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Code structure for U-Mo fuel performance analysis in high performance research reactor

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1. Introduction

The need to develop an advanced performance and safety analysis code for research reactor fuel grows in Korea. A performance analysis modeling applicable to research reactor fuel is being developed with available models describing fuel performance phenomena observed from in-pile tests. We established the calculation algorithm and scheme to best predict fuel performance using radio-thermo-mechanically coupled system to consider fuel swelling, interaction layer growth, pore formation in the fuel meat, and creep fuel deformation and mass relocation, etc.

In this paper, we present a general structure of the performance analysis code for typical research reactor fuel and advanced features such as a model to predict fuel failure induced by combination of breakaway swelling and pore growth in the fuel meat.

2. Code structure

Drastic microstructure changes in the dispersion fuel meat have been observed and investigated including fuel swelling [1], interaction layer (IL) formation by fuel-Al matrix interdiffusion [2], fuel-Al matrix consumption, and large pore formation, particularly at the interface of IL and Al matrix. It is necessary to take into consideration of the coupling between thermal and mechanical response to predict those microstructure variation of the meat.

The coupling among thermal, mechanical, and irradiation-related performance issues is critical to fuel performance modeling. Typical operation temperature for U-Mo/Al dispersion fuel meat for plate type is below 200^{o}C, but it is dependent on fuel meat thermal conductivity which is influenced by fuel meat morphology and material composition. Particularly, Al matrix depletion by IL growth is the most dominant on fuel meat thermal conductivity degradation since it is believed that IL has poor thermal conductivity.

The variation of fuel meat morphology is induced by three major phenomena: fuel swelling, IL formation, and pore formation

Finite element analysis will be employed to calculate the temperature distribution in the fuel meat and cladding region. A schematic of fuel plate is shown in Fig. 1. Typical plate length is longer than any other dimension, so that it is assumed that heat conduction in the length direction is negligible. It also allows strain out of plane to be constant or zero, which is plane strain condition.

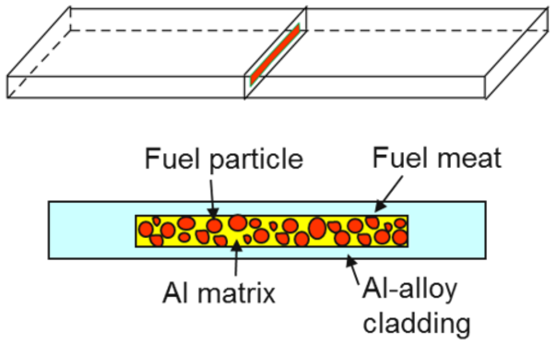

Fig. 1 A schematic of dispersion fuel plate and cross section at axial mid-plane.

The temperature distribution throughout the fuel meat and cladding in 3-dimension is calculated at each node. The models used in the temperature calculations assume a transversally symmetrical fuel plate surrounded by coolant.

User supplied conditions such as coolant information including coolant inlet temperature, coolant flow velocity, and coolant mass will be used to determine boundary conditions. User supplied fission rate will be used to calculate temperature distribution from the coolant to the meat centerline. A film temperature rise from the bulk coolant to cladding surface is calculated by finding film heat transfer coefficient for a given coolant and geometry. The temperature at the interface between clad and meat is calculated by using Fourier's law. The temperature rise to the meat centerline is determined by solving heat conduction equation for fuel particle, Al matrix, and IL with heterogeneously.

The modeled governing equations for temperature distribution calculation is given as follows:

$$
\begin{aligned}
-\nabla \cdot (k_{fuel}(\mathrm{T})\nabla T) &= q''' \\
q''_{\mathrm{meat}} &= -k_{clad}\nabla T \\
q''_{clad} &= h_c(T_{c,o} - T_{coolant})
\end{aligned}
\quad (1)
$$

Where q''' is the power density in the meat, k the thermal conductivities, q''_{meat} the total heat flux from the meat, q''_{clad} the heat flux from the cladding surface, $T_{c,o}$ the cladding outer surface, and $T_{coolant}$ the bulk coolant temperature.

With assumption on strain condition as mentioned, meat and cladding deformation calculation will be performed after obtaining temperature distribution. An accurate calculation of stresses in the meat and the cladding is needed to accurately calculate the strain and evaluate a potential of large pore formation and fuel failure.

Strain caused by irradiation can be obtained by solving the mechanical equilibrium equation as follows :

$$\sigma + \rho(\mathrm{T}) f''' = 0 \qquad (2)$$

Where ρ is the density, f’’’is volumetric forces induced by fission, and σ the stress tensor.

Fig. 2 shows the overall structure of the new code system. Each performance model will be classified in several modules.

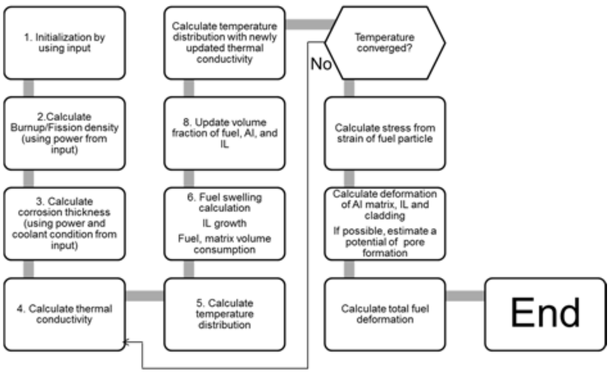

Fig. 2 Overall structure of research reactor fuel performance code.

3. Conclusion

Thermo-mechanical code dedicated to the modeling of U-Mo dispersion fuel plates is being under development in Korea to satisfy a demand for advanced performance analysis and safe assessment of the plates. The major physical phenomena during irradiation are considered in the code such that interaction layer formation by fuel-matrix interdiffusion, fission induced swelling of fuel particle, mass relocation by fission induced stress, and pore formation at the interface between the reaction product and Al matrix.

The framework of performance analysis code for U-Mo dispersion fuel has been established with newly updated models with studies on advanced fuel performance modeling.

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