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Large-eddy simulation, fuel rod vibration and grid-to-rod fretting in pressurized water reactors

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ABSTRACT

Grid-to-rod fretting (GTRF) in pressurized water reactors is a flow-induced vibration phenomenon that results in wear and fretting of the cladding material on fuel rods. GTRF is responsible for over 70% of the fuel failures in pressurized water reactors in the United States. Predicting the GTRF wear and concomitant interval between failures is important because of the large costs associated with reactor shutdown and replacement of fuel rod assemblies. The GTRF-induced wear process involves turbulent flow, mechanical vibration, tribology, and time-varying irradiated material properties in complex fuel assembly geometries. This paper presents a new approach for predicting GTRF induced fuel rod wear that uses high-resolution implicit large-eddy simulation to drive nonlinear transient dynamics computations. The GTRF fluid–structure problem is separated into the simulation of the turbulent flow field in the complex-geometry fuel-rod bundles using implicit large-eddy simulation, the calculation of statistics of the resulting fluctuating structural forces, and the nonlinear transient dynamics analysis of the fuel rod. Ultimately, the methods developed here, can be used, in conjunction with operational management, to improve reactor core designs in which fuel rod failures are minimized or potentially eliminated. Robustness of the behavior of both the structural forces computed from the turbulent flow simulations and the results from the transient dynamics analyses highlight the progress made towards achieving a predictive simulation capability for the GTRF problem.

1. Introduction

Grid-to-Rod Fretting (GTRF) is a complex flow-induced vibration phenomenon that causes cladding wear in the fuel rod assemblies of Pressurized Water Reactors (PWRs). Fuel rod wear due to GTRF is currently one of the primary causes of fuel failure. It is responsible for over 70% of the fuel leaks in PWRs in the United States, and costs power utilities millions of dollars in preventative measures. Understanding and predicting the GTRF wear is fundamental to estimating the interval between fuel assembly failures.

In the fuel assembly of a pressurized water reactor, shown in Fig. 1, fuel rods are separated by spacer grids that have small preloaded retention springs that contact the rods. In order to augment the heat transfer, mixing vanes are appended

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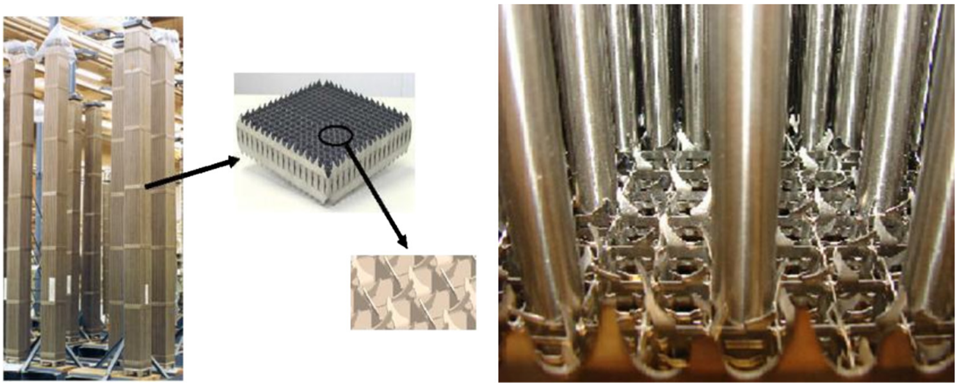

Fig. 1. PWR fuel rod assembly, rod spacer grid and mixing vanes. Reproduced without permission from Liu [1].

to the spacer grids. As the coolant flows through the fuel assembly in a primarily axial direction, fluid forces generated by the turbulent flow induce fuel rod vibration resulting in fretting wear. As radiation induced creep and growth effects take place, the preloads in the retention springs relax and the so-called cladding "creep-down" and spacer grid growth occurs. Under these conditions, the springs, that secure the fuel rod, may lose contact with the fuel rod, forming a gap between the spacer grid and the fuel rod. This magnifies the effects of flow-induced vibration and causes both normal and tangential cyclic contact forces to be generated between the retention springs and the fuel rods, further aggravating the fretting wear. In addition, the changes in the mechanical behavior and wear characteristics of the materials in the radiation environment, present during reactor operation, have a direct effect on the GTRF mechanisms. To date, it has not been possible to completely characterize the flow-induced Fluid–Structure Interaction (FSI) problem for GTRF. Indeed, given the turbulent nature of the coolant flow, the relatively high Reynolds number, and the flexible character of the fuel rods, the FSI problem at the reactor core scale is daunting.

There are a number of flow-induced vibration problems in a nuclear power plant that involve the reactor, associated piping, heat exchangers, steam generators, and ancillary diagnostic equipment [2]. Pettigrew, et al. [3] consider a broad array of flow-induced vibration problems, albeit specialized to the CANDU reactor configuration. We note that the CANDU reactor can experience wear at the appendages of the outer ring of the fuel rod bundle, but this is not to be confused with GTRF. A complete review of the work associated with all possible flow-induced reactor vibration problems is beyond the scope of this work. However, a brief review of the work related to the application of Computational Fluid Dynamics (CFD) for flow-induced vibration problems in reactor cores and fuel assemblies is presented.

Ikeno and Kajishima [4] applied Large-Eddy Simulation (LES) to the flow downstream of mixing vanes in a rod bundle. They used an immersed-boundary technique to treat the complex geometry and a dynamic subgrid-scale turbulence model to examine the mixing grid wake and downstream swirl. Benhamadouche, et al. [5] performed an LES of the flow in the subchannels surrounding a single rod, and subsequently used the turbulent forces to compute the elastic vibration of the fuel rod. Here, a relatively coarse mesh with 8 million cells was used for the $Re = 30{,}000$ flow. Related work by Kim [6–8] has considered GTRF wear models for PWRs as well as the effects of the rod support conditions on fuel rod vibration.

Conner, et al. [9] present a validation study using a 5 × 5 rod bundle, representative of a fuel assembly and compare the mixing-vane-induced swirl with Particle Image Velocimetry (PIV) data. Here, the RNG k–ϵ model was used with a wall resolution corresponding to $40 \le y^+ \le 100$ to compute a steady-state solution. Yan, et al. [10] performed time-accurate CFD computations and compared the effect of the so-called "protective grid" at the fuel-inlet region of a reactor. For this study, meshes with 7, 16, and 60 million cells were used. Here, it was shown that a time-accurate CFD calculation can be used to determine transient fuel rod forces for subsequent dynamic analyses. This work also demonstrated that the protective grid significantly reduces flow-induced vibration at the reactor core inlet. Zhang and Yu [11], and Bhattacharya, et al. [12] have performed LES of flow in CANDU fuel bundles and observed the vortex shedding phenomena associated with the end plates. The work by Delafontaine and Ricciardi [13] used LES to determine the time-dependent rod forces in a 3 × 3 PWR rod bundle. Here detailed information about the angular variation of pressure forces on the fuel rod are presented. The work by Liu, et al. [14] considered fluid–structure interaction in simplified fuel assemblies where a rod buckling instability was demonstrated to occur with large axial flow velocities. Mohany and Hassan [15] modeled the flow-induced vibration and associated pressure tube fretting in a CANDU fuel bundle.

This paper presents a rigorous approach for predicting GTRF induced fuel rod wear using high-resolution Implicit Large-Eddy Simulation (ILES) coupled to nonlinear transient structural dynamics. The GTRF problem is separated into sequential steps that involve: a) simulation of the turbulent flow field in the complex-geometry fuel-rod bundles, b) calculation of the resulting statistics of the fluctuating structural forces, and c) the nonlinear transient dynamics of the fuel rod using the computed structural loads. The ILES are performed using *Hydra-TH* which is built on the Hydra Toolkit, a C++ multiphysics toolkit for the rapid development of parallel scalable simulation tools. The methodology presented here may ultimately be used to improve reactor core designs so that fuel failures are minimized or potentially eliminated.