Status on the Development of High-Temperature Irradiation Technology for a Future Nuclear System in HANARO

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ABSTRACT

The irradiation tests of the materials in HANARO have usually been performed at temperatures below 300℃, at which the RPV (Reactor Pressure Vessel) materials of commercial reactors such as a light water reactor and CANDU are operated. As future nuclear systems will be operated under conditions of high temperature and a high neutron flux, the requirements for the irradiation of the materials at very high temperatures have recently been gradually increasing. To overcome the restriction in the use of the existing Al thermal media at high temperature, a new capsule with double thermal media composed of two kinds of materials such as Al-Ti and Al-graphite was designed and fabricated, enabling it to be tested at higher temperature than a single thermal media capsule. Graphite and Ti materials combined with Al are used as thermal media instead of Al in this capsule because Al might melt at high temperature. At the irradiation test of the capsule until now, the temperature of the specimens successfully reached 700℃ and the integrity of Al, Ti and graphite materials was maintained. The expected operating temperature of VHTR is 1,000 ℃, which is much higher than the irradiation temperatures of the material capsules tested at HANARO up to recently. For this, the soundness of the Al material and the instruments such as a thermocouple and heater will be reviewed. In the near future, an irradiation capsule operating well at such a high temperature will be designed and fabricated.

1. Introduction

The nuclear systems have evolved in accordance with concerns over energy resource availability, climate change, and energy security. Among them, Gen-IV nuclear systems are in the spotlight as future energy sources. Sustainability, safety, cost-effectiveness, and proliferation risk reduction are pursued for future commercial development, which includes SCWR (Super critical water reactor), SFR (Sodium-cooled fast reactor), GFR (Gas-cooled fast reactor), LFR (Lead-cooled fast reactor), MSR (Molten salt reactor), and VHTR (Very high temperature reactor). KAERI (Korea Atomic Energy Research Institute) takes part in the development of VHTR and SFR among them. The characteristics of these reactors are a higher operating temperature and neutron fluence than those of the existing reactors. In HANARO, irradiation devices that require high-temperature and relatively low fluence are recently being developed to meet the irradiation needs.

2. Irradiation test holes in HAHARO

Fission chain reactions in the HANARO core produce fast neutrons. They slow down to epithermal neutrons and then to thermal neutrons by colliding with a moderator. Among fast, epithermal, and thermal neutrons, each area of HANARO utilization usually uses one of them. While the fast neutron flux is high in the core, the epithermal neutron flux is high at near the boundary of the core, and the quality of thermal neutron flux is high at the reflector rather far from the core. HANARO is a typical multipurpose research reactor using all three kinds of neutrons. Though it cannot be equivalent to a reactor using only one or two kinds of neutrons, HANARO provides most areas of its utilization capabilities for global competition.

In HANARO, there are 32 vertical and 7 horizontal test holes. The vertical test holes are used for irradiation tests. The horizontal holes are all embedded in the reflector area, which are used for neutron scattering. Among the 32 vertical holes, 3 are located in the inner core, 4 in the outer core, and 25 in the reflector tank. The CT, IR1, and IR2 holes are used for the material irradiation test using a high flux neutron and the fuel irradiation test requiring a high output density. The 4 OR holes are used for RI production and fuel burn-up test as they have a high thermal/epi-thermal neutron flux. There are various test holes in the reflector area, which are used in applied fields using thermal neutrons. Among them, 17 IP holes, and LH and HTS holes, are used for RI production, and 3 NAA holes for neutron activation analysis using a pneumatic transfer system. 2 NTD holes are used for Si doping for semi-conductor production. The important irradiation holes are listed in Table 1.

Table 1. Important irradiation holes

Location	Hole		Dia. (cm)	Neutron Flux(n/cm^2 sec)		Use
	Name	No.		Fast (>0.82MeV)	Thermal (<0.625eV)	
Core	CT	1	7.44	2.10×10^{14}	4.39×10^{14}	Irradiation
	IR	2	7.44	1.95×10^{14}	3.93×10^{14}	Irradiation
	OR	4	6.00	2.23×10^{13}	3.36×10^{14}	RI production
Reflector	NAA	3	6.0	1.34×10^{12}	1.62×10^{14}	NAA
				6.33×10^{9}	3.63×10^{13}	
	IP	17	6.0	1.51×10^{12}	2.44×10^{13}	RI production
				2.2610^{12}	1.99×10^{14}	

3. Development of the capsule for irradiation at high temperature

A high-temperature irradiation capsule has been developed as one with a concept of double thermal media, as shown in Fig 1. Because the Al thermal media used in the standard capsule might be melted at high temperature, Ti was used as the inner thermal media around the specimen, and Al had been used as the outer thermal media. The high-temperature irradiation capsule in HANARO has been developed in 3 steps. The first step was to irradiate specimens at the middle high temperature of 600℃ to investigate the integrity of the capsule components. The second step was to raise the temperatures of the specimens to around 700℃ and irradiate to investigate the integrity of the thermal media, thermocouples, and heaters. In the third step, the capsule will be irradiated at 1,000℃ and the temperatures of the thermal media will be calculated to evaluate the soundness of the components and instruments.

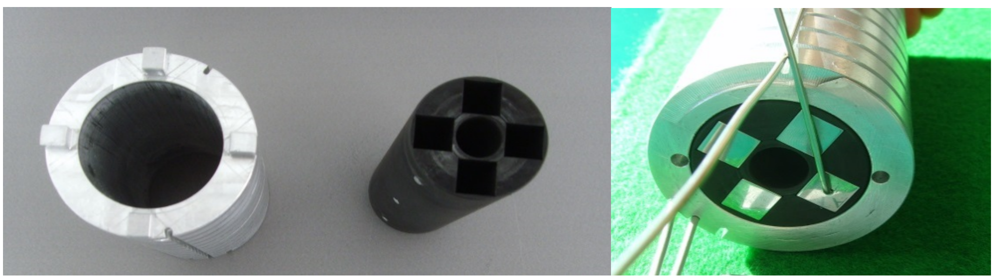

Fig. 1. Structure of double thermal media

a) Irradiation of capsule for high-temperature(<700℃) irradiation

This capsule was designed and fabricated for irradiation at a temperature of around 700℃. In fabricating the holder of the specimen, the concept of a double thermal media was introduced. It uses Al as the outer thermal media, and other materials durable at high temperature as inner thermal media. Various materials such as Ti, graphite, Mo, or Ni for the inner material were used as the inner thermal media. They were tested for investigating the performance of the processing and welding at a manufacturing shop before irradiation, and then irradiated for 60 days at HANARO. Mo is very hard, and thus the processing is difficult during fabricating. Ni has a high ability of neutron absorption, Fe is easily rusty at high temperature, and graphite has a good thermal conductivity. Ti and Zr have a good performance for use as thermal media, but the processing is difficult. In the capsule for irradiation around 700℃, Ti and graphite were used as the inner thermal media, and Al was used as the outer thermal media. Ti is lower in density and price when compared with other materials such as Zr, Nb, Mo, etc., but the absorption cross-section of thermal neutron is relatively high. Graphite was selected as a candidate material because the mechanical properties are excellent at high temperature and thus used as the in-core material in a VHTR.

The temperatures of the specimen and outer thermal media in the irradiation tests performed twice previously are listed in Table 2. When the temperature of the specimen is to be 700℃, the temperature of the outer thermal media was lower than 550℃, and thus there is not much possibility of melting.

Table 2. Comparison of the specimen temperatures between the measurement and analysis

Stage	From fuel center (cm)	Gap size (mm)	No heater power at 101kPa		Error (%)
			Calculation	Measured	
1	22.45	0.36	413	355	16.3
2	10.05	0.16	435	431	0.9
3	0.5	0.19	549	521	5.4
4	-14.75	0.17	691	553	24.9
5	-27.15	0.18	500	458	9.2

Error=(Calculated-Measured)/Measured x 100(%)

In comparison with the calculated and measured temperatures of the specimens, there was no difference at stage 2, and little at stages 3 and 5. However, the differences are bigger at stages 1 and 4. In particular, the measured temperature at stage 4 is about 25% lower than the calculated value. The temperatures in the calculation generally come out higher than the measured values. It is inferred from the facts that in the calculation, the maximum value is given, and the radiation heat transfer is not considered, and the adiabatic condition at the top and bottom is applied in a 2-dimensional analysis. It also seemed to result from the wrong estimation of the neutron flux and gamma heat generation.

b) Design of a capsule for high-temperature(<1,000℃) irradiation

When the inner thermal media is Ti, and the outer is Al in the design of the double thermal media capsule, the analysis of the temperatures when the temperature of specimen rises to 1,000℃ is important to evaluate the integrity of the components during irradiation. The temperature of the outer thermal media was calculated and reviewed to determine whether the material Al would be melted. The calculation model was as shown in Fig. 2, which is same as the 11M-22K capsule irradiated previously. The gap between the holder and specimen is 0.1mm, and between the inner and outer thermal media that is 0.2mm, between the outer thermal media and outer tube the gap is changed, which was effectively designed to control the temperature of each stage. All gaps were filled with He gas.

Nuclear data were analyzed at the condition of the HANARO equilibrium core, I.e., 30 MW and 450 mm of the control rod position. The candidate materials instead of Al, Fe, and Ni were selected to evaluate the integrity at high temperature. The reactivity was calculated to be +1.0–9.6 mk .The irradiation test was proved to be safe as it is less than +12.5 mk of the limit value required in HANARO [2]. The neutron flux was reduced by a relatively large absorption cross section of Ti; however, the fast neutron flux is not affected by the kinds of thermal media. The heating rates are different according to the materials of the thermal media. The heating rates at stage 3 are shown in Table 3.

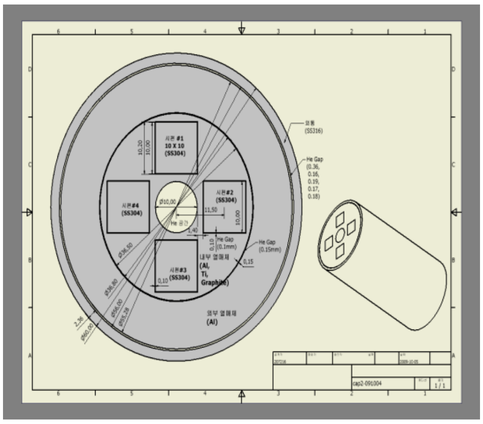

Fig. 2. Calculation model

Table 3. Heating rate of various materials

Thermal Media In/out	Heating rate(W/g)			
	Specimen SS304	Inner holder(Ti)	Outer holder Al/Fe/Ni	Outer tube SS316
Ti/Al	6.4	6.2	5.5	6.0
Ti/Fe	5.4	5.1	5.4	5.6
Ti/Ni	5.1	4.9	5.8	5.6

ANSYS program [3] was used for a thermal analysis. The two-dimensional model for the specimen section was generated. The temperature of the cooling water in the reactor in-core is about 33 ℃ and the heat transfer coefficient at the outer surface of the external tube is 30.3 x 10^3 W/m^2℃, which was experimentally determined [4]. The gap was selected such that the specimen temperature become 1,000℃ when the He pressure is 0.6$K_{He, 1atm}$. The results of the temperature calculation for Ti/Al thermal media are shown in Fig. 3. In the case of Ti/Al thermal media, the temperature of outer thermal media becomes around 633℃, at which Al might melt. Table 4 shows the temperatures for various thermal media. According to the result, Al should not be used as thermal media in a high-temperature irradiation capsule. Instead, Fe or Ni are recommended as the outer thermal media when a capsule will be utilized for irradiation at up to 1,000℃.

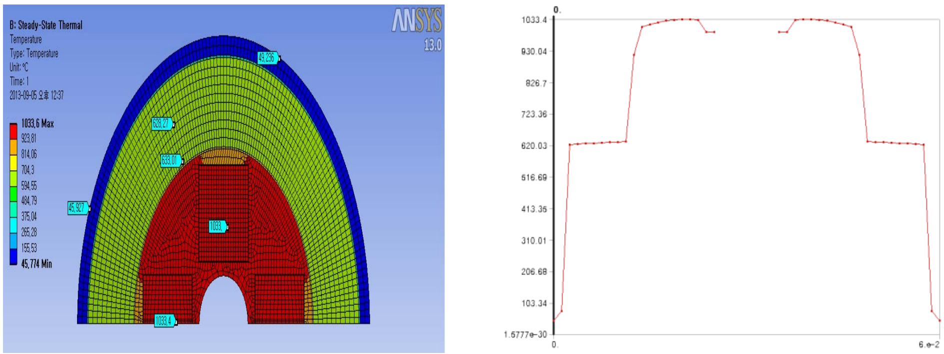

Fig. 3. Temperature calculation for Ti/Al thermal media

Table 4. Temperatures of outer thermal media when specimen reaches 1,000℃

Thermal Media In/out	Outer gap (mm)	$0.6K_{He,\ 1atm}$	
		specimen	outer thermal media
Ti/Al	0.25	1,033	633
Ti/Fe	0.16	1,019	654
Ti/Ni	0.13	1,021	704

4. Conclusions

As future nuclear systems such as SFR and VHTR are to be operated at high temperatures, the performance of the materials to be used should be verified through the irradiation tests at high temperatures. In accordance with this requirement, a capsule suitable for an irradiation test at high temperatures was being developed to overcome a restriction on the use of aluminum at high temperature. The new capsule with the thermal media of double structure, the inner material of which is Ti, and the outer materials are Fe and Ni, is being designed and fabricated for irradiation at high temperature. This capsule will be applied to irradiation tests at up to 1,000 ℃.

Acknowledgements

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIP)

5. References

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