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A DIGITAL TWIN-BASED SIMULATOR FOR SMALL MODULAR AND MICROREACTORS

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ABSTRACT

This paper presents the development and implementation of a mechanistic/physics–based Digital Twin (DT) simulator for a conceptual 4.5 MWth Lead-cooled Fast Reactor (LFR). The simulator leverages the MQTT protocol and MATLAB’s App Designer to enable real-time visualization and interaction with the reactor’s operational parameters. The system’s Graphical User Interface (GUI) mimics a reactor control room, facilitating risk-free experimentation, design visualization, testing, and optimization. The integration of virtual sensors and the ThingSpeakTM platform allowed for the seamless transition to real-time data streaming and analysis, enhancing the simulator's utility for training and visualization/demonstration of operational transients.

1 INTRODUCTION

The pressing need for zero-emission technologies to combat climate change has intensified interest in nuclear energy, a reliable and eco-friendly power source that does not emit greenhouse gases. In response, the International Atomic Energy Agency (IAEA) has advocated for the accelerated deployment of Advanced Small Modular Reactors (SMRs) and Micro Reactors (MRs) through the 14th Generation IV International Forum (GIF). These reactors, characterized by **lower initial capital costs**, **shorter construction times**, **scalability**, **enhanced safety**, and **compatibility with small grids**, are poised to serve diverse applications, including industrial heat generation and electrification of remote areas.

However, the complexity of these novel technologies necessitates advanced technical expertise for their development and maintenance. Digital Twins (DTs) offer a promising solution by enabling **design visualization**, **testing**, and **system optimization**. This paper therefore presents preliminary work on a mechanistic/physics-based DT model for Generation IV reactors, focusing on a 4.5 MWth Small Modular Research Lead-cooled Fast Reactor (LFR). This mechanistic/physics-based approach is recommended to utilize the extensive experience and understanding of nuclear reactor systems, with potential augmentation through model-free techniques (Kochunas and Huan, 2021).

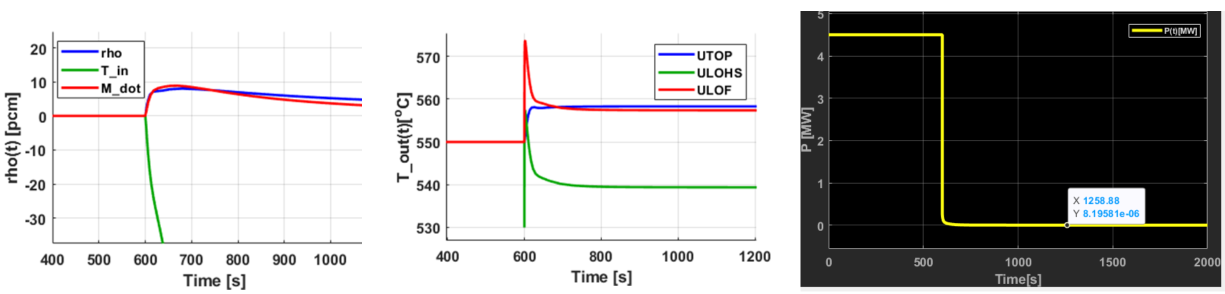
The LFR, conceptualized and designed at Texas A&M University's Department of Nuclear Engineering, aims to be an ultra-safe research reactor. It integrates elements from various Gen IV LFR families (Alemberti et al., 2020) and is designed to be installed at the university's Nuclear Engineering Science Center (NESC) alongside the existing 1 MWth TRIGA reactor. The innovative design allows the LFR to drive the TRIGA reactor, creating a Fast and Thermal (FAT) Neutron Spectra Research Reactor, thereby enhancing research and isotope production capabilities.

2 MATERIALS AND METHODS

As mentioned above, the case study involved a 4.5 MWth LFR, designed to be ultra-safe by integrating features from existing LFR families. The Neutronics Thermohydraulic Coupling (NTC) model, which is a system of ordinary differential equations (ODEs), was implemented to represent the reactor's behavior. The simulator was built on a modular architecture using SIMULINK and MATLAB’s App Designer, allowing for the addition of new modules without disrupting system performance. MQTT protocol was employed to facilitate real-time data communication, while ThingSpeakTM served as the virtual sensor platform. This setup enabled the streaming of recorded simulation data into and from the simulator, mimicking real-time operational scenarios. The simulator's ability to simulate various accidents, including uncontrolled transient overpower (UTOP), uncontrolled loss of heat sink (ULOHS), and uncontrolled loss of flow (ULOF) was demonstrated.

3 RESULTS AND DISCUSSIONS

This DT-bases simulator demonstrated the capability to visualize and interact with operational transients both as a stand-alone simulator and in real-time using MQTT. This real-time interaction is crucial for training purposes and operational testing. The system's GUI (not shown here for brevity) mimics a reactor control room, facilitating risk-free experimentation, design visualization, testing, and optimization. As shown in **Figure 1 (a, b & c)**, the benchmarking tests validated the model against known behaviors reported in the literature (Colombo et al., 2010; Lorenzi et al., 2013), thus, confirming the reliability and accuracy of our DT model. The system maintained a constant power and temperature during steady-state conditions, with expected impulse responses under step inputs. These results align with those reported for the ALFRED reactor, validating the DT model's performance. Finally, the reactor's response to a SCRAM (safety control rod actuation mechanism), demonstrated the system's ability to safely shutdown



(a) (b) (c)

Figure 1: Reactor response showcasing (a) Sensitivity analysis; (b) Transient analysis; and (c) SCRAM.

4 CONCLUSION

This study successfully demonstrated the feasibility of a mechanistic/physics-based DT for a 4.5 MWth LFR. Future work will focus on integrating AI-driven techniques to further enhance the system's predictive capabilities. The DT model offers a promising tool for improving the safety and efficiency of next-generation nuclear reactors.

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