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A New Approach to Effective Thermal Conductivity for VHTR Fuels

Nam Zin Cho and Hui Yu
Korea Advanced Institute of Science and Technology
373-1 Kusong-dong, Yusong-gu, Daejeon, Korea 305-701; nzcho@kaist.ac.kr

1. Introduction

Several proposed advanced reactor concepts involve double heterogeneous systems, in which heterogeneous fuel particles are randomly dispersed in solid graphite matrix of fuel elements and in turn these fuel elements themselves are loaded into coolant, moderator and reflector regions. Thus, treatment of the heterogeneity is of great concern not only for neutronics analysis but also for thermal analysis. Nowadays, volumetric averaged effective thermal conductivity [1] is widely used for simplified thermal-hydraulic analysis of heterogeneous fuel materials. However, it might underestimate the maximum fuel temperature. We are seeking new approach to represent the effective thermal conductivity better in this paper.

2. Methods and Results

In this section, some existing methods and a proposed method are described to model the effective thermal conductivity for heterogeneous heat structures. The study is performed for TRISO particle heat conduction now and will be extended to the fuel pebble scale later.

2.1 Analytic Solution

The TRISO particle has heat source in the kernel region and organized structure in other four coating layers. We can get the exact solution of temperature distribution by solving the following one-dimensional spherical heat conduction equation:

$$\frac{1}{r^2}\frac{d}{dr}(kr^2\frac{dT}{dr})+q'''=0, \quad (1)$$

with boundary condition as $T(R)=0$. We can obtain the temperature profile analytically shown as black line in Figure 1.

2.2 Wiener Bounds

If conduction is the only mechanism of heat transfer involved, Wiener bounds [2] provide the effective thermal conductivity of heterogeneous materials, where the serial and parallel models serve as lower and upper bounds, respectively:

$$k_{serial}=\frac{1}{(1-v_2)/k_1+v_2/k_2}, \quad (2)$$

$$k_{parallel}=(1-v_2)k_1+v_2k_2. \quad (3)$$

The TRISO particle is serially structured. But even for this, the well known Wiener bounds did not show good performance. As compared in Figure 1, both the serial model (harmonic averaged) and the parallel model (volumetric averaged) underestimate the maximum temperature at the particle center.

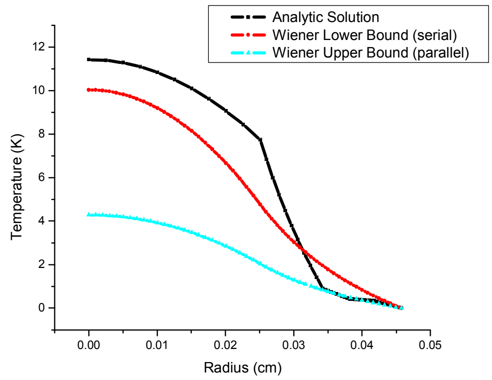

Figure 1. Comparison of Analytic Solution and Wiener Bounds for TRISO Particle

2.3 New Method – A Homogenization Theory

We propose a new method to provide representative effective thermal conductivity based on homogenization of heterogeneous structures. We require that effective thermal conductivity preserve some key parameters of engineering importance, such as: 1) the maximum temperature, one of the important safety criteria; 2) the heat flux at the interface where homogenization occurs; 3) the heat flux at the boundary; 4) the average temperature of the homogenized region, by which average behavior is effected. To satisfy these, we should loosen some other conditions, that is we may allow temperature discontinuity at the interface by analogy with the neutron flux in nodal methods [3]. The discontinuity factor may be defined as the ratio of the exact heterogeneous temperature to the homogenized temperature at the interface:

$$DF=\frac{T^{\text{het}}}{T^{\text{hom}}}. \quad (4)$$

2.3.1 Example 1

First, let us consider homogenization of non-source heat structures. The five-layer TRISO particle is to turn into an inner kernel shell and an outer homogenized shell. Heat source and thermal conductivity is retained in the kernel region, while the other four coating layers are homogenized and one effective thermal conductivity is presented.

As shown in Figure 2, the new method preserves the maximum and average temperature well. The heat flux at the discontinuous interface is continuous (as required). The discontinuity factor is about 1.78.

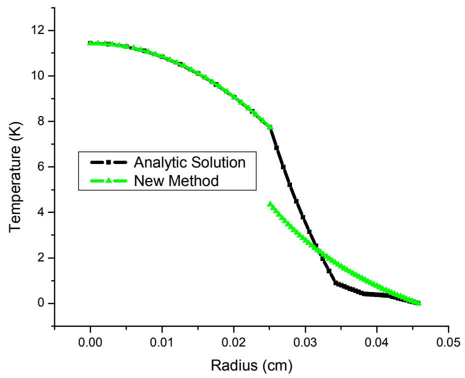

Figure 2. Comparison of Temperature Profiles for Example 1

2.3.2 Example 2

Example 2, sketched in Figure 3, is a problem of homogenization of heterogeneous material regions containing heat source. Suppose that we have a spherical particle with 4 layers, where different heat sources are dispersed in the inner three shells. Now let us homogenize the inner three shells, and we may use the volumetric averaged heat source and one effective thermal conductivity. The structure and the material property in the last shell (which is source-free and of one material) are kept intact.

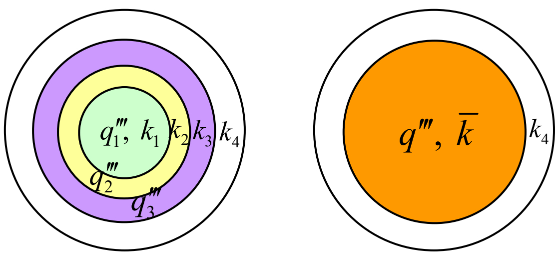

Figure 3. Description of Example 2 Problem

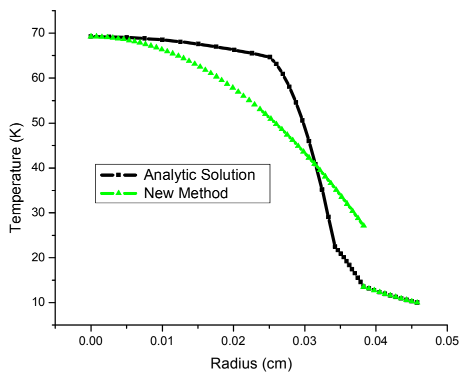

Figure 4. Comparison of Temperature Profiles for Example 2

Temperature distributions for the analytic solution and the new method proposed above are compared in Figure 4. The temperature discontinuity at the interface is about 0.5. The temperature discontinuity depends on the strength of heat sources, the boundary temperature, the problem size and the material properties. More study is needed to obtain a useful and practical relation.

3. Conclusions

The well-known bounds of effective thermal conductivity do not seem to be accurate or even appropriate for thermal analysis of heterogeneous heat structures such as in pebble fuels. A new approach to effective thermal conductivity is provided in this paper. By preserving the maximum temperature, heat fluxes at the interface and at the boundary, and average temperature, the effective thermal conductivity so obtained would provide information of more engineering importance.

Temperature discontinuity is introduced in this paper, here we get the discontinuity factor from the effective thermal conductivity, but in the future, we may do in a reverse way to predict the effective thermal conductivity.

ACKNOWLEDGEMENT

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