A Multiphysics Framework to Characterize the Fuel Rod and Assembly Bowing Effect in PWRs

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INTRODUCTION

Fuel rod and fuel assembly bowing is a phenomenon known as lateral deflections from their normal positions of the nuclear fuel structures during normal operation conditions. Fuel rod bow and assembly bow have been observed in many nuclear fuel designs, to some extent, especially in pressurized water reactor (PWR) fuel designs that have the largest span and most slender fuel rods. Fuel rod and assembly bowing are one of the major nuclear fuel performance issues in water-cooled nuclear reactors. Fuel assembly bowing would affect the reactor power and flow distribution, which causes many practical engineering operation problems such as space grid damage and incomplete control rod insertion events. Excessive fuel rod bowing can lead to local coolant flow restriction, which results in a reduction of critical heat flux (CHF) and thereby a decreasing departure from nucleate boiling (DNB) heat transfer (cladding overheating) [1]. Under certain circumstances, fuel rod bowing may cause enhanced corrosion and even rod-to-rod contact, which poses great safety concerns for nuclear reactor operations.

While similar in definition, the fuel rod bow and assembly bow differ from each other in their constraint conditions and deformation mechanisms. It is widely accepted that the fuel assembly bow is a result of combined effects under external forces (primarily hold-down loads), thermal gradient across the reactor core, as well as irradiation creep deformation. The fuel rod bow appears to be more complex and there lacks a complete mechanistic understanding of the phenomenon. Analysis of the individual and combined data sets leads to the conclusion that spacer grid forces dominate the rod bow, with secondary contributions derived from differential axial growth of guide tubes and fuel rods, cladding creep strength, fuel pellet perpendicularity in the tube, and tube wall eccentricity [1].

While the structural behavior of PWR fuel assembly bow and its impact on fuel performances have been extensively studied, few were reported with respect to fuel rod bow, partly because of lacking experimental data in the open literature. In the past, fuel rod bow was analyzed through empirical models based on measurements, with limited efforts on analytical approaches. Since then computational modeling on fuel rod bow concerns mainly on the impact to critical heat flux (CHF) and departure from nucleate boiling (DNB) from a thermal hydraulic perspective. As a matter of fact, the fuel bowing phenomenon is naturally a multiphysics problem, and a completely understanding of its mechanism requires a more comprehensive approach that consists of a variety of physics complements including mechanics, neutronics, and thermal hydraulics aspects. These observations basically initiate the motivation of the work presented in this paper.

CURRENT STATUS

A thorough literature review was conducted with the intention to have a clear view of the current status towards the investigation of PWR rod/assembly bow phenomena in both industrial and academia.

The earliest attempt to predict fuel rod bow, both quantitatively and experimentally, can be dated back to 1964 by Ergen from ORNL [2]. Ergen's work was performed on low-enrichment UO2 core at SPERT-I stainless-steel-clad fuel rods. The author attributed fuel rod bow to differential thermal expansion and claimed that the computation and experiment are in good agreement from a time dependence and maximum deflection standpoint. Although thermal gradient may contribute to the bending of fuel structures, external loading such as lateral hydraulic forces due to cross flow was not considered. With the purpose of eliminating operational challenges from fuel assembly distortion and fuel rod bow, EPRI has developed computer codes to perform parametric studies to determine the design features or core operational parameters that have the greatest effect on distortion [3]. However, it did not incorporate considerations on neutronic and thermal-hydraulic impacts due to the distortion.

Two recent studies [4, 5], focused on the influence of fuel rod and fuel assembly bow on the neutronics using Monte Carlo simulation, have not only produced interesting findings but also laid out framework for further investigations. In an effort to assess the subchannel code COBRA-TF v3.5 in addressing the effect of rod bowing on DNBR, Munkin et al. [4] performed modeling work on four different rod bowing geometries in a 4 × 4 rod bundle from the CHF data bank: rod bowing with a gap closure of 50% and 85% of the nominal gap, and two configurations of rod bowing to contact. The subchannel method predicts a reducing critical power due to decreasing of the flow rate in the affected subchannel. Rod bowing configurations with contact to neighbor rods lead to a more substantial decrease of the critical power than the cases with partly rod bowing. The authors did point out a drawback of the subchannel model that it does not take into account the heat exchange between contacted rods and concluded that CHF models require an additional function, which can take into account the substantial reduction of the critical power due to rods in contact. One interesting aspect along with the subchannel modeling is that the authors qualitatively evaluated the power redistribution due to rod gap closure (bow to contact) with a simplified 2-D model using SERPENT. The results showed that the power of the bowed pin is tilted, with higher power regions located in the opposite direction of the bowing, because of the higher moderation experienced in that region. The relative difference in maximum power reaches a value of +5.4% compared to the reference case.

Li et al. [5] investigated fuel assembly bowing effects on isotopic concentrations during depletion for a range of full-scale fuel assembly bow models for Pressurized Water Reactor (PWR) assemblies and full cores. Similar as the neutronics model by Munkin et al., this work is also performed using SERPENT, by first starting from a two-dimensional array with a central member (fuel assembly) displaced. The difference is the members being investigated are fuel assemblies instead of fuel rods. Investigations are carried out on burn-up evolutions and horizontal re-distributions of nuclide concentrations resulting from assembly bowing effects. In addition, the authors further investigated the longitudinal distributions of the fuel content changes by simulating a three-dimensional assembly bowed in C-shape. A measured bowing map from an operating reactor was also simulated for 2D PWR full cores with CASMO-5 to reveal the bowing impacts in terms of assembly locations.

Based on the findings from Munkin et al. [4] and Li et al. [5], it might be reasonable to question whether and how the re-distributed power or flow conditions exert a feedback effect on the fuel rod/assembly structural behavior. To date, there has not been discussions made on such effects as a result of neutronics and thermal-hydraulics impacts.

MULTIPHYSICS FRAMEWORK

The fuel rod/assembly bowing in PWRs would cause many interconnected phenomena that are complicated with different physics involved. As the flow area changes, the reactivity and thermal-hydraulic parameters change in the vicinity of the affected rod/assembly, and thus the irradiation level the rod/assembly experiences as well as the flow mixing conditions, which may in turn affect the fuel rod/assembly bowing progressively. Therefore, a multiphysics framework that incorporates multiphysics modeling capabilities and enables a multiphysics simulation environment is inevitably needed to effectively capture the fuel rod and assembly bowing phenomena in PWRs. A schematic view of the multiphysics framework enabled in our work is shown in Fig. 1, in which the multiphysics framework essentially encompassed three physics components, namely the mechanical/structural, neutronics, and thermal-hydraulics considerations.

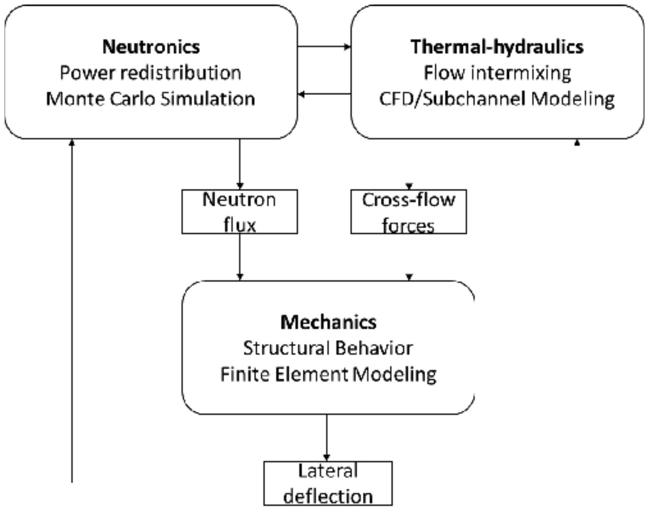

Fig. 1. The data flow and components in the multiphysics framework for fuel rod/assembly bow modeling.

The mechanical/structural modeling of fuel rod bowing can be accomplished using the finite element analysis (FEA) method. It is widely accepted that irradiation creep is the primary driving force of rod bowing phenomenon. Initial deflections and external loadings due to cross flow are potentially the two major causes of the bowing behavior at the very beginning of reactor operations. An effective FEA model that accounts for the structural mechanisms of a fuel rod bowing should consider the following aspects: fuel rod and guide tube differential irradiation growth model, constitutive equations for stress strain as a function of time, temperature, and fluence, characterization of mechanical behavior of structural components, and measurements for validation of results. [4]

The neutronics impacts of fuel rod bowing such as reactivity change, power re-distribution, and so on can be captured via Monte Carlo transport calculations. An effective neutronics model in this regard should consider: the impact of single rod spacing [2] to power re-distribution in both radial and axial directions, the sensitivity of such impact and incorporate the deflections from the structural model and the thermal properties variations from the thermal-hydraulics model to check the feedback effect, and how individual rod bowing effect translates to fuel assembly performance variations. [5]

The thermal-hydraulics impact of fuel rod bowing includes the variations of coolant flow condition, temperature and density during the bowing, and the influences of these changes on neutronics and structural aspects. The flow and heat transfer conditions can be characterized by a CFD model on local effect and a subchannel model for a larger size. An effective thermal-hydraulics model in this regard should consider: the interaction of the neutronics model by exchanging the heating source and thermal feedback between the two models, and the coupling with the structural model for proper thermal properties and flow conditions.

In the level of assembly bowing, a similar approach can be accordingly implemented with emphasis paid to understand the separate and integral impacts of one single assembly bowing to a full core performance variation.

SINGLE ROD PERTURBATION MODELING

To demonstrate the approach described above, we focus on a single fuel rod that is perturbed (displaced or deformed) within a simplified bare rod bundle, which is sufficient to represent the appropriate boundary conditions for the rod of interest. Two different models are developed for different purposes: 1) a 2-rod bundle with periodic boundary conditions for CFD modeling; 2) a 3×3 rod bundle with reflective boundary conditions for the neutronics simulation. A displaced rod situation, where a fuel rod is translationally deviated from its regular position (Fig. 2), is included along with the rod bowing configuration to comprehensively study the response of flow and heat transfer conditions as well as neutron transport to geometric perturbations.

A simplified CFD model is created in ANSYS Fluent Version 2020R1 to illustrate the impact from geometric perturbation only, by neglecting the cladding thickness and the effects from spacer grids. The coolant flow is considered to be incompressible Newtonian flow with turbulence. The material properties are considered uniform at a temperature of 530.0 K and pressure of 15.6 MPa. The inlet flow velocity is set to be 2.35 m/s and the pressure is fixed at the outlet. In addition, a uniform volumetric heating rate of 372×10^6 W/m^3 is applied to every fuel rod element. Steady-state flow and heat transfer are then solved using k-epsilon turbulence model with coupled energy equations.

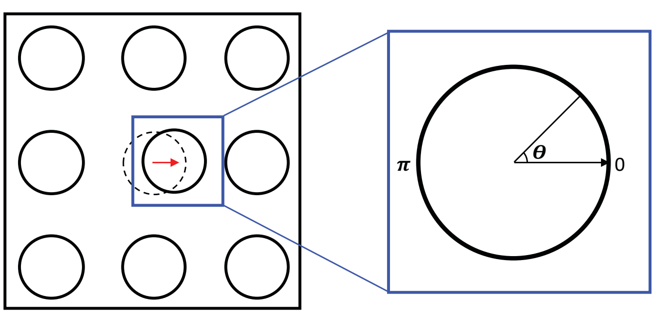

Fig. 2. Illustration of a 3×3 fuel rod bundle with the center rod deviated from its regular position.

Three cases, including a control case along with two displaced rod cases with 50% and 90% gap closure, are performed for comparison. A shift of temperature distribution towards the gap closure direction, as shown in Fig. 3, is observed: temperature increases in the rod displacement direction while decreases in the opposite, especially when two rods are extremely close. This is understood as a result of cooling effect due to changes in flow area.

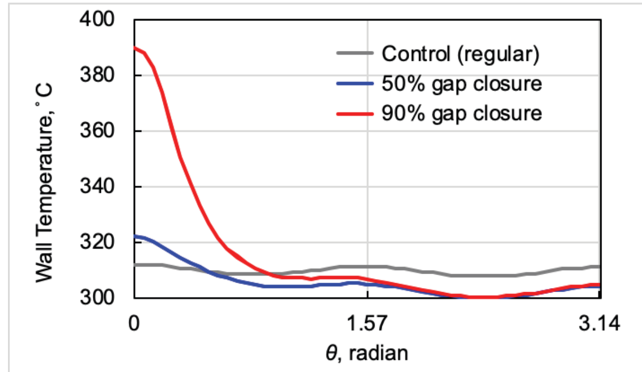

Fig. 3. Wall temperature distributions around the fuel rod surfaces plotted for comparison: regular rod vs. displaced rods with 50% and 90% gap closure.

Monte Carlo simulation is also performed using MCNP6.2 to study the impact of geometric perturbation on neutron transport. The model consists of fresh uranium fuel and water (as the moderator), with neutron reflective spatial boundary conditions. A slight increase of k_{eff} coefficient is noticed (0.0004 with an estimated standard deviation of 0.00017) as the center rod displaces to a 90% gap closure. Fission power density is also tallied in the perturbed fuel rod to investigate the power re-distribution at a local level.

The re-distributed power is then fed back to the CFD model as a non-uniform heating source to evaluate the impact on temperature distribution. On the other hand, the shifted temperature distribution around the circumference of the fuel rod, mentioned earlier (Fig. 3), may cause additional fuel deformation as the thermal gradient translates to global bending.

CONCLUSIONS

To sum up, a multiphysics framework that incorporates multiphysics concepts and enables multiphysics modeling is proposed to effectively capture the fuel rod and assembly bowing phenomena in PWRs. Geometric perturbation from nuclear fuel, such as fuel rod displacement and bowing, has been studied with regards to the neutronic and thermal-hydraulic performances. Recognizing the interconnected influences, the feedback effects will be examined, especially how power re-distribution further affects the structural and thermal-hydraulic responses.

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