Shell-Fuel Pebble Design and Its Nuclear and Thermal Performance

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1. Introduction

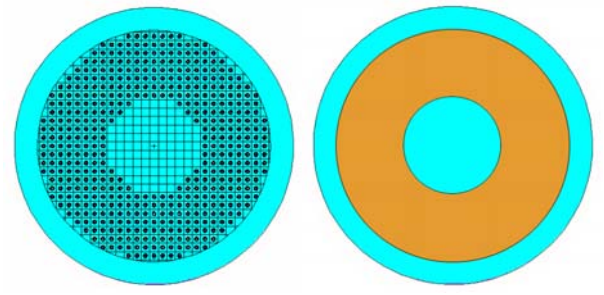
A typical fuel pebble to be loaded in very high temperature gas-cooled reactors consists of over ten thousand TRISO particles dispersed throughout in graphite matrix. We have proposed previously a shell-fuel pebble design [1, 2] to reduce peak temperature at the pebble center. On the other hand, we developed a two-temperature homogenized model to facilitate thermal analysis of a regular fuel pebble [3, 4]. In this paper, we extend the two-temperature homogenized model to the shell-fuel pebble design and provide its results of nuclear and thermal performance analyses.

2. Shell-Fuel Pebble and Homogenized Model

In this section, the shell-fuel pebble is described along with its nuclear performance and two-temperature homogenized model for thermal analysis.

2.1 Shell-Fuel Pebble

The design of shell-fuel pebble was first proposed in [1, 2] and sketched in Fig. 1(a). Compared to the regular fuel pebble, the only difference is in the way how the particles are dispersed in graphite matrix, i.e., particles are not dispersed in the internal region ($r \le r_0$) in the shell-fuel pebble design. This design helps to reduce the maximum fuel temperature and soften the neutron spectrum.



(a) (b)

Fig. 1. Shell-fuel pebble with (a) CLCS distribution and (b) homogenized model.

2.2 Burnup Calculation

Burnup calculations for the regular and shell-fuel pebbles were performed by MONTEBURNS and the results are compared in Fig. 2. The characteristics are practically the same.

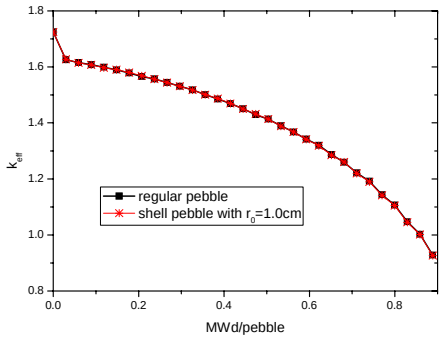


Fig. 2. Burnup characteristics in comparison.

2.3 Two-Temperature Homogenized Model

The two-temperature homogenized model [3, 4] has been used in thermal analysis of a regular fuel pebble, and it provides realistic temperature distributions compared to the volumetric-averaged model. In this paper, we are extending the model to the shell-fuel pebble design.

For internal graphite region ($0 \le r \le r_0$), graphite thermal conductivity is k_g and temperature T_g, and the heat conduction equation is written as

$$k_g \nabla^2 T_g(r,t) = \rho c_g \frac{\partial T_g(r,t)}{\partial t}. \quad (1)$$

In the homogenized model, the shell-fuel region is represented by a mixture of two imaginary homogeneous media, as in Fig. 1(b). 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. Then for the fuel region $r_0 \le r \le r_f$, we use the following heat conduction equations with homogenized parameters $k_f, k_m, \rho c_f, \rho c_m$ and a coupling coefficient μ (to be determined later) :

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

$$k_m \nabla^2 T_m(r,t) + \mu\left[T_f(r,t) - T_m(r,t)\right] = \rho c_m \frac{\partial T_m(r,t)}{\partial t}, \quad (3)$$

where the volumetric heat production rate q''' is a function of t only in the homogenized fuel region.

In outer graphite shell ($r_f \le r \le r_s$), the heat conduction equation is the same as Eq. (1).

In steady state, the right hand sides of Eqs. (1) – (3) equal zero, and analytic solutions can be found. After some algebra, the solutions are obtained as follows:

$$T_g(r) = -\frac{c_1}{r} + c_2, \tag{4}$$

$$T_m(r) = c_3 \frac{\sinh\left(\sqrt{A}r\right)}{Ar} + c_4 \frac{\cosh\left(\sqrt{A}r\right)}{Ar} - \frac{B}{6A} r^2 - \frac{c_5}{r} + c_6, \tag{5}$$

$$T_f(r) = -\frac{k_m}{\mu} \nabla^2 T_m(r) + T_m(r), \tag{6}$$

$$T_g(r) = -\frac{c_7}{r} + c_8, \tag{7}$$

where

$$A = \frac{\mu\left(k_f + k_m\right)}{k_f k_m} > 0,\ B = \frac{\mu q'''}{k_f k_m} > 0. \tag{8}$$

There are eight unknown constants in the solution forms in Eqs. (4) to (7). They can be determined by applying i) finite temperature at center, ii) temperature and heat flux continuity at two interfaces, iii) total heat conservation at two interfaces and iv) convective boundary condition.

The next step is a procedure to determine the homogenized parameters k_f, k_m and μ. The idea is to require the analytic solutions for the homogenized pebble obtained above to match the reference solutions of the heterogeneous pebble. The way to "match" the two solutions is the least squares discrepancy of the two solutions. The reference heterogeneous solutions are provided by the Monte Carlo method [5].

2.4 Test and Results

For our analysis, one shell-fuel pebble containing 9392 particles was used. The detailed configuration and properties are listed in Table I (with r_0 =1cm). Pebble power is 757.576 W with peaking factor 2.5. Helium temperature is 900 ^{o}C with heat transfer coefficient of 0.1006 W/cm^{2}K.

Table I: Problem Description

Material	Radius or Thickness (cm)	Thermal Conductivity (W/cmK)	Homogenized Model
Internal Graphite	1.0	0.25	k_g, T_g
Kernel	0.02510	0.0346	k_f, T_f
Buffer	0.03425	0.01	k_m, T_m
Inner PyC	0.03824	0.04	
SiC	0.04177	0.183	
Outer PyC	0.04577	0.04	
Graphite Matrix	2.5	0.25	
Outer Graphite Shell	0.5	0.25	k_g, T_g

In Fig. 3, the steady state temperature profiles are compared. We find that the maximum fuel temperature is reduced more than 40 degrees by the shell design. The homogenized model solutions are in excellent agreement with those of the heterogeneous Monte Carlo results. Table II shows the resulting homogenized parameters.

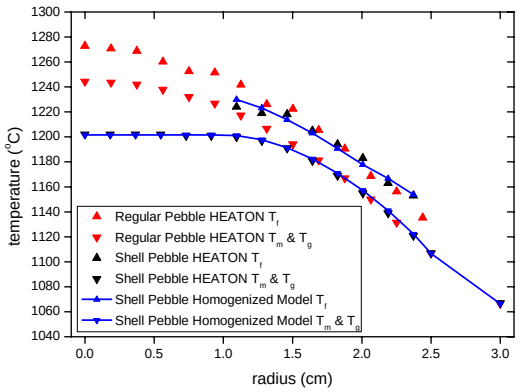


Fig. 3. Steady-state temperature distributions in comparison.

Table II: Resulting Homogenized Parameters

k_f (W/cmK)	0.03
k_m (W/cmK)	0.18
μ (W/cm^{3}K)	0.63

3. Conclusions

The results of steady-state nuclear and thermal analyses were presented and compared for the regular and shell-fuel pebble designs. The shell-fuel pebble exhibits reduced maximum temperature in the fuel region, while producing same power. The burnup characteristics are practically the same. In a future work, transient thermal analysis will be performed incorporating the Doppler fuel temperature feedback.

REFERENCES

[1] N. Z. Cho, S. H. Yun, and H. Yu, HTGR Core Design Analysis by Using the MONTEBURNS Code, Basic Research Report, KAIST, 2006.
[2] N. Z. Cho, S. H. Yun, and H. Yu, Shell-Fuel Pebble Nuclear Fuel Element for Very High Temperature Gas-Cooled Reactors, Patent Number 10-0756440, 2007.
[3] N. Z. Cho and H. Yu, Two-Temperature Homogenized Model for Thermal Analysis of a Pebble with Distributed Fuel Particles, *Trans. Am. Nucl. Soc.*, Vol.98, p.539, 2008.
[4] N. Z. Cho, H. Yu, and J. W. Kim, Thermal Transient Analysis of Pebble Fuels Based on the Two-Temperature Homogenized Model, *Transactions of the Korean Nuclear Society Spring Meeting*, Gyeongju, Korea, 2008.
[5] J. H. Song and N. Z. 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, 2007.