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A parallel multi-domain solution methodology applied to nonlinear thermal transport problems in nuclear fuel pins ☆

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ABSTRACT

This paper describes an efficient and nonlinearly consistent parallel solution methodology for solving coupled nonlinear thermal transport problems that occur in nuclear reactor applications over hundreds of individual 3D physical subdomains. Efficiency is obtained by leveraging knowledge of the physical domains, the physics on individual domains, and the couplings between them for preconditioning within a Jacobian Free Newton Krylov method. Details of the computational infrastructure that enabled this work, namely the open source Advanced Multi-Physics (AMP) package developed by the authors is described. Details of verification and validation experiments, and parallel performance analysis in weak and strong scaling studies demonstrating the achieved efficiency of the algorithm are presented. Furthermore, numerical experiments demonstrate that the preconditioner developed is independent of the number of fuel subdomains in a fuel rod, which is particularly important when simulating different types of fuel rods. Finally, we demonstrate the power of the coupling methodology by considering problems with couplings between surface and volume physics and coupling of nonlinear thermal transport in fuel rods to an external radiation transport code.

1. Introduction

Many real world engineering problems involve multiple coupled nonlinear physical processes that occur both within and across several interacting physical domains. Robust, accurate, and efficient three dimensional simulations for some of these complex problems pose significant challenges that require a combination of powerful numerical algorithms, efficient parallel implementations, and massive computing resources to tackle. These challenges include developing the numerical methods and the parallel software infrastructure for coupling physical phenomena that occur on the surface and within the interior of physical domains, coupling structured and unstructured mesh calculations, coupling models with different discretizations,

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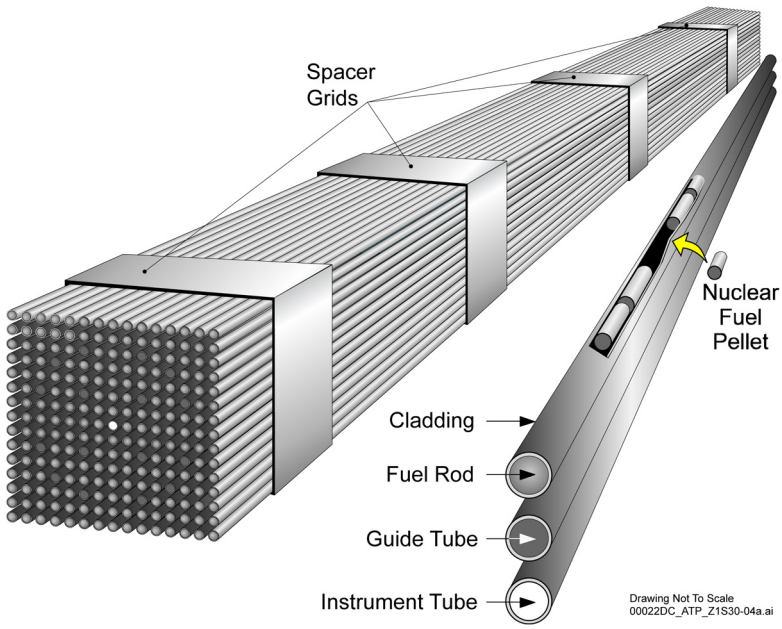

Fig. 1. Fuel assembly containing nuclear fuel rods that are filled with fuel pellets [1].

and using tightly coupled solution methods to solve certain coupled physics problems and loosely coupled approaches for others. Developing such simulation capabilities is a nontrivial task.

In this article, we will focus primarily on one such complex application where all of the features outlined above are present: thermal transport in nuclear fuel rods. However, we will also devote some effort to describing the parallel code infrastructure that was developed to provide the necessary meshing, discretization, linear algebra, linear and nonlinear solvers, physics modules (conservation laws and constitutive models), material property databases, and parallelization mechanisms for simulating this application in the hope that it will be beneficial to the broader scientific community.

A nuclear fuel assembly consists of several hundred nuclear fuel rods (shown in Fig. 1) bound together by spacer grids. While some of the rod locations are reserved for instrumentation and safety, most of the rods contain nuclear fuel. Each individual nuclear fuel rod in turn consists of several hundred nearly cylindrical nuclear fuel pellets (each with a height to diameter ratio of approximately one) stacked one on top of another to form a long column enclosed within a metal tube called the clad. Heat is generated within the pellets by nuclear fission and is distributed within the pellets and clad via a diffusive process. There is thermal contact (modeled as a convective process) between neighboring pellets and between the pellets and the clad. Each fuel rod is cooled with water flowing axially up the outer surface of the clad.

Modeling the heat transfer, along with other physics, leads to a very high-aspect ratio problem with many interdependent domains. Traditional nuclear fuel simulation eliminates the computational challenge by approximating the heat transfer as entirely radial and neglecting the axial and azimuthal components, which are only coupled through the coolant temperature and other simplified physics [2,3]. Recent efforts to develop advanced modeling and simulation tools for nuclear fuel rods [4,5], which include simulating full three-dimensional fuel rods with resolved pellets, have relied upon standard solution and preconditioning strategies that do not necessarily take advantage of the physics and geometry of the problem. This manuscript will not however address the challenges of structural dynamics and the associated feedback on heat transfer.

With respect to specific work related to heat transfer within nuclear fuel rods, there are several existing efforts to develop parallel codes that model three-dimensional heat transfer within nuclear fuel rods, including PLEIADES/ALCYONE [4,6], MOOSE/Bison [4], and BACO [7]. These codes are all focused on the integration of the many physics required for modeling nuclear fuel performance in steady-state and transients to improve the underlying material science, including fracture/contact mechanics, fission gas generation and release, and corrosion chemistry.

We have developed an efficient scalable parallel simulation framework for solving such multi-domain, multi-physics problems and have used it to solve the specific nuclear fuel problem described above. Within our particular application a nonlinearly consistent Jacobian Free Newton Krylov (JFNK) method is used (though the ability to use alternative solution methods also exists) across all the domains for each fuel rod. Physics-based preconditioning is used to accelerate the solution process and the multi-domain (pellets and clad) aspect of the problem is leveraged in developing methods that minimize communication as well as avoid the formation of full matrices over the whole domain.

In the next section, we present a mathematical description of the problem under consideration. Section 3 will describe the finite element discretization of the models in Section 2. The algorithms used to solve the resulting nonlinear system of equations are described in Section 4. The computational framework that was used in this work is briefly described