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Impact of Fuel Heterogeneity on Neutronic Characteristics of U-Mo Dispersion LEU Fuel

H. Unesaki and T. Sano
Kyoto University Research Reactor Institute (KURRI),
Kumatori-cho, Sennan-gun, Osaka 590-0494, Japan

ABSTRACT

U-Mo based fuel is currently considered as the most promising candidate of the high density LEU fuel for high performance research reactor conversion. The dispersion type fuel, in which the U-Mo particles are dispersed in aluminum matrix, is also considered to be the candidate for the LEU conversion of the Dry core of the Kyoto University Critical Assembly (KUCA), at the Kyoto University Research Reactor Institute (KURRI).

The neutronic characteristics of such dispersion fuel usually neglects the fine heterogeneity of the U-Mo particles and its random distribution in the aluminum matrix, and the fuel meat is treated as homogeneous matter. Such microscopic heterogeneity can affect the detailed neutronic performances, and thus has been studied especially in the case of particle fuel in high-temperature gas-cooled reactor and MOX fuel to investigate the effect caused by the heterogeneous presence of fuel particles.

In this paper, the influence of the microscopic heterogeneity of U-Mo dispersion fuel to the basic neutronic characteristics is investigated. The results based on simple pin-type fuel show that. although the heterogeneity effect depends on the U-Mo particle size and the neutron spectrum of the core, the effect is insignificant for the current design of the U-Mo dispersion fuel, which confirms the validity of the current core analysis based on homogeneous model.

1 Introduction

In some complex fuel design having heterogeneous structure of fuel particles distributed in matrix materials, the heterogeneity of the system can cause significant impact to neutronic characteristics of the core (Figure 1). The most well- known and well-studied example is the high-temperature gas-cooled reactor, where spherical fuel particles are randomly distributed in graphite matrix to form fuel pebbles or pins and then arranged again to form the reactor core.

The microscopic heterogeneity affects the neutronic characteristics of the system through the heterogeneous presence of strong absorber randomly distributed in neutronically transparent (or less absorbing) media; this structure affects the neutron transmission probability and thus the reaction rate in the media. This microscopic heterogeneity, embedded in higher macroscopic heterogeneity such as fuel/moderator structure, is known as "double heterogeneity". The double heterogeneity problem has been discussed in association with the adequacy of resonance self-shielding evaluation and spatial homogenization to obtain cell averaged cross section used in deterministic core calculations.

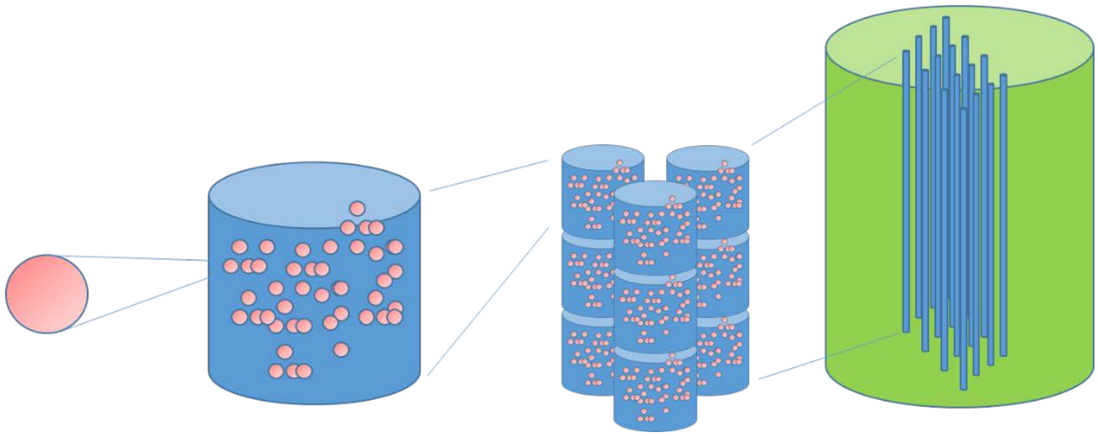

Figure 1. Example of multiple layer of heterogeneity in reactor fuel

On the other hand, the adequate treatment of the randomness of the particle distribution lead to development of sophisticated methodology, today known as the statistical geometry model and has enable to directly handle this randomness in Monte Carlo calculations [1][2]. This methodology has been widely adopted in neutronics analysis of gas-cooled high-temperature reactor.

In criticality safety evaluation of fuel-water mixture, the heterogeneity of fuel particles distributed in media has also gained interest [3][4]. Recent needs for further investigating the particle heterogeneity in media could be found in particular to investigate the criticality safety of fuel debris / water mixture for Fukushima core removal for decommissioning.

Despite the possible difference in the geometric scale (i.e. the size of the fuel particles), dispersion type fuel widely adopted in research reactor fuel could also be considered to have the similar micro-heterogeneity. This could be said to the U-Mo based fuel, which currently is considered as the most promising candidate of the high density LEU fuel for high performance research reactor conversion; the dispersion type fuel, in which the U-Mo particles are dispersed in aluminum matrix, is also considered to be the candidate for the LEU conversion of the Dry core of the Kyoto University Critical Assembly (KUCA), at the Kyoto University Research Reactor Institute (KURRI).

This U-Mo dispersed fuel is a mixture of high-density nuclear material which is a strong neutron absorber and matrix of aluminum which is optically transparent to neutrons. Although having different geometrical scale as mentioned above, the physical condition of the micro-heterogeneity is analogous to the known examples of distributed fuel particle issues. This microscopic heterogeneity of U-Mo distributed fuel is usually not considered in neutronic analysis and the fuel is commonly treated as a homogeneous mixture; this assumption is hitherto not confirmed to be valid.

Based on the observations and discussions presented above, this study focuses on the investigation of influence of the microscopic heterogeneity of U-Mo dispersion fuel to the basic neutronic characteristics, i.e. the k-infinity by directly considering the random distribution of the U-Mo particles in aluminum matrix using Monte Carlo code MVP.

The methodology and fuel cell models investigated are described in Section 2. The results, discussions and observations are summarized in Section 3. The conclusion and future works are summarized in Section 4.

2 Methodology and Fuel Cell Model

The analysis was performed using Statistical Geometry Model (SGM) [1] capability of continuous energy Monte Carlo code MVP (version 2.0) [5], together with JENDL-4.0 as neutron cross section library. In the calculations, U-Mo particles are modelled as sphere, and its location is randomly generated and is sampled probabilistically along the particle flight path from the spatial probability distribution of spherical fuels. The Analytical Nearest Neighbor Distribution (the default option for MVP SGM) depending on the fuel particle radius and packing fraction is used in this study;

$$\frac{dF(r)}{dr} = \frac{3}{2} \cdot \frac{f_p}{1 - f_p} \exp\left(-\frac{3}{2} \cdot \frac{f_p}{1 - f_p} r \right)$$

Where *F(r)* is the distribution probability, *fp* is the packing fraction of the spherical fuel particles in the matrix and *r* is the radius of the spherical fuel particles, respectively.

An infinite array of simple pin fuel with Al clad and light water moderator was adopted as the fuel model in this study (Figure 2). Material composition is based on U-10Mo (density data taken from Ref. [6]) with packing fraction of 0.5 in aluminum matrix, corresponding to 7-8gU/cc loading. Two cases with different moderator-to-fuel volume to investigate the impact of neutron spectrum. The specifications of the fuel model are summarized in Table 1.

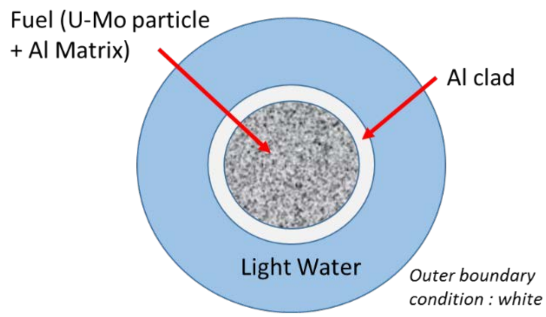

Figure 2. Fuel Cell Model

Table 1. Fuel Cell Model Specifications

Parameter	Case 1	Case 2
Cell radius (outer radius)	**1.0**	**2.0**
Fuel Pin radius (incl. clad)	0.5	0.5
Fuel radius (fuel meat)	0.4	0.4
Vm/Vf	**4.7**	**23.4**
H/U5	**77**	**387**

For each cases, the radius of U-Mo sphere particles was varied as 20, 50, 100, 200, 500 and 750 μm. The homogenized U-Mo-Al mixture is taken as reference. 10000 particles x 120 cycles (20 skip cycles) were tracked for each calculation, yielding the standard deviation of 0.02% to 0.04%.

3 Results and Discussions

Dependence of infinite multiplication factor (k-infinity) to U-Mo particle size are shown in Fig. 3. In the figures, the particle size of "0 mm" corresponds to homogeneous mixture. The k-infinity value decreases with increasing particle radius for both cases, but shows more significant change for Case 2 with larger H/U5 value. This k-infinity change is considered to be caused by increased probability of neutron capture by fuel particle and change in the mean flight probability through the matrix media. Similar result has been observed for UO2 particles distributed in light water [7].

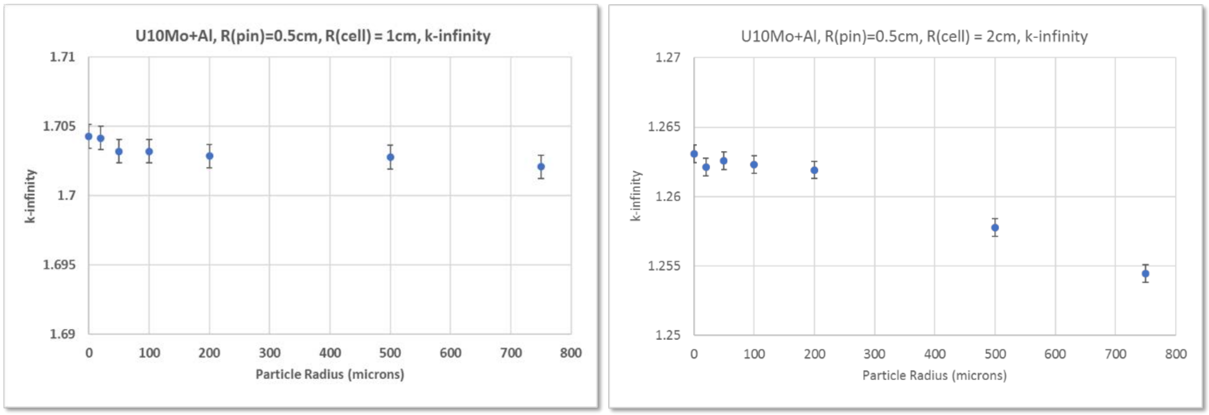

Figure 3. Dependence of k-inf to U-Mo particle radius for Case 1 (left) and Case 2 (right).

Figure 4 shows the reactivity difference from homogeneous model and its dependence on particle radius. It should be noted that the reactivity difference between homogeneous and heterogeneous model does exist even for small particle radius, but could be considered as practically negligible (approximately less than 50pcm, comparable to statistical error of MC calculation) when particle radius is less than 100μm in the investigated fuel cell.

The reactivity difference between homogeneous and heterogeneous model shows strong dependence on fuel-to-moderator ratio, i.e. softer neutron spectrum yields larger reactivity difference. As could be observed in Case 2, the reactivity difference may become significant if large clusters of fuel particles are present in the fuel meat. This indicates the increased importance of assuring the homogeneity of the fuel particle dispersion during the fabrication of high density fuel, especially for reactors with well-thermalized spectrum.

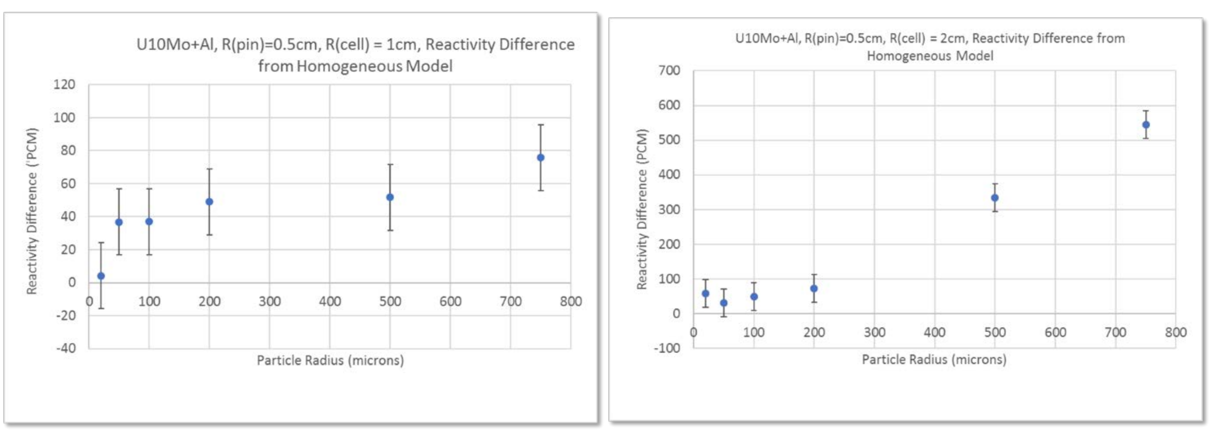

Figure 4. Reactivity difference from homogeneous model for Case 1 (left) and Case 2 (right).

During the study, it has been observed that for smaller particle radius (<20μm in this case) the calculation results tend to show abnormalities such as significant (and non-physical) deviation from the overall trend. This is currently considered to be caused by the increased number of fuel particles to be tracked in the calculation and the spatial resolution in particle tracking, and should be investigated in detail to improve the accuracy and reliability of the present results. Also to improve the accuracy, multiple simulations with different random seed for geometric sampling should be performed to quantify the effect of different “randomness” for the particle distribution in SGM calculation.

4 Conclusions

The influence of microscopic heterogeneity structure of U-Mo fuel particles dispersed in aluminum matrix on reactivity has been investigated using statistically distributed particle modeling capability of Monte Carlo code MVP. A simplified pin-type fuel with packing fraction of 0.5 (corresponding to 7-8gU/cc loading) with light water moderator was used for investigation.

The calculation results show that with particle radius of less than 100μm, the U-Mo dispersed mixture could be satisfactory considered as homogeneous media in terms of reactivity, with reactivity difference less than 50pcm which is comparable to the statistical accuracy of present calculations.

Justification of the present conclusions through improvement of calculation accuracy and analysis of plate type fuels with various fuel cell parameters (neutron spectrum, loading density, geometry) remains as works to be performed in the future.

5 References

[1] I. Murata, T. Mori and M. Nakagawa, “Continuous energy Monte Carlo calculations of randomly distributed spherical fuels in high-temperature gas-cooled reactors based on a statistical geometry model”, Nucl. Sci. Eng. 123(1); p. 96-109 (1996).

[2] T. Mori, K. Okumura, Y. Nagaya and H. Ando, “Monte Carlo analysis of HTTR with the MVP statistical geometry model”, Transactions of the American Nuclear Society, Vol. 83, pp.283-284 (2000).

[3] H. Okuno, Y. Naito and Y. Okuda, “Computation on Fuel Particle Size Capable of Being Regarded as Homogeneous in Nuclear Criticality Safety Analysis”, Journal of Nuclear Science and Technology, 31:9, pp.986-995 (1994).

[4] H. Okuno, Y. Naito and Y. Sakurai, “Effect of Fuel Grain Size on Reactivity”, Journal of Nuclear Science and Technology, 28:10, pp. 958-960 (1991).

[5] T. Mori and M. Nakagawa, "MVP-GMVP: General Purpose Monte Carlo Codes for Neutron and Photon Transport Calculation based on Continuous Energy and Multigroup Methods," JAERI-Data/Code 94-007 (1994) (in Japanese).

[6] D. E. Burkes, G. S. Mickum and D. M. Wachs, “Thermophysical Properties of U-10Mo Alloy”, INL/EXT-10-19373, Idaho National Laboratory (2010).

[7] T. Endo, private communication (2017).