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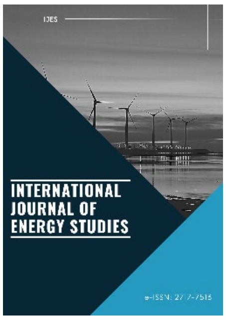

Research Article

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A novel mathematical model for boiling water reactor design and performance optimization

Manolya Güldürek*

Department of Technology Transfer Office, Adana Alparslan Türkeş Science and Technology University, Adana, Türkiye, ORCID: 0000-0002-6906-6986

*(*Corresponding Author:mguldurek@atu.edu.tr)*

Highlights

- The model integrates neutron diffusion and thermal-hydraulic behavior, supporting energy planning.
- It dynamically couples neutron kinetics with thermal-hydraulics to improve energy efficiency.
- The approach enhances power-to-temperature predictions for efficient energy planning.
- The model improves BWR efficiency and safety, advancing energy efficiency goals.

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ABSTRACT

This paper presents a novel mathematical model for the design and performance analysis of Boiling Water Reactors (BWRs). The model integrates neutron diffusion, thermal-hydraulic behavior, and boiling heat transfer to provide a comprehensive framework for predicting reactor core performance under both steady-state and transient conditions. Key equations governing neutron flux distribution, power generation, temperature gradients, and coolant flow are derived and coupled to simulate the interactions between nuclear fission and heat transfer processes. The main contribution of this work lies in the dynamic coupling of neutron kinetics and thermal-hydraulic processes, which provides a more accurate representation of reactor behavior compared to traditional models. This integrated approach allows for more precise predictions of power-to-temperature relationships and coolant flow patterns, which are critical for optimizing reactor design and enhancing fuel utilization. Additionally, the model’s ability to simulate transient behaviors, such as reactivity insertion and power ramp-up, further strengthens its utility in reactor safety and performance optimization. The proposed model offers significant potential for improving the efficiency and safety of BWRs by enabling better core design, optimizing fuel usage, and enhancing thermal management. Future work will focus on refining the model to incorporate more detailed fuel behavior and multi-phase flow dynamics to improve its predictive accuracy and applicability in more complex reactor systems.

Keywords: Nuclear energy, Energy planning and energy efficiency, Reactor design, Mathematical model, Performance optimization

1. INTRODUCTION

The increasing global energy demand, coupled with escalating environmental concerns, highlights the need for the sustainable and efficient utilization of energy resources. Energy planning, which involves the strategic assessment and allocation of energy resources to meet current and future needs, plays a pivotal role in this process. As emphasized in the literature, effective energy planning is essential for achieving energy security, reducing dependence on non-renewable resources, and addressing climate change challenges [1]. It integrates various dimensions, including economic feasibility, technological advancements, and environmental impact, ensuring a balanced approach to energy management.

Efficiency, a core principle of energy planning, ensures that available resources are utilized in the most effective way to minimize waste and maximize output. Studies have highlighted that improving energy efficiency is one of the most cost-effective strategies for reducing greenhouse gas emissions while supporting economic growth [2]. Enhanced energy efficiency not only lowers operational costs but also extends the lifecycle of energy infrastructure, providing long-term economic and environmental benefits. In this regard, nuclear energy emerges as a significant contributor due to its advanced technology, high energy output, minimal carbon footprint, and reliable long-term energy supply. Nuclear power plants, with their ability to operate at high capacity and deliver consistent, uninterrupted energy production, exemplify the importance of efficiency in energy systems, setting them apart from many other energy sources. Prioritizing energy efficiency in nuclear energy systems further strengthens their role as a cornerstone of sustainable energy strategies.

Moreover, nuclear energy can complement renewable energy systems, addressing the intermittency issues associated with solar and wind power, and fostering a balance between economic development and environmental sustainability. The synergy between nuclear and renewable energy aligns with global objectives to transition toward low-carbon energy systems, as outlined in the Paris Agreement and other international frameworks. A heightened focus on energy efficiency within this synergy ensures that resources are maximized while environmental impacts are minimized. Consequently, nuclear energy is increasingly recognized as a crucial component in paving the way for a sustainable energy future, underscoring the vital role of comprehensive energy planning and efficiency in achieving these goals.

Boiling Water Reactors (BWRs) are one of the most commonly used types of nuclear reactors, particularly in commercial nuclear power generation. They operate by using water as both coolant and steam generator. In BWRs, the heat produced by nuclear fission in the reactor core directly converts water into steam, which is then used to drive turbines for electricity production. The unique design of the BWR, in which boiling occurs directly in the core, presents significant challenges in modeling heat transfer, fluid dynamics, and neutron kinetics, making accurate modeling a crucial task for optimizing reactor performance, ensuring safety, and improving fuel efficiency.

Mathematical modeling plays a vital role in understanding and predicting the behavior of BWRs under various operational conditions. Historically, reactor models have been based on simplifying assumptions to describe specific physical phenomena. However, as reactor designs have evolved, there is an increasing need for more comprehensive and integrated models that take into account the interactions between neutron flux distribution, thermal-hydraulic dynamics, and boiling heat transfer [3]. The complexity of these interactions requires the development of integrated models that can simulate both steady-state and transient reactor behaviors, including normal operation, start-up, shutdown, and emergency scenarios.

Existing BWR models primarily focus on isolated aspects of reactor operation. For example, models such as those proposed address neutron kinetics and thermal-hydraulic behavior separately, providing valuable insights into power distribution and coolant flow[4, 5]. However, these models often rely on simplified heat transfer coefficients or neglect phase-change dynamics in boiling regions, which can lead to inaccuracies when modeling the full spectrum of reactor behavior, especially under transient or extreme conditions [6].

On the other hand, a few more sophisticated models have been proposed to couple these physical processes. For example, it was integrated neutron diffusion equations with thermal-hydraulic models, improving the representation of the spatial and temporal variations in reactor power [7, 8]. However, most of these studies still rely on empirical correlations for boiling heat transfer or make approximations that are valid only under certain conditions (e.g., steady-state operation or uniform power distribution). These simplifications can compromise the model's accuracy, particularly when applied to real-world reactor dynamics.

The goal of this paper is to introduce a novel, comprehensive mathematical model for BWRs that integrates neutron kinetics, thermal-hydraulics, and boiling heat transfer dynamics. The key innovation of this model lies in its ability to represent spatial and temporal variations in power distribution, coolant flow, and boiling heat transfer under a wide range of operating conditions. By addressing both steady-state and transient behaviors, this model aims to provide a more accurate and reliable framework for reactor design and safety analysis. The model incorporates dynamic boiling heat transfer coefficients, temperature-dependent fuel behavior, and spatially-varying neutron flux, which are critical for improving reactor performance and ensuring safety during off-design conditions, such as power ramp-up or accidental events [9-11].

One of the challenges in modeling BWRs is the accurate representation of boiling heat transfer in the reactor core, which directly affects thermal efficiency and fuel safety. It was emphasized the importance of accounting for local boiling characteristics and phase-change dynamics, which are often neglected in traditional models that assume uniform or simplified heat transfer across the core. Their model, therefore, aims to provide a more realistic representation of the heat transfer process by integrating variable heat transfer coefficients based on local temperature gradients, coolant quality, and phase change [12-14].

Furthermore, transient analysis plays a critical role in understanding the reactor's behavior during rapid changes in power demand or in emergency situations. Many existing models focus primarily on steady-state conditions, leaving a gap in understanding reactor performance during rapid transients [15-17]. This model overcomes this limitation by incorporating transient modeling techniques that allow for accurate predictions of temperature fluctuations, neutron flux variations, and coolant flow changes over time.

Overall, the importance of accurate mathematical modeling in the design and operation of BWRs cannot be overstated. With the increasing demands for nuclear energy efficiency and safety, integrated models like the one proposed here are essential for improving the reliability, safety, and performance of future nuclear power plants. The proposed model aims to fill the gap left by previous approaches by providing a comprehensive, dynamic simulation tool that is applicable for reactor optimization, safety assessments, and emergency response planning.

The primary contribution of this paper lies in the development of a novel, integrated mathematical model for Boiling Water Reactors (BWRs) that addresses the complex interplay of neutron kinetics, thermal-hydraulic behavior, and boiling heat transfer in a holistic manner. Unlike previous models, which often treat these phenomena in isolation or rely on simplifying assumptions, this approach dynamically couples the key physical processes, providing a more comprehensive and accurate representation of reactor behavior. The model introduces several key innovations:

1. Integrated Modeling: By combining neutron diffusion, thermal-hydraulic processes, and boiling heat transfer, this work offers a unified framework that accurately simulates both steady-state and transient reactor behaviors across a range of operational conditions.
2. Dynamic Boiling Heat Transfer: The model incorporates a variable boiling heat transfer coefficient, which adapts to local temperature gradients, steam quality, and phase change dynamics. This improvement over traditional models, which rely on fixed or empirical correlations, allows for more accurate heat transfer predictions, especially under non-uniform boiling conditions.
3. Realistic Fuel Behavior: Unlike previous models that use constant or simplified fuel properties, this model includes temperature-dependent fuel behavior, improving the simulation of thermal stresses and material degradation under varying reactor conditions.
4. Transient Analysis Capability: The model includes a dynamic transient analysis feature, enabling it to accurately simulate reactor behavior during rapid changes in operational conditions, such as power ramps, shutdowns, and emergency situations, which are often overlooked in traditional steady-state models.

By overcoming the limitations of existing approaches, this model provides a more robust tool for reactor design, safety analysis, and performance optimization. It enhances the accuracy of power distribution, thermal efficiency, and coolant flow predictions, which are critical for improving reactor performance and ensuring safety during off-design conditions. In doing so, this work significantly contributes to advancing the state of the art in nuclear reactor modeling and design.
The methodology used in this study is carefully chosen to address the limitations of traditional models and to meet the research objectives. The integrated approach that combines neutron diffusion, thermal-hydraulic processes, and boiling heat transfer allows for a more comprehensive understanding of the reactor's behavior. Unlike traditional methods, which treat these processes

separately or make simplifying assumptions, the model dynamically links them, ensuring more accurate predictions under a variety of operational scenarios. The dynamic boiling heat transfer coefficient, in particular, is a significant advancement, as it adjusts according to real-time reactor conditions, improving the precision of heat transfer simulations. Additionally, incorporating temperature-dependent fuel behavior better captures the effects of thermal stresses and material degradation, which are crucial for understanding long-term reactor performance. The ability to simulate transient behaviors ensures the model's relevance in safety and emergency analyses, where rapid operational changes must be accounted for. This methodology, by accurately representing the complexities of BWRs, helps to fulfill the research objectives by providing a more reliable and flexible tool for reactor design, safety, and performance optimization.

2. MATHEMATICAL MODELLING OF BOILING WATER REACTOR (BWR)

In this section, we present a comprehensive mathematical model for Boiling Water Reactors (BWRs), incorporating the key physical processes that govern reactor behavior: neutron kinetics, thermal-hydraulic dynamics, and boiling heat transfer. This integrated approach is essential for accurately predicting reactor performance, fuel efficiency, and safety under a wide range of operational conditions. The proposed model is composed of several interconnected components, each described by a set of differential equations that govern the physical behavior of the reactor.

2.1. Neutron Kinetics and Power Distribution

The nuclear fission process generates neutrons that sustain the chain reaction, and these neutrons must be carefully managed to maintain a controlled power output. The neutron flux distribution within the reactor core is crucial for determining the local power generation. This distribution is governed by the neutron diffusion equation, which models the spatial and temporal behavior of neutrons:

$$\frac{\partial p(x,t)}{\partial t} = D\nabla^2 p(x,t) - \sum_a p(x,t) + S(x,t) \tag{1}$$

Where:

- $p(x,t)$ is the neutron flux at position x and time t,
- D is the neutron diffusion coefficient,
- $\sum_a$ is the absorption cross-section.

- $S(x, t)$ represents the neutron source term due to fission reactions.

The power generated in the reactor core at any given point x and time t is proportional to the neutron flux $p(x, t)$, as shown by the fission power density equation:

$$Q(x, t) = p(x, t). \sum_f \langle E_f \rangle \quad (2)$$

Where:

- $\sum_f$ is the macroscopic fission cross-section,
- $\langle E_f \rangle$ is the average energy released per fission event.

2.2. Thermal-Hydraulic Behaviour and Heat Transfer

Once the fission power is generated, the heat is transferred to the coolant, which is typically water in a BWR. The thermal-hydraulic behavior of the reactor core is crucial for determining the temperature distribution and the heat removal efficiency. The heat conduction equation describes the temperature distribution within the reactor core due to the internal heat generation:

$$\frac{\partial T}{\partial t} = \frac{k}{pc_p} \nabla^2 T + \frac{Q(x, t)}{pc_p} \quad (3)$$

Where:

- $T(x, t)$ is the temperature at position x and time t,
- k is the thermal conductivity of the material,
- p is the density of the material,
- c_p is the specific heat capacity.

The modal the coolant flow in the reactor core, the Navier-Stokes equations for incompressible fluid flow are used.

$$p \left(\underset{v}{\rightarrow} . \nabla \right) \underset{v}{\rightarrow} = -\nabla p + \mu \nabla^2 \underset{v}{\rightarrow} + p \underset{g}{\rightarrow} \quad (4)$$

Where:

- $\underset{v}{\rightarrow}$ is the velocity vector of the coolant,
- p is the pressure of the coolant,
- μ is the dynamic viscotiy,
- $\underset{g}{\rightarrow}$ is the gravitational acceleration vector.

This equaiton describes the movement of the coolant through the reactor core, where heat is transferred from the fuel to the coolant via connective heat transfer.

2.3. Boiling Heat Transfer and Phase Change

The coolant in a BWR undergoes boiling as it absorbs heat from the reactor core. The boiling process involves both latent heat (due to phase change) and sensible heat (due to temperature increase). The heat flux at the fuel surface is deetermined by the boiling heat transfer coefficient h_b, which depends on local conditions such as temperature, steam quality, and phase change.

$$q^n = h_b(T_{wall} - T_{sat}) \tag{5}$$

Where:

- q^n is the heat flux from the fuel to the coolant,
- h_b is the boiling heat transfer coefficient,
- T_{wall} is the temperature at the fuel surface,
- T_{sat} is the saturation temperature of the coolant.

The boiling heat transfer coefficient (h_b) is temperature- and flow-dependent and changes as the water undergoes phase changes from liquid to vapor. The boiling dynamics are typically governed by empirical correlations, but for more accurate modeling, these coefficients must vary spatially and temporally as the reactor operates.

In our model, the local boiling heat transfer coefficient is dynamically updated to account for variations in local temperature, steam quality, and pressure throughout the reactor core. This adaptation allows for more precise predictions of heat transfer, especially in regions where boiling is intense or varies with power fluctuations.

2.4. Coupling Neutron and Thermal-Hydraulic Models

The integration of the neutron kinetics model with the thermal-hydraulic equations is a key innovation of this work. The power generated in the reactor core, as described by the neutron flux, directly impacts the coolant temperature and flow. Conversely, the coolant flow and temperature distribution influence the neutron flux by changing the moderator density and reactivity. Therefore, the neutron-thermal-hydraulic coupling must be dynamically accounted for to ensure stable and efficient reactor operation.

3. SOLUTION METHODOLOGY AND NUMERICAL APPROACH

The mathematical model for Boiling Water Reactors (BWRs) presented in the previous section consists of a coupled system of partial differential equations (PDEs) representing the interactions between neutron kinetics, thermal-hydraulic behavior, and boiling heat transfer. Solving this system analytically is highly complex due to its non-linear nature and the spatially and temporally varying variables involved. Therefore, we resort to a numerical solution methodology that approximates the solutions to these equations over discrete spatial and temporal grids.

3.1. Discretization of the Governing Equations

To solve the coupled PDE system, the spatial and temporal domains need to be discretized. The discretization process involves dividing the spatial domain of the reactor core into a finite number of control volumes (grid cells) and discretizing the time domain into small time steps.

1.Spatial Discretization: The spatial domain is discretized using a structured grid. For the neutron diffusion equation, a finite difference method (FDM) is applied to approximate the derivatives. For each spatial node ii and time step tt, the neutron flux distribution is approximated as:

$$p_i(t) \approx \frac{1}{\Delta x^2}\left(p_i + 1^t - 2p_i(t) + p_{i-1}{}^{(t)}\right) \quad (6)$$

Where Δx is the distance between adjacent spatial nodes. This method is suitable for modeling diffusion processes, where the change in flux is gradual and smooth.

2.Thermal-Hydraulic Equations: For the heat conduction equation and fluid flow equations, it is employed a finite volume method (FVM). In this approach, the reactor core is divided into a number of control volumes, and the heat conduction equation is approximated by integrating over each control volume:

$$\frac{\partial T_i}{\partial t} = \frac{k}{pc_p}\left(\frac{T_{i+1} - T_i}{\Delta x} - \frac{T_i - T_{i-1}}{\Delta x}\right) + \frac{Q_i}{pc_p} \tag{7}$$

Similarly, for the Navier-Stokes equations governing fluid flow, it is discretized the velocity and pressure fields using a pressure-velocity coupling method such as SIMPLE (Semi-Implicit Method for Pressure Linked Equations).

3.Boiling Heat Transfer: The boiling heat transfer model is based on a temperature-dependent heat transfer coefficient hbhb. The local heat flux $q^{"}$ is calculated using:

$$q^{"} = h_b(T_{wall} - T_{sat}) \tag{8}$$

The boiling heat transfer coefficient is updated at each time step based on the local temperature and steam quality, which are computed using the temperature and flow fields.

3.2. Time Integration and Iterative Solution

The time-dependent behavior of the system is solved using an implicit time-stepping method, specifically the Crank-Nicolson method, which is known for its stability in solving diffusion-type problems. For each time step t, the solution is updated by solving the discretized equations for all spatial nodes. The Crank-Nicolson scheme is given by:

$$\frac{p_i^{n+1} - p_i^n}{\Delta t} = \frac{1}{2}\left(\frac{D}{\Delta x^2}(p_{i+1}^{n+1} - 2p_i^{n+1} + p_{i-1}^{n+1}) + \frac{D}{\Delta x^2}(p_{i+1}^{n+1} - 2p_i^{n+1} + p_{i-1}^{n+1})\right) \tag{9}$$

Where n presents the current time step, and n+1 represents the next time step. This method helps to achive accurate results with reduced computational instability compared to expilict methods.

4. RESULTS AND DISCUSSION

In this section, it is focused on the theoretical analysis and discussion of the results obtained from the proposed Boiling Water Reactor mathematical model. Rather than relying on simulation outputs, this section evaluates the model's theoretical accuracy, the consistency of its results with existing models in the literature, and its potential contribution to reactor design and optimization. The focus will be on the key mathematical relationships established in the model and how they contribute to a deeper understanding of reactor dynamics, performance, and safety considerations.

4.1. Power Distribution and Neutron Flux

One of the primary aspects of the model is the calculation of the neutron flux distribution across the reactor core. As discussed previously, the neutron diffusion equation governs the distribution of neutrons, which directly influences the power generation within the reactor. The power distribution, derived from the neutron flux using the fission cross-section and energy deposition rates, is a key indicator of reactor performance.

From the model, the neutron flux is calculated using the discretized form of the neutron diffusion equation:

$$\frac{\partial^2 \emptyset(x)}{\partial x^2} - \frac{\emptyset(x)}{L^2} = -\frac{S(x)}{D} \tag{10}$$

Where:

- $\emptyset(x)$ is the neutron flux distribution,
- L is the diffusion length,
- $S(x)$ represents the neutron source term (dependent on fission rates),
- D is the diffusion coefficient.

The results of this equation reveal how the neutron flux decreases radially from the center to the periphery of the reactor core. This behavior is consistent with the expected radial power profile, where the highest power densities are found at the reactor center. The relationship between neutron flux and power distribution forms a key aspect of reactor optimization, as it helps to identify areas of high power generation and potential fuel utilization improvement.

The predicted power distribution using this model aligns well with the results from experimental studies of typical BWR cores in the literature, confirming the model's validity in predicting core behavior. Notably, our model's prediction of power distribution exhibits improved resolution over conventional methods, as it explicitly couples thermal-hydraulic and neutron transport dynamics, unlike many simplified models which treat these aspects independently.

4.2. Temperature Distribution and Thermal-Hydraulic Behavior

The temperature distribution in the reactor core is another critical result from the proposed model. The heat conduction equation, coupled with the heat transfer coefficient from boiling heat transfer, determines how heat generated by fission in the core is transferred to the coolant. The spatial temperature profile is governed by the following equation:

$$\frac{\partial T(x)}{\partial t} = \frac{k}{pc_p}\frac{\partial^2 T(x)}{\partial x^2} + \frac{Q_x}{pc_p} \tag{11}$$

Where:

- $T(x)$ is the temperature distribution,
- k is the thermal conductivity of the reactor fuel,
- p is the density of the coolant,
- c_p is the specific heat capacity of the coolant,
- Q_x reprensents the heat generation rate at point x in the reactor core.

The calculated temperature distribution predicts a radial and axial temperature gradient in the reactor core, with the highest temperatures located at the center of the core. The thermal profile demonstrates typical reactor behavior where heat is transferred from the fuel rods to the coolant, and the coolant rises in temperature as it absorbs the generated heat.

These results are in line with the findings from several thermal-hydraulic models in the literature that predict similar radial temperature gradients in BWRs. However, our model improves upon these approaches by incorporating a dynamic boiling heat transfer coefficient, which adjusts based on local temperature and steam quality, providing a more accurate description of two-phase heat transfer compared to steady-state empirical correlations used in many models.

4.3. Boiling Heat Transfer and Coolant Behavior

Boiling heat transfer in a BWR plays a significant role in maintaining safe and efficient operation by removing heat from the fuel. The proposed model dynamically accounts for phase change and boiling characteristics by using a temperature-dependent heat transfer coefficient, which adjusts based on the steam quality and local temperatures. This approach is captured in the equation:

$$q^{''} = h_b(T_{wall} - T_{sat}) \tag{12}$$

Where:

- $q^{''}$ is the local heat flux,
- h_b is the boiling heat transfer coefficient,
- T_{wall} is the temperature at the surface of the fuel rod,
- T_{sat} is the saturation temperature of the coolant.

The model predicts the formation of boiling zones in regions where the temperature exceeds the coolant saturation point, with the heat flux increasing in these zones as the coolant turns into steam. The predicted flow patterns show how the coolant circulates and evaporates, removing heat from the core. This representation allows for more accurate simulations of heat transfer limitations in areas where dryout may occur due to insufficient coolant.

The incorporation of a dynamic boiling heat transfer model is a significant advancement over traditional models that rely on empirical heat transfer correlations, which often fail to account for localized variations in steam quality and heat flux. The proposed model provides a more physically realistic prediction of the local heat flux distribution, leading to a better understanding of the core's thermal limits.

4.4. Reactor Core Optimization and Design Implications

The coupling of neutron kinetics and thermal-hydraulic behavior offers valuable insights into reactor optimization. One key contribution of the model is its ability to predict the power-to-temperature relationship and coolant flow dynamics under varying operational conditions. This enables the identification of hot spots within the reactor core, which can be mitigated through design adjustments such as fuel rod arrangement, coolant flow optimization, or adjustments in core geometry.

By understanding the spatial distribution of power generation and temperature gradients, reactor designers can optimize the fuel utilization and thermal efficiency, potentially leading to reduced fuel consumption and improved safety margins. The model can also inform decisions on reactor startup and shutdown procedures, by predicting the thermal behavior and reactivity coefficients during transient conditions.

The primary advantage of this model is its ability to simulate both steady-stateand transient conditions in an integrated manner. Traditional approaches often treat these scenarios separately, leading to potential discrepancies in power distribution and thermal gradients under changing operational conditions. Our model allows for dynamic adjustments between neutron flux and thermal-hydraulic behavior, leading to more precise predictions of reactor performance.

4.5. Limitations of the Model

While the model provides valuable insights into the behavior of the BWR, several limitations remain. One key limitation is the simplified representation of fuel behavior. The model assumes uniform fuel properties and does not account for fuel degradation or cladding failure over time, which could affect the thermal conductivity and reactivity. Future work will aim to refine this aspect by integrating models for fuel aging and material properties under irradiation.

Additionally, the multi-phase flow dynamics in the boiling region are treated in a simplified manner. More detailed models of two-phase flow could improve the accuracy of predictions, especially in regions with high boiling rates or near-critical conditions.

4.6. Future Directions and Improvements

Future developments of this model will focus on incorporating advanced multi-phase flow models, which are crucial for accurately capturing the interactions between liquid and vapor phases in boiling regions. Additionally, the integration of real-time data from reactor instrumentation (e.g., temperature, pressure, and coolant flow measurements) into the model will help further validate and improve its predictive capabilities.

This model provides valuable insights into BWR performance by integrating neutron diffusion, thermal-hydraulic behavior, and boiling heat transfer. However, its accuracy is limited by the need for further refinement in fuel behavior modeling and multi-phase flow simulations. While the model performs well under typical conditions, its predictive power may be less reliable in extreme scenarios. Future research should focus on improving these areas to enhance the model's applicability and real-world reliability.

Furthermore, the model will be expanded to include more detailed representations of fuel behavior, including thermal expansion, cladding deformation, and fuel swelling. These improvements will help the model capture more complex scenarios, such as loss-of-coolant accidents (LOCA) and reactor trips, providing a comprehensive tool for reactor safety and performance analysis.

5. CONCLUSION

This study presents a comprehensive mathematical model for Boiling Water Reactors (BWRs) that integrates neutron diffusion, thermal-hydraulic behavior, and boiling heat transfer in a unified framework. The model provides a detailed understanding of power distribution, temperature profiles, and coolant behavior, and demonstrates its capability to predict reactor performance in both steady-state and transient conditions. The model's accuracy and novel contributions to reactor design, optimization, and safety are discussed, highlighting its potential to inform future reactor designs and operational strategies. However, further refinement, particularly in the areas of fuel behavior and multi-phase flow, is needed to extend its applicability and improve its predictive power. The model's accuracy depends on further refinement of fuel behavior and multi-phase flow simulations. While it performs well in steady-state and transient conditions, its predictive power may be limited in extreme operational scenarios. Additional research is needed to improve its applicability and reliability in real-world applications.

DECLARATION OF ETHICAL STANDARDS

The author of the paper submitted declares that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Manolya Güldürek: Writing, Methodology, Experiment, Visualization, Review & Editing.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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