Analysis of the Molten Salt Fast Reactor using reduced-order models

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A B S T R A C T

In this paper, we present a reduced-order modeling approach to study the Molten Salt Fast Reactor (MSFR). Our approach is nonintrusive and based on the proper orthogonal decomposition method. We include adaptivity in selecting the sampling points both in time and parameter space. Steady-state and transient analysis were both performed using the developed models. In the steady-state analysis, we capture the effect of 30 model parameters on the spatial distributions of fission power and temperature, and on the multiplication factor. The dimensionality of the fission power was reduced from the 104288 nominal dimensions in the physical space to 10 dimensions in the reduced space, whereas the temperature was reduced from 220972 dimensions to 3. The reduced model was then used for uncertainty and sensitivity study of the maximum temperature in the reactor and the multiplication factor. In the transient analysis, the reduced model captured the effect of perturbations in the flow rate of salt in the intermediate circuit on the fission power density and temperature. The reduced models were successfully tested on a set of points that were not part of the snapshots used during the construction stage.

1. Introduction

Molten salt reactors have gained interest due to their potential safety, reliability, and sustainability (Generation IV International Forum, 2002). Different designs of this concept have been proposed in the literature (Dolan, 2017). In this work, we consider the Molten Salt Fast Reactor (MSFR) (Allibert et al., 2016). A key design feature of this unmoderated reactor is the use of a liquid salt fuel, which also plays the role of the coolant. This design introduces a unique modeling challenge because of the tightly coupled neutronics and thermal-hydraulics phenomena (e.g., transport of delayed neutron precursors, distributed thermal energy deposition directly in the coolant, a strong negative temperature feedback coefficient). To address these challenges, high-fidelity coupled models are used to provide an insight into the behavior of the reactor (e.g., Aufiero et al., 2014, Fiorina et al., 2014, Laureau et al., 2017, Cervi et al., 2019, Tiberga et al., 2020b). For safety assessment applications, an accurate and explicit quantification of the propagation of uncertainties through these complex models is required (International Atomic Energy Agency, 2019). Quantifying uncertainties and analyzing sensitivities in reactor physics can be accomplished using adjoint methods (Gilli et al., 2013; Perkó et al., 2013). However, adjoint-based methods require the availability of an adjoint solver, which might not always be feasible for coupled problems. Another approach is using forward-based methods, which requires repeated evaluation of the high-fidelity model for different parameter configurations (Cacuci, 2003). For example, automatic differentiation tools can be used to sample the forward model and reconstruct a discrete version of the adjoint problem (Marta et al., 2007). However, for large-scale, coupled, high-fidelity models with multiple input parameters such approaches are computationally demanding. For such applications, reduced-order modeling (ROM) techniques can be used to simplify the high-fidelity model and produce an efficient, cheap, and accurate model of the system.

Amongst the classical ROM methods found in literature, proper orthogonal decomposition (POD) is the method most suited for non-linear systems (Antoulas et al., 2001; Schilders et al., 2008; Benner et al., 2015). In the POD approach, a reduced basis space for the system is built using snapshots of the high-fidelity model. In nuclear reactor application, POD has been applied to solve criticality eigenvalue problems (Buchan et al., 2013; Senecal and Ji, 2019; German and Ragusa, 2019; Prince and Ragusa, 2020), for fuel pin reactor core calculations (Cherezov et al., 2018), in fuel burnup calculations (Castagna et al., 2020), in thermal hydraulics modeling (Vergari et al., 2020), in stability analysis (Prill and Class, 2014; Manthey et al., 2019), in spent fuel pool modeling (Escanciano and Class, 2019), and to model the lead cooled fast reactor (Sartori et al., 2016). In all of these applications, the original set of model equations were projected onto the constructed reduced basis. Projection-based approaches are intrusive because of the need to access the operator of the original high-fidelity model in...