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Editorial: Multi-physics and multi-scale modeling and simulation methods for nuclear reactor application

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Editorial on the Research Topic
Multi-physics and multi-scale modeling and simulation methods for nuclear reactor application

A nuclear reactor works within an intricate circumstance characterized by complicated multi-physics and multi-scale interactions. Its operation necessitates a comprehensive analysis of the interplay among neutronics, fuel property, thermal and hydraulic engineering, chemical kinetics, and the interconnection among the reactor core and the primary loop. By utilizing high fidelity numerical simulations, taking into account the coupling between diverse physics, and providing formidable numerical simulation tools, achieving security, reliable, and cost-effective operation is attainable. Historically, reduced models were employed to represent certain physics phenomena. However, recent advancements in numerical calculation theory, software development, and the capabilities of HPC have propelled the evolution of reactor computational tools towards a paradigm that embraces multi-physics and high-fidelity simulations.

Many research has been conducted by coupling multi-physics and multi-scale codes, such as deterministic/Monte Carlo neutronics codes (Liu et al., 2017; Fang et al.), fuel thermodynamics codes (Yu et al., 2020a; Liu et al.), system codes (Barbe et al., 1999), subchannel codes (Wang et al., 2017; Yu et al., 2020b), Computational Fluid Dynamics (CFD) codes (Bakanov et al., 2004; Dai et al., 2020), etc. The modeling and simulation of multi-physics and multi-scale phenomena will benefit the nuclear industry by capturing more realistic physical behaviors inside the reactor core.

We have collected three papers on nuclear reactor multi-physics and multi-scale coupling approach advance by Hu et al., Fang et al., and Liu et al. Hu et al. pioneered the application of the FEM to imitate the fluid-structure interplay between fuel assembly and cooling material within the Xi'an Pulsed Reactor core. Their work revealed that, under the specified earthquake conditions, the fluid-structure interplay effect in this reactor core is notably weak. Consequently, it has been established that this interaction does not pose a threat to the security of the reactor core and is safely disregarded. In a separate study, Fang et al. conducted a comprehensive analysis of the full-core neutronics/thermal-hydraulics (NE/TH) coupling in the Small Lead-based Fast Reactor (SLFR). The interconnection evaluation results for SLFR demonstrated that crucial thermal-hydraulic factors, such as the cladding, fuel's highest temperature, and coolant, as well as the peak flow rate of coolant, all conform to the specified design criteria. Furthermore, the thermal-hydraulic response imparted negative reactivity feedback (approximately −200 pcm), exerting only a minimal impact upon power dispersion (less than 0.5%). In another noteworthy contribution, Liu et al. developed a sophisticated several physics interconnected model for fuel rod behavior using the COMSOL in conjunction with the 3D Monte Carlo neutron transport code RMC.

We have gathered three articles on phase field study of nuclear reactor materials by Ma et al., Wu et al., and Ma et al. In their study, Ma et al. utilized a phase-field model to explore the nucleation and growth phenomena of grains in U_3Si_2, and a statistical Rayleigh distribution was formulated to depict the grain size distribution. This statistical analysis shows that grain size evolution behavior in U_3Si_2 obeys Rayleigh distribution. Wu et al.'s work studied the statistical and dynamic characteristics of material structure and flaw evolution in materials with varying alloying element compositions and temperatures. Ma et al.'s work studied the time-space kinetics of Xe bubble development in U_3Si_2 by using the mesoscopic phase field method. It is found that a effective phase field method for studying the evolution of Xe bubbles in U_3Si_2. This methodology exhibits potential for further exploration into swelling behaviors in various fuels, laying a robust foundation for the advancement of Accident Tolerant Fuel (ATF) assembly development.

We have collected two papers on advanced coupling algorithm developments by Zhang and Zhou and Wang et al. Zhang and Zhou's work proposed a parallel Jacobian-Free Newton Krylov discrete ordinates method (comePSn_JFNK) in their work to address the solution of multi-dimensional multi-group pin-by-pin neutron transport models. This approach maximizes the effectiveness and parallel processing capabilities offered by the JFNK structure, while conc urrently leveraging the high-precision associated with the Sn method for extensive simulations. In their research, Wang et al. successfully developed a full neutron spectrum code known as FSAR, specifically tailored to meet the demands of advanced reactors characterized by a broad neutron energy range. This innovative code serves as a valuable tool for simulations targeting advanced reactor scenarios.

We have collected one paper on reactor behavior analyses using advanced coupling tools by Hu et al. Hu et al.'s work developed a novel nuclear data processing code named AXSP, outlining its methodology and evaluating its operational efficiency.

Through the incorporation of modeling and simulation that spans various physics and scales, a "digital reactor" can be constructed, which can improve efficiency, reduce costs, and enhance safety by providing assistances on the design and construction of new reactors, operation and maintenance of in-service reactors, retirement and lifespan extension of old reactors. In the future, the efficiency, versatility and flexibility of coupling should be improved by unified solving framework, which is a key direction for the advance of digital reactor technique.

Author contributions

XP: Writing–original draft, Writing–review and editing. SL: Conceptualization, Funding acquisition, Writing–original draft, Writing–review and editing. QH: Writing–original draft, Writing–review and editing. JL: Writing–original draft, Writing–review and editing. JY: Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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