18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18)
Beijing, China, August 7-12, 2005
SMiRT18-J10-5

TEMPERATURE EVALUATION OF AN INSTRUMENTED CAPSULE AFTER IRRADIATION TESTS IN HANARO

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ABSTRACT

An instrumented capsule has been used for an irradiation test of various nuclear materials in the research reactor, hi-flux advanced neutron application reactor (HANARO). The capsule is designed to have a standard 4-hole structure for the economical test of a reactor pressure vessel material at 290±10°C, and composed of 5 stages having various rectangular specimens such as Charpy, hardness, small punch, small tensile, TEM and PCVN etc.. During the irradiation test, the temperature of the specimens for the reactor powers, 0~24MW is measured by 12 thermocouples installed in the capsule. To compare and verify the irradiation test results, the 2D and 3D finite element (FE) analyses are performed using the FE analysis program, ANSYS, and the temperature of the specimens inserted in the capsule's mainbody by a γ-flux is calculated for the sectional area of the stage containing the specimen. As a result of the test and analysis, the maximum temperature on the reactor power of 24MW is 255 °C for an irradiation test and 258 °C for a FE analysis at stage3 of the capsule. Also for the arbitrary stage, the temperature difference of the specimen in the axial direction is very small within 10 °C. It is expected that the results presented in this paper will be useful in designing the instrumented capsules for an irradiation test.

Keywords: Instrumented Capsule, Irradiation Test, Temperature, HANARO.

1. INTRODUCTION

The national research and development program on nuclear reactors and nuclear fuel cycle technology requires numerous in-pile tests in HANARO. Extensive efforts have been made to establish design and manufacturing technology for irradiation facilities. Since HANARO is one of the world's most powerful multipurpose research reactors, this reactor provides a variety of irradiation tests that benefit from the exceptionally high neutron flux available. The main activities of the capsule development and utilization programs are focused on 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. Now, capsules have been developed and they are being utilized for the irradiation test of materials and nuclear fuel in HANARO (Kang, 2003).

Especially, the instrumented capsule for material irradiation tests has an important role in the integrity evaluation of reactor core materials and the development of new materials through the precise irradiation tests of specimens such as RPV, reactor core, pressure tube, fuel cladding and high-technology materials. The material capsule called 02M-02K was designed and manufactured to evaluate the fracture toughness of the irradiated RPV materials in 2003. The capsule was irradiated in the CT test hole 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>1.0MeV) for about 6 days (Choo, 2003).

As a part of the analysis for the irradiation test results, a comparison of the temperatures by the irradiation test and the analysis is necessary to verify the design data and to estimate the reliability of the model using a finite element analysis program. Thus, in this study the temperature evaluation of the 02M-02K capsule after the irradiation tests and the thermal analysis by using the ANSYS program (ANSYS, 2005) is conducted. The two-dimensional (2D) model for the specimen section with the thermocouple and the three-dimensional (3D) model for an arbitrary one stage 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 trend of the temperature distribution with the reactor power is also analyzed.

2. CAPSULE MODEL

Fig. 1 shows the geometrical shape of the instrumented capsule for the material irradiation tests which consists of the bottom structure, the mainbody, the protection tube and the guide tube etc.. The rod tip of the bottom structure is assembled with a receptacle in the reactor core, and the protection and guide tube play the guide part role of various lines such as the thermocouples, micro-heaters and helium supply tubes up to the control unit system on the reactor outside. The mainbody is a major part of the capsule in which specimens, measuring devices and various components are installed, and includes the external tube of a cylindrical shell with 60 mm in external diameter, 2.0 mm in thickness and 870 mm in length.

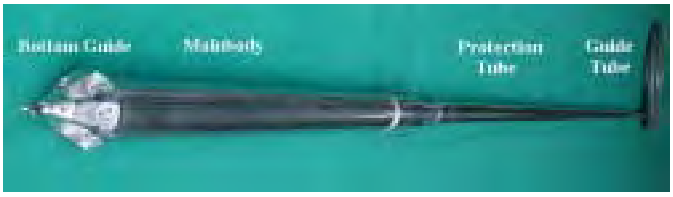


Fig. 1 Instrumented capsule for the material irradiation tests

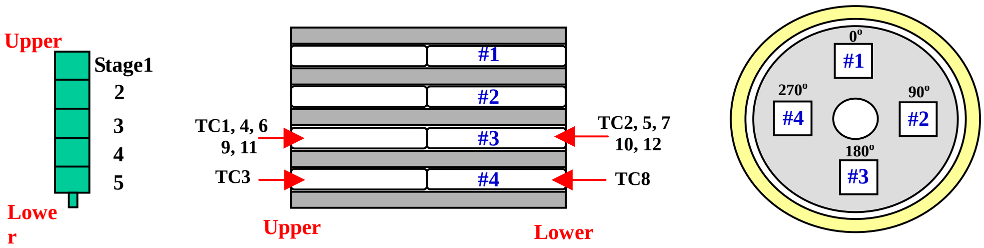


Fig. 2 Schematic view of the specimen arrangement and thermo-couple position

Table 1. Gap size and gamma heating rate for the 2D analysis of 02M-02K capsule

Stage	Thermo-Couple	Y-Coor. (cm)	Gap size (mm)	Gamma heating rate (W/g)		
				Specimen	Holder	Tube
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

The specimen holder is a cylinder with four rectangular specimen holes and one circular center hole. It has a length of 114 mm, and is used for fixing the test specimens. The holder in the mainbody consists of 5 stages 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 the schematic view of the holder and its section for the arbitrary one stage. The number of thermocouples used is a total of 12 (3 for stages 1&3 and 2 for stages 2&4&5) and they are installed on the top and bottom edges of the specimen inserted in hole #3 and/or #4. The gap between the holder and the specimens is designed as 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 1 presents the gap size and the gamma-heating rate of each stage at the thermocouple position.

3. THERMAL ANALYSIS

3.1 Modeling

For the thermal analysis, two FE models are generated using a finite element analysis program, ANSYS. 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 using a PLANE13 element with a two-dimensional thermal capability. Also this model consists of four main parts: specimens (SA508), 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 with the length of 114 mm, an eighth sectional model in the circumferential direction is generated. Fig. 4 shows the 3-D model using a SOLID5 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 helium gap space in the capsule is small, only the heat conduction can be considered as a heat transmission, thus ignoring the convection and the radiation in the gap space (Lee, 2002).

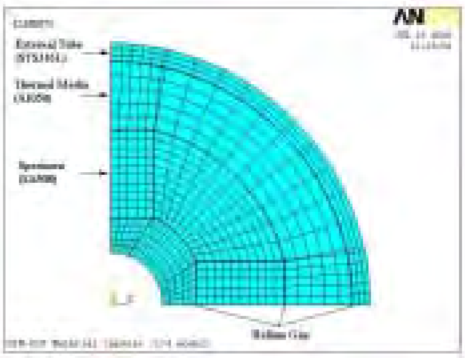


Fig. 3 2-dimensional model of the 02M-02K capsule

(a) Schematic view (b) ANSYS model

Fig. 4 3-dimensional model of the 02M-02K capsule

3.2 Force and Boundary Conditions

The temperature of a cooling water in the reactor in-core is about 40 ^{o}C, and the heat transfer coefficient at the outer surface of the external tube is 30.3×10^{3} W/m^{2} ^{o}C, which is experimentally determined (Lee, 2001). The above two conditions are considered as boundary conditions in the FE analysis, and the symmetric conditions are also applied for the symmetric axes of the 2-D and 3-D models. In the reactor in-core, all the materials of the capsule work as a heat source due to a gamma ray irradiation by varying the axial position.

Generally, it is known that the gamma flux in the middle of the reactor core has the highest value. The gamma-heating rates of the 02M-02K capsule materials used as an input force in the thermal analysis are listed in Table 1.

4. RESULTS AND DISCUSSION

Table 2 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 233 ^{o}C to a maximum 256 ^{o}C. For the specimens of each stage, the temperature between the top and the bottom of the specimen has nearly the same, except for the specimen of stage5 with a temperature difference of 12 ^{o}C. For the specimens located at the same level in the axial direction and the 90^{o}-shifted position in the circumferential direction (For example, TC1 and TC3 of the stage1), the temperature difference with the position shows at about 10 ^{o}C for stage1 and 3. From above test results, it is found that the specimens have similar temperature environments before starting the temperature control of the capsule specimen by using a helium gas pressure and the micro-heater power.

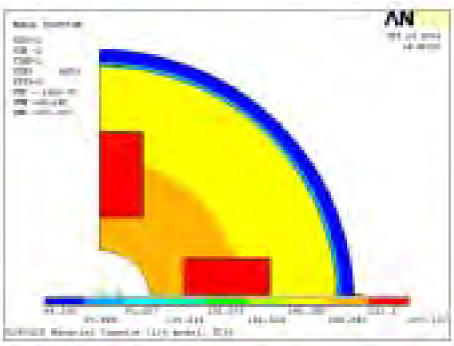
The calculated specimen temperatures show higher values than those of the irradiation test except for stage1. The maximum temperature is 263.9 ^{o}C at the TC7 position of stage3 similar to the measured one. Among the five stages stage4 has relatively large errors between two methods, but the maximum error is below 9%. Thus, the 2D FE model simulates the test results well and is reasonable for the thermal analysis of the capsule.

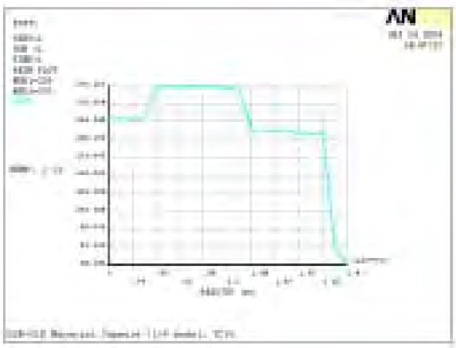
Table 2. Comparison of the specimen temperature between the test and the analysis at a 24 MW power

Stage	Thermocouple	Measured	Calculated (ANSYS)	Error*
1	TC1 (top)	246	229.7	6.6
	TC2 (bot)	241	232.9	3.4
	TC3 (top)	236	(229.7)	2.7
2	TC4 (top)	233	237.6	-2.0
	TC5 (bot)	234	243.3	-4.0
3	TC6 (top)	255	257.1	-0.8
	TC7 (bot)	256	263.9	-3.0
	TC8 (bot)	245	(263.9)	-7.6
4	TC9 (top)	238	259.2	-8.9
	TC10(bot)	238	256.6	-7.8
5	TC11(top)	250	252.3	-0.9
	TC12(bot)	238	244.7	-2.8

* Error = (Measured-Calculated)/Measured×100(%)

For the five stages of the capsule, the temperature distribution has a similar trend because of the same arrangement of the components at each stage. Fig. 5(a) shows the temperature distribution for the TC6 position of stage3, and (b) presents that in the radial direction at $\theta = 0$ position. The maximum is 257.1 ^{o}C at the rectangular specimen because this stage has the highest gamma heating rate, and the temperature of the thermal media is varied in the 200~215 ^{o}C range. Also the temperature is rapidly decreased at the gap. Especially the gap between the thermal media and the external tube is larger than that between the specimen and the thermal media, and it has an important influence on the control of the temperature of the specimen using a helium pressure.





(a) Temperature distribution (b) Temperature profile in the radial direction

Fig. 5 Temperature and stress distributions of the capsule at the TC6 position of stage3

The comparison of the specimen's temperature with the reactor power between the test and the analysis is shown in Fig. 6. The calculated temperature is linearly increased in proportion to the power increment, but the measured one shows a slightly parabolic increment. The absolute values of the temperature are changed at 18 MW power because the gap size between the thermal media and the external tube is changed. That is, the temperature increment of the capsule material by increasing the reactor power induces an expansion of the thermal media in the radial direction, and the gap size is decreased due to the thermal expansion. Finally, the decreased gap size causes the temperature of the specimen to decrease. The test results at stage3 show nearly the same temperatures for the specimens of the same hole (TC6 and TC7), but the temperature difference between TC7 and TC8, which are located in the same axial level, is increased according to the increment of the reactor power.

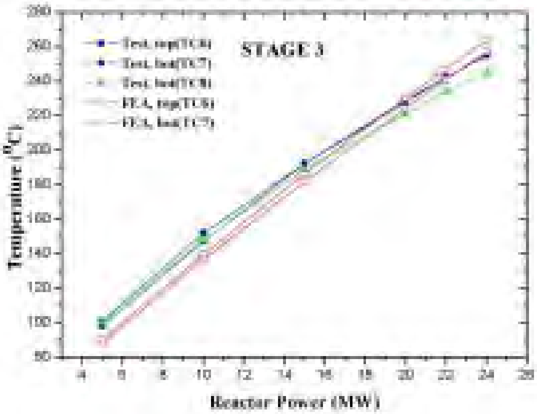
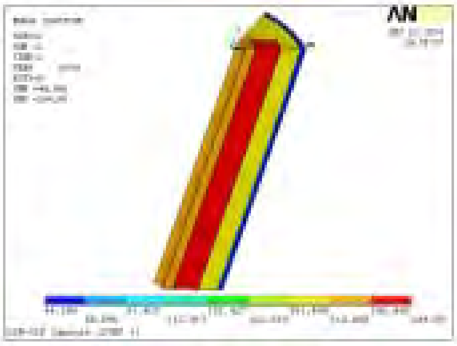


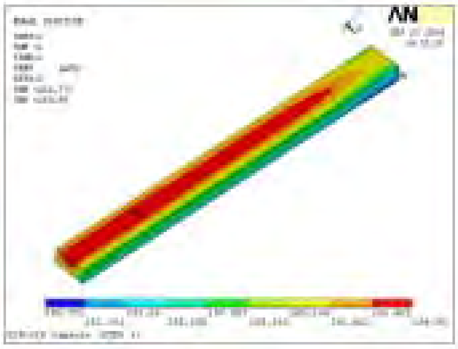
Fig. 6 Comparison of the measured and analyzed temperatures at stage3 with the reactor power.

Fig. 7 shows the temperature distribution of the specimen and the capsule of stage3 using a 3D model. Similar to the results using a 2D model, the highest temperature occurs at the specimen, and the thermal media has a temperature of about 200 ^{o}C. Also we can confirm a large variation of the temperature at the gap. Fig. 7(b) shows the detailed temperature of the specimen. The maximum value is 264.9 ^{o}C at the bottom of the specimen center, and the minimum is 251 ^{o}C at the corner, which can increase the heat transfer due to the decreased gap size. In this case the temperature of the top and the bottom along the center of the specimen in the axial direction is 261.5 ^{o}C and 264.9 ^{o}C, respectively. These values vary with the gap sizes and the gamma heating rates, but the difference of the temperature at the specimen is very small at 3.4 ^{o}C.

The 3D analysis results agreed with the 2D results to within 5 ^{o}C for the section with the thermocouple. It is found that the FE model using the 2D and the 3D elements shows nearly the same temperature. For the arbitrary stage, the temperature difference between the top and the bottom of the specimen occurs at 11.3 ^{o}C at stage5, but the other stages show a lower difference than 7 ^{o}C. The analysis results show a good agreement with those of the irradiation test, and they mean that 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 direction.



(a) Temperature distribution



(b) Temperature distribution of the specimen

Fig. 7 Temperature of the specimen at stage3

5. CONCLUSIONS

1) For the HANARO power of 24 MW, the measured temperature of the specimens for the five stages is 233~256 ^oC, and the maximum difference of the temperature between the top and the bottom of the specimen is 12 ^oC at stage5. The temperature of the specimens located at the same level in the axial direction shows a difference of about 10 ^oC for stage1 and 3. However, because this difference is very small, we estimate the irradiation tests should be performed in a constant temperature environment for each stage.
2) The calculated temperature is linearly increased with the reactor power, and the measured one shows a slightly parabolic increment due to a variation of the gap size.
3) The FE model using the 2D and the 3D elements has nearly the same temperature showing a difference within 5 ^oC at the section with the thermocouple.
4) The analysis results at a 24 MW power show a slightly higher temperature than the measured one except for stage1. But the temperature between the test and the analysis has a good agreement to within 9 percents, and we can confirm the reliability of the FE model for the thermal analysis of the capsule.

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