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Editorial: Multiphysics methods and analysis applied to nuclear reactor systems

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Editorial on the Research Topic

Multiphysics methods and analysis applied to nuclear reactor systems

The nuclear industry stands at a turning point. Demand for carbon-free energy sources is increasing, while aging reactors and the need for enhanced safety require new and innovative solutions. Central to this progress is multiphysics modeling and simulation, a relatively up-and-coming approach by which the design, analysis, and operation of nuclear reactor systems are being reexamined. This Research Topic explores the leading edge of this field, showcasing cutting-edge research and providing insights into the essential role that advanced simulations play in driving nuclear technologies forward.

Traditional nuclear engineering has relied heavily on experimentation, often involving costly and potentially hazardous procedures. Multiphysics simulations provide a robust framework for reactor experiment and full system evaluation. By integrating models that accurately represent the inherent coupling of physical phenomena: neutronics, thermal hydraulics, structural mechanics, heat transfer, etc., these simulations offer a complete view of reactor behavior under a wide set of conditions. This unified approach enables designers and analysts to optimize designs, predict performance, and enhance safety in ways previously unattainable.

With the wide variety of reactor types on the horizon, advanced multiphysics modeling and simulation offers clear advantages of the use of traditional physics codes and workflows. Generally, the tightly coupled nature of multiphysics methods allows for more flexible code application and deeper physics insights than what can be obtained with loosely or one-way coupled tools. This is especially important for exploring the technical merits of novel reactor concepts with less experimental pedigree.

This Research Topic highlights contributions that showcase the breadth and depth of multiphysics applications in nuclear engineering. From innovative computational methods to rigorous experimental validation, the articles presented here underscore the critical role that simulation plays in representing the complexities of modern nuclear reactor technology.

A notable advancement within this domain is described in [Imron and Lee](#) through the development of on-the-fly thermal expansion methodologies for multiphysics Monte Carlo reactor simulations as This method allows the problem geometry to dynamically expand

during particle tracking by incorporating local temperature data, such as pin-averaged temperatures obtained from thermal-hydraulics solvers. Numerical experiments demonstrate that modeling thermal expansion with local temperature data can significantly improve the accuracy of simulations, including eigenvalue predictions and pin power distributions, compared to models using only global core-averaged temperatures.

A central theme emerging from this Research Topic is the development and application of innovative computational methods. For instance, [Harter and DeHart](#) details the application of stochastic methods and sensitivity analysis to a full-core model of a nuclear thermal propulsion system. This research showcases the development of a reduced-order model that allows for rapid evaluation of system behavior under various input conditions, a critical advancement for optimizing the design and control of these complex reactors.

The integration and coupling of different physical models is another area of focus. Advanced nuclear reactor cores are governed by multiple physical phenomena which should all be resolved, and the coupling of these physics would also need to be resolved spatially in a high-fidelity approach. [Giudicelli et al.](#) presents field transfer capabilities implemented in the Multiphysics Object-Oriented Simulation Environment (MOOSE), and numerous technical details such as mapping heuristics, conservation techniques and parallel algorithms. In a similar vein, [Yang et al.](#) explores hybrid, matrix-based, and matrix-free solver technologies within a voxel-dominated Cartesian mesh framework, offering a novel approach to simulating neutronics and thermal hydraulics in nuclear reactor cores. This approach enables accurate boundary representation and efficient resolution of complex geometries. The coupling of different physical models, such as neutronics and thermal hydraulics, is crucial for accurate reactor analysis.

The application of these advanced simulations extends to design optimization, with several articles demonstrating how multiphysics models can inform and refine reactor designs. Presents the development of a multiphysics coupled framework of [Kim et al.](#), which provides significant insights into the analysis of MSRs. [Zavala et al.](#) discusses a high-detail steady-state analysis of one VVR-KN fuel assembly. The VVR-KN is a plate-type fuel assembly, with fuel elements arranged hexagonal with fuel-plate tubes that challenges both their neutronic and thermal-hydraulic modeling. The paper describes the thermal-hydraulic code Subchanflow and how the properties are solved and provided.

The Research Topic also emphasizes the role of multiphysics simulations in safety analysis. [Kutlu et al.](#) highlights the continuous development and improvement of the CTF sub-channel tool for thermal hydraulics, including new functionalities and multiphysics applications for VVER core modeling. These advancements are critical for ensuring the safe and reliable operation of these reactor types.

A cornerstone of credible simulation is rigorous experimental validation. [Colvin and Palmer](#) compares simulations to experimental results from the Sanida Annular Core Research Reactor, exploring potential improvements for feedback purposes, allowing additional iterations of the multiphysics coupling and checking for convergence, and evaluation of uncertainties in provided specific heat capacity values. These validation efforts are essential for establishing confidence in the predictive capabilities of multiphysics models.

[Kendrick and Forget](#) presents coupled neutronic/thermal-mechanical simulation of the Kilowatt Reactor Using Stirling Technology (KRUSTY) using OpenMC and MOOSE in order to analyze the neutronic and thermal impact of including thermal expansion at steady state. The results show that while thermal expansion has a significant effect on global neutronic tallies, it has relatively minor impact on spatial heating rates or temperatures in the system. This remains true even when simulating a multiple heat pipe failure scenario to introduce thermal asymmetry.

Looking ahead, the continued advancement and application of multiphysics methods hold significant promise for the future of nuclear energy modeling and design. By fostering collaboration between industry, academia, and research laboratories, and by prioritizing rigorous validation and uncertainty quantification, the nuclear community can unlock the full potential of these powerful simulation tools. This Research Topic serves as a valuable resource for researchers, engineers, and regulatory personnel alike, providing a comprehensive overview of the state-of-the-art and paving the way for a safer, more efficient, and more sustainable nuclear future.

This Research Topic provides evidence to the significant impact of multiphysics simulation capabilities in nuclear engineering. By including these advanced techniques, the nuclear industry can work to address the challenges of advanced reactor concepts.

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