Microreactor Simulation Performance Analysis for Real-Time Hardware-in-the-Loop Testbed[1]

Jono McConnell,* Pradeep Ramuhalli,* and Wesley C. Williams,*

*Oak Ridge National Laboratory, Oak Ridge, TN, mcconnelljh@ornl.gov
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INTRODUCTION

Considering the expected deployment of microreactors in remote areas, the need to maintain high-capacity factors on demand, and the need to manage operations and maintenance (O&M) costs to mitigate some of the loss of economies of scale [1], a key aspect of microreactor research is the automation of operations [2]. The use of technologies to increase the level of automation in control and operation of microreactors can potentially enable faster decision-making in operational modes with characteristics different from those used in the current fleet. A further benefit of these automated control systems is the ability to respond quickly to abnormal conditions (such as failure of one or more components) to ensure that the plant remains in a safe condition.

In collaboration with Idaho National Laboratory (INL), Oak Ridge National Laboratory (ORNL) has been supporting the development of a robust, high-fidelity microreactor automated control system (MACS) that requires minimal human-in-the-loop action. This work leverages prior research outcomes on automated control systems and autonomous supervisory control systems [2, 3, 4], existing concepts for microreactors, and available testbeds [5], with the goal of demonstrating automated controls using the MACS hardware-in-the-loop (HIL) testbed.

Development and deployment of an HIL testbed demands cooperation between multiple technologies: dynamic reactor modeling, data communication, and hardware response. This document outlines the current state of MACS development and presents a study on the balance of real-time simulation and external input update rate for a dynamic Modelica microreactor model.

MODELICA MODEL

A Modelica model of a reference microreactor concept was created using the TRANSFORM library [6, 7]. A schematic of the model is shown in Fig. 1. This model captures the thermohydraulic effects of a NaK primary coolant loop to approximate the geometry and performance of a sodium-cooled microreactor. The model includes reactor point kinetics—the coefficients for which were derived from higher-fidelity models in RELAP [8]—for simulating the behavior of the reactor at different power levels. Initial tests with a proportional–integral (PI) control algorithm have demonstrated the strong stability characteristics of the natural convection design of the primary coolant; however, these tests controlled reactivity insertion directly, with no delay in control action. Implementation in an HIL testbed will provide a realistic environment for developing robust control strategies with control drum dynamics and hardware-related delays. This effort will also provide the opportunity to explore realistic failure modes that can inform robust control design.

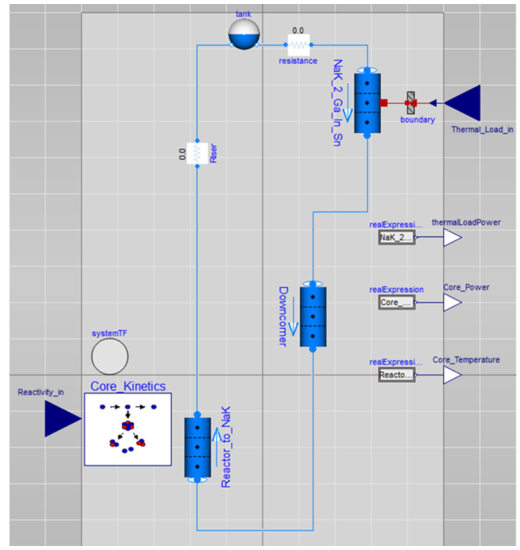


Fig. 1. A Modelica model capturing the natural convection and thermohydraulic behavior of a reference microreactor primary coolant loop and reactor core [7].

The model was exported as a Functional Mock-up Unit (FMU) for FMPy simulation in Python [9] employing a DASSL solving method provided by the Dymola Modelica software environment [10]. This approach allows for flexibility in applying alternative control algorithms and communicating with hardware for HIL simulation, which is discussed below.

LABVIEW INTEGRATION

The MACS hardware at INL employs a LabVIEW environment exploiting the software's innate ability to interface with hardware and to control various integrated actuators. The hardware system includes motors to move control elements (control drums) and lighting control for simulated power visualization [5]. Classical control techniques (PI, proportional–integral–derivative, etc.) are utilized for low-level control of hardware elements. At present, the physical system focuses on the reactor core with control drum mockups modulating the simulated reactivity insertion and consequently the simulated reactor power. The hardware platform requires the final drum position and the associated reactor power level; the lighting levels are then adjusted to mimic the change in the reactor

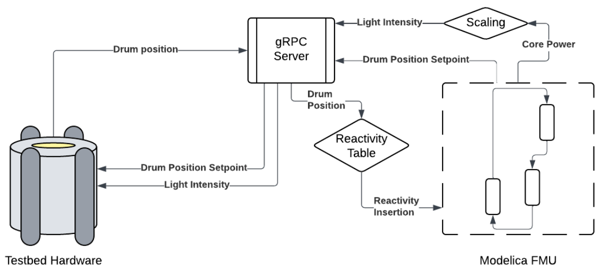


Fig. 2. MACS gRPC communication for HIL simulation.

power. The actual estimation of the reactor power levels is done in simulation, as is the heat removal from the core by the coolant system (the "plant"). For the present work, the Modelica model described earlier is used for testing the integration with LabVIEW, though other models may be explored in future work.

A gRPC protocol [11] was implemented in a LabVIEW environment to simplify integration of external software elements for demonstrating control automation or other aspects of microreactors. A visualization of gRPC communication is provided in Fig. 2. For the purposes of testing gRPC communication, a LabVIEW-based simulator developed by INL was used. The LabVIEW simulator acts as the gRPC server and mimics the HIL functions. Note that the gRPC server acts as the intermediary between the control algorithms and the HIL testbed, passing commands sent by the control algorithm to the HIL actuators, and sending status information on the actuators and the HIL testbed to the control algorithms. Successful integration and communication with this LabVIEW simulator will ease future integration with the HIL testbed, as the underlying LabVIEW modules are similar and include gRPC server functionality for interacting with the hardware components. Transition from the simulated environment to a true HIL configuration will, however, pose a valuable challenge, generating insights on overcoming signal delay and control drum dynamics in the deployment of a robust system control algorithm.

To ensure proper communication and cooperation between all three layers of the system, it is necessary to investigate the optimal time step for FMU simulation, which is necessary to maintain a faster-than-real-time processing speed for robust HIL interfacing. The results of this effort are presented in the following section.

SIMULATION PERFORMANCE ANALYSIS

A study was performed to analyze the range of usable external-input update frequencies for real-time FMU simulation. For control implementation, more frequent input updating will allow for increased responsiveness of the control algorithms; however, an increased update rate can increase processing requirements, thereby reducing the real-time capability of the simulation. Four update rates of differing magnitude have been explored to gain insight into the trend of increasing processing time with increasing update rate: 1, 10, 100, and 1000 Hz. Two transient scenarios were considered: ramp and sinusoidal change in reactivity insertion. A PI control was applied to force the modeled system to equilibrium at a steady 85 kW power output. It was found that the steady-state external reactivity insertion necessary was approximately −\$0.02. This steady-state settling was conducted in the first 100 simulated seconds. The system was allowed to proceed in an open-loop manner in response to the changing inserted reactivity for the remaining 100 seconds of simulation. The inserted reactivity was constant between updates.

For the ramp reactivity dynamics, a \$0.001 increase was applied, with a constant slope from 100 to 150 simulated seconds. From 150 to 200 simulated seconds, a \$0.002 decrease was applied with a constant slope. The power and temperature responses of the system updated at the four chosen frequencies are displayed in Fig. 3.

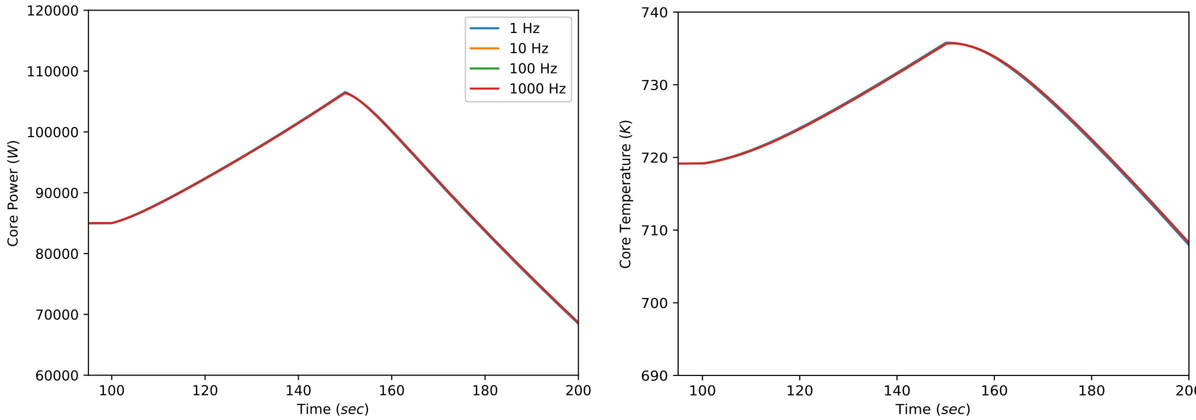
For the sinusoidal reactivity dynamics, a sinusoidal reactivity insertion was applied, centered around the steady-state reactivity insertion value with an amplitude of \$0.001. An oscillation at a frequency of 0.4 Hz was applied from 100 to 150 simulated seconds, followed by a frequency of 0.1 Hz from 150 to 200 simulated seconds. The power and temperature responses of the system updated at the four chosen frequencies are displayed in Fig. 4.

Visually, the trends displayed in Figs. 3 and 4 show strong agreement in both value and timing of response. The goal of this analysis is to provide a metric that can be used to select the appropriate update frequency for real-time dynamic simulation with HIL integration. It is necessary to compare the difference in the response of the model with coarse input changes to the response under continuous input reactivity adjustment. Table I displays the average error of the three lower frequency simulations compared to that of the 1000 Hz simulation. Additionally, a normalized percent error is also provided in the form of Eq. (1).

$$\%Error = 100 * \frac{\sum_{i=1}^{n} |P_i^{'} - P_i|}{nP_{ref}} \tag{1}$$

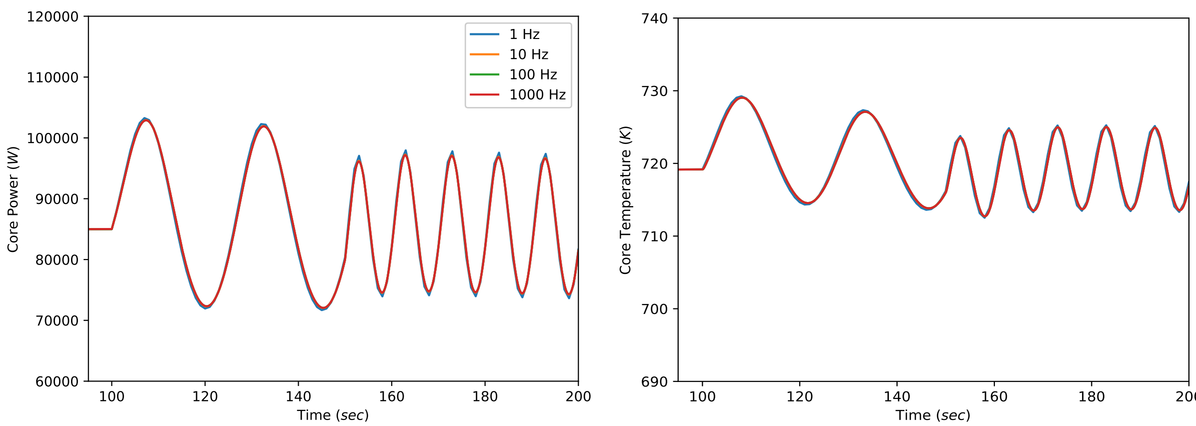
where P_i is the power at each time step for a given update frequency, $P_i^{'}$ is the power of the 1000 Hz simulation at the same corresponding simulated time, n is the number of time steps taken for the lower frequency simulation over the final 100 seconds, and P_{ref} is the nominal steady-state power of 85 kW. Here, 1000 Hz more closely represents the ideal case of continuous reactivity change. Table I shows a noticeable trend of deviation from the 1000 Hz simulated power response as the coarseness of inputs increase. The average magnitude of this deviation, however, is consistently below 1% of the nominal steady-state power, suggesting that the thermodynamic inertia of the system provides a sufficient filtering effect, even for the coarse 1 Hz input update rate simulations.

Table II displays the average processing time necessary to simulate the final 100 seconds of each trial for the three lower update frequencies. All speed tests were performed on an HP Z2 Mini G3 Workstation with Intel Core i7-7700 CPU and 32 GB RAM under similar background load. Three trials were performed at each update rate, and minimal variation was observed. It was found that the 1000 Hz simulations were significantly slower than real time and are thus undesirable for HIL integration.



(a) (b)

Fig. 3. Response of the FMU at 1, 10, 100, and 1000 Hz simulation update rates to \$0.001 ramp increase from 100 to 150 seconds and a \$0.002 ramp decrease from 150 to 200 seconds: (a) core power and (b) core temperature.



(a) (b)

Fig. 4. Response of the FMU at 1, 10, 100, and 1000 Hz simulation update rates to \$0.001 amplitude sinusoidal input about steady-state reactivity insertion with frequency of 0.4 Hz from 100 to 150 seconds and 0.1 Hz from 150 to 200 seconds: (a) core power and (b) core temperature.

TABLE I. Average error and percent error normalized by 85 kW nominal power level for 1 Hz, 10 Hz, 100 Hz simulation update rates compared to reference 1000 Hz simulation update rate.

	1 Hz		10 Hz		100 Hz	
Ramp	137.6 W	0.162%	13.79 W	0.016%	3.401 W	0.004%
Sine	531.5 W	0.625%	55.29 W	0.065%	17.15 W	0.020%

TABLE II. Average simulation time for three trials of FMU simulation at 1, 10, and 100 Hz; 1000 Hz simulation was significantly slower than real time and has been omitted for brevity.

	1 Hz	10 Hz	100 Hz
Ramp	10.65 sec	61.58 sec	368.1 sec
vs. Real Time	9.39×	1.62×	0.27×
Sine	13.46 sec	73.75 sec	417.5 sec
vs. Real Time	7.43×	1.36×	0.24×

The processing speed of the employed DASSL solving algorithm is highly dependent on the transient behavior of the modeled dynamics: the closer to steady state, the faster the time step is solved [10]. Rather than selecting a single update frequency for all simulations, it may be necessary to inform simulation time step selection based on the expected severity of the transient response. Furthermore, it is important to consider this dynamic processing time change as an argument against overly aggressive control; any chattering will significantly reduce the speed of the simulation.

Figures 3 and 4 as well as Table I show minimal change in dynamic response in simulations as coarse as 1 Hz for reactivity insertions of similar magnitude to those explored in this study. It should be noted that increased time step size increases the likelihood of numerical instability: some minor numerical oscillations occurred in the PI-controlled settling of the system for the 1 Hz simulations, which suggests that a higher update rate should be selected. Table II shows that the 100 Hz cases could not maintain real-time simulation. Therefore, an update rate on the order of 10 Hz should be considered for simulation of the microreactor FMU for real-time deployment.

CONCLUSIONS

A microreactor control testing environment is under development in the form of an HIL testbed as part of a collaboration between ORNL and INL. A Modelica model has been generated to serve as a representative microreactor design for the purpose of simulating reactor kinetics and plant heat extraction. A LabVIEW/gRPC control and data communication environment has been developed by INL to facilitate the interaction of simulated physics and hardware response.

Two test cases were investigated to explore the real-time simulation capability of the developed Modelica model at differing magnitudes of external input update rate. The transient response of the system to a ramp and sinusoidal change in inserted reactivity was analyzed. It was found that an update rate of 10 Hz was satisfactory for all explored metrics. Further robustness with respect to faster-than-real-time simulation can be achieved at lower simulation update rates; however, coarse input adjustment rates can increase the likelihood of numerical instability in more aggressive transient dynamics. Therefore, the simulation update rate should be adjusted on a case-by-case basis to provide the maximum accuracy while maintaining real-time simulation.

Future work will explore the added time delay of gRPC communication as well as the limitations of hardware dynamic response as is relevant for developing robust control algorithms.

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