth can be adjusted
- **Automatic** – the movement of the regulating CR is adjusted in such a way, that constant predefined reactor power is maintained. In addition the user can set the desired power level, which is then achieved and maintained by the simulator itself.
- **Pulse** – in pulse mode the user can shoot the regulating rod out of the reactor

The RR simulator also features SCRAM button and scram signal, which causes reactor trip or immediate insertion of all control rods. The reactor scram is induced by the following signals, period, power, fuel temperature, water temperature. The value of the scram signal can be individually adjusted. Moreover the scram signals can be individually disabled.

The physics settings include:

- delayed neutron fractions and decay constants for 6 groups of delayed neutron precursors
- enable/disable temperature feedback
- excess reactivity
- water cooling power
- neutron source intensity
- prompt neutron lifetime

All of these settings can be adjusted individually and on the fly, i.e. while the RR simulator is running. Hence the effects are immediately observed.

For studies of delayed neutron precursor's behaviour, the RR simulator has a feature of plotting deviation of delayed neutron precursor's concentration from the stationary values.

The user can save or load its settings to a file. A hardware console with buttons (mode selector and control rod drive buttons) has been developed to allow operation of the simulator without keyboard. The console connects to the PC via USB port.

5. Future plans

In the future we plan to improve the thermo dynamical model and develop a cooling model that would accurately describe cooling of the fuel elements in the power range from point of heat to the maximum power in continuous operation in point kinetics approximation. Such model could eliminate the need of using a semi empirical polynomial to model stationary fuel temperature during continuous operation.

In the near future the temperature feedback via temperature reactivity coefficient would be adjustable by allowing user to define temperature dependent temperature reactivity coefficient.

We also plane to include water boiling and evaporation from the tank, which would lead to increased dose rates above the reactor.

Currently the spatial effect of neutron flux redistribution due to control rod movement are not taken into account. In the future we plan to couple 3D Monte Carlo neutron transport calculations with the RR simulator and visualise 3D neutron flux and power distributions.

6. Conclusion

The RR simulator is a great tool for studying reactor physics of research reactors. It can be used as an educational and training (E&T) tool for better preparation before real reactor practically exercises or as an E&T tool instead of a real reactor. Having a possibility of changing so many reactor parameters, makes using this simulator very versatile. Although it was designed based on the experience on TRIGA reactors, it can be easily applied to other research reactors.

The RR simulator can be used for performing basic reactor physics exercises, such as:

- Subcritical multiplication, 1/M diagram
- Reactor response to reactivity changes (step, sin, saw tooth)
- Reactor feedback
- Control rod worth calibration (rod swap method)
- Pulse experiment
- Power calibration
- Delayed neutron studies
- and more

Its main advantages compared to other simulators are; high degree of flexibility, user friendliness, robustness, high speed, support for many platforms.

The RR simulator has undergone of 1 year of testing and development and is ready to be released. Currently it is in the process of being patented together with a hardware console. Demo version of the simulator can be obtained from the RR simulator webpage [11].

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