CONTRIBUTIONS TO FUEL ELEMENT BEHAVIOR ASSESSMENT USING THE FINITE ELEMENT METHOD

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Abstract

The purpose of the paper is to study the possibility of evaluating the CANDU fuel element behaviour, using the open-source finite-volume nuclear fuel performance code, OFFBEAT (OpenFOAM Fuel BEhavior Analysis Tool), based on the OpenFOAM C++ library. Therefore, in order to achieve the aforementioned purpose, an experimental CANDU type fuel element, irradiated in the TRIGA reactor from RATEN – ICN was chosen for analysis, employing OFFBEAT fuel performance code. The main outcomes of the simulation are related to fuel element temperatures, internal pressure of the irradiated fuel element and the volume of fission gas released in the free volume. As a main conclusion, the simulation results were similar with the available experimental data as well as with the results obtained using ROFEM code. Therefore, it can be concluded that the OFFBEAT can be a suitable tool for evaluating the CANDU fuel element behaviour, in normal operating conditions.

Keywords: *OFFBEAT code, Thermo-mechanical behaviour, CANDU fuel, Finite volume method*

Introduction

Fuel performance evaluation codes are essential tools used to ensure safety and economic operation of nuclear reactors. Nuclear fuel is subjected to an intense radiation field under severe thermo-mechanical and corrosive conditions, its evolution during reactor operation being characterised through a set of complex phenomena. Therefore, to evaluate the complex nuclear fuel behaviour during irradiation, computer codes are being developed and can be accurately applied.

The present work aims to present the possibility to use the open-source nuclear fuel performance code, OFFBEAT (OpenFOAM Fuel BEhavior Analysis Tool) for analysing the CANDU type fuel behaviour.

The methodology used included a preliminary study of the OFFBEAT test cases and workflow, to get familiar with the code structure. To create a case applicable to CANDU fuel, an experimental CANDU type fuel element was chosen from the literature. By using OFFBEAT, CANDU fuel behaviour was simulated based on the constructive and fabrication data and irradiation history. The results were compared with experimental data and with ROFEM code's predictions, for the same fuel element. OFFBEAT capabilities to assess CANDU fuel behaviour were highlighted.

OFFBEAT code

OpenFOAM Fuel BEhavior Analysis Tool (OFFBEAT) is a three-dimensional finite-volume nuclear fuel performance code based on the OpenFOAM® C++ library.

The code was jointly developed by the Laboratory of Reactor Safety (LRS) at École Polytechnique Fédérale de Lausanne (EPFL) and the Laboratory for Reactor Physics and Thermal-Hydraulics (LRT) at the Paul Scherrer Institut (PSI) [1, 2].

OFFBEAT is developed according to a cell-centered finite-volume framework for total Lagrangian, small strain solid mechanics. This is combined with a framework for the thermal analysis and with numerical developments concerning the treatment of the gap heat transfer and contact, based on a mapping algorithm that allows the use of independent non-conformal meshes for fuel and cladding. The code considers the material properties' dependence on temperature and burnup, and it can model complex phenomena such as: fuel densification, relocation, swelling, growth, fission gas release, creep, plasticity, and other relevant fuel behavior phenomena.

To be able to run an OFFBEAT simulation, the main case directory needs to have a standard structure, as follows:

- *0/ folder*. It contains files regarding the initial and boundary conditions for the main fields, usually:
  - T, Initial and boundary conditions for the temperature field.
  - D, Initial and boundary conditions for the total displacement field.
  - gapGas, information on the initial gapGas pressure and composition.
- *constant/ folder*. It contains:
  - The polyMesh/ folder, with information about mesh.
  - The solverDict , is the main OFFBEAT dictionary used to select the solvers and model activation.

- *system/folder*. It contains minimum the following files:
  - controlDict, provides the main parameters controlling the simulation.
  - fvSchemes, indicates the settings for the discretization schemes used by the code.
  - fvSolution, indicates the settings for the numerical solvers used by the code.

Experimental element description

To perform the study on the applicability of OFFBEAT code to analyse the CANDU fuel element, an experimental fuel element was chosen, namely element no. 89 which was fabricated at RATEN ICN Pitesti and irradiated in the TRIGA Research Reactor [3, 4].

The main design differences between the experimental fuel element and a typical CANDU fuel element are, as follows: smaller fuel element length (292 mm); UO_2 fuel pellets with 3.92 wt% enrichment in U^{235} (to reach the designed linear power); smaller axial gap (to compensate the lower UO_2 mass per fuel element) and, consequently, a smaller amount of fission gas expected to be released during the irradiation; a particular shape of the end caps (to allow their compatibility with the irradiation device and the pressure transducer). Otherwise, the fuel element no.89 has the same characteristics as an outer fuel element of the CANDU type fuel bundle, in term of fuel geometry, fuel density, radial gap, brazed appendices (inter-element spacers and bearing pads). The fuel pellets density was between 10.54 – 10.62 g/cm^3, close to the nominal value of 10.6 g/cm^3. The appendices were made of Zircalloy-4 and attached to the cladding by brazing with beryllium. A more detailed description of the experimental fuel element no.89 along with description of the irradiation device and the parameters of irradiation can be found in [3, 4].

The experimental fuel element was instrumented with pressure transducers which measured the internal pressure online. The amount of fission gas released was measured post irradiation.

The power history used for the OFFBEAT simulation was taken from the experimental documentation [2] and it is represented in Fig. 1. Other irradiation conditions used for the analysis as neutron fast flux, coolant temperature and pressure and heat transfer coefficient between coolant and cladding were also taken from [2].

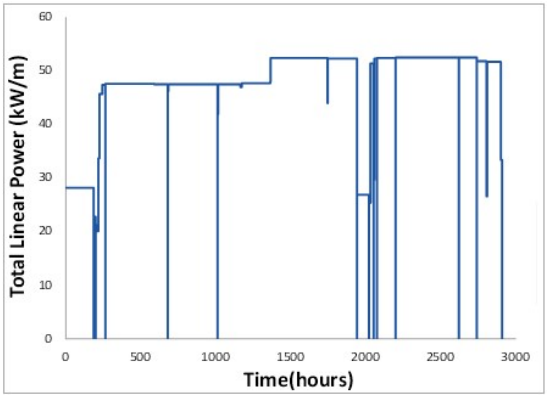


Fig. 1. Experimental power history

Fuel element modelling

The workflow involved in setting up the main case folder and the input files needed for an OFFBEAT simulation along with some modelling aspects relevant to the current simulation are provided in the following.

OFFBEAT operates, as well as OpenFOAM C++ Library, using a cell-centered finite-volume framework. In general, for OFFBEAT simulations, hexagonal meshes are used due to the relatively simple geometry of the fuel rod design. Fig. 2 illustrates an example of the computational domain for a 2-D axis symmetric model of a typical fuel rod used in OFFBEAT.

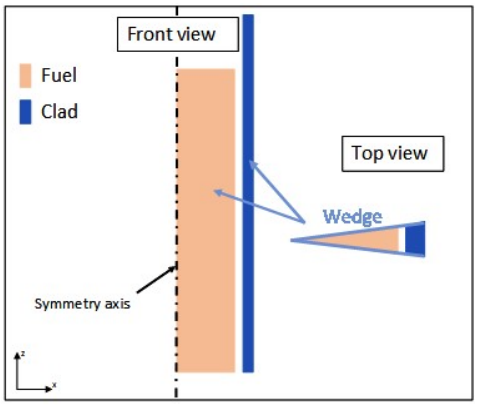


Fig.2. 2-D computational domain for fuel rod

First of all, the geometry and mesh should be created, using the "rodDict" dictionary and the "rodMaker" script which are provided along with the code. The resulted mesh for the simulated experimental fuel element no. 89 is shown in Fig. 3.

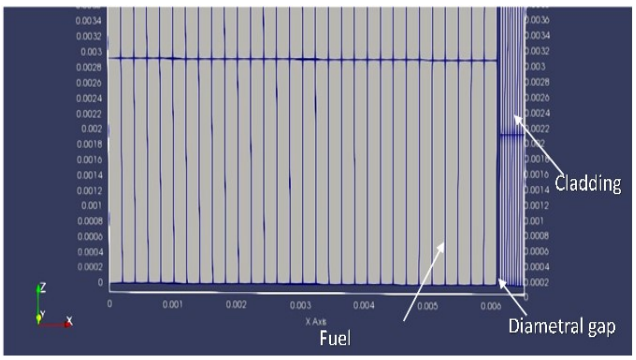


Fig. 3. Mesh used for experimental fuel element no. 89

The mesh created for the simulation is delimited by the boundary regions which will be used for setting the boundary conditions for simulation. Through "rodMaker" script, the boundary regions are set along with the mesh construction. These regions are general for OFFBEAT simulations and are represented in Fig. 4.

As the input files are developed for the OFFBEAT simulation, the boundary regions created in the meshing process need to be associated with specific mechanical, thermal and neutronic boundary conditions. The boundary conditions used for the simulation performed in the present study are shown in Fig. 5.

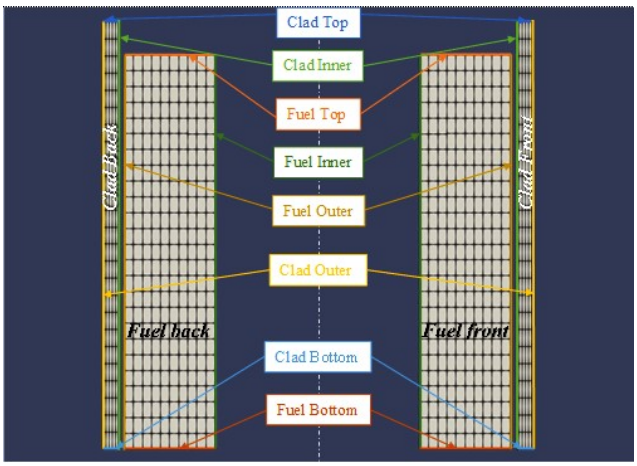


Fig. 4. Boundary regions for OFFBEAT fuel element model

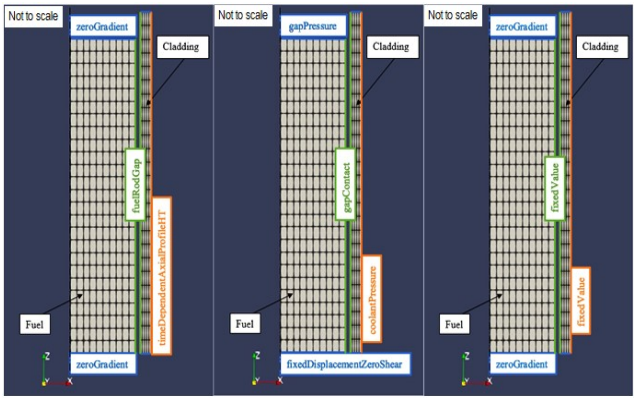


Fig. 5. Boundary conditions used for the simulation: thermal (left), mechanical (middle), neutronic (right)

For the filling gas, the initial properties such as composition, initial pressure and calculation model for internal pressure, are introduced in the "gapGas" file located in 0/ folder.

The main dictionary for the OFFBEAT code is called "solverDict" and it is located in the *constant/ folder* of the main case folder. In this file all the options for the specific solvers and classes used in the code (as example, the solvers *thermalSolver, mechanicsSolver, neutronicsSolver, elementTransport,* and classes *rheology, heatSource, burnup, fastFlux, gapGas, FGR (fission gas release), corrosion, sliceMapper*) are set. The materials used for the fuel and cladding (UO_2 for fuel and Zircaloy for cladding) and their properties and calculation models are also set here, through the *materials* class.
The SCIANTIX code [5] calculates the fission gas release and in addition to activate the *fgr* class in the solverDict dictionary, the code needs a file named "input_settings.txt" located in the main folder, which contains the calculation models used by SCIANTIX.

The controlDict file, which is located in the system/ folder in the main directory of the simulation, provides the key parameters used to control the calculation. The start and finish times are set here, as well as the time step and other parameters required to control the simulation's results writing. The fvSchemes and fvSolution files in the system/ folder are also used to configure the discretization schemes and numerical solvers used by the code.

After creating all of the input files and selecting the appropriate settings for solvers and calculation models, the simulation may be started by using the "offbeat" command in a terminal located in the main case folder. The "end" line showed in terminal after running the simulation indicates that the run completed successfully, without errors, and the results can be extracted. The results are post-processed using ParaView, which is a multi-platform scientific data analysis and visualization tool [6].

Results and discussions

The results obtained from OFFBEAT simulations will be presented in the following by comparison with the available experimental data, as well as using a code-by-code comparison, based on ROFEM code predictions.

Evolution of the main parameters is presented related to: fuel temperatures, internal pressure and volume of fission gas released (FGR) in the free volume. In order to show the OFFBEAT capability to assess CANDU fuel behavior, the evolution of the main parameters during irradiation is graphically represented, along with the available results extracted from de experiment documentation, only in terms of fuel internal pressure and FGR (only the value extracted from gas puncturing after irradiation) [1].

ROFEM simulations carried out in a previous work [7] are also presented in the graphs to offer an overview of the present simulation's accuracy.

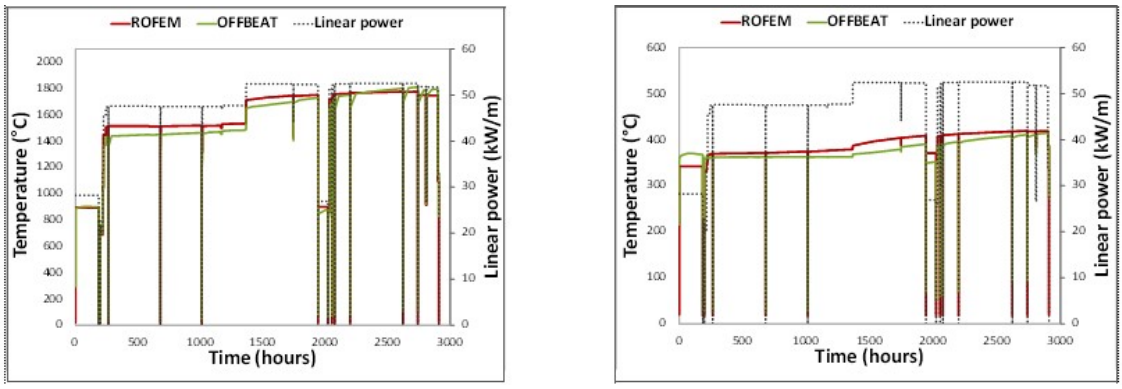


Fig. 6. Experimental fuel element 89: center pellet temperature (left) and outer pellet temperature (right)

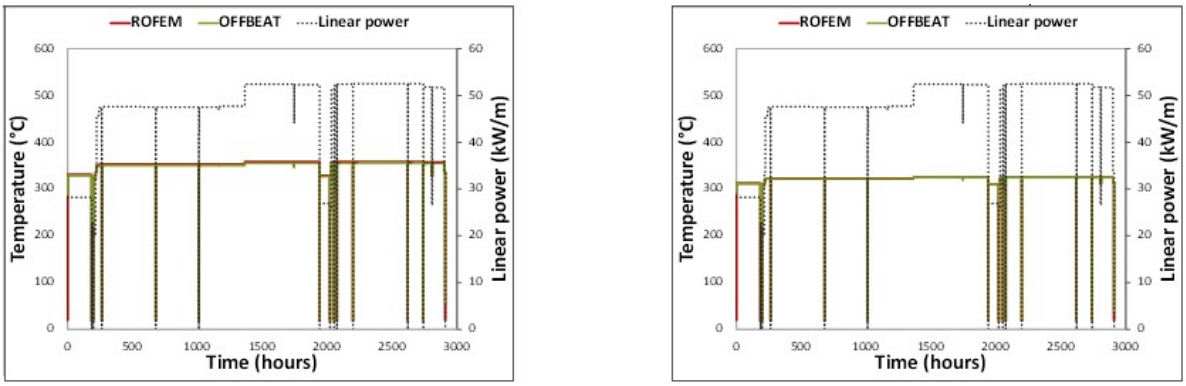


Fig. 7. Experimental fuel element 89: inner cladding temperature (left) and outer cladding temperature (right)

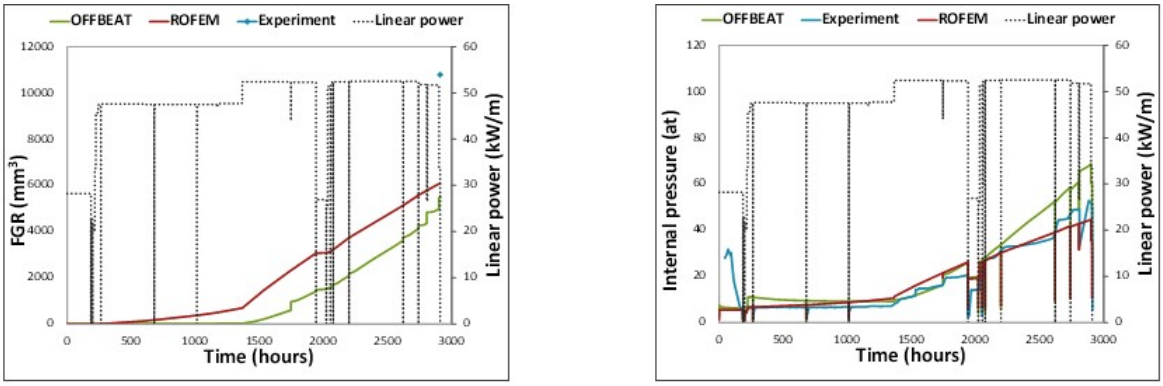


Fig. 8. Experimental fuel element 89: fission gas release (left) and internal pressure (right)

In the graphs presented in Figs. 6 and 7, the fuel element temperature evolution is represented both for the fuel pellet and cladding. As it can be seen, the temperatures' evolution is comparable with ROFEM predictions, during the whole irradiation period. However, there are some quite small differences between the codes results.

OFFBEAT results for the center fuel temperature slightly underestimate the values obtained with ROFEM in the first part of the irradiation period, and for the last part of the simulation the differences are much smaller, with OFFBEAT slightly overestimating the ROFEM results. The fuel surface temperature is also slightly underestimated by the OFFBEAT compared to ROFEM, over the most period of the simulation. This might be due to the different computation models used by the two computer codes. Regarding the inner and outer cladding temperature, the predictions between the two codes are very similar.

The evolution of fission gas release and element internal pressure can be observed in Fig. 8. The results obtained in the present analysis are in a good agreement with the experimental measurements for the internal pressure.

Over the most part of the irradiation, OFFBEAT results in terms of internal pressure are higher than the values recorded during the experiment, as well as than the ROFEM predictions, especially in the final half. The internal pressure evolution is strongly connected to the fission gas release. The predicted release of fission products begins at about 1400 h out of a total of 3000 h. Only one value was recorded during the experiment, taken from the gas puncturing after the irradiation, therefore the evolution of fission gas release can be only compared using both code's predictions perspective. The OFFBEAT code estimates a lower volume of fission gases released during irradiation than the ROFEM code. Both codes also underestimate the measured FGR value at the end of the irradiation.

Conclusions

In this paper, OFFBEAT capabilities to predict CANDU fuel behaviour were investigated. For this reason, an experimental fuel element was chosen for simulation, and the available experimental data were compared to the code predictions.

To conduct the simulation, great consideration was given to the computational aspects and models used, as well as for the process of creating the suitable geometry and mesh for the analysed fuel element. Furthermore, appropriate boundary conditions were applied in the simulation.

The fuel and cladding performance have been investigated in the light of ROFEM results. At the same time, internal pressure and fission gas released were estimated in comparison to experimental data. After examining the results obtained, it can be concluded that OFFBEAT predictions are comparable both to measurements and the ROFEM values.

In conclusion, the methodology adopted in present study was satisfactory, and the OFFBEAT capabilities showed to be appropriate for analysing the behaviour of a CANDU type fuel element.

This study represents an important step forward in applying a finite volume method to evaluate the behaviour of nuclear fuel in general, under various conditions. Future plans include conducting OFFBEAT assessments on various types of fuel elements proposed for use in advanced nuclear systems.

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