A glass box coupling methodology for rigorously solving strongly coupled phenomena in nuclear reactors

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ABSTRACT

High fidelity computational modelling of coupled multi-physics problems occurring in several scientific fields require solution to large, stiff, nonlinear systems of equations with disparate spatio-temporal variations in physical scales. While there are multiple strategies that can be pursued in resolving the heterogeneous descriptions of physical models, the needs for creating a verified multiphysics solver requires usage of existing monophysics solvers seamlessly together, with minimally intrusive interfaces. Reuse of existing codes also offers the advantage of leveraging validated and computationally efficient solvers on petascale architectures thereby preserving several man-years of previously invested efforts. Traditionally, numerical methodologies to tackle such problems have relied on partitioned or operator-split schemes but iterative splitting with fully implicit treatment of the coupled fields can restore higher order accuracy and consistency in the solution [1].

In this talk, we present the Coupled Physics Environment (CouPE) based on SIGMA [2] components, to generate/import/query/manipulate complex unstructured meshes that are used as a data-backplane to transfer and transform the dependent solutions between physics codes consistently. These components are utilized to solve several nonlinearly coupled steady-state and pseudo-transient problems involving neutron transport, thermal-hydraulics and structural deformation physics, defined on fully heterogeneous single assembly [3] and full reactor core geometries. Due to the variations in the spatial scales and discretizations relevant to each physical model, the need for a global or local conservative transfer from one physics mesh to another becomes imperative. The multiphysics solver utilizes iterative splitting (optionally staggered or simultaneous partitioning using a predictor [4]) with Picard or nonlinear Richardson scheme to converge the nonlinearities in the solution fields. The overall goal of the presented glass-box methodology is to enable researchers to perform fully resolved reactor physics analysis on explicit geometry representations, in order to reduce the overall numerical uncertainty, while utilizing available computational resources efficiently.

Verifying the accuracy preservation in this setting is fundamental to effective resolution of the disparate characteristic physical scales, even if the process is nontrivial. Convergence studies are presented for several relevant demonstration problems to illustrate the preservation in accuracy via global and subset based conservative solution transfer mechanisms for different fields of interest. In this context, we also analyze the efficiency gain due to the usage of Aitken and Anderson acceleration schemes to improve the linear convergence rates of fixed-point methods. The presented methodology to integrate the three strongly coupled physics components establishes the flexibility and feasibility of the approach for solving a large array of relevant reactor problems.

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