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Operator Assistance Framework for Heat Pipe Cooled Microreactor using Domain-Specific Language Model

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1. Introduction

Recent advances in energy system deployment have revealed limitations of conventional large-scale nuclear reactors for flexible and distributed operation. Dependence on centralized power grids, high capital investment, and complex active cooling systems restricts applicability in remote or infrastructure-limited environments including data centers. Therefore, microreactors have been considered for off-grid power generation, emergency energy supply, military applications, and space utilization. Heat pipe cooled microreactors enable core heat removal utilizing phase change heat transfer while preserving structural simplicity and transportability. Based on the experience from space reactor development, heat pipe cooled concepts have emerged as a representative configuration for microreactor deployment.

Considering the remote deployment conditions limit continuous human access, reliable condition monitoring is required. Although heat pipes reduce mechanical failure, phase change heat transfer within heat pipes is sensitive to boundary conditions, resulting in variability and instability in thermal performance. Therefore, condition monitoring requirements for heat pipe cooled microreactors would be more strict compared to other microreactor concepts. To address limitations of conventional monitoring, digital twin frameworks and machine learning models have been developed for automated operation and temperature prediction, including predictive control [1-2]. However, operational decision making remains dependent on human operators with variability and cognitive bias despite advanced monitoring capability.In this study, a domain-specific language model is proposed for operational decision support in a heat pipe cooled microreactor. Model development utilized outputs from deep learning models trained using experimental facility datasets. Analysis of operator input and automatic integration of condition monitoring results were enabled, supporting improved operational efficiency.

2. Modeling and Methodology

A digital condition monitoring platform was employed to provide structured facility state information for language model interaction [3]. Figure 1 represents the digital condition monitoring platform. The platform integrates heater temperature measurement and prediction models with component-level and system-level condition classification models to enable multi-layer diagnostic assessment [4-5]. Visualization of the heater temperature field is generated to support evaluation of peak cladding temperature and associated thermal margin. Temporal behavior of heater temperature is provided to assist in the interpretation of operational states and transient characteristics. Component-level classification identifies abnormal components and provides localized diagnostic information, while system-level condition identification represents overall reactor status.Identified fault locations and system states are represented within an integrated interface, enabling structured interpretation of reactor condition and providing monitoring information required for automated decision-support applications.

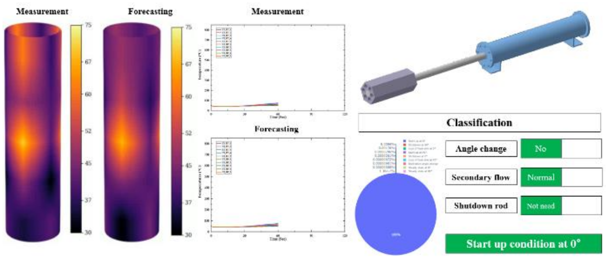

Fig. 1. Digital condition monitoring platform used for development of language model

A domain-specific GPT-based language model was developed to support operational decision making using the monitoring platform derived from reactor information. A pretrained GPT-2 model was adopted and transfer learning was applied using dialogue datasets generated from experimental facility data. The developed language model was designed for utilization under both operator-initiated interaction and autonomous monitoring modes, and the corresponding operational flow is presented in Figure 2. A total of 253 dialogue samples were constructed, with 90% used for training and 10% used for validation. The maximum input sequence length was limited to 512 tokens to enable real-time interaction. To compensate for context length limitations, essential operational information required for reactor condition assessment was selectively propagated across dialogue turns based on trained representations. The model was trained for 50 epochs with a batch size of 3 using the AdamW optimizer and cross-entropy loss.

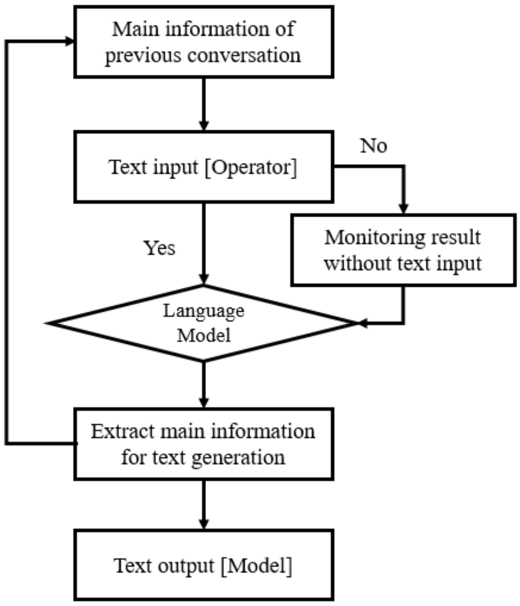

Fig. 2. Flowchart of proposed language model

3. Results and Discussions

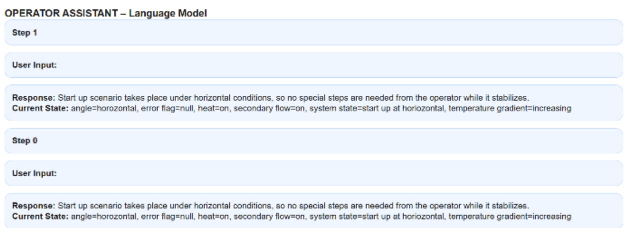

Fig.3. Dialogue of language model under start up condition without user input

Performance of the operator-support discussion model was evaluated through representative dialogue sequences. Figure 3 demonstrates that reactor state information can be processed autonomously by the language model without operator input during startup conditions. Monitoring data generated from the experimental facility are automatically incorporated into the model, allowing interpretation of reactor condition based solely on system-provided information. Operational parameters associated with thermal behavior and system configuration are evaluated, followed by classification of reactor state. Under validated startup conditions, no corrective action is recommended. Automatic incorporation of monitoring-derived information enables continuous assessment of reactor condition without reliance on operator-initiated interaction. Accumulated operational context obtained from preceding system states is utilized to support transition assessment. The presented interaction demonstrates the capability of the language model to perform autonomous interpretation of monitoring results and to provide operational guidance under unattended deployment conditions.

4. Conclusions

Recent interest in remote and unattended operation of microreactors has increased the need for operator assistance methods that reduce cognitive bias in decision making. Therefore, the domain-specific language model was developed to support operational decision making for a heat pipe cooled microreactor by integrating monitoring results generated from previously developed condition monitoring models. Operator support capability was confirmed. In addition, autonomous processing of monitoring-derived reactor information without operator input was also demonstrated, indicating applicability to remote deployment environments. Integration of monitoring information with dialogue-based decision support provides a framework that can enhance operational consistency and support timely operator response during transient conditions, resulting in improved safety of the microreactor.

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