Advanced modeling and simulation for multiphysics analysis of next-generation nuclear reactors: granular flow simulation and radiation transport computation in pebble-bed reactors
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Abstract:
Design and analysis of next-generation nuclear reactors present a computational challenge to the capabilities of the current modeling and simulation tools. The expected higher operation temperature, higher heterogeneity of the core design, and longer fuel-reloading period require a high-fidelity multiphysics analysis method for the reactor safety assessment. High temperature pebble-bed reactor (PBR) designs are typical examples that present the computational challenges for safety analysis. PBRs have been demonstrated to be the only meltdown-proof design to date. The meltdown-proof feature is rooted in their unique fuel designs and fuel management operations. PBR uses microsphere fuel particles (~1mm diameter) as the basic fuel element, with the uranium in the fuel kernel surrounded by four protective coating layers. About 15,000 fuel particles are embedded in a fuel pebble (6cm diameter) and half to one million fuel pebbles are loaded in the reactor core. Helium gas or liquid salt passes around pebbles to take the fission heat out for the electricity generation. Such a design presents substantial challenges to the current modeling and simulation capability for reactor analyses. Pebbles are moving constantly under pebble-pebble, wall-pebble and coolant-pebble interactions. Pebble flow and coolant flow are tightly coupled by strong drag/buoyancy force interactions. This fully coupled interaction is further complicated by changes in the power and temperature distributions, which affect forces among pebbles, coolant, and walls. A coupled computational framework that can account for mechanical-neutronic-thermal fluid interactions is needed in order to accurately predict the behavior of the reactor.

This talk will present the research on multi-physics modeling and simulation for pebble bed reactors including the HTR10, PBMR400 and PB-FHR designs. The emphasis is on the pebble flow and coolant flow coupling and the pebble-fluid interaction effects on the pebble dynamics, pebble stress distribution, dust generation, coolant pressure and velocity. In addition, advanced on-the-fly sampling Monte Carlo methods in speeding up the neutronic analysis of random distribution of fuel particles or fuel pebbles, and the sampling of temperature-dependent $S(\alpha,\beta)$ cross sections at arbitrary temperatures will also be discussed. These methods can be applied to other general reactor designs in addition to PBRs.

Biography:
Wei Ji received his B.S. (1999) and M.S.E. (2002) in Engineering Physics from Tsinghua University at Beijing, China. He received his Ph.D. (2008) from the University of Michigan at Ann Arbor in Nuclear Engineering. Currently, he is an Associate Professor of Nuclear Engineering Program at RPI, leading the Rensselaer Nuclear Engineering Advanced Modeling and Simulation Group (R-NEAMS). Dr. Ji’s research focuses on the development of advanced computation methodologies that are applied to the areas of nuclear energy, medical physics, and nuclear criticality safety. These methods include Monte Carlo modeling of radiation transport in stochastic media, on-the-fly sampling of thermal inelastic scattering reaction at any temperature based on $S(\alpha,\beta)$ nuclear data, multi-physics models for coupled granular flow and fluid flow simulations in pebble-bed reactors, and new algorithms on heterogeneous parallel CPU-GPU-Coprocessor architectures to accelerate simulations. Dr. Ji has been leading or co-leading research projects funded by Nuclear Regulatory Commission, Department of Energy, and National Institute of Health in the past years. He has authored over seventy peer-reviewed publications and served on the program and organizing committees of various national and international professional societies, workshops and conferences.