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Evolution of grid-to-rod fretting of nuclear fuel rods during burnup

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ABSTRACT

Nuclear fuel rod consists of the cladding and fuel pellets stack. Fuel rods are mounted in fuel assemblies and they are linked by spacer grids. Due to vibration of a fuel assembly during the reactor operation, grid-to-rod fretting (GTRF) occurs in contact points between the cladding of the fuel rod and spacer grid cells. The GTRF phenomenon causes the loss of mass of the cladding in contact points and it can possibly lead to leakage of fission products into a coolant. The paper presents a complex modelling concept for the GTRF analysis of fuel rods due to vibration caused by pressure pulsations of the coolant. The method deals with several essential subproblems. The key part of the method is a dynamic model that simulates vibration of the fuel rod. To estimate wear properties of the cladding, an experimental procedure is used and to determine the state of burnup, a physical model is used. Based on the simulated vibration of the fuel rod and the subsequent GTRF analysis, the evolution of the GTRF during burnup can be determined.

1. Introduction

Fuel rods (FRs) in nuclear fuel assemblies (FAs) of pressurized water reactors (PWRs) are linked by spacer grids (SGs). Due to flow and pressure pulsations of the coolant, the FA vibrates. In contact surfaces between the FR cladding and prestressed spacer grid cells, a relative motion occurs. It causes local loss of the cladding material. This phenomenon is called grid-to-rod fretting (GTRF) and it can lead to an undesirable thinning of the cladding or even the exposure of fuel pellets that are placed inside the cladding. Therefore, the estimation of the GTRF evolution during the FR lifetime gives an important information about the FAs.

From the mechanical point of view, the FR is a long thin tube and it can be modelled as a beam. In Fig. 1 on the left, a part of the fuel rod is depicted – a fuel rod cladding is a zirconium tube that is filled with the fuel pellets. Basically, FAs of square or hexagonal cross-sections are used in the PWR reactors. In the application part, the paper focuses particularly on the hexagonal-type FAs, nevertheless, the proposed methodology can be used for any other type of the FAs with slight modifications. Particularly in the case of TVSA-T FA applied in the VVER-1000 type reactors, which will be discussed further, there is 312 FRs in one assembly. They are linked together by eight spacer grids, whose shape is shown in Fig. 1 on the right. At the level of each spacer grid, the particular FR is held by three prestressed cells.

Generally, the GTRF can be analyzed using different experimental or numerical approaches. An important construction aspect influencing the GTRF is a shape and geometry of spacer grid cells. Therefore its optimization is a frequent problem, which is solved computationally (Kovács et al., 2009; Christon et al., 2016; Kim et al., 2001) or experimentally (Lee and Kim, 2007; Kim et al., 2008). There are several works focusing on the GTRF failure observed on the real FAs (Kim, 2010). In the field of numerical simulations, detailed FEM analyses were performed (Jiang et al., 2016) focusing on contact phenomena occurring between spacer grid cells and the fuel rod cladding, or wear mechanism simulations including creep (Wang et al., 2017), which show the evolution of the wear in the contact surface. A multi-stage description of the wear is shown in (Blau, 2014) where the different phases of the wear are discussed in detail. Another complex concept of modelling was introduced in (Rubiolo, 2006). Therein, a dynamic model excited by turbulent flow is considered and the GTRF is estimated using a probabilistic approach.

There are two possible mechanisms of the excitation of the FAs that occur during a standard operation of the reactor – flow-induced vibration of the coolant and pressure pulsations of the coolant given by the rotation of main circulation pumps. The flow induced vibration occurs if fuel assembly is exposed to axial or cross flow (Gagnon and Païdoussis, 1994; Modarres-Sadeghi et al., 2003; Jamal, 2014). The problem is described from the fluid-structure interaction point of view (Santis and Shams, 2017). Some works (Bakosi et al., 2013) show the distribution of the coolant velocity in the FA that influences the FR vibration.

The pressure pulsations of the coolant (Bulavin et al., 1995; Lee and Im, 1994), (Kaneko et al., 2008, Chapter 5) cause the vibration of FA as well because the FAs are fixed in the mounting plates that are directly

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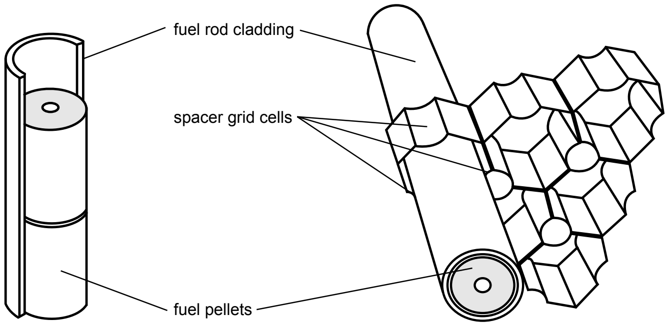

Fig. 1. A part of the fuel rod filled with the fuel pellets (left) and a fuel rod fixed into spacer grids of the hexagonal-type fuel assembly (right).

exposed to the pressure pulsations. There are analytical methods to estimate the pulsations (Cheong, 2000) that are observed in the real reactors (Mohany and Hassan, 2013; Yu and Fadaee, 2016; Fadaee and Yu, 2017; Lee et al., 2012). E.g. the linearized model, which will be further used to estimate vibration of the VVER-1000 reactor components caused by pressure pulsations of the coolant, was shown in (Zeman and Hlaváč, 2008, 2009, 2011).

The proposed method for the estimation of the GTRF of the FRs introduces a complex approach that combines the numerical simulation of the FR vibration, the experimentally obtained fretting wear parameter and a numerical model of the FR for calculation of the gap between fuel pellets and the cladding. In the numerical simulations of the FR vibration, all of the relevant mechanical nonlinearities are taken into account: impact between the fuel pellets stack and the FR cladding, the prestress of the SG cells with a possible loss of contact and friction forces in the contact between the cladding and the cells. The pressure pulsations of the coolant are considered a dominant excitation mechanism of the FA vibration.

2. A concept of the modelling

A schematic diagram of the proposed method is depicted in Fig. 2. The highlighted parts of the diagram will be discussed in detail because they are novel or highly improved compared to the preceding ones. The problem of the estimation of the GTRF evolution consists of several subproblems, which are solved separately.

2.1. A dynamic model of a single FR

A dynamic model a the single FR is a part of the algorithm that is used to numerically simulate the FR vibration. It is a detailed model of the FR consisting of two flexible subsystems – the FR cladding (C) and the fuel pellets (P) stack. The model respects all the relevant mechanical nonlinearities such as contact forces between both subsystems, contact forces between the cladding and SG cells with prestressing effect and a possible loss of contact. The preceding dynamical model (Zeman et al., 2015) was widely improved by a priori inclusion of friction forces in the dynamic model and by the consideration of torsional and axial degrees of freedom. Both of the two improvements make the sliding velocities in contact areas more precise. Preliminary analyses of the GTRF were also published in (Zeman and Hlaváč, 2016). However, the impact-interactions between fuel pellets and cladding were neglected in this paper and the burnup was not taken into account at all. Hence, it did not allow to describe an evolution of the GTRF and its dependency on the FR burnup. A detailed description of the model is presented in Sec. 3 and it forms the key part of the presented paper.

2.2. A global model of the reactor and a linearized model of the FA

A global model of the reactor and a linearized model of the FA are used to obtain an appropriate excitation of the FR caused by pressure pulsations of the coolant. In the dynamic model of the FR, the kinematic excitation caused by motions of the mounting plates and the SG cells centres is considered. These motions are excited by the pressure pulsations of the coolant and they are investigated using a global model of the reactor VVER-1000 (Zeman and Hlaváč, 2008) and a linearized model of the FA (Zeman and Hlaváč, 2009). The motions of the mentioned components are described by polyharmonic functions. The pressure pulsations are caused by the rotation of four main circulation pumps where first three harmonic components generated by every pump are considered.

2.3. GTRF analysis

The GTRF analysis is performed using two inputs – the simulated motion of the FR cladding and the experimentally obtained fretting wear parameter (see the scheme in Fig. 2). The improved formula originally introduced in (Zeman et al., 2015) is extended for the case in which the friction forces are included a priori in the dynamic model of the FR.

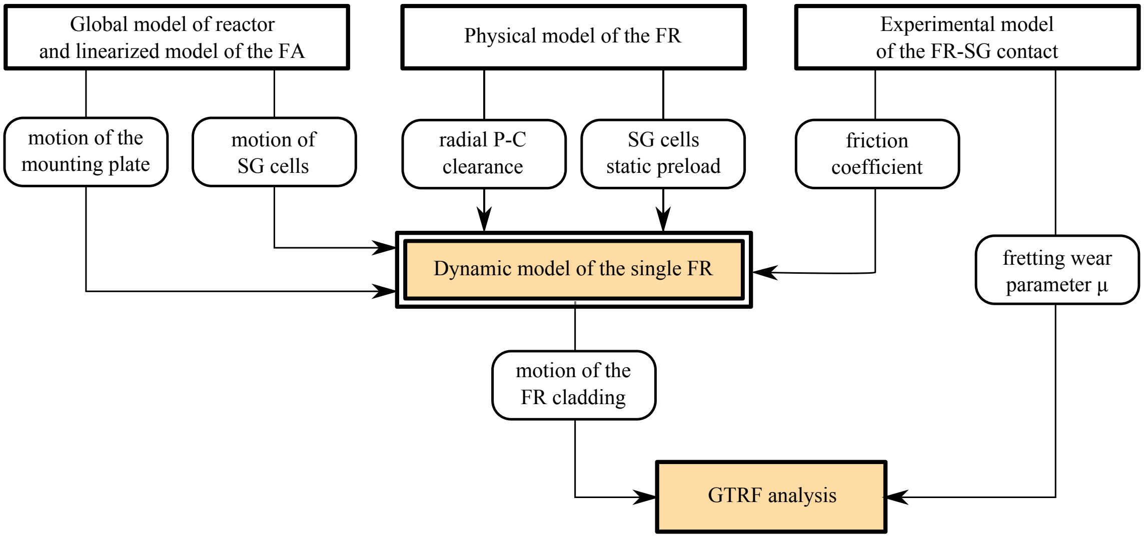

Fig. 2. Scheme of the proposed concept of modelling.