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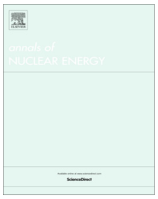

Multiphysics modeling of novel UO_2-BeO sandwich fuel performance in a light water reactor

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ABSTRACT

The relatively poor thermal conductivity of the UO_2 fuel is a major challenge for optimizing reactor operation and safety performance despite its widespread use in the majority of power reactors. The already low thermal conductivity further degrades with burnup due to accumulation of defects, fission product precipitates and fission gas bubbles. The high thermal stresses cause significant pellet cracking, leading to more pellet expansion and causing pellet cladding interaction and the release of fission product gases. Mitigation of these phenomena is currently accomplished by limiting operating power and ramp rates at high burnup. This study presents a novel design of the fuel pellet. The pellet was a combination UO_2 fuel and ceramic BeO, and three types of geometry were proposed to mitigate the thermal stress. The corresponding fuel performances were compared based on the modified version of our previously developed CAMPUS code. The fuel pellets with BeO inner or middle layers in the radial direction were found to greatly decrease fuel centerline temperature, and mitigate the fuel and cladding mechanical interaction by delaying the gap closure time. So, the corresponding fuel performance and reactor safety would be improved. The fabrication cost of these two types of fuel pellets would also be decreased significantly compared to the UO_2-BeO composite fuel due to the simplicity of the pellet design.

1. Introduction

The vast majority of operating commercial power reactors are fueled with sintered uranium dioxide (UO_2) pellets. This is the fuel of choice for most reactor designs including PWR, BWR, PHWRs, and gas and metal cooled reactors. This popularity is a result of several very desirable chemical and physical properties such as: high melting point, good high-temperature stability, good chemical compatibility with cladding and coolant, reasonable resistance to radiation and fission product swelling and adequate uranium density. However, a major disadvantage of UO_2 is its low thermal conductivity, which causes both a high temperature for the fuel pellets and a large temperature gradient. When fuel thermal expansion is considered, the high temperatures and temperature gradients lead to fuel cracking, pellet cladding interaction and the release of fission product gases as demonstrated (Bailly et al., 1999; Belle, 1961; Frost, 1982; Holden, 1966).

In principle, the high fuel temperature and temperature gradients can be decreased and the reactor performance improved by developing a higher thermal conductivity variant of UO_2 fuel. Such a fuel would experience a reduction in pellet cladding interaction through lower thermal expansion and lower thermal stresses as described (Bailly et al., 1999; Frost, 1982). Additionally, lower temperatures reduce fission product mobility thereby reducing fission gas release, grain boundary swelling, and stress-corrosion cracking. This would enable higher fuel burn-up, and improved reactor safety due to faster thermal response, lower grain boundary inventory of fission products and less thermal energy in the fuel pins.

The improved thermal conductivity could be achieved by producing a composite material with UO_2 and a suitable high thermal conductivity material with appropriate chemical and physical properties. A large number of materials have been proposed including carbon (in the form of graphite, diamond and nanotubes) (Cartas et al., 2015; Chen et al., 2015), ceramics (such as ThO_2, SiC, UN and BeO) (Cooper et al., 2015; Yeo, 2013; Yang et al., 2015; Latta et al., 2008; Kim et al., 2015), and some high temperature metals in various configurations such as homogenous or heterogeneous materials or heat-pipes (Kim et al., 2015).

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Nomenclature

α	coefficient of thermal expansion
α	radius of particle (μm)
bu	burnup (%)
Bu	burnup (fissions/atoms-U)
C_p	specific heat (J/(kg · K))
E	Young's modulus (Pa)
$\dot{F}$	volumetric fission rate (fissions/(m^3 · s))
f_d	dissolved fission products correction
f_p	precipitated fission products correction
f_{por}	porosity correction
f_r	radiation damage correction
f_x	deviation from stoichiometry
g	surface jump distance (m)
g_{mix}	temperature-jump distance for mixed gases (m)
$g_{0,i}$	reference temperature jump distance of each gas (m)
h_c	interfacial thermal conductance (W/(m^2 · K))
k	thermal conductivity (W/(m · K))
k_{mix}	mixed gas thermal conductivity (W/(m · K))
k_{95}	thermal conductivity of 95%TD fuel (W/(m · K))
$\frac{\Delta L}{L}$	thermal expansion
M_i	molecular weight of component i (kg)
M_m	molar mass of the mixed gases (kg/mol)
m	matrix
k_{eff}	effective thermal conductivity(W/(m · K))
k_{mix}	thermal conductivity of gas mixtures(W/(m · K))
k_{low}	mixed gas thermal conductivity at a low reference temperature (W/(m · K))
n	number of components in mixture
p	fuel porosity fraction
p	particle
P	pressure (Pa)
P_i	interface pressure (Pa)
P_{lin}	linear power (W/m)
p_0	fuel initial porosity fraction
Q	heat generation rate (W/m^3)
T	temperature (K)
t	time (s)
V	volumetric fraction
v	phonon velocity (m/s)
v_l	longitudinal phonon velocity (m/s)
v_t	transverse phonon velocity (m/s)
W	weight fraction
X_{dev}	oxygen to metal ratio deviation
x_i	mole fraction component i
a_{pellet}	fuel pellet radius (m)
ρ	density (kg/m^3)
v	Poisson's ratio
ε	radiating surface emissivity
Φ	fast neutron flux (n/(m^2 · s))
LWR	light Water Reactor
STP	standard condition for temperature and pressure
TD	theoretical density

Ceramic-ceramic composites are advantageous for their high melting point and chemical stability.

Silicon Carbide and Beryllium Oxide are two of the most promising materials that demonstrate compatibility with UO_2, and have high thermal conductivities but have received less attention (Slack, 1973; Kuchibhotla, 2004). The enhanced thermal conductivity UO_2-BeO composite fuel performance has been studied recently by Liu et al. (2015) through the development of computer models with augmented material properties. According to Kim's cost analysis of UO_2-BeO composite fuel (Kim et al., 2010), the manufacturing process is a complex process and cold pressing in the prior sintering process is needed for the homogeneous mixture of beryllium and uranium, while the fabrication cost of sandwich fuel may be cut down due to the simple fuel geometry design. So, a novel design of sandwich fuel pellet is presented in this paper. In this design, the pellet was a combination UO_2 fuel and ceramic BeO, and three types of geometry were proposed to mitigate the thermal stress. The corresponding sandwich fuel and composite fuel performances were compared based on our modified version of previously developed CAMPUS code (Liu et al., 2015, 2016). The new developments in the CAMPUS code include a theoretical Hasselman and Johnson model for the thermal conductivity of UO2-BeO composite fuel to replace the empirical correlation previously used, and the implementation of multiphysics models to the sandwich fuel.

The CAMPUS code (CityU Advanced Multiphysics Nuclear Fuels Performance with User-defined Simulations) is based on the framework of COMSOL Multiphysics and uses user-defined multiple physical models. Almost all the related physical models are considered, including heat generation and conduction, species diffusion, thermomechanics (thermal expansion, elastic strain, densification, and fission product swelling strain), grain growth, fission gas production and release, gap heat transfer, mechanical contact, gap/plenum pressure with plenum volume, cladding thermal and irradiation creep and oxidation, which are tightly coupled thermal, mechanical and chemical phenomena associated with a large number of control parameters and uncertainties. Through fully coupled multiphysics modeling, a more complete and quantitative understanding of the benefits of sandwich UO_2-BeO fuel performance in a light water reactor is demonstrated in this paper.

2. Material properties

In this part, we present the properties of composite fuel UO_2-BeO, ceramic fuel UO_2, ceramic BeO, the cladding and gas properties are also presented in the following.

2.1. UO_2-BeO composite fuel and BeO properties

(1) Thermal conductivity

In general, the UO_2-BeO composite fuel thermal conductivity is given as in Eq. (1) accounting for the effects of dissolved fission products, precipitated fission products, porosity, deviation from stoichiometry, and radiation damage, as for UO_2 fuel (Lucuta et al., 1996; Fink, 2000)

$$k = k(UO_2 - BeO) \cdot f_d \cdot f_p \cdot f_{por} \cdot f_x \cdot f_r \tag{1}$$

where f_d – dissolved fission products correction; f_p – precipitated fission products correction; f_{por} – porosity correction; f_x – deviation from stoichiometry; f_r – radiation damage correction. The as-fabricated UO_2-BeO composite fuel thermal conductivity accounting for the porosity of the fuel is calculated by multiplying a factor to 95% theoretical density UO_2-BeO composite fuel thermal conductivity as shown in Eq. (2)