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Development and Validation of a FEM-Based One-Dimensional Model for Coupled Thermal–Oxidation Analysis of Plate-Type Nuclear Fuel (PROPER-COMSOL 1D)

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1. Introduction

Plate-type nuclear fuels used in research reactors are operated under high heat flux conditions, which leads to the gradual growth of an oxide layer on the cladding surface. The formation of this oxide layer increases thermal resistance, raises fuel temperature, and reduces thermal margins during long-term irradiation, making it an important factor in fuel performance and safety assessments [1]. For aluminum cladding, hydroxide-based oxidation behavior has been described by an empirical growth model proposed by Kim et al. [2], which allows the time-dependent evolution of oxide thickness to be predicted in a relatively simple form based on coolant conditions and effective temperature.

Meanwhile, the PROPER code has been under development for performance analysis of research reactor fuels, incorporating thermal behavior, oxidation of the cladding, and fuel swelling phenomena for plate-type nuclear fuels. In this study, a one-dimensional FEM-based performance analysis model for plate-type nuclear fuel, denoted as PROPER-COMSOL1D, was developed using the commercial multiphysics code COMSOL Multiphysics, and its calculation results were examined against published reference data. The developed model is expected to support future verification of the PROPER code and to be extended to higher-dimensional analyses for broader applications in plate-type fuel performance evaluation.

2. Methods and Results

2.1 Governing Equations

In this study, the plate-type nuclear fuel was idealized as a one-dimensional structure consisting of the fuel meat, cladding, and coolant boundary, and thermal analysis was performed accordingly. Steady-state heat conduction in the fuel and cladding regions, including internal heat generation, is governed by the one-dimensional heat conduction equation [1], as given by Eq. (1):

$$-\frac{d}{dx}\left(k\frac{dT}{dx}\right)=q''' \qquad (1)$$

where k is the thermal conductivity, T is temperature, and q''' is the volumetric heat generation rate in the fuel region. Continuity conditions for temperature and heat flux were applied at the fuel–cladding and cladding–coolant interfaces, while a convective heat transfer boundary condition was imposed at the coolant boundary.

The thickness of the oxide layer growing on the outer surface of the aluminum cladding was calculated as a function of time using the empirical oxidation growth model proposed by Kim et al. [2]. In this model, the oxide thickness x is expressed as Eq. (2):

$$x=\left[x_0^{p+1}+(p+1)kt\right]^{1/(p+1)} \qquad (2)$$

where x_0 is the initial oxide thickness, p is the oxidation growth exponent, and t is time. The growth coefficient k is defined as a function of the effective temperature, as shown in Eq. (3):

$$k=3.9\times10^5\exp\left(-\frac{6071}{T_{eff}}\right) \qquad (3)$$

where T_{eff} is the effective temperature governing the oxidation reaction and was defined in this study based on the outer surface temperature of the cladding. The calculated oxide thickness was incorporated as an additional thermal resistance on the cladding exterior, and the thermal boundary conditions were updated accordingly as the oxide layer evolved. Through this formulation, the heat transfer equation and the oxide growth model are coupled via temperature, allowing the degradation of heat transfer performance due to oxide growth to be continuously reflected in the analysis.

2.2 Configuration of PROPER-COMSOL 1D

The coupled thermal–oxidation model was implemented using the commercial multiphysics code COMSOL Multiphysics (Fig. 1). The plate-type nuclear fuel was modeled using a one-dimensional geometry, and the Heat Transfer in Solids module was employed to simulate heat conduction in the fuel and cladding regions. Oxide layer growth on the outer surface of the aluminum cladding was calculated using the Global ODEs and DAEs interface, which evaluates the time-dependent evolution of oxide thickness.

The effective temperature required for the oxidation model was obtained from the thermal analysis as the cladding outer surface temperature, and the resulting oxide thickness was introduced as an additional thermal resistance at the cladding exterior. The thermal analysis and oxide growth calculation were updated sequentially at each time step, enabling automatic reflection of oxide growth effects on heat transfer performance. This coupling strategy was implemented entirely using built-in COMSOL functionalities without additional user-defined coding.

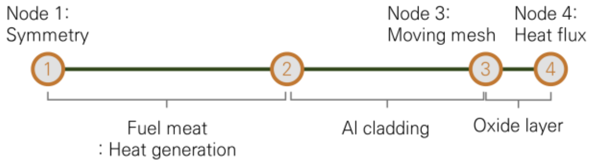

Fig. 1. PROPER-COMSOL 1D model geometry and boundary conditions.

2.3 Validation Model

To validate the developed COMSOL-based coupled thermal–oxidation model, comparative analyses were performed using data from the RERTR-6 B2 plate-type fuel test reported by Kim et al. [2]. This test provides a representative validation case in which both the time-dependent evolution of aluminum cladding oxide thickness and the corresponding thermal conditions are well documented. The input parameters used for comparison are summarized in Table 1.

Fig. 2 compares the calculated oxide thickness as a function of time for the RERTR-6 B2 plate with the measured values reported in the literature. The analysis results obtained using the present model closely reproduce the measured oxide growth behavior over the entire irradiation period, showing nearly identical oxide thickness values in a quantitative sense.

Fig. 3 shows the temperature distribution across the plate thickness at five days after the beginning of irradiation under the same conditions. The thermal analysis incorporating oxide layer formation yields a physically consistent temperature profile, with temperature gradually decreasing from the fuel interior toward the outer surface of the cladding. The additional thermal resistance introduced by the oxide layer is reflected in the temperature gradient, demonstrating stable coupling between oxide growth and heat transfer through temperature-dependent feedback.

These results confirm that the PROPER-COMSOL1D model developed in this study can reliably reproduce experimentally validated oxidation behavior and thermal characteristics of plate-type nuclear fuel.

Table 1. Test parameter of RERTR-6, B2 plate [2]

Irradiation time (day)	135
pH level	5.1 to 5.3
Coolant speed (m/s)	2.8
Heat flux (MW/m^2)	1 → 0.75
Variation of Oxide-water interface temperature (^{o}C)	114 → 98

3. Conclusions

In this study, a coupled thermal–oxidation analysis model for plate-type nuclear fuel was developed using COMSOL Multiphysics. Validation against RERTR-6 B2 plate data reported by Kim et al. [2] demonstrated that the model accurately reproduces measured oxide thickness evolution and corresponding thermal behavior. These results confirm that the proposed FEM-based model can reliably evaluate oxidation behavior and heat transfer characteristics in plate-type nuclear fuels. Future work will extend the model to include fuel swelling and mechanical behavior, as well as higher-dimensional analyses to broaden its applicability.

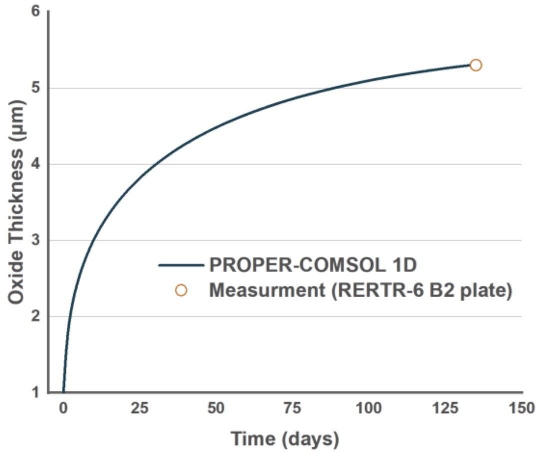

Fig. 2. Comparison of oxide layer growth calculated by the present model with measured data at the rear side of the RERTR-6 B2 plate.

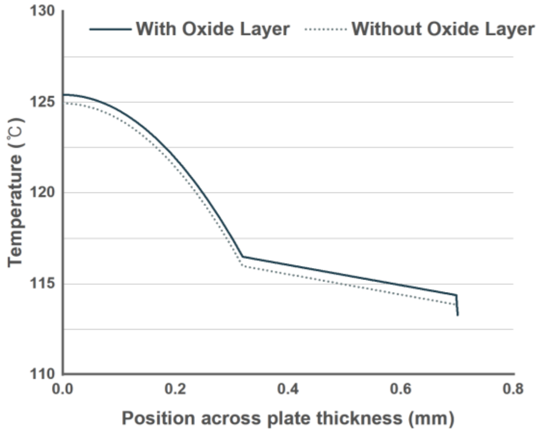

Fig. 3. Temperature distribution across the plate thickness at day 5, including the oxide layer, calculated using the PROPER-COMSOL1D model.

ACKNOWLEDGEMENT

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