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Thermal Transient Analysis of Pebble Fuels Based on the Two-Temperature Homogenized Model

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1. Introduction

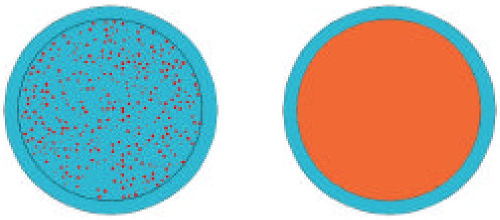
A two-temperature homogenized model [1] has been proposed for thermal analysis of a heterogeneous pebble fuel with distributed fuel particles. This model is not only easy to implement but also provides more realistic temperature distribution in pebble fuels. In this paper, the model is used for thermal transient analysis of a pebble fuel.

2. Methods and Results

In this section some of the ideas used in the homogenized model are briefly described. And some representative results of the thermal transient calculations are presented.

2.1 Two-Temperature Homogenized Model

Fig. 1 shows a heterogeneous pebble as manufactured, in comparison with a homogenized pebble that we like to construct as a model.



(a) (b)

Fig. 1. Heterogeneous pebble vs. homogenized pebble.

In the homogenized model, the inner fuel region of the pebble is composed by a mixture of two imaginary homogeneous media. The medium representing fuel kernels is to be characterized with thermal conductivity k_f and temperature T_f. Similarly, the medium representing graphite matrix is to be characterized with k_m and T_m. The outer graphite shell which is already homogeneous is then retained as k_g and T_g. The homogenized heat conduction equations are written below for "f", "m", and "g" region, respectively. The homogenized parameters and coupling coefficient m are determined in Table I.

$$k_f\nabla^2 T_f(r,t) - m\left[T_f(r,t)-T_m(r,t)\right] + q'''(r,t) = rc_f\frac{\partial T_f(r,t)}{\partial t} \quad (1)$$

$$k_m\nabla^2 T_m(r,t) + m\left[T_f(r,t)-T_m(r,t)\right] = rc_m\frac{\partial T_m(r,t)}{\partial t} \quad (2)$$

$$k_g\nabla^2 T_g(r,t) = rc_g\frac{\partial T_g(r,t)}{\partial t} \quad (3)$$

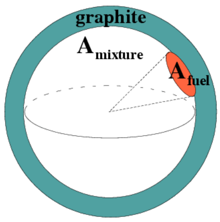
2.2 FDM Discretization

Finite difference method is widely used in thermal analysis. By a cell centered scheme, heat conduction equations (2) and (3) are discretized, and numerical solutions are obtained by preserving temperature and heat flux continuity conditions at interface.

One of the heat flux continuity conditions at the interface is given as

$$k_g A\left.\frac{dT_g}{dr}\right|_{\text{interface}} = k_f A\Gamma_{f\to g}\left.\frac{dT_f}{dr}\right|_{\text{interface}} + k_m A\Gamma_{m\to g}\left.\frac{dT_m}{dr}\right|_{\text{interface}} \quad (4)$$

Since the shaded area of cone (A_{fuel}) is proportional to the volume of the cone (V_{fuel}) with this model, area factors $\Gamma_{f\to g}$ and $\Gamma_{m\to g}$ are calculated as



$$\Gamma_{f\to g} = \frac{A_{fuel}}{A_{fuel}+A_{mixture}} = \frac{V_{fuel}}{V_{fuel}+V_{mixture}},$$
$$\Gamma_{m\to g} = 1 - \Gamma_{f\to g}. \quad (5)$$

Fig. 2. Model for area factor.

2.3 Numerical Tests

One fuel pebble as in Fig. 3 is chosen for test. Bulk helium temperature is set to 1173 K. After one reference run by the HEATON Monte Carlo code [2] of the heterogeneous pebble, the homogenized parameters and coupling coefficient are obtained [1] and presented in Table I.

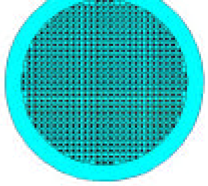


Fig. 3. Heterogeneous fuel pebble with CLCS distribution.

Table I: Homogenized Parameters

i	f	m	g
k_i (W/cmK)	0.01	0.21	0.25
rc_i (J/cm^{3}K)	3.2448	2.95378	3.01875
m (W/cm^{3}K)	1.18		–

2.3.1 Steady State Calculation

Fig. 4 compares the steady state temperature distributions from reference solution, the analytic and FDM numerical solutions of the proposed homogenized model. Note that the agreement is very good.

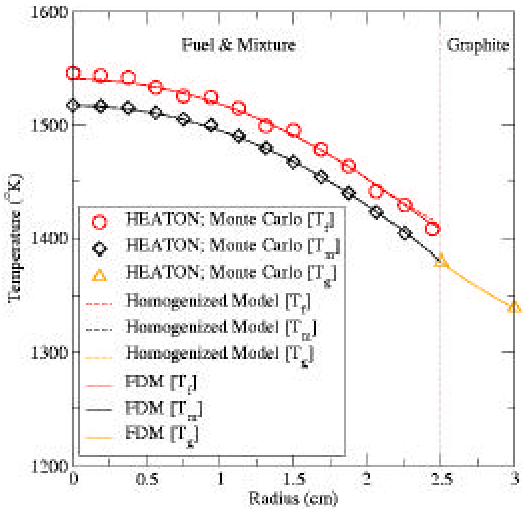


Fig. 4. Steady state temperature distribution in pebble.

2.3.2 Transient Tests

Using the explicit scheme of time discretization, two transient tests are performed. As sketched in Fig. 5, the volumetric heat production rate is changed with time. The corresponding transient temperature results are shown in Fig. 6 and Fig. 7 for test I and test II, respectively.

The area factor in Eq. (5) is a vague concept and the typical value of ~ 5% is considered upper bound. Sensitivity studies show that fuel temperature is not affected significantly by its value (including zero value, which implies no direct interface between particle fuels and the graphite shell).

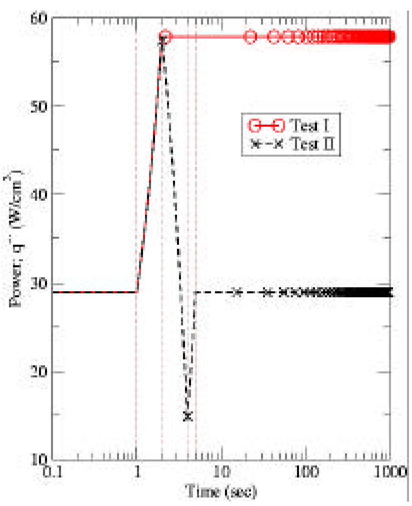


Fig. 5. Power histories for transient tests.

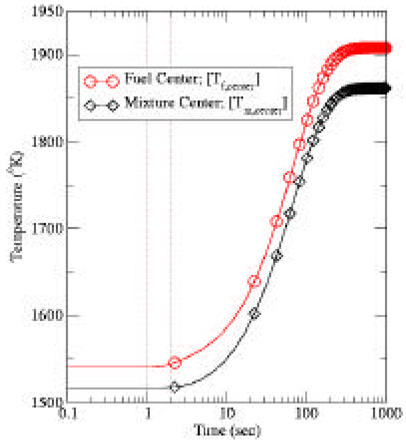


Fig. 6. Temperature change in transient test I.

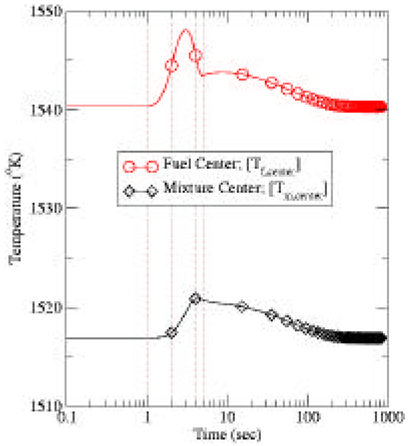


Fig. 7. Temperature change in transient test II.

3. Conclusions

Steady state and transient numerical analyses of the two-temperature homogenized model were presented. This model gives realistic temperature distributions in a fuel pebble by providing fuel-kernel temperature and graphite-matrix temperature distinctly. Thus it can be used for more accurate neutronics evaluation such as the Doppler temperature feedback. In a future work, a reactor kinetics model will be coupled with the thermal transient model in this paper.

ACKNOWLEDGEMENT

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REFERENCES

[1] Nam Zin CHO and Hui YU, Two-Temperature Homogenized Model for Thermal Analysis of a Pebble with Distributed Fuel Particles, *Trans. Am. Nucl. Soc.*, to be presented, June 2008.

[2] Jae Hoon SONG and Nam Zin CHO, An Improved Monte Carlo Method Applied to Heat Conduction Problem of a Fuel Pebble, *Transactions of the Korean Nuclear Society Fall Meeting*, Pyeongchang, Korea, October 2007.