MAT 430 Final Project Report: AI-Enhanced Mathematical Modeling of Neutron Capture in Hybrid Nuclear Reactors

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I. Introduction

A. Topic:

This study focuses on applying artificial intelligence (AI) to enhance mathematical modeling of neutron capture in hybrid nuclear reactors. Hybrid reactors combine nuclear fusion and fission processes to improve energy output and reactor safety. The incorporation of AI enables real-time adaptive modeling, improving predictive accuracy, operational efficiency, and overall safety by continuously adjusting to reactor conditions based on real-time data.

B. Research Question:

"How can AI-enhanced mathematical modeling optimize neutron capture and utilization efficiency in hybrid reactors that combine nuclear fusion and fission processes?"

C. Information Gathering:

This project draws from both theoretical and empirical sources to construct the model. Foundational understanding of neutron behavior in nuclear reactions is derived from works such as Theoretical Physics by Georg Joos. This text provides critical information on neutron flux, cross-sections, and fuel density, which are key to constructing equations that model neutron population dynamics in hybrid reactors.

Additionally, peer-reviewed articles by Ripani (2022) and Wilkins (2024) inform contemporary approaches to neutron capture within hybrid reactors, providing insights into the latest reactor designs and neutron management strategies. These articles contributed to refining assumptions regarding realistic neutron flux values and absorption rates, which were essential for developing the AI model.

Data sourced from the International Atomic Energy Agency (IAEA) forms the empirical basis for training the AI models. These datasets cover neutron flux distributions, cross-sections for Helium-3 in fusion reactions, and Uranium-235 in fission reactions, making them highly relevant to the hybrid reactor environment. The IAEA datasets help inform AI predictions that dynamically adjust to real-time reactor conditions, allowing the model to more accurately simulate neutron dynamics.

D. Assessment:

By combining foundational theoretical models and real-world data, this project seeks to address gaps in traditional neutron transport equations. The AI-enhanced approach provides dynamic optimization of key reactor parameters, which are informed by real-time data from experimental reactor environments. This integration offers a more responsive and adaptable model, improving both safety and operational efficiency in hybrid reactors.

II. AI-Enhanced Mathematical Model Development

A. Model Selection:

The selected model integrates traditional deterministic differential equations describing neutron dynamics with AI-based parameter predictions. The AI component allows for real-time adjustments, providing a more flexible and adaptive management system for both fusion and fission reactions. This approach addresses the unique challenges posed by the hybrid nature of the reactor.

B. Model Creation:

1. Fusion Reaction Dynamics:

$$\frac{dN_{fusion}}{dt} = AI\_predict(density\_fuel,\ \sigma_{fusion}, \phi)$$

This equation models neutron production during fusion reactions, with the AI component dynamically adjusting neutron yield predictions based on real-time fuel density, fusion cross-section σ_{fusion}, and neutron fluxϕ.

2. Fission Reaction Dynamics:

$$\frac{dN_{fusion}}{dt} = AI\_predict(density\_fuel,\ \sigma_{fission}, N) - \lambda \cdot N$$

For fission reactions, the AI model adjusts for neutron production and absorption rates, using real-time data to modify neutron flux predictions. The term $\lambda \cdot N$ accounts for neutron absorption.

3. Overall Neutron Population Dynamics:

$$\frac{dN}{dt} = \frac{dN_{fusion}}{dt} + \frac{dN_{fission}}{dt}$$

This equation integrates the fusion and fission reaction dynamics to predict overall neutron population changes in the reactor.

C. Real-World Data Integration:

The datasets sourced from the IAEA provide the necessary empirical data for training the AI models. These datasets focus on critical parameters such as neutron yield, cross-sections, and flux distributions in Helium-3 fusion and Uranium-235 fission reactions. By training the AI models on these datasets, the model is able to dynamically adjust predictions for reactor behavior based on real-time data, offering improved accuracy in neutron population dynamics simulations.

III. Model and Approach

A. Discussion of Equations:

The equations utilized in the AI model are derived from traditional neutron transport models but have been enhanced with AI-based dynamic predictions. The AI component continuously adjusts key parameters such as neutron flux and cross-sections based on real-time data, allowing the model to adapt to fluctuating reactor conditions.

1. Fusion Dynamics: The AI-enhanced fusion equation uses the real-time IAEA data to predict neutron production more accurately. This ensures that changes in fuel density and neutron flux are captured by the model as they occur.

2. Fission Dynamics: The AI-based adjustments improve the accuracy of predictions for neutron absorption rates, which are critical in maintaining a balanced neutron population in hybrid reactors. The dynamic prediction model allows the reactor to operate more efficiently under changing conditions.

B. Applicability of the Model:

The AI-enhanced model is designed to be highly applicable to hybrid nuclear reactors. By dynamically adjusting to changes in neutron flux, fuel density, and cross-sections, the model provides real-time predictions of neutron behavior. While the current version of the model performs well under simulated conditions, further data collection from operational reactors will improve its robustness and accuracy.

IV. Analysis and Results

A. Results:

The AI-enhanced model was tested in a simulated hybrid reactor environment. By training the AI models on IAEA datasets, the model demonstrated strong performance in predicting neutron population dynamics in both fusion and fission reactions. The AI component was able to adjust predictions in real time based on variations in reactor conditions, leading to more accurate simulations of neutron production and absorption.

For example, when testing with variations in fuel density and neutron flux, the model accurately reflected changes in neutron production and absorption rates, demonstrating its ability to respond to real-time data inputs.

B. Limitations:

While the AI-enhanced model shows promise, its performance is currently limited by the availability of real-world data. Although the IAEA datasets provide valuable empirical evidence, more comprehensive data from operational reactors are needed to further refine the model. Additionally, the model assumes simplified reactor geometries, which may limit its application to more complex reactor designs.

V. Conclusion

The integration of AI into mathematical models for neutron capture in hybrid nuclear reactors offers significant benefits in terms of predictive accuracy and adaptability. By leveraging real-time data inputs, the AI-enhanced model can dynamically adjust key reactor parameters, improving both safety and operational efficiency. While further refinement is needed, particularly in the integration of more comprehensive datasets, this project demonstrates the potential for AI to enhance the management of neutron dynamics in hybrid reactors.

VI. References

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