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Temperature evaluation of an instrumented capsule after material irradiation tests in HANARO

M.H. Choi *, K.N. Choo, H.R. Kim, B.G. Kim

Korea Atomic Energy Research Institute, Deokjin-dong 150, Yuseong-gu, Daejeon 305-353, Republic of Korea

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Abstract

An instrumented capsule has been used for an irradiation test of various nuclear materials in the research reactor, HANARO. The capsule is designed to have a standard 4-hole structure for the economical test of an RPV material at 290 ± 10 °C. The temperature of the specimens for the reactor powers, 0–24 MW, is measured by 12 thermocouples, and finite element (FE) analyses are also performed to compare and verify the irradiation test results. As a result of the tests and analyses, the maximum temperature at the reactor power of 24 MW is 256 °C for an irradiation test and 202.6 °C for an FE analysis at Stage 3 of the capsule. Also, for each stage of the capsule, the temperature difference of the specimen in the axial direction is very small to within 10 °C. It is expected that the results presented in this paper will be useful when designing the instrumented capsules for an irradiation test.

1. Introduction

The national research and development program on nuclear reactors and the nuclear fuel cycle technology requires numerous in-pile tests in a high-flux advanced neutron application reactor (HANARO) in Korea. Extensive efforts have been made to establish the design and manufacturing technology for irradiation facilities. Since HANARO is one of the most powerful multipurpose research reactors in the world, this reactor provides a variety of irradiation facilities that benefit from the exceptionally high neutron flux which is available from the reactor. The main activities of the capsule development and utilization programs are focused on the in-reactor material tests, new and advanced fuel research and development, safety-related research and development for nuclear reactor materials and components, and basic research [1]. At present, capsules have been developed and are being utilized for the irradiation tests of materials and nuclear fuels in HANARO [2–4].

The instrumented capsule for material irradiation tests has an especially important role in the integrity evaluation of reactor core materials and the development of new materials through precise irradiation tests of specimens such as the RPV (reactor pressure vessel), reactor core, pressure tube and fuel cladding materials. The material capsule called 02M–02K was designed and manufactured to evaluate the fracture toughness of irradiated RPV materials in 2002. The capsule was irradiated in the CT test hole

* Corresponding author. Tel.: +82 42 868 8531; fax: +82 42 863 6521.
E-mail address: cmh2002@orgio.net (M.H. Choi).

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of HANARO at a 24 MW thermal output at 290 ± 10 °C up to a fast neutron fluence of 0.64×10^{20} n/cm^2 ($E > 1.0$ MeV) for about 6 days in 2003 [5].

A comparison of the measured temperatures from the irradiation tests and the analyses is necessary to verify the design data and to estimate the reliability of the finite element model. Thus, in this study the temperature evaluation of the 02M–02K capsule after the irradiation test and the thermal analysis by using the ANSYS program [6] is conducted. The two-dimensional (2D) model for the specimen section with the thermocouple and the three-dimensional (3D) model for the capsule region including one holder are generated. The gamma heating rate of the materials due to the gamma flux in the reactor core is used as the body force to calculate the temperature in the FE thermal analysis. The analysis results are compared with those of the irradiation tests, and the reliability of the FE model is verified by a comparison of the results between the two methods. The influence of the helium pressure and the reactor power on the specimen's temperature is also described.

2. Capsule model

Fig. 1 shows the geometrical shape of the instrumented capsule for the material irradiation tests which consists of the bottom guide structure, the mainbody, the protection tube and the guide tube etc. The rod tip of the bottom guide structure is assembled with a receptacle in the reactor core, and the protection and guide tubes play the part of a guide for various lines such as the thermocouples, micro-heaters and helium supply tubes up to the control unit system on the outside of the reactor. The mainbody 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 with 60 mm in external diameter, 2.0 mm in thickness and 870 mm in length. Table 1 represents the geometrical data of a cross section including the specimens. The specimen's dimensions for the rectangular shape are $10 \times 10 \times 114$ mm, and the centers of the specimen holes are located at an equal distance, 15 mm from the center of the holder.

Table 1
Geometrical data for the cross section of the capsule

Descriptions	Dimension (mm)
Outer diameter of the external tube	60
Inner diameter of the external tube	56
Center hole diameter of the holder	12
Specimen size (width × height × length)	10 × 10 × 114
Distance between the center hole and the specimen hole	15

The specimen holder is a cylinder with four rectangular specimen holes, one circular center hole of 12 mm in diameter, and a length of 114 mm. The five holders in the mainbody are arranged in the axial direction, and the insulators, made of alumina between the holders, are placed to prevent the heat from transferring between the stages and to control the temperature of each stage independently. Fig. 2 shows a schematic view of the holder and its section including the thermocouple positions. A total of 12 thermocouples are used (three for Stages 1 and 3, and two for Stages 2, 4 and 5), and they are installed on the top and bottom edges of the specimen

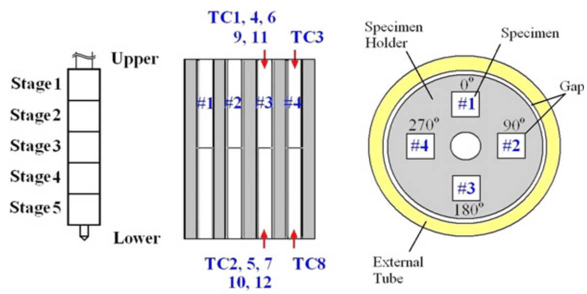


Fig. 2. Schematic view of the specimen arrangement and thermocouple positions.

Fig. 1. Instrumented capsule for the material irradiation tests.

Table 2
Gap size and gamma heating rate for the 2D analysis of the material capsule

Stage	Thermocouple	Y-Coor. (cm)	Gap size (mm)	Gamma heating rate (W/g)		
				Specimen (SA 508)	Holder (Aluminum)	Tube (STS 316L)
1	TC1 (top)	27.45	0.33	1.9	1.76	1.91
	TC2 (bot)	17.45	0.19	2.9	2.64	3.04
2	TC4 (top)	15.05	0.175	3.16	2.85	3.23
	TC5 (bot)	5.05	0.115	4.19	3.78	4.25
3	TC6 (top)	2.65	0.12	4.42	3.96	4.47
	TC7 (bot)	−7.35	0.11	4.80	4.29	4.86
4	TC9 (top)	−9.75	0.105	4.78	4.32	4.90
	TC10 (bot)	−19.75	0.125	4.29	3.88	3.37
5	TC11 (top)	−22.15	0.13	4.11	3.70	4.15
	TC12 (bot)	−32.15	0.23	2.70	2.50	2.72

inserted in hole #3 and/or #4. The gap between the holder and the specimens is designed to be 0.1 mm, and that between the holder and the tube is 0.105–0.33 mm, which is designed to effectively control the temperature of each stage. Table 2 presents the gap size between the holder and the external tube and the gamma-heating rate of each material at the thermocouple positions.

3. Thermal analysis

For the thermal analysis, two FE models are generated using the ANSYS finite element analysis program. One is the two-dimensional model of a quarter section with two specimens and one center hole as shown in Fig. 3, and the model is generated by using a PLANE223 element which has a structural-thermal capability of 2D eight nodes. Also this model consists of four main parts: the specimens (SA508), the helium gaps, the thermal media (Al1050) and the external tube (STS 316L). Another is the three-dimensional model to obtain the temperature distribution for the axial direction of the capsule. For the capsule region with a length of 114 mm, an eighth sectional model in the circumferential direction is generated. Fig. 4 shows the 3D model using a SOLID226 element with three different gap sizes in the axial direction. In the FE analysis model the micro heaters for controlling the temperature of the specimens are neglected. Also since the space for the helium gap in the capsule is small and the temperature is relatively low, only heat conduction is considered for heat transmission, thus ignoring a convection and radiation in the gap [7].

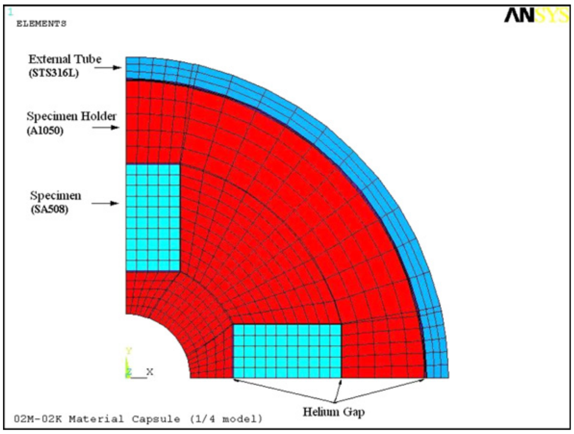


Fig. 3. Two-dimensional model of the material capsule.

The temperature of the cooling water in the reactor in-core is about 40 °C, and the heat transfer coefficient at the outer surface of the external tube is 30.3×10^3 W/m^2 °C, which is experimentally determined [8]. The two conditions above are boundary conditions in the FE analysis, and adiabatic conditions are applied for the symmetric axes of the 2D and 3D models. In the reactor in-core, all the materials of the capsule work as a heat source due to a gamma ray irradiation, which is a function of the axial position. Generally, it is known that the gamma flux in the middle of the reactor core has the highest value [9]. The gamma-heating rates of the 02M–02K capsule materials used as an input force in the thermal analysis are listed in Table 2 [10].

4. Results and discussion

The irradiation test for the 02M–02K capsule was conducted at 290 ± 10 °C for six days. The target temperature was controlled by using a

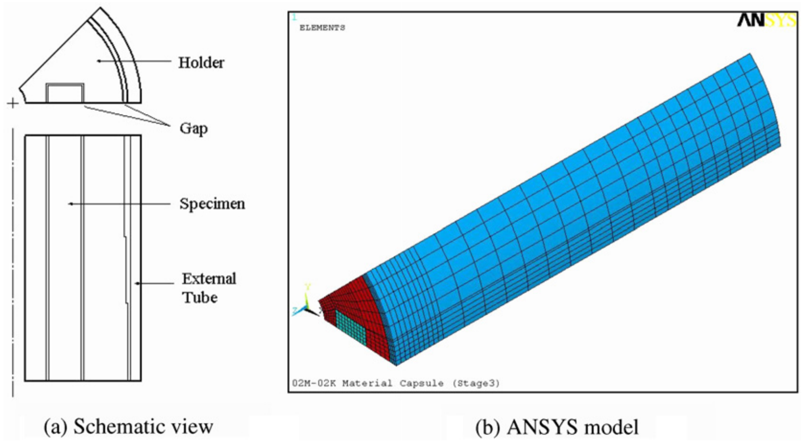


Fig. 4. Three-dimensional model of the material capsule.

micro-heater and helium pressure. However there are many difficulties when conducting a comparison of the results between the irradiation test and the FE analysis with the condition of a controlled temperature. Thus it is necessary to obtain the irradiation test results before activating temperature control. Fig. 5 presents the measured temperature of the specimens with the reactor power using the 12 thermocouples. These results were obtained at the control rod position from 410 to 430 mm, a zero heater power, and a helium pressure of 101 kPa.

Fig. 6 shows the influence of the helium pressure on the temperature of the specimen at the reactor power of 10 MW and at the control rod position of 420 mm. According to the decrement of the helium pressure, the temperature increases because the thermal conductivity of the helium gas becomes small. Also the influence of the pressure on the temperature at a low pressure is greater than that at a high pressure. The variation of the temperature in the pressure ranges of 101–14 kPa is within 15 °C, but below 14 kPa the temperature is rapidly increased by about 30–60 °C. Temperature TC6 is higher than the other measured temperatures because it is located in the axial midplane where gamma heating is peaked.

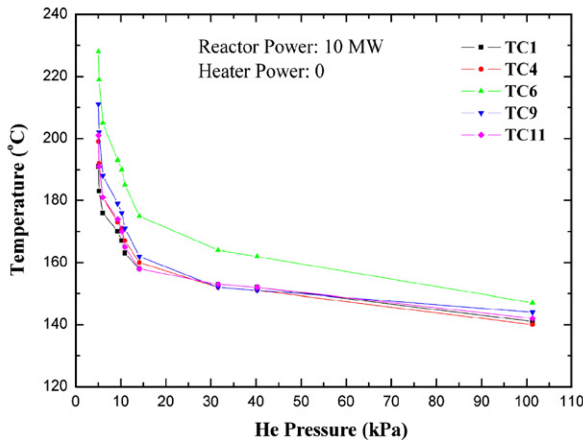


Fig. 6. Temperature of the specimen's top part with the helium pressure.

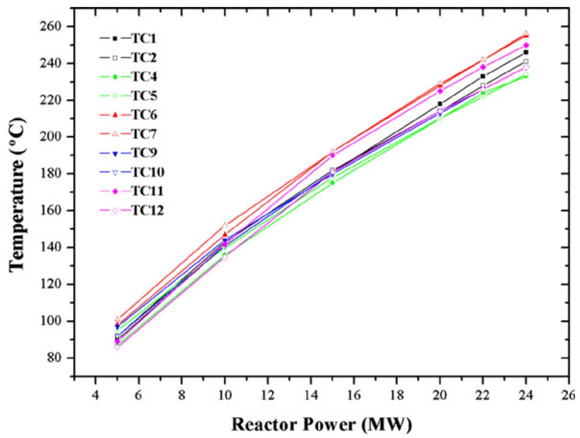


Fig. 5. Measured temperature of the specimen with the reactor power.

Table 3 presents the measured and calculated temperature of the capsule specimens at a 24 MW HANARO power. The temperature of the specimen by the irradiation tests is in the range from a minimum of 233 °C to a maximum of 256 °C. For the specimens of each stage, the temperature between the top and the bottom of the specimen is nearly the same, except for the specimen of Stage 5 with

Table 3
Comparison of the specimen temperature between the test and the analysis at a 24 MW power

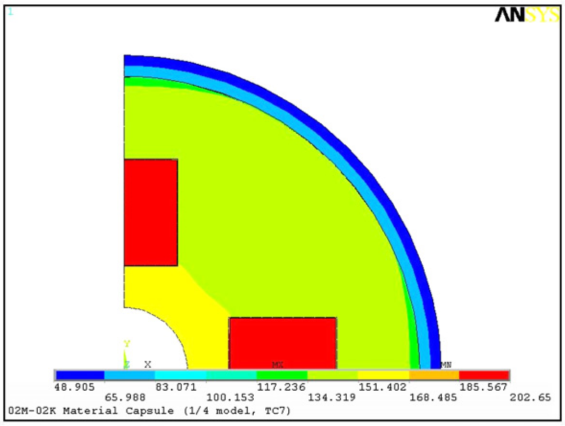
Stage	Thermocouple	Measured	Calculated (ANSYS)	Error[a]
1	TC1 (top)	246	196.8	−20.0
	TC2 (bot)	241	190.0	−21.2
	TC3 (top)	236	(196.8)	−16.6
2	TC4 (top)	233	191.5	−17.8
	TC5 (bot)	234	190.8	−18.5
3	TC6 (top)	255	199.2	−21.9
	TC7 (bot)	256	202.6	−20.8
	TC8 (bot)	245	(202.6)	−17.3
4	TC9 (top)	238	199.6	−16.1
	TC10 (bot)	238	199.1	−16.3
5	TC11 (top)	250	197.0	−21.2
	TC12 (bot)	238	199.8	−16.1

[a] Error = (Calculated − Measured)/Measured × 100(%).

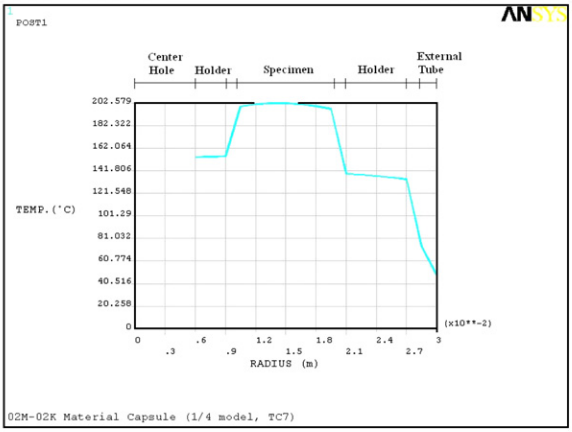
a temperature difference of 12 °C. For the specimens located at the same level in the axial direction and the 90°-shifted position in the circumferential direction (for example, TC1 and TC3 of Stage 1), the temperature difference regarding the position is shown as about 10 °C for Stages 1 and 3. From the above test results, it is found that the specimens have similar temperature environments before starting temperature control of the capsule specimen by using the helium gas pressure and the micro-heater power.

The calculated specimen temperatures show lower values with an average of 19% than those of the irradiation test, and the maximum temperature is 202.6 °C at the TC7 position which is similar to the measured one. Generally it is known that the FE analysis presents a higher result than the test because it has the upper bounded one. However, in this study the calculated temperatures are on a whole low, and we think the reason is the neglect of a groove to install the micro-heater of 2 mm in diameter and 1.5 m in length. That is, the specimen holders of the capsule have a groove which is filled with the helium gas and the heater at the outer surface. In the FE model this groove is not considered, and the temperature of the capsule should be decreased due to the neglect of a groove, although the effect can not be estimated exactly.

The temperature distribution for each model of the capsule has a similar trend because of the same arrangement of the components at each stage. Fig. 7(a) shows the temperature distribution for the TC7 position of Stage 3, and (b) presents that in the radial direction at the $\theta = 0$ position. The



(a) Temperature distribution



(b) Temperature profile in the radial direction

Fig. 7. Temperature of the capsule at the TC7 position of Stage 3.

maximum is 202.6 °C at the rectangular specimen because this region has the highest gamma heating rate, and the temperature of the thermal media is varied in the range of 134–155 °C. Also the temperature is rapidly decreased at the gap. Especially, the gap between the holder and the external tube is larger than that between the specimen and the holder, and it has an important influence on the control of the temperature of the specimen when using the helium pressure.

The comparison of the specimen's temperature with the reactor power between the test and the analysis is shown in Fig. 8. The measured and calculated temperatures with the reactor power show a slightly parabolic increment. These phenomena are because the temperature depends on the reactor power and the change of the gap size between the components. The temperature increment of the

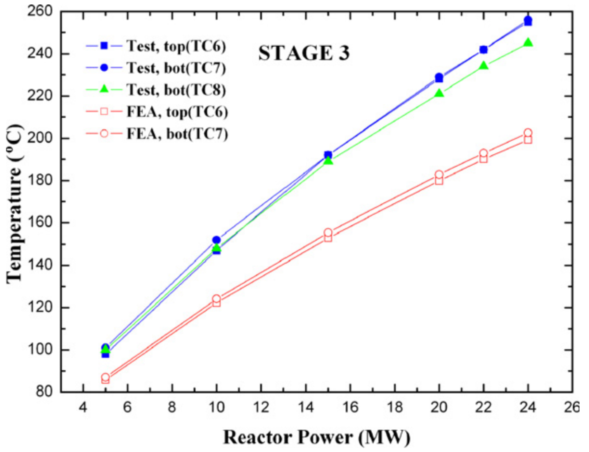


Fig. 8. Comparison of the measured and calculated temperatures at Stage 3 with the reactor power.

materials by increasing the reactor power induces an expansion of the specimen holder having a relatively large thermal expansion coefficient, and the gap size is decreased due to the expansion. Finally, the decreased gap size causes the temperature of the specimen to decrease. The test results for three TC positions in Fig. 8 have small deviations at below 12 °C with the reactor power including the experimental uncertainty and the difference of the measurement positions at Stage 3. The FE results are lower than those of the test for all the powers. However, the temperature increment with the power has exactly the same tendency as each other. Thus we are sure the 2 D FE model simulates the test results well and it is reasonable for a thermal analysis of the capsule, although the results between the two methods show an average difference 19%.

Fig. 9 shows the temperature distribution of the specimen and the capsule of Stage 3 when using a 3D model. Similar to the results using a 2D model, the highest temperature occurs at the specimen, and the temperature of the thermal media is distributed in the range from 140 to 160 °C. Fig. 9(c) shows the detailed temperature distribution of the specimen. The maximum and minimum values are 209 °C at the middle of the specimen center and 196 °C at the corner, which can increase the heat transfer due to the decreased gap size. In this case the temperature of the top (TC6) and the bottom (TC7) along the center of the specimen in the axial direction is 206 °C and 209 °C, respectively. These values vary with the gap sizes and the gamma heating rates, but the temperature difference in the specimen is very small.

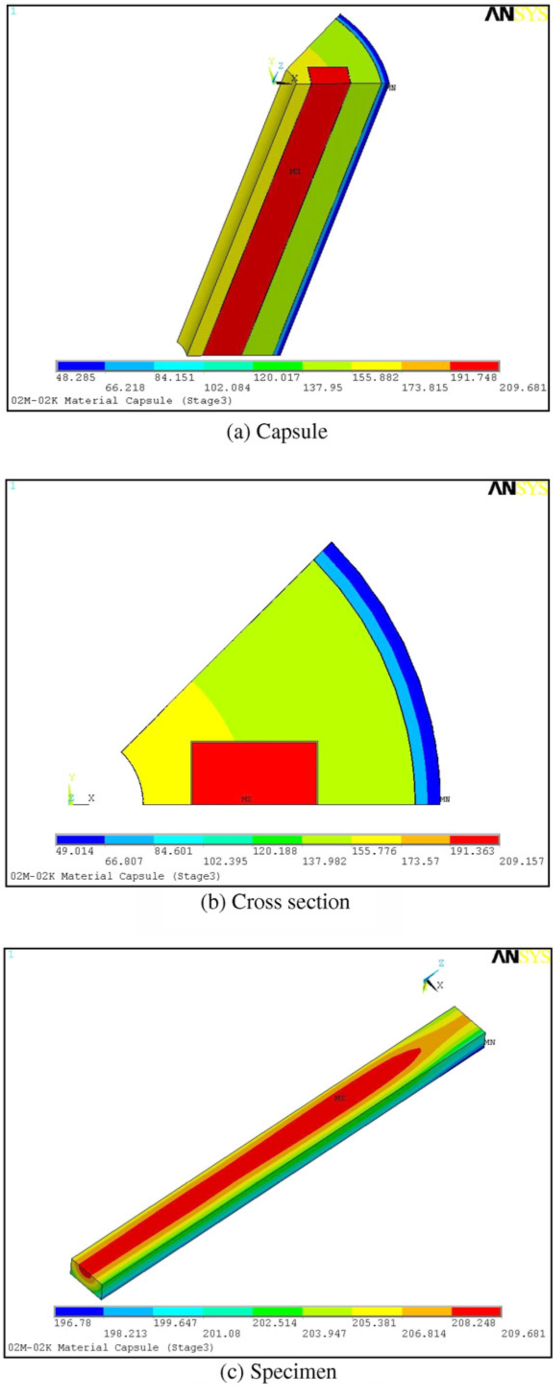


Fig. 9. Temperature distribution of the capsule and specimen at Stage 3.

The 3D analysis results agreed with the 2D results to within 10 °C for the section with a thermocouple. For 5, the temperature difference between the top and the bottom of the specimen occurs at 10 °C, but the other stages show a lower difference than 7 °C. It is found that the FE model using the 2D and the 3D elements shows nearly the same temperature thus a reliability of the FE analysis results. If we consider many uncertainties can occur in the process of the FE analysis and the irradiation test, the analysis model simulates the measured temperature well. Also, from these results we can confirm that the specimens of the 02M–02K material capsule are irradiated in a similar environment without a large variation of the temperature in the axial and radial directions.

5. Conclusions

(1) For the HANARO power of 24 MW, the measured temperature of the specimens for the five stages is in the range of 233–256 °C, and the maximum difference of the temperature between the top and the bottom of the specimen is 12 °C at Stage 5. The temperature of the specimens located at the same level in the axial direction shows a difference of about 10 °C.
(2) The calculated and measured temperatures with the reactor power show a slightly parabolic increment because of a change of the gap size, which depends on a thermal expansion of the capsule material with the temperature.
(3) The FE model using the 2D and the 3D elements has nearly the same temperature, showing a difference to within 10 °C at the section with a thermocouple.
(4) The analysis results at a 24 MW power show lower temperatures with an average of 19% than the measured ones. These discrepancies are because the groove placed at the outer surface of the holder to install the micro-heater is neglected in the FE model.

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