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Neutronic and thermal analysis of composite fuel for potential deployment in fast reactors

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HIGHLIGHTS

- Neutronic and heat transfer performance of composite fuels on the macro-scale.
- Methodology to guide flexible fuel design using high fidelity simulation tools.
- Viability of composite fuels for ultra-high burnup fast reactor deployment.

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ABSTRACT

Composite fuels are promising candidates for high-burnup fast reactors because of their accommodation of swelling, limited fuel-cladding interactions and flexibility in design. While a proof-of-concept fuel consisting of granules of U-alloys and PuO_2 dispersed within a porous zirconium matrix was successfully manufactured and irradiated, its neutronic and thermal performance remains to be optimized as compared to currently utilized fuels. MCNP6, COMSOL and a sphere packing algorithm were employed to perform the analysis. We found that both the theoretical maximum burnup reached and the temperature profiles are comparable to that of the currently considered alternative fuel. The results are promising and do not indicate any substantial limitation to the deployment of composite fuel. The fuel type merits further research, including full-core simulations. The methodology followed herein also provides a basis for screening different material compositions and guiding materials selection in composite fuels.

1. Introduction

Disposal of nuclear waste has always been a hugely contentious issue for governments. This has led many nuclear programs to emphasize the need for advanced fast reactors. Despite this, many previous projects, for example the Integral Fast Reactor, were canceled on the basis that reprocessing nuclear fuel poses a weapons proliferation threat (Till and Chang, 2011). Modern fast reactor designs have since emphasized on extending fuel burnup and avoiding any form of reprocessing. The ability to reach higher fuel burnup would both limit strains on uranium resources and generate significantly less waste. However, extended burn times can bring new material and proliferation challenges to fast reactors.

Many fast reactor designs have employed the same uranium dioxide fuel used in conventional light water reactors (LWR) due to its proven reliability and manufacturability. However, main limitations of oxide fuels are their fissile density, thermal conductivity, softer spectrum and reactions with sodium coolant. Due to these concerns, the US fast reactor program has focused on metallic fuels, which have higher fuel density, high thermal conductivity and are compatible with the coolant (Hofman et al., 1997). Nonetheless, high swelling rate and fuel-cladding chemical and mechanical interactions limit maximum achievable burnup.

Heterogeneous fuels, notably of granular type, can help balance the advantages of different materials and offer more design flexibility. For instance, oxide granules can be placed in a metal matrix to improve thermal conductivity, or metal fuel can be placed in a porous matrix that accommodates swelling. Granular fuels have already experienced a wide range of applications, from power to research reactors (Berghe et al., 2010). These fuel types are also being proposed for a wide range of Generation IV reactors, most notably as TRISO particles in a graphite matrix (Barrachim et al., 2010). Typically, granular fuels in cylindrical rods are classified into two distinct types: dispersion fuels and cermets. In the former, fuel in metallic form is dispersed as small 'islands in a sea of nonfissile metal' (Frost, 1982). Cermets, on the other hand, consist of ceramic fuel particles in a metal matrix (Frost, 1982). The main limitation of granular-type fuels, especially in fast reactors, is their low

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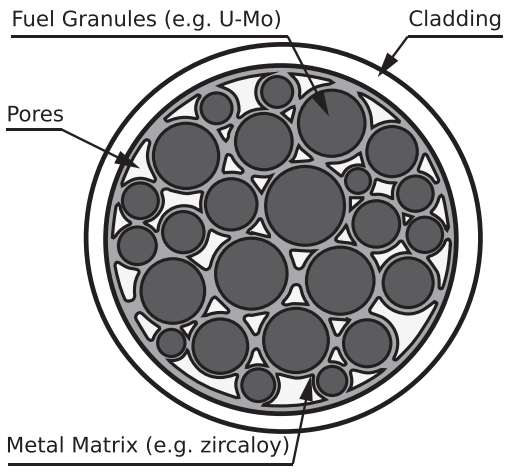

Fig. 1. Cross section of the composite fuel, a porous metal matrix binds the fuel granules together and is fully adhered to the inner cladding wall. The pores can be infiltrated with a powder of UO_2 or PuO_2.

heavy metal inventory. Because a significant fraction of their volume is occupied by an inert metal, such as zirconium or aluminum, the heavy metal content in each kilogram of fuel is reduced. This leads to lower power densities and higher fuel enrichment requirements, two significant drawbacks. Fuel designs that densely pack fuel granules are therefore very desirable.

Savchenko et al. (2009) have proposed a novel granular composite fuel, illustrated in Fig. 1, that is a hybrid between the cermet and dispersion types. Uranium alloy granules are tightly packed in the cladding and bound with a porous metal matrix. A mixture of uranium and metal (e.g. zirconium) granules are vibro-packed and heated to cause capillary impregnation, such that the metal granules melt and form a barrier around each uranium granule. The final fuel pin contains approximately 60% fuel, 10% metal matrix and 30% void. To further increase the fuel loading, powdered oxide fuel may be added to the pores to achieve an overall fuel volume fraction of around 75%.

The resulting composite fuel element has the potential to solve many of the problems encountered by traditional fuel designs. Even with oxide fuel powder added within the structure, pores still occupy around 10–15% of the total volume (30–40% without the powder) (Savchenko et al., 2009); this helps accommodate fuel swelling and increases thermal conductivity relative to oxide fuels. Additionally, the matrix is fully adhered to the clad providing a protective layer alleviating fuel-cladding mechanical and chemical interactions. At high temperature, uranium can react with the clad to form uranium-iron eutectics at the interface. Since there is no direct contact between uranium granules and the clad, eutectic formation in the composite fuel is reduced. Channels in the pores also ease the movement of fission gases which can be vented into a gas plenum above the fuel or to the outside of the rod. This has already been proposed for metallic fuels in order to help decrease inner plenum pressure (Ohta et al., 2014).

While this novel fuel has been manufactured and irradiated in multiple reactors up to a burnup of 100 MWd/kg (Savchenko et al., 2010), computer models that simulate its performance are absent. Simulation results can lend insight into the suitability of the fuel in fast reactors and its potential limitations compared with current alternatives. Furthermore, virtual models can be easily modified to screen different material combinations of the composite fuel. This can guide further research and development into their structure. Accurately performing the necessary evaluations requires a physically-representative model of the fuel. To this end, a code that mimics the fuel manufacturing process was developed. It replicates the granule packing process in a cylindrical container and outputs each granule position. This can then be used to construct geometry models for neutron transport and heat transfer simulations. The widely used Monte Carlo Neutral Particle code (MCNP6, Goorley et al., 2013) was selected for the neutronic analysis. The code does not have an inherent function for modeling the composite fuel structure, but can use the geometry generated by the sphere packing algorithm. COMSOL Multiphysics (COMOL Inc, 2012) was selected for the thermal analysis because it provides useful capabilities, such as 2D meshing and data visualization. The key metrics for the analysis are the maximum burnup and the peak fuel temperature. The end objectives of this paper are twofold: (1) compare the performance of the composite fuel with more conventional U–Zr and UO_2 fuel pins and (2) guide further material research on composite fuel.

2. Modeling the composite fuel microstructure

2.1. Challenges of modeling and simulating heterogeneous fuels

Building representative models of complex heterogeneous fuel geometry is a challenging and computationally expensive task. Most whole-core analyses can yield accurate results by avoiding this issue, and simply homogenizing the inner fuel composition. More in-depth analyses such as evaluating the isotopic composition of different regions of the fuel, or studying thermal variation across the fuel require higher order models. Our research sets out to develop higher-fidelity models of the fuel to address this issue.

From a neutron transport standpoint, this simulation challenge has been well documented in the literature, notably for TRISO fuels. Bomboni et al. (2009) have shown that sparsely packed granular fuels can be accurately modeled with the built-in repeated structures in MCNP5. The main requirements are that the heavy-metal inventory be carefully accounted for and that no granule is cutoff at the rod walls. Going further, Brown and Martin (2004) developed a semi-stochastic method, now built-into MCNP6, that introduces a small degree of randomness in the granular arrangements by displacing the spheres within their lattice. While this method was shown to be slightly more accurate than the repeated structure arrangement, it only applies to sparsely packed fuels. Additionally, codes such as SERPENT have built-in even more complex sphere packing features, but these are also intended for low packing fraction fuels (Leppanen, 2015). Since the composite fuel has a high packing fraction, an alternative method is needed. This can be in the form of an algorithm that computes the positions of packed spheres and outputs the corresponding geometry. Many of these types of algorithms have already been developed in nuclear engineering to solve the challenge of packing fuel pebbles in advanced pebble-bed reactors (Li and Ji, 2012). The methodologies can be re-applied for the current problem of packing spheres within a cylindrical rod. In this work, an algorithm was constructed based on the methodology proposed by Salvat et al. (2005). We previously outlined how this algorithm can be used to generate fuel pin geometries in MCNP6 (Abou-Jaoude and Erickson, 2015).

This algorithm is also useful for heat transfer analysis in granular fuels. Various methods have been proposed for estimating temperature distributions through complex geometries, especially with recent interest in the thermal properties of open cell foams (Coquard et al., 2012). However, few evaluate the effects of heat generation interspersed within the matrix structure. Finite element models are able to closely replicate complex fuel microstructure and derive more representative temperature profiles. These models can then be used for further analysis of the fuel structure and to predict the thermal behavior of different material configurations of the composite fuel.