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Safety analysis of TRISO fuel for an irradiation test in HANARO

Moon-Sung Cho*, Bong Goo Kim
Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, 305-353, Korea
**Corresponding author:mscho1@kaeri.re.kr*

1. Introduction

KAERI has been developing a TRISO (Tri-structural Isotropic)-coated particle fuel technology as a part of the Korean VHTR (Very High Temperature modular gas cooled Reactor) project, which started in 2004, and is planning an irradiation test of TRISO fuels in its research reactor, HANARO, for an evaluation and prediction of the irradiation behavior of the fuel.

The TRISO-coated fuel particle for a VHTR has a diameter of about 1 mm, and is composed of a nuclear fuel kernel and four different outer coating layers. These coating layers consist of a buffer PyC (pyrolytic carbon) layer, an inner PyC layer, a SiC layer, and an outer PyC layer. The fuel kernel is a source of a heat generation by the nuclear fission of fissile uranium. The role of each of the four coating layers is different in view of retaining the generated fission products and other interactions during in-reactor service[1].

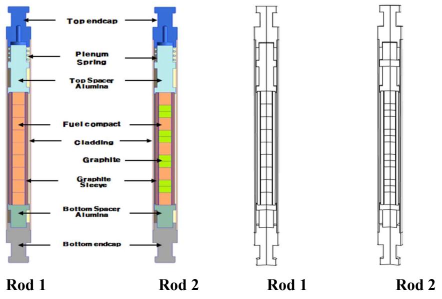
This paper describes a thermal performance and safety analysis of TRISO fuel in its irradiation test at HANARO in steady state and transient conditions of the control rod withdrawal and rocked rotor events. The objective of this study is to demonstrate the safety of the TRISO fuel irradiation in HANARO in terms of the fuel and sheath temperatures during normal and transient conditions.

2. Methods and Results

2.1 FE Model Buildup

Two types of irradiation test rods were designed and fabricated as shown schematically in Figure 1(a). One rod contains nine fuel compacts, and the other contains five fuel compacts with eight graphite test specimen in-between. A fuel compact has a circular cylindrical shape, 8 mm in diameter and 10 mm in height, normally with a volume fraction of 20%, approximately. The graphite specimen has the same diameter but is half the height of the compact. Test specimens are loaded into a graphite sleeve to secure a gap between the specimens and the metallic cladding. The gap is filled with a mixed gas of Ar and He, which provides a high-temperature environment for the test specimens and prevents thermal load on the metallic cladding. General descriptions of the test rods are summarized in Table 1.

Figure 1(b) shows COMSOL[2] based two-dimensional axi-symmetric finite element models of rods 1 and 2. Fuel compacts, graphite specimens, graphite inner cladding, stainless steel outer cladding, and gap gas were considered in this FE model.



(a) (b)

Fig. 1. (a) Schematic configurations and (b) FE models of test rods

Table 1. Descriptions of test rods

Components	Rod 1	Rod 2
Cladding	STS 316L(outer)/Graphite(inner)	
End cap	STS 316L	
Fuel	9 compacts	5 compacts
Graphite Specimen	N/A	VHTR structural graphite
		Matrix graphite,
Spacer	Al_2O_3(top and bottom)	
Spring	STS304	
Gap gas	He 45% + Ar 55%	He 30% + Ar 70%

The heat generated from the heating element is transferred through the gap and tube and, finally transferred to the flowing water by convective heat transfer. The heat flux from the fuel compacts and γ-heat from the other rod components were obtained for the steady state and transient conditions[3]. The heat transfer coefficient in the gap is computed by summing up the contributions from the two components, as in Eq. (1): radiative and gas-conductive heat transfer coefficients.

$$C_{gap} = H_{rad} + H_{gas} \quad (1)$$

The surface temperature of the external cladding was obtained from Eq. (2).

$$T_w = T_{fluid} + q''/h \quad (2)$$

T_w and T_{fluid} are the temperatures of the cladding surface and cooling water, respectively. q'' is the linear heat flux and h is the convective heat transfer coefficient which was calculated using Dittus-Boelter correlation[4]. The conductivity was assumed to be in steady state in each component of the test rods including the gap gas. The temperature of the cooling water was assumed to be constant.

The properties of structural components were obtained from the material library of COMSOL as a function of temperature. The properties of the fuel and He and Ar gases were obtained from a KAERI technical report[5] and Chemical Engineering Research Information Center [6][7], respectively.

2.2 Results of the steady state

Figure 3 shows the axial temperature profiles through the centerline of the test specimens in steady state. The hottest temperature is observed in the middle of the fuel or graphite mix in both rods. The maximum temperatures are 1027 ^{0}C and 759 ^{0}C in rod 1 and 2, respectively. The peak temperature of 1027 ^{0}C in rod 1 is less than the normal operation limit of 1250 ^{0}C of TRISO fuel.

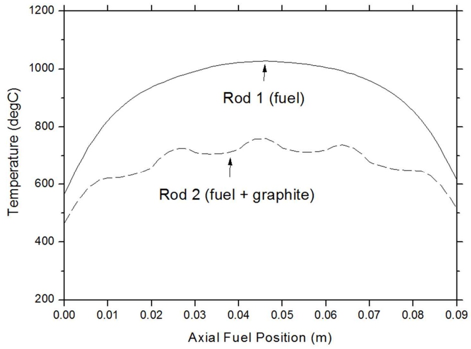


Fig. 3. Axial temperature profiles of the test specimens in steady state

Figure 4 shows the temperature profiles across the hottest cross-sections of the test rods in steady state. The temperature drops mostly in the gaps and the temperatures at the surfaces of the external claddings are less than 42 ^{0}C.

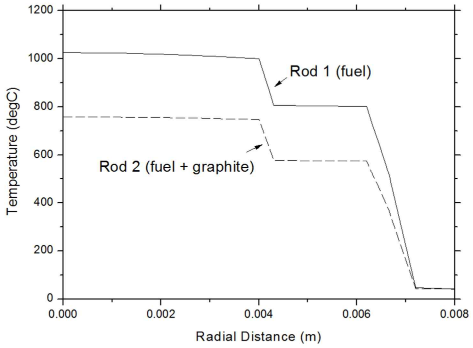


Fig. 4. Temperature profiles across the cross-sections of the test rods in steady state

2.3 Results of the transient conditions

The peak fuel temperatures and surface temperatures of the test rods during the control rod withdrawal and rocked rotor events were calculated and are summarized in Table 2. A peak fuel temperature of 1,224 ^{0}C was observed in rod 1 during the control rod withdrawal event. The temperature, however, is low enough when compared to the fuel failure limit of 1600 ^{0}C. A maximum rod surface temperature of 43.3^{0}C is observed in rod 1 during the rocked rotor event. However, the temperature is far less than the onset-of-boiling temperature of 122 ^{0}C, which was calculated from Bergles and Rohsenow correlation[8] using the reactor core conditions.

Table. 2. Peak fuel temperatures and surface temperatures of the test rods during the transient conditions

Events	HTC (W/m^2K)	Linear heat flux (kW/m^2)		Rod surface temp. (^{0}C)		Peak fuel temp.(^{0}C)	
		Rod 1	Rod 2	Rod 1	Rod 2	Rod 1	Rod 2
Control rod withdrawal	66,109	136	130	42.6	42.5	1,224	906
Rocked rotor	42,159	119	114	43.3	43.2	1,122	830

3. Summary

A thermal performance and safety analysis of TRISO fuel during its irradiation test at HANARO in steady state and transient conditions of the control rod withdrawal and rocked rotor events was carried out. A peak fuel temperature of 1,224 ^{0}C was observed in rod 1 during the control rod withdrawal event. The temperature, however, is low enough when compared to the fuel failure limit of 1600 ^{0}C. A maximum rod surface temperature of 43.3^{0}C was observed in rod 1 during the rocked rotor event. However, the temperature is far less than the onset-of-boiling temperature of 122 ^{0}C, which was calculated from the Bergles and Rohsenow correlation[7] using the reactor core conditions.

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