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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

Implementation and assessment of a coolant-channel model for the analysis of fuel rods under reactivity-initiated accident conditions

Laurea Magistrale in Nuclear Engineering - Ingegneria Nucleare

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1. Introduction

A Reactivity-Initiated Accident (RIA) is one of the main design-basis accidents in light water reactors. It is characterised by an unintended insertion of reactivity, which produces a rapid increase in reactor power and a sudden energy deposition in the fuel. The simulation of this type of transient is particularly challenging, since the fast power excursion gives rise to steep temperature gradients and to strongly coupled thermal and mechanical phenomena.

From a thermal point of view, the cladding may undergo a rapid temperature increase and transient heat-transfer conditions at the clad-to-coolant interface. In particular, different boiling regimes can occur at the outer cladding surface, making steady-state heat-transfer correlations inadequate to describe the evolution of the heat flux during the transient. From a mechanical point of view, the fast thermal expansion of the fuel pellets can induce pellet-cladding mechanical interaction (PCMI), generating significant stresses and axial loads in the cladding while it is still relatively cold and mechanically stiff.

The work carried out in this thesis focuses on the extension of the fuel performance code OFFBEAT [1] for the simulation of RIA scenarios. A coolant-channel model was implemented in order to describe the heat exchange between the coolant and the outer cladding surface under fast transient conditions. The model is inspired by the empirical formulation proposed by Bessiron [2] and aims to reproduce the main transient boiling regimes governing clad-to-coolant heat transfer during rapid power excursions.

The simulations are performed using a 1.5D modelling approach, in which the fuel rod is discretised along the axial direction while the radial thermo-mechanical behaviour is described under axisymmetric assumptions. This approach allows the main features of radial heat transfer and pellet-cladding interaction to be captured with a reduced computational cost. In addition, the mechanical solver was modified to include friction forces during pellet-cladding contact. This improvement allows a more realistic evaluation of the axial forces transmitted from the expanding fuel pellets to the cladding during the transient.

The extended OFFBEAT code was finally applied to the FK-1 and FK-2 tests of the NSRR[1]

[1]The Nuclear Safety Research Reactor (NSRR) is a TRIGA design nuclear research reactor operated by the

FK [3] experimental series, selected as reference cases within the OperaHPC project. The numerical results were compared with available experimental data and reference calculations in order to assess the capability of the implemented models to reproduce the main thermal and mechanical features of fuel rod behaviour under RIA conditions.

2. Coolant-channel

The Bessiron-based coolant-channel model was implemented in OFFBEAT to improve the description of clad-to-coolant heat transfer under RIA conditions. Unlike conventional boiling models, where the heat flux is generally expressed as a direct function of the wall superheat, the implemented formulation computes the heat-flux evolution during the transient. As a result, the boiling curve is not fixed a priori, but depends on the imposed power history and on the thermal response of the cladding.

In the implementation, the heat transfer coefficient at the cladding outer surface is updated at each iteration and is used to impose the thermal boundary condition for the solid domain. The wall temperature is obtained by enforcing the continuity between the conductive heat flux coming from the cladding and the convective heat flux transferred to the coolant. Therefore, the accuracy of the heat transfer coefficient directly controls the predicted cladding temperature evolution during the transient.

The model distinguishes seven heat-transfer regimes, each associated with a prescribed temperature interval: heat conduction, vaporization, transition boiling, film boiling, rewetting, post-rewetting and natural convection. In the heat conduction phase, heat transfer is described as transient conduction in stagnant liquid water until the wall temperature reaches the onset of nucleate boiling. During vaporization, the wall temperature is kept at the critical temperature by computing an equivalent heat transfer coefficient, reproducing the experimentally observed temperature plateau. The critical heat flux is not imposed through a steady-state correlation, but is stored as the heat flux reached when the equivalent layer of liquid water that has been vaporized at the cladding surface during the temperature plateau exceeds the prescribed threshold.

After the boiling crisis, transition boiling is represented through an exponential interpolation between the critical heat flux and the film-boiling heat flux. Once the Leidenfrost temperature is reached, the model switches to film boiling, evaluated through Sakurai's correlation with a time-dependent correction factor. During the cooling branch, the rewetting phase is treated by following backwards the same transition and film-boiling paths used during heating, avoiding the introduction of an additional empirical correlation. Finally, the post-rewetting phase provides a linear interpolation between the boiling regime and natural convection, while below saturation temperature the heat transfer coefficient is evaluated using the Churchill-Chu correlation.

This implementation allows OFFBEAT to reproduce the main transient boiling phenomena observed during RIA experiments while remaining consistent with the boundary-condition structure of the code.

3. Modified plane strain

During a Reactivity-Initiated Accident, the rapid energy deposition in the fuel may cause a sudden thermal expansion of the pellets, leading to pellet-cladding mechanical interaction. In 1.5D OFFBEAT simulations, the mechanical response of the fuel rod is handled by the `rheologyByMaterial` framework, which evaluates the stress and strain fields in both fuel and cladding under small-strain assumptions. However, in the original formulation, the axial equilibrium did not explicitly include the mechanical effects associated with pellet-cladding friction. This represented a limitation for RIA applications, since the axial load transfer from the expanding fuel pellets to the cladding can significantly affect the prediction of cladding elongation.

For this reason, the mechanical solver was extended by modifying the global axial force balance used to determine the axial deformation of each slice. In the original model, the equilibrium included the axial resultant of the stress field, the spring force and the pressure force. The pressure force accounts for the axial loads exerted by the internal gas pressure and by the external coolant pressure, while the spring force

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represents the equivalent axial stiffness used to keep the fuel stack mechanically constrained. In this work, an additional friction-force contribution was introduced once pellet-cladding contact is established. The resulting formulation therefore accounts for spring, pressure and friction effects, providing a more physically consistent description of the axial forces acting on the cladding during fast transients.

The friction force is evaluated using a Coulomb contact law regularised through a penalty-based approach. The gap width between fuel and cladding is monitored during the simulation, and the friction model is activated when contact occurs. The maximum transferable tangential force is given by the Coulomb limit, which depends on the normal contact pressure and on a user-defined friction coefficient. At the same time, an elastic predictor is computed from the relative axial slip between the coupled fuel and cladding slices. This slip is evaluated incrementally, using the relative displacement between neighbouring regions at the pellet-cladding interface.

The final friction force is obtained as the minimum between the Coulomb limit and the elastic predictor, with a sign opposite to the direction of slip. A penalty stiffness and a saturation factor are introduced to control the numerical response and improve convergence during the iterative solution. With this implementation, OFFBEAT can represent the axial force transfer associated with pellet-cladding contact more realistically, improving the prediction of cladding deformation during RIA simulations.

4. Test case

After the implementation of the thermal and mechanical models, the extended OFFBEAT code was applied to the simulation of the NSRR FK-series rodlets. In particular, the FK-1 and FK-2 tests were selected as reference cases, since they provide well-characterised experimental data for the validation of fuel performance codes under RIA conditions. The rodlets were refabricated from irradiated BWR fuel rods with an average burn-up of about 45 MWd/kgU, and were instrumented to measure the time evolution of relevant quantities such as axial elongation and, for FK-1, the cladding outer surface temperature.

The numerical procedure was divided into two main stages. First, a base irradiation calculation was performed on the full-length parent rod in order to obtain representative end-of-irradiation conditions, including temperature, burn-up dependent quantities and mechanical state variables. The irradiation history was simulated up to approximately 5.1 years. The final fields obtained from this calculation were then mapped onto a reduced rodlet model using the OpenFOAM `mapFields` utility. This second model represented the refabricated FK rodlet and was used as the initial condition for the pulse simulations.

The RIA pulse tests were then reproduced for both FK-1 and FK-2. FK-1 was subjected to the most severe transient, with a peak linear heat rate of about 95 MW/m and a full width at half maximum of approximately 11.1 ms. FK-2 experienced a milder pulse, with a peak linear heat rate of about 34 MW/m and a full width at half maximum of approximately 12.8 ms. For each rodlet, two simulations were performed: one using the standard OFFBEAT `coolantChannel` boundary condition, configured consistently with the modelling assumptions adopted in the reference SCANAIR calculations [4], and one using the newly implemented Bessiron-based coolant-channel model.

The mechanical behaviour of the cladding during the pulse was described using the `fastNeutronGPLS` model, which is suitable for Zircaloy cladding under fast transient loading. The modified friction model was activated during pellet-cladding contact, using parameters chosen to approximate strong sticking conditions during the rapid PCMI phase. The analysis focused on the main thermal and mechanical quantities relevant to RIA behaviour. The results were compared with the available experimental measurements and with SCANAIR reference calculations to assess the capability of the implemented models.

5. Results

From the thermal point of view, the results obtained for FK-1 and FK-2 show different behaviours. For FK-1, the Bessiron model predicts a more severe thermal transient, with higher cladding temperatures than those obtained with the standard OFFBEAT model and the SCANAIR reference calculation, as shown in Figure 1. This difference is mainly related to the different treatment of the boiling crisis and of the subsequent vapour film evolution.

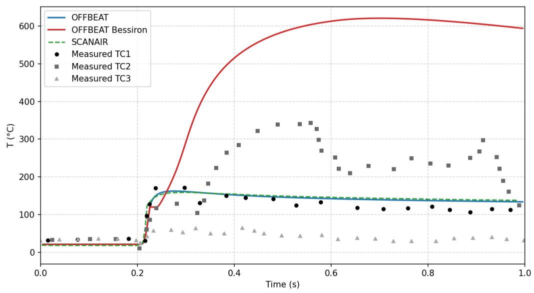

Figure 1: FK-1 temperature at clad outer surface

For FK-2, the differences between the two coolant models are much smaller, as shown in Figure 2. This indicates that the milder pulse imposed in FK-2 is not sufficient to produce a fully developed boiling crisis and film boiling phase.

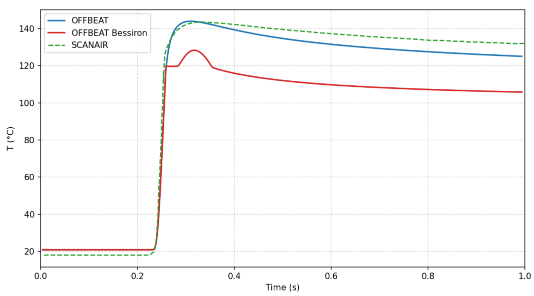

Figure 2: FK-2 temperature after the pulse at clad outer surface

For FK-1, the Bessiron model predicts two distinct heat-flux peaks, consistently with the transient boiling behaviour expected under RIA conditions, whereas the standard model gives a single peak as shown in Figure 3. For FK-2, Figure 4, the differences are much smaller, confirming that the milder pulse does not lead to a clearly developed transition boiling phase.
The boiling curves further highlight the different thermal response of the two rodlets. For FK-1, the Bessiron formulation reproduces the main regimes of the transient boiling process, including vaporization, transition boiling and film boiling, as shown in Figure 5. In contrast, the standard model does not fully reproduce the post-CHF evolution. For FK-2, Figure 6 shows that

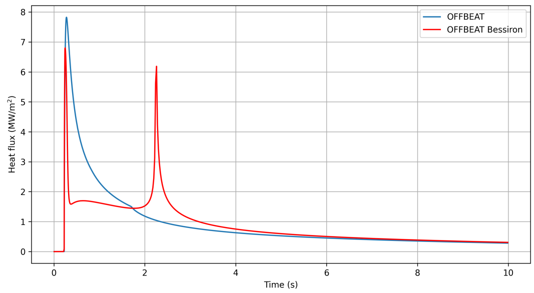

Figure 3: FK-1 heat-flux after the pulse

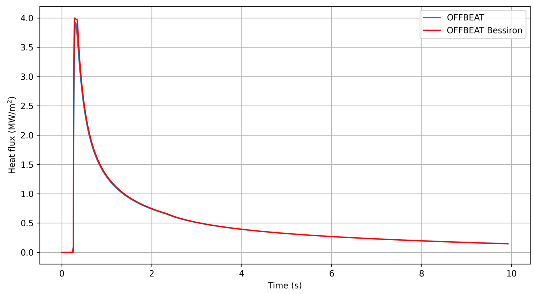

Figure 4: FK-2 heat-flux after the pulse

the wall temperature decreases before a fully developed film boiling phase is reached.

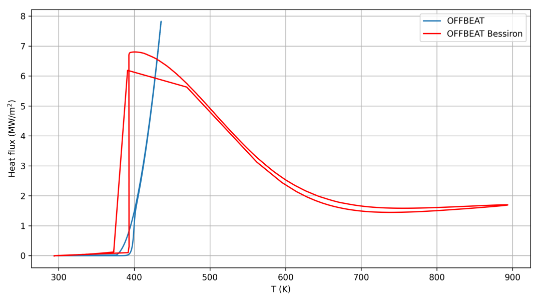

Figure 5: FK-1 boiling curve

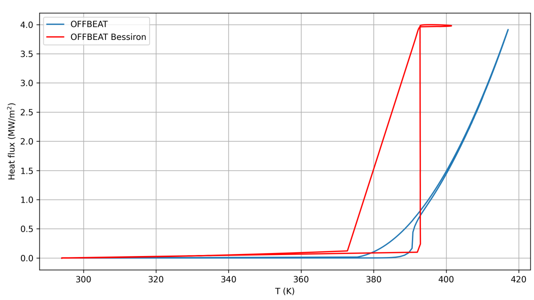

Figure 6: FK-2 boiling curve

The fuel elongation results, reported in Figures 7 and 8, show that both OFFBEAT models reproduce the overall experimental trend. The Bessiron formulation improves the agreement for FK-

1, while producing only limited differences for FK-2.

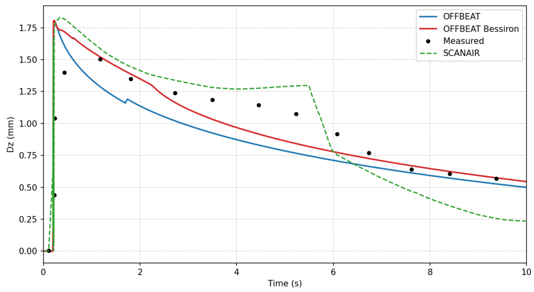

Figure 7: FK-1 fuel elongation

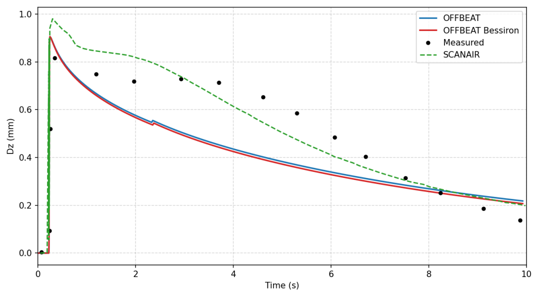

Figure 8: FK-2 fuel elongation

The cladding elongation, shown in Figures 9 and 10, is more sensitive to the adopted modelling choices, especially for FK-1, where the stronger thermal transient predicted by the Bessiron model leads to a different deformation history.

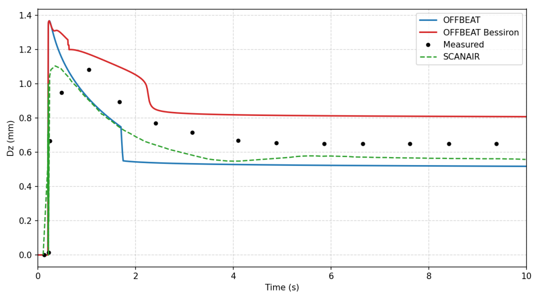

Figure 9: FK-1 cladding elongation

Finally, the comparison between simulations with and without friction highlights the importance of the mechanical modification introduced in this work. For FK-1, Figure 11 shows that neglecting friction produces an unrealistic downward axial displacement of the cladding during pellet-cladding contact. The inclusion of friction removes this non-physical behaviour and

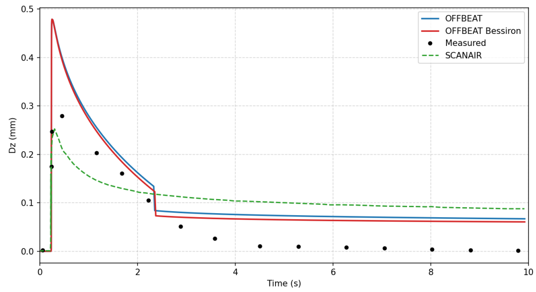

Figure 10: FK-2 cladding elongation

improves the agreement with the experimental data. For FK-2, Figure 12 shows a less pronounced effect, although friction still improves the overall prediction of cladding elongation.

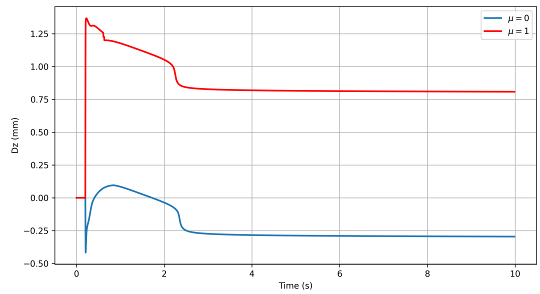

Figure 11: FK-1 comparison of cladding axial elongation with and without friction force

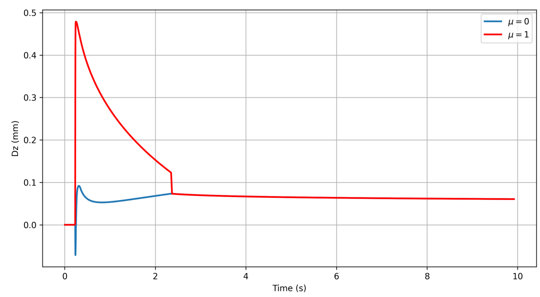

Figure 12: FK-2 comparison of cladding axial elongation with and without friction force

6. Conclusions

The work presented in this thesis showed that the extended OFFBEAT code is able to reproduce the main thermo-mechanical phenomena occurring in fuel rods during RIA transients. From the thermal-hydraulic point of view, the Bessiron-based coolant-channel model allowed the main transient boiling regimes observed in RIA experiments to be described, including vaporization, transition boiling, film boiling and rewetting. This represents an improvement with respect to the standard modelling approach, which is not specifically designed to reproduce the heat-transfer evolution occurring after the boiling crisis under fast transient conditions.

The comparison between FK-1 and FK-2 highlighted the different response of the two rodlets. In the more severe FK-1 pulse, the model predicted the onset of film boiling and consequently higher cladding temperatures, while FK-2 experienced a milder transient without a fully developed film boiling phase. Although some discrepancies remain, especially regarding the overestimation of the cladding temperature in FK-1, the overall evolution of the boiling regimes and the associated heat-flux behaviour were found to be physically consistent.

From the mechanical point of view, the modification of the `rheologyByMaterial` solver to include friction forces during pellet-cladding contact improved the description of axial load transfer in 1.5D simulations. The implemented penalty-based Coulomb friction model allowed the effect of gap closure on cladding axial deformation to be represented more realistically. The results showed that friction is particularly important for the prediction of cladding elongation, especially when strong pellet-cladding mechanical interaction occurs during the first phase of the transient.

Overall, the developments introduced in this work extend the applicability of OFFBEAT to fast reactivity transients by providing a more consistent coupled description of clad-to-coolant heat transfer, transient boiling, pellet-cladding mechanical interaction and frictional effects. The comparison with experimental data and SCANAIR calculations is encouraging, although further refinement of the post-CHF heat-transfer treatment and of the mechanical coupling during contact remains necessary. Future work should therefore focus on the calibration of the Bessiron-type coolant-channel model and on the extension of the validation to additional rods of the FK experimental series.

7. Acknowledgements

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