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State of art in FE-based fuel performance codes

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1. Introduction

Nuclear fuel operates in an extreme environment that induces complex multiphysics phenomena, occurring over distances ranging from inter-atomic spacing to meters, and times scales ranging from microseconds to years. This multiphysics behavior is often tightly coupled, a well known example being the thermomechanical behavior. Adding to this complexity, important aspects of fuel behavior are inherently multidimensional, examples include pellet-clad mechanical interaction (PCMI), fuel fracture, oxide formation, non-axisymmetric neutronics and cooling, and coupling to lower length scale models.

Currently, fuel performance codes approximate this complex behavior using an axisymmetric, axially-stacked, one-dimensional radial representation to save computation cost. However, the need for improved modeling of PCMI and, particularly, the importance of multidimensional capability for accurate fuel performance simulation has been identified as safety margin decreases. Finite element (FE) method that is reliable and proven solution in mechanical field has been introduced into fuel performance codes for multidimensional analysis.

The present state of the art in numerical simulation of FE-based fuel performance predominantly involves 2-D axisymmetric model and 3-D volumetric model. The FRAPCON and FRAPTRAN own 1.5-D and 2-D FE model to simulate PCMI and cladding ballooning [1, 2]. In 2-D simulation, the FALCON code, developed by EPRI, is a 2-D (R-Z and R-Θ) fully thermal-mechanically coupled steady-state and transient FE-based fuel behavior code [3]. The French codes TOUTATIS and ALCYONE which are 3-D, and typically used to investigate localized behavior [4, 5]. In 2008, the Idaho National Laboratory (INL) has been developing multidimensional (2-D and 3-D) nuclear fuel performance code called BISON [6].

In this paper, the current state of FE-based fuel performance code and their models are presented. Based on investigation into the codes, requirements and direction of development for new FE-based fuel performance code can be discussed.

2. FE-based fuel performance codes and Models

To analyze models of FE-based fuel performance codes, four benchmarks codes, which are ALCYONE, BISON, FRAPTRAN and FALCON, were chosen. Characteristics of the chosen codes are as follows; multidimensional analysis using FEM, progressing code development, performing verification and validation.

As shown in Table.1, the codes are able to simulate fuel behavior for steady state (SS), transient state (TR) and accident state (AC) except BISON. In terms of pellet modeling, the codes include fundamental models, for instance, swelling/densification, thermal/irradiation creep, fission gas release (FGR) model for SS. For consideration of TR and AC, stress-dependent gaseous swelling model and FGR model for TR are added into ALCYONE, FRAPTRAN and FALCON. To improve accuracy of PCMI behavior, BISON and ALCYONE consider smeared crack and cracked pellet model, respectively. In cladding model, all codes employ elasto-plastic model to calculate elastic and plastic strain in accurate. Exclusively ALCYONE has anisotropic plastic model called Hill’s model to consider anisotropy of cladding by manufacturing process.

In fuel performance code for LWR, gap between pellet and cladding is difficult issue because gap conductance is strongly coupled with thermomechanical behavior. In particular, FEM increases complexity of gap due to increase of degree of freedom. Therefore, reasonable assumption should be defined to approximate the problem. In the case of BISON, fully coupled thermomechanical model has been established using high computation performance. On the contrary, other codes employ approximated gap model such as equivalent convection exchange coefficient.

Numerically contact model can be expensive owing to large amount of iteration and difficulty of convergence. Most of the codes consider frictional contact to simulate PCMI behavior in accurate.

Cladding failure criteria is significant to evaluate the cladding integrity at certain condition. The codes classify the failure modes (High temperature (HT) or Low temperature (LT)) and apply the criteria into model. Typically, development of 3-D FE module is labor-intensive and time consuming work. Therefore, ALCYONE and BISON which simulate 3-D FE employ specified FE solver such as CAST3M and MOOSE, respectively.

Table. 1 Comparison of models in FE-based fuel performance code

Code name	ALCYONE	BISON	FRAPTRAN	FALCON
Owner	CEA (France)	INL (USA)	NRC (USA)	EPRI (USA)
Analysis Target	TR/AC	SS/TR	TR/AC	SS/TR/AC
Pellet	-Irradiation/ scattering/dislocation Creep -Densification/Solid swelling -Cracking -Gaseous swelling (stress-dependent) -Porosity model -FGR model (SS/TR)	-Swelling/densification -Thermal/irradiation creep -Fracture (relocation or smeared crack) -FGR model(SS)	-Fission heat -Decay heat -FGR model (TR)	-Melting model -Swelling / densification -Relocation -Radial power distribution -Fission heat -Decay heat -HBS model -Internal void volume and gas pressure -FGR model(SS/TR)
Cladding	-Irradiation-induced creep -Low stress creep / High stress creep -Elasto-plastic model -Anisotropic plastic (Hill's criterion)	-Elasto-plastic model -Thermal/irradiation creep -Irradiation growth	-Thermal effect of oxide layer -Elasto-plastic model (von-mises yield criterion) - HT corrosion -Constant volume Creep -Oxidation heat generation	-Elasto-plastic model -Creep model -Plastic model (von-Mises/kinematic hardening) -Thermal/irradiation creep -Irradiation growth -Oxidation (LT/HT)
Gap	-Equivalent convection exchange coefficient	-Thermomechanical contact	-1D Gap conductance (gas/radiation/solid)	-Locally Gap conductance
Contact	-Frictional contact (Lagrangian multiplier method)	-Frictionless Or tied contact	-Frictional contact (penalty method)	-Gap element with pseudo elastic and shear moduli
Cladding failure	-PCI failure criterion : Contact pressure, interfacial shear stress	N/A	-PCMI failure : uniform plastic elongation -Ballooning model : effective plastic strain / peak strain	-HT transient failure model (Burst) / LT PCI failure model (SCC) - PCMI failure :Strain Energy Density
FEM	-2D / 3D Quad. Element -FE solver : CAST3M -Updated Largrangian	-2D / 3D Quad. Element -FE solver (MOOSE) -Updated Largrangian	-1.5D / 2D axisym. Quad. Elem. -Plenum element -Direct matrix solver -Updated Largrangian	-1D / 2D linear/Quad. quadrilateral/triangular Element -Updated Largrangian

3. Conclusions

Based on comparison of models in FE-based fuel performance code, status of art in the codes can be discussed. A new FE-based fuel performance code should include typical pellet and cladding models which all codes own. In particular, specified pellet and cladding model such as gaseous swelling and high burnup structure (HBS) model should be developed to improve accuracy of code as well as consider AC condition. To reduce computation cost, the approximated gap and the optimized contact model should be also developed.

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