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Analyses of deformation and thermal-hydraulics within a wire-wrapped fuel subassembly in a liquid metal fast reactor by the coupled code system

Tomoyuki Uwaba *, Hiroyuki Ohshima, Masahiro Ito

Japan Atomic Energy Agency, 4002, Narita-cho, Oarai-machi, Ibaraki 311-1393, Japan

HIGHLIGHTS

- The coupled computational code system allowed for mechanical and thermal-hydraulic analyses in a fast reactor fuel subassembly.
- In this system interactive calculations between flow area deformations and coolant temperature changes are repeated to their convergence state.
- Effects on bundle-duct interaction on coolant temperature distributions were investigated by using the code system.

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ABSTRACT

The coupled numerical analysis of mechanical and thermal-hydraulic behaviors was performed for a wire-wrapped fuel pin bundle subassembly irradiated in a fast reactor. For the analysis, the fuel pin bundle deformation analysis code BAMBOO and the thermal-hydraulic analysis code ASFRE exchanged the deformation and temperature analysis results through the iterative calculations to attain convergence corresponding to the static balance between deformation and temperature. The analysis by the coupled code system showed that the radial distribution of coolant temperature in the subassembly tended to flatten as a result of the fuel pin bundle deformation governed by cladding void swelling and irradiation creep. Such flattening of temperature distribution was slightly observed as a result of fuel pin bowings due to the cladding-wire interaction even when no bundle-duct interaction occurred. The effect of the spacer wire-pitch on deformation and thermal-hydraulics was also investigated in this study.

1. Introduction

Fast breeder reactors (FBRs) are a promising system candidate for the future generation of nuclear reactors because they can improve the efficiency of nuclear fuel utilization for the stable supply of energy. For their commercialization, increasing fuel burnups is essential for reducing the fuel cycle cost and the amount of spent fuels. In the liquid metal-cooled FBRs such as Phénix in France, Fast Test Flux Facility (FFTF) in the United States and Joyo in Japan, wire-wrapped fuel pin bundle subassemblies have been used as their driver fuels because of the structural simplicity of fuel pins and their flexibility against dimensional changes of subassembly under high temperature and fast neutron fluence environment.

When the fuel burnup is increased, cladding void swelling and cladding irradiation creep by the internal fission gas release will occur due to increased fast neutron fluence, causing diameter increases of fuel pins (Shibahara et al., 1993; Maeda et al., 2005; Uehira et al., 2001). Since the cladding diameter increases faster than the fuel pellet diameter, pellet-cladding mechanical interaction (PCMI) probably does not matter in the increased burnup. Diameter increases of the cladding, however, result in radial dilation of the fuel pin bundle and mechanical interactions between adjacent fuel pins and those between outer most fuel pins and the duct occur via spacer wires when the dilation is significant. This phenomenon is the bundle-duct interaction (BDI), under which fuel pin helical bowings occur to accommodate the dilated fuel pin bundle in the less dilated duct as schematically shown in Fig. 1 (Uwaba and Tanaka, 2001).

* Corresponding author.
E-mail address: uwaba.tomoyuki@jaea.go.jp (T. Uwaba).

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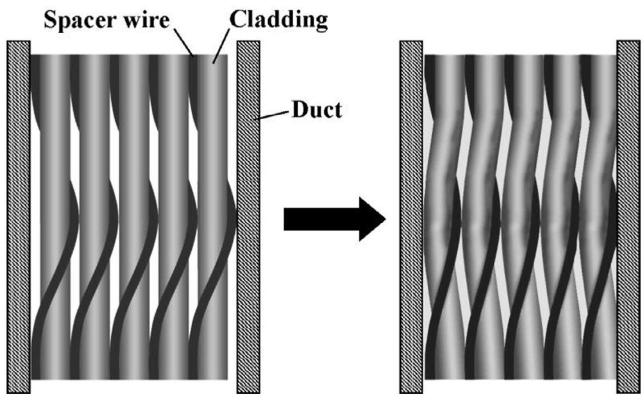

Fig. 1. Schematic of a fuel pin bundle deformation due to BDI.

In severe BDI, the fuel pin bowings may become excessive enough to block coolant flow locally, which gives rise to cladding local hot spots. Even though such local blockages are not caused, deformed flow areas affect the thermal hydraulics in some measure, changing coolant temperature distribution in the subassembly. Thus, the thermal hydraulics of the deformed fuel pin bundle is of significant importance in the safety assessment of the fuel subassembly. Furthermore, the fuel pin deformations are also affected by the temperature distribution as the feedback of deformations. However, the detail evaluation for interactions between fuel pin bundle deformation and coolant thermal hydraulics in the actual scale of the subassembly with more than one hundred fuel pins seems to be almost impossible from the experimental approach because of the difficulties in measuring fuel pin deformations, coolant flow and temperature distributions. Considering recent progress of computer systems and numerical simulation technologies, Japan Atomic Energy Agency has been developing the numerical coupling analysis system using the two computational codes: fuel pin bundle deformation code (BAMBOO) and fuel subassembly thermal-hydraulic analysis code (ASFRE).

In the previous study, Miki developed a coupling system of bundle deformation analysis code (SHADOW) and thermal-hydraulic analysis code (DIANA) and using the system evaluated effects of the fuel pin bundle deformation on coolant temperature distribution in sodium cooled FBR subassemblies (Miki, 1977, 1979). In this study various parameters were chosen such as spacer wire diameter, fuel pin pitch, spacer wire-pitch, radial power gradient and duct bowing and the effects of these parameters were investigated on mechanical and thermal points of view. However, radial dilation of the fuel pin bundle, which is the primarily cause of BDI, was not considered because of the lack of the irradiation data concerning BDI available at that time.

Irradiation data of the FBR fuels subassemblies that experienced BDI in high burnups have recently been accumulated and were used for the validation of the bundle deformation analysis with BAMBOO (Uwaba et al., 2005, 2008), where irradiation-induced deformations such as void swelling and irradiation creep were taken into account. The verification analyses revealed that deviation of the spacer wire positions causes fuel pin dispersion to relax a few mechanical interactions in a fuel pin bundle and cladding oval deformations effectively delay cladding-to-duct contact (mitigation of BDI).

In the field of the thermal-hydraulic analysis for a fuel subassembly, the subchannel analysis code ASFRE was developed for efficient analyses of a wire-wrapped fuel pin bundle under various operating conditions such as normal operation, transient condition or flow blockage condition from the viewpoint of the assessment of fuel pin structure integrity (Ohshima et al., 1997). ASFRE was modified on the spacer wire volumetric effects and their calibration factors in order to improve the accuracy of the coolant temperature calculation. The modification was validated through the analyses of out of pile sodium experiments with small pin bundles (Kikuchi et al., 2016).

Hence, BAMBOO and ASFRE can be currently the practical codes for bundle deformation and thermal-hydraulic analyses in wire-wrapped FBR fuel pin bundle subassemblies. Interactive operation of these codes can increase the accuracy of both analyses. Thus, these codes were coupled as a numerical simulation system for mechanical and thermal-hydraulic analyses. The original of this simulation system (coupled code system) was reported by Ohshima et al. (2015) and the improvement has been continued until recently.

Development of the coupled code system and mechanical and thermal-hydraulic analyses by the system for a deformed fuel pin bundle under irradiation are the subject of this paper.

2. Analytical method

2.1. Outline of the BAMBOO and ASFRE codes

Brief descriptions of these codes are presented in the following; the details for BAMBOO are explained by Uwaba and Tanaka (2001) and Uwaba et al. (2005, 2008), and those for ASFRE are by Ohshima et al., 1997 and by Kikuchi et al. (2016).

BAMBOO calculates deformations of all fuel pins and a duct in a wire-wrapped FBR subassembly by using the finite element method. Fuel pin deformations calculated by BAMBOO are as follows: radial expansion due to the thermal expansion, cladding void swelling and irradiation creep driven by the fission gas internal pressure, bowing due to the circumferentially thermal expansion difference and mechanical interaction between adjacent pins and that between pins and a duct via spacer wires, and cladding oval distortion by mechanical interaction between adjacent pins and that between pins and a duct via spacer wires. Fuel pin bowing and cladding oval distortion are calculated in the elastic and creep deformation analyses so that the stress relaxation due to the creep can be considered. Each fuel pin is modelled by using beam elements connected in a series with the bottom end of the pin rigidly supported. Each beam is axially subdivided into 12 beam elements per spacer wire-pitch. Since the subdivided beam has two nodal points at its both ends, each nodal plane in the bundle is selected at the pin wire contact plane (pinch plane) or the pin-duct contact plane (normal plane) as shown in Fig. 2. A cross section of the beam element at each nodal point has sex integral points in the cladding wall at 60 deg intervals as shown in Fig. 3; cladding stress, strain and void swelling are calculated in the integral points.

Irradiation time is divided into small time step intervals and at each time step the code calculates thermal, void swelling, creep

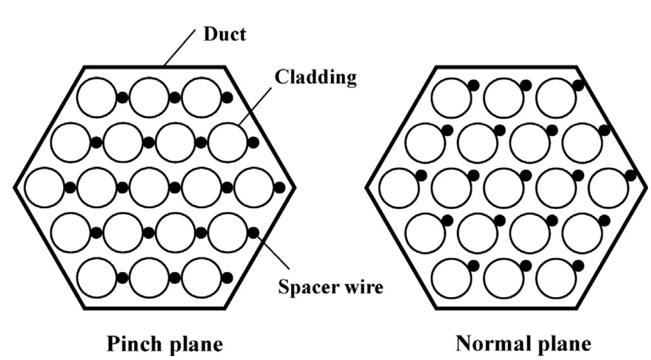

Fig. 2. Schematic of nodal planes of a fuel pin bundle subassembly in BAMBOO.