Finite Element Modelling of Pellet-cladding Interaction in Advanced Gas-cooled Reactors

Rizgar Mella

Supervised by Dr. M R. Wenman
Location of several AGR type reactors sites within the United Kingdom. AGRs generating typically 660MW of electrical power.
The Advanced Gas-Cooled Reactor

Properties

- 650°C coolant outlet temperature.
- Coolant pressure 4MPa. High gas temperature improves thermal efficiency, requiring stainless steel fuel cladding.
- CO₂ coolant.
- Large grained UO₂ for improved fission product release.
- Built for efficiency, typically electricity generation/heat generated ratio of 0.41 more efficient than many modern pressurised water reactor.
Introduction to Pellet-Cladding Interaction

A point of great interest is the interface region between the fuel and cladding.

The purpose of this work is to develop a finite element model describing the fuel cladding interface.

This requires computing of a variety of different fuel properties and how they impact behavior of the interface.

Contrary to a trend of production of custom codes for nuclear problems, this is to be attempted in a commercial finite element package.

Olanders’ depiction of pellet-cladding interaction, showing the three early life heat flux contributions in PCI.
Modelling Pellet-Cladding Interaction

**URGAP**

\[
\frac{1}{h_{\text{gap}}} = \frac{1}{h_{\text{rad}}} + \frac{1}{h_{\text{conv}}} + \frac{1}{h_{\text{press}}} + \frac{1}{h_{\text{oxide}}}
\]

\[
h_{\text{conv}} = \frac{\lambda_g}{s + l_f + l_{cl}}
\]

\[
h_{\text{rad}} = C_f,_{cl} \left( \frac{T_f^4 - T_{cl}^4}{T_f - T_{cl}} \right)
\]

\[
h_{\text{press}} = \beta_5 \tilde{\lambda} \Delta \bar{R} \left( \frac{P}{\Delta R^2 H} \right)^{\beta_6}
\]

Perhaps, easier said than done?
A whole pin model remains computationally expensive for any study at a resolution that will capture the PCI features of interest. To constrain a higher resolution model an approach of sub-modelling was used, with a 300,000 element axisymmetric model of the whole pin.
Whole Pin Model II

Axisymmetric model of an AGR fuel pin, showing radial displacement (A), typical pellet internal pressures (B), axial and radial temperature (C) and pellet von Mises stress in locking and normal pellets (D). Showing only 3 pellets of 64 (including spacer pellets).
No significant plastic region forms while cladding elongates. Temperatures agree with analytical solution and fuel performance code. An elastic cladding and correct temperatures are an indicator that the 2D model is behaving correctly.
Boundary conditions are extracted from nodal data then approximated by a fifth order polynomial. The extracted time dependent polynomial is used as the boundary conditions of a 3D model.
Moving to the Third Dimension

Third Dimension
Moving to the Third Dimension II

Problems and solutions

- 100,000’s to million elements.
- Quasi-static, sequentially coupled fields.
- Adaptive step sizes.
- Iterative solvers.
- Modelling months of fuel time.

Drawback

- No accident conditions.
- Adaptive logic.
- Time to completion of simulation now uncertain.
- High computational cost.

Current workflow for completion of a 3D model, the flow is controlled by a series of scripts mixed with some user judgements.
What Does 3D Bring Us?

Typical straight crack approximation to pellet damage on power ramping. In this model 8 radial and equally spaced cracks are inserted. (At 125 MW/m³)

Moving away from the idealised crack model. There exists some statistical data for fracture during heat up for the AGR reactor. This data can be used to produce more accurate models of pellet and cladding stress.
Diffusion of oxygen over cracked fuel geometry (at 150 MW/m$^3$), a difference in fuel stoichiometry coupled with heat transfer will produce a non-uniform mechanical response.

The plot to the left is the temperature profile change in a coupled problem of oxygen and thermal fields for an un-cracked geometry running for 1.5 years.
Peridynamics

Early 2D peridynamics models. Top image is from a heat up to full power. Bottom image is a heat up to a 10% power.

Peridynamics is a non-local structural mechanics formulisation, capable of predicting fracture with as few as one parameter.

Building on previous work on integrating peridynamics into Abaqus to include thermo mechanical damage.
Conclusion and Future Work

Conclusions

• 2D axisymmetric model for whole pin behaviours, modelling near whole life.
• 2D model now serves as boundary conditions for high resolution 3D models.
• 3D models capture the stress state of damaged pellets and their interaction with cladding.
• A variety of fracture geometries from many sources can be modelled with a high resolution.
• Models for predicting fracture are being developed.
• Long life studies of oxygen stoichiometry and its fuel behaviour impact can now be explored on fractured pellet geometry.

Future Work

• Automatic coupling of all these models.
• Further comparisons with current fuel performance codes.
• Trials with transplanting results from finite element models to performance codes.
• Accurate modelling of damage to claddings.
Thank You

Questions Are Welcome

Some references

