PBMR COUPLED NEUTRONICS/THERMAL HYDRAULICS TRANSIENT BENCHMARK

THE PBMR-400 CORE DESIGN

Fuel kernel temperature profiles for fast reactivity transients

A suggested mathematical model and subroutine for fuel kernel temperature profile calculation

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Reminder of fuel design

**Fuel Sphere**
- Dia. 60mm

**Section**
- 5mm Graphite layer
- Coated particles imbedded in Graphite Matrix
- Pyrolytic Carbon 40/100mm
- Silicon Carbide Barrier Coating 35/100mm
- Inner Pyrolytic Carbon 40/130mm
- Porous Carbon Buffer 25/100mm

**TRISO Coated Particle**
- Dia. 0.92mm

**Fuel Kernel**
- Dia. 0.5mm
- Uranium Dioxide
Traditional approach

The traditional approach for time dependent temperature calculation for fuel spheres:

– The fuel sphere is discretised into a number of shells for solving the differential equation of heat conduction

– Nuclear heat sources are considered to be **homogeneously distributed** (i.e., smeared out) throughout the shells which are inside the inner 2.5 cm of the fuel sphere
The physical truth:

The nuclear heat sources are **heterogeneously distributed** throughout each of the shells inside the inner 2.5 cm of the fuel sphere.

- Sources are concentrated in the small UO$_2$ kernels, which are coated with several layers.
- Thermal properties of UO2 and coatings different than graphite.

This is a well known problem (Kindt & Kohtz developed the computer codes ZKIND and RZKIND).
Effect of approximation

During steady state operation or slow reactivity transients the homogenisation of nuclear heat sources and homogenization of the kernel and graphite are justified – temperature difference between fuel kernels and surrounding graphite matrix is small

When fast reactivity transients occur:

– There is a strong power surge
– The temperature of the UO2 kernels and coatings rise well above that of the surrounding graphite matrix
– Large differences between results obtained by considering homogeneously as compared to heterogeneously distributed sources and explicit coated particle models
Effect of approximation

Relative power for the use of the homogeneous model and the heterogeneous particle model. Calculated with the kinetic codes RZKIND and ZKIND.

COUPLING OF NEUTRONICS AND THERMAL-HYDRAULICS CODES FOR THE SIMULATION OF TRANSIENTS OF PEBBLE BED HTR REACTORS

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Material properties

Thermal conductivities
- $\text{UO}_2$: $3.7 \times 10^{-2}$ W.cm$^{-1}$.K$^{-1}$
- $\text{PyC}$ buffer layer: $0.5 \times 10^{-2}$ W.cm$^{-1}$.K$^{-1}$
- Inner / Outer $\text{PyC}$: $4 \times 10^{-2}$ W.cm$^{-1}$.K$^{-1}$
- SiC layer: $16 \times 10^{-2}$ W.cm$^{-1}$.K$^{-1}$
- graphite matrix: $0.54 \times 10^{-2}$ W.cm$^{-1}$.K$^{-1}$

Specific heat capacity
- $\text{UO}_2$: $0.04 \times 10^{-1}$ J. g$^{-1}$. K$^{-1}$
- $\text{PyC}$ buffer layer: $3.5 \times 10^{-1}$ J. g$^{-1}$. K$^{-1}$
- Inner / Outer $\text{PyC}$: $3.5 \times 10^{-1}$ J. g$^{-1}$. K$^{-1}$
- SiC layer: $0.25 \times 10^{-1}$ J. g$^{-1}$. K$^{-1}$
- graphite matrix: $0.5 \times 10^{-1}$ J. g$^{-1}$. K$^{-1}$

All values are dependent on temperature, etc
Summary of method to be implemented

- Discretization of fuel sphere into shells, as usual
- Assign a homogeneous (independent of \( r \)) heat source to each shell within the inner 2.5 cm of fuel sphere, as usual
- Define a representative microsystem for each shell within the inner 2.5 cm of fuel sphere. Each consists of UO\(_2\), four kernel coatings and a part of the graphite matrix, as shown on the right.
- Temperature dependent thermal conductivity and heat capacity values for UO\(_2\), kernel coatings and graphite are used
- Outer boundary of representative microsystem assigned the average temperature of the fuel sphere shell (as usually calculated)
Summary of method to be implemented

- Time-dependent discrete mathematical model for heat conduction is solved and written in matrix form for each representative microsystem.

- Heat sources, calculated by a dummy driver program in place of TINTE, are used for the shells in the microsystem’s UO$_2$ kernel.

- System of first order differential equations – solved by finite difference method. Use a predictor-corrector method to solve. Use Runge-Kutta-Verner 5$^{th}$ and 6$^{th}$ order method for both predicted and corrected values.

- End result is average temperatures in shells of each representative microsystem, at each time point.
Test case results

Algorithm tested as follows

Initial temperatures in shells of each representative microsystem taken as 800 degrees C
– Temperature on boundary of each representative microsystem taken to be constant at 800 degrees C
– Heat sources in the UO₂ taken as zero
– Time = 3 seconds

Result:
– The temperatures in the shells of each representative microsystem remained constant, as they should
Results

- The sources in all shells of the UO2 kernel of each representative microsystem were taken as constant at $5 \times 10^2$ W/cm$^3$.

Movie 1
- constant heat source but with all temperatures starting at 800 °C
- constant profile in representative coated particle model seen
- difference from surrounding material only 8 °C

Movie 2
- The sources in all shells of the UO2 kernel of each representative microsystem were taken as a linear upward ramp from $q_{\text{min}}$ to $q_{\text{max}}$, lasting 1 second,
- followed by a linear downward ramp from $q_{\text{max}}$ to $q_{\text{min}}$, lasting 1 second,
- thereafter constant at $q_{\text{min}}$.
- $q_{\text{min}} = 5 \times 10^2$ W/cm$^3$; $q_{\text{max}} = 10 \times q_{\text{min}}$
- difference from surrounding material over 70 °C
Results

Movie 1: constant heat source
Results

Movie 2: Ramp
Results

Movie 2: Ramp
Approximate method in TINTE

Fission Powers for Changes in Factor PUEBH: TCRW over 0.1 seconds
Conclusions

– simple homogenised models work well for steady state and slow transients
– for fast reactivity transients
  • the importance of modelling the local heat sources in the coated particle explicitly is well known
  • lack of the heterogeneous model lead to large over prediction of the power excursion
  • approximate models as currently in TINTE (temperature difference link to power density) does not look too bad but does not necessarily lead to an accurate solution (some time delayed effect not modelled)

– FORTRAN 90 module developed
– to be supplied with benchmark package