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Coolant-cladding interaction models in FINIX fuel behaviour module

Jussi Peltonen*
VTT Technical Research Centre of Finland
Kivimiehentie 3, 02044 Espoo, Finland
jussi.peltonen@vtt.fi

Henri Loukusa
VTT Technical Research Centre of Finland
Kivimiehentie 3, 02044 Espoo, Finland
henri.loukusa@vtt.fi

ABSTRACT

This paper discusses the implementation of cladding oxidation model and updates in the coolant model in FINIX fuel behaviour module. These topics have been the focus point of the writing authors Master's thesis in spring 2019.

1 INTRODUCTION

The analysis of the behaviour of nuclear fuel rods is mandatory to ensure the safe operation of all the nuclear reactors. With further research, reactors can also be operated more efficiently. The lifespan of a nuclear fuel rod is largely limited by cladding corrosion and rod burnup which is a measure of how much energy is extracted from a primary nuclear fuel source. In order to develop longer-lasting fuel rods, the corrosion resistance of the cladding must be improved. The research in this field is often backed up by large economic interests, especially considering how expensive it is to perform actual experiments on nuclear fuel, or to fix the damage caused by a failed fuel rod.

FINIX is a fuel behaviour module developed at VTT Technical Research Centre of Finland since 2012. It has been simplified in comparison to the full-fledged fuel performance codes to improve its usability in coupled applications, by reducing the amount of required input information. It has been designed to be coupled on a source-code level with other reactor core physics solvers, so that passing input and output files between the core solvers is not necessary. This relationship between different solvers is depicted in fig. 1.

While the stand-alone performance of FINIX has been the main focus point during the previous stages of development, in the past it has been coupled with reactor dynamics codes HEXTRAN, TRAB1D and TRAB3D[1,2,3]. Its lower complexity in comparison to the full-fledged fuel performance codes improves its usability in coupled applications by reducing the amount of required input information. Recently, it has been used as the primary fuel performance solver of the new reactor core analysis framework Kraken.

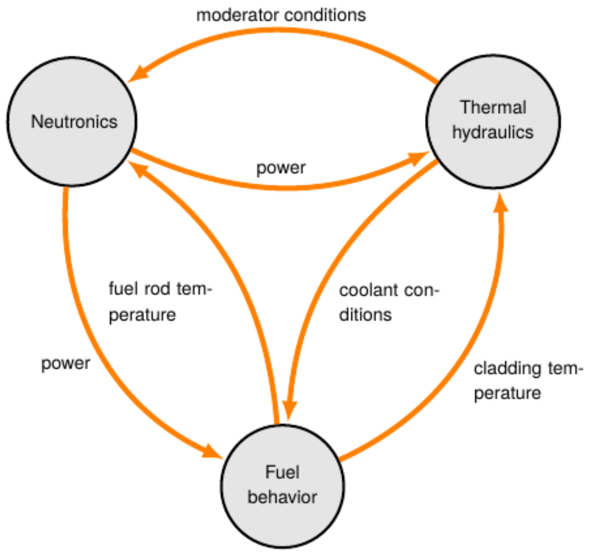

Figure 1: The relationship between reactor core physics solvers

In the past year, the development of FINIX has focused on the implementation of new models and interface development. Some smaller updates were applied to the older models as well in the validation process [4]. These updates can be seen in fig. 2, which presents the general logic and procedures of FINIX. Among the new models are fission gas release (FGR) and cladding oxidation, both of which have an impact on the key fuel performance parameters cladding integrity and rod internal pressure.

In addition to increasing the depth of FINIX calculations, the implementation of oxidation model offered a topic for the author’s master’s thesis [5]. The topic was expanded to include coolant-cladding heat transfer and thermal properties of coolant, due to the heat flow between cladding and coolant playing a major role in the oxidation process.

This article aims to briefly present the theory and results of the different oxidation models, as well as the impact of coolant model calculations on the oxidation results.

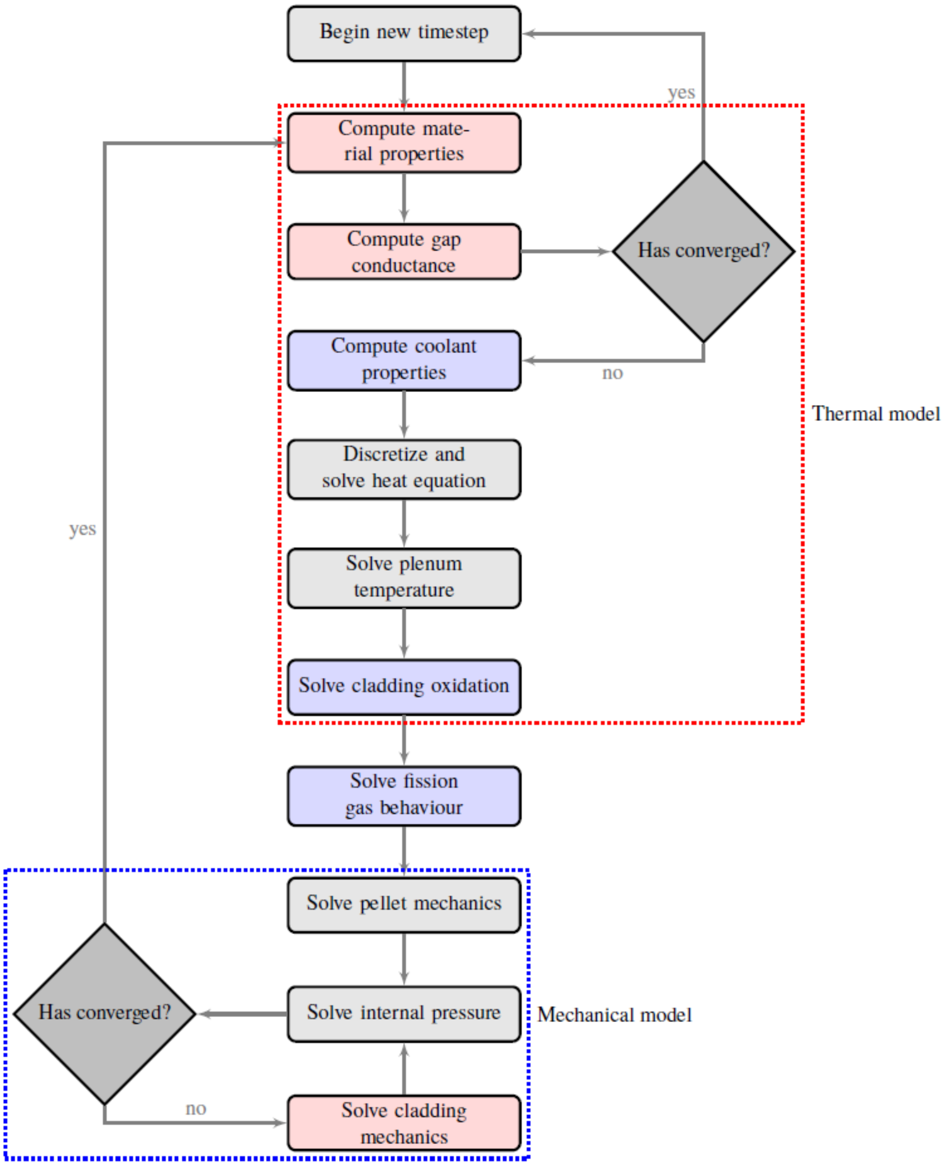

Figure 2: The logic and procedures of the FINIX in a flowchart. Blue elements represent new models that have been implemented recently, whereas red elements have been slightly modified in the past year. Gray elements have remained unchanged.

2 COOLANT-CLADDING INTERACTION MODEL

Oxidation occurs both on the inner and outer surfaces of the fuel rod. Inner surface oxidation of an intact fuel rod is caused by a near-instantaneous chemical reaction between the UO_2 pellet and the inner surface of the cladding when the pellet-cladding gap closes. Outer surface oxidation, on the other hand, is a continuous stochastic process that depends mostly on the temperature of the cladding-coolant interface. As seen in eq. 1, the zirconium of

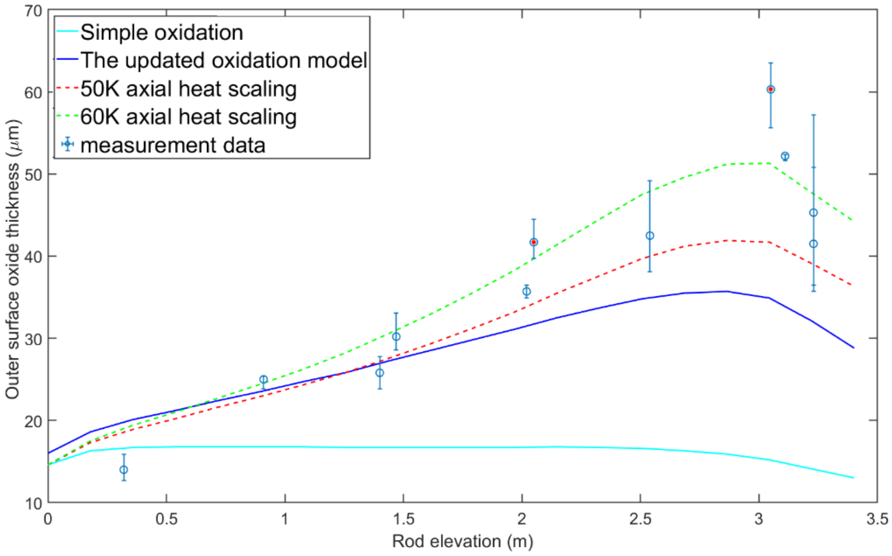

Figure 3: The FINIX cladding oxide thickness predictions of Assembly 1D45 (rod 15309). The solid curves represent the progress of the oxidation model, whereas the dashed curves showcase the ideal results that were created via artificial temperature scaling.

the cladding reacts with the coolant water, forming zirconium-dioxide and releasing gaseous hydrogen.

$$Zr + H_2O \rightarrow ZrO_2 + H_2 \qquad (1)$$

Outer surface oxidation growth of Zircaloys can be calculated with various semi-experimental models, of which two were implemented in FINIX. The first one is so-called Kättö model, based on Enigma calculations made at VTT [6]. The initial results of this model can be seen in fig. 3. The solid cyan line represents the starting point of thesis development, in which the oxidation model had been implemented. These predictions were heavily underestimated due to the calculations using axially constant coolant temperature.

As suggested by the experimental results [7], more oxidation occurs at the top end of the fuel rod cladding due to temperature difference between the two ends of the rod. To account this, the coolant model had to be updated to calculate the axial temperature distribution in the coolant.

Furthermore, the heat transfer model between cladding and coolant required an update to enable realistic estimates of cladding surface temperature. To calculate the heat transfer from cladding to coolant, several models for thermal properties of coolant had to be first implemented. Oxide thickness predictions improved after these updates, as can be seen in fig. 4, where both of the oxide growth correlations used in FINIX were compared to the predictions of FRAPCON 4.0.

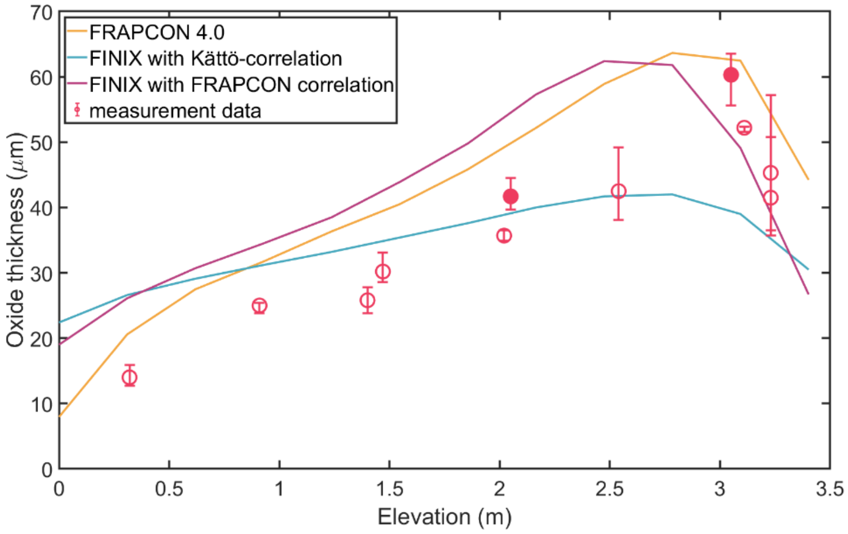

Figure 4: Cladding oxide thickness predictions of Assembly 1D45 (rod 15309) calculated with FINIX and FRAPCON-4.0.

The oxidation model of FRAPCON-4.0 [8] was also implemented in FINIX, and its results can also be seen in fig. 4. The estimates of this model were quite conservative in both FINIX and FRAPCON. While the coolant model update improved the predictions of Kättö model too, it tends to overestimate the oxide width at the bottom half of the rod, and underestimate it at the top half.

These predictions are currently studied by coupling FINIX with thermal hydraulics solver Kharon. This coupling should calculate the critical parameters such as cladding surface temperature more accurately, thus improving the predictions of oxidation models.

3 CONCLUSIONS

The initial goal of the thesis was to implement the oxidation model into the FINIX fuel behaviour module, in order to add one of the missing features required for LOCA simulations. Due to the coolant model assuming homogenous temperature distribution in the coolant, the predictions of the oxidation model were inaccurate.

This was corrected by implementing a new coolant-cladding interaction model, in which the axial temperature distribution of the coolant and cladding-coolant heat transfer are calculated by FINIX. Calculation of these parameters using a coupled thermal hydraulics code is currently in the works.

4 ACKNOWLEDGEMENTS

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