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Design Analysis of the Capsule for Irradiation of High-temperature Materials to be used in the Future Nuclear System

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1. Introduction

As the reactors used in the future nuclear system will be operated at high temperature and high neutron flux, the requirements for irradiation of materials at high temperature are gradually increasing. Up to the present, the irradiation tests of the materials in HANARO have usually been performed at temperatures below 300℃, at which the reactor materials of nuclear power plants are operated. To overcome the restrictions for the high-temperature use of Al thermal media of the existing standard capsule, a new capsule with double thermal media composed of two kinds of materials, Al-Ti and Al-graphite, was designed and fabricated as a more advanced capsule than a single thermal media capsule. The irradiation temperatures and fluence of the specimens were in the range of 700-900℃ and 2.0×10^{21} (n/cm^2) (E>0.821 MeV) [1]. The temperatures of the specimens for reactor powers of 30MW were measured by thermocouples to verify the irradiation test results.

2. Design of Capsule

Fig. 1 shows the geometrical shape of the irradiation capsule, which consists of a bottom guide structure, main body, protection tube, and the guide tube. The main body is a major part of the capsule in which specimens, measuring devices and various components are installed, and it includes an external tube of a cylindrical shell 60 mm in external diameter, 2.0 mm in thickness, and 870 mm in length. The inner structure has a specimen holder composed of two kinds of materials, the outer one of which is aluminum and the inner one contains material such as graphite and Ti.

Fig. 1. Instrumented capsule for the material irradiation test

This capsule is made in 5 stages inside, each of which has a double cylinder structure. The materials are graphite/Al at stage 1 and Ti/Al at stage 2 to 5, respectively. The inner structure of the capsule is a 4-hole scattered type, as shown in Fig. 2. The specimens are all made of alloy 690 with a size of 9.8 x 9.8 x 114 mm, and a gap of 0.1 mm between the specimen hole and specimen. The specimen holder is a cylinder with four rectangular specimen holes and one circular center hole of 10 mm in diameter.

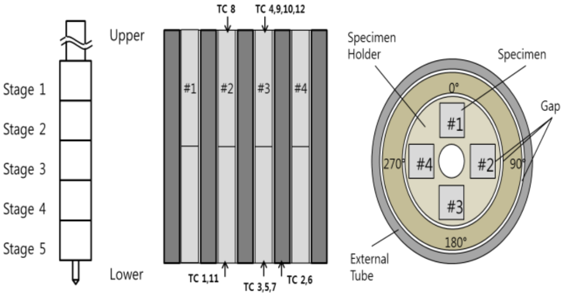

Fig. 2. Schematic view of the specimen arrangement and thermo-couple positions

Table 2 presents the gap size between the holder and external tube and the gamma-heating rate of each material at the thermocouple positions.

Table 2. The gap and gamma heating rate

	Thermal	Gap	Gamma heating rate (W/g)		
			Specimen (Alloy 690)	Thermal Media	
1	Graphite /Al	0.45	3.0	3.2	2.7
2	Ti/Al	0.25	5.0	5.1	4.2
3	Ti/Al	0.11	6.0	6.4	5.3
4	Ti/Al	0.15	6.0	5.8	5.2
5	Ti/Al	0.20	4.0	4.0	3.5

For thermal analysis, the calculation model is generated using a finite element analysis program. In addition, this model consists of four main parts: specimen (Alloy 690), helium gap, specimen holder - inner (Ti or graphite) and outer (Al 1050), and external tube (STS 316L). The analysis aims to find the suitable gap by calculating temperatures corresponding to the reactor power. The target temperatures are finally reached by controlling the internal helium pressure and the power of the micro-heater. Also, since the space for the helium gap in the capsule is small, only the heat conduction can be considered as a heat transmission, thus ignoring the convection and radiation in the gap space [2].

3. Results and Discussion

The irradiation test was conducted between 700 and 900°C for 58 days, which corresponds to the 2-cycle operation of HANARO. Fig. 3 presents the measured temperatures of specimen in accordance with the reactor power. Two thermocouples of TC 2 and TC 6 were placed in the outer holder to check the temperature of Al when the specimens reach a high temperature during irradiation. These results were obtained at zero heater power, and helium pressure of 760torr before the reactor reaches the normal operation. The target temperatures were reached later by adjusting the helium pressure inside the capsule, and the micro-heater output.

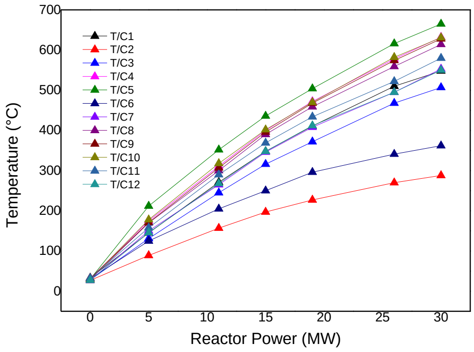

Fig. 3. Measured temperatures at heater off with the reactor power

Fig. 4 shows the effect of the helium pressure on the temperature of specimen. According to reduction of the helium pressure, the temperature increases because the thermal conductivity of the helium gas becomes smaller and interferes with the outward heat flow to the radial direction. Also, the influence of the pressure on the temperature at a high vacuum pressure is greater than that at a low vacuum pressure. Actually, the variation of the temperature in the pressure ranges of 760 to100 torr is within 30 °C, but for the degree of a vacuum below 100 torr, the temperature is rapidly increased by about 100 °C when it reduces to 20 torr.

Table 3 shows the measured and calculated temperature of the specimens at 30 MW. The temperatures of the specimen by the irradiation test are in the range from a minimum of 592 °C to a maximum of 665 °C. For the specimens of each stage, the temperatures between the top and bottom of the specimen are within a temperature difference of 10 °C. For the specimens located at the same level in the axial direction and the 90°-shifted position in the circumferential direction (for example, TC1 and TC3 of Stage1), the temperature is distributed homogeneous within 5°C in the analysis, which occurs because the CT hole is located at the center of symmetry for the fuels distributed at the reactor core.

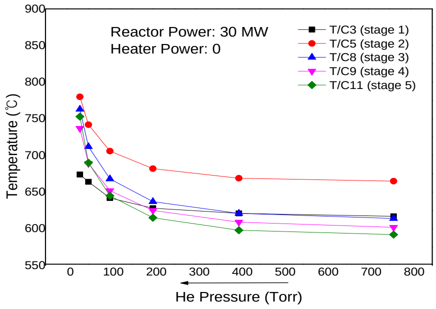

Fig. 4. Temperature of the specimen with the helium pressure

From the above test results, it was found that the specimens have similar temperature environments before starting the temperature control of the capsule specimen to reach the target temperature by using the helium gas pressure and the micro-heater power.

Table 3. Comparison of the specimen temperatures between measurement and calculation

	T/C	Measured (°C)	Calculated (°C)	Error*
1	TC3	617	590	4.4
2	TC5	665	712	-7.1
3	TC8	614	639	-4.1
4	TC9	602	632	-4.9
5	TC11	592	621	-3.2

3. Conclusions

For a HANARO power of 30 MW, the measured temperatures of the specimens without any adjustment of the He pressure and micro heater were in the range of 592 to 665 °C. The temperatures of the specimens between the top and bottom at the same hole show a difference of less than 10 °C. The analysis results for temperatures of specimen in Ti-Al holder show a slightly higher temperature than the measured value whereas that in graphite-Al holder indicates a slightly lower temperature than the measured value. Nonetheless, the temperatures between measurement and analysis show a good agreement of within 7 %, and thus the reliability of the 2-D finite element model for a thermal analysis of the capsule could be confirmed.

Acknowledgements

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