Thermal-Hydraulic Analysis of a NTD System during Irradiation

Jong-Hark Park,a Hak-Sung Kim,a Sang-Jun Park,a Heonil Kim,a
a Korea Atomic Energy Research Institute, Deokjin-dong 150, Yuseong-gu, Deajeon, Korea
pjh@kaeri.re.kr, haksung@kaeri.re.kr, sjpark6@kaeri.re.kr, hkim@kaeri.re.kr

1. Introduction

HANARO has a utility for the neutron transmutation doping(NTD) of silicon(Si), which can produce a high quality semiconductor by neutron absorption of a Si crystal ingot[1]. The Si ingot generates heat during the irradiation process. A NTD system is designed to remove heat by a natural circulation of reactor pool water through a small gap between the silicon ingot and its cylindrical irradiation can.

If the heat released from a Si ingot can not be removed sufficiently by natural convection, a boiling occurs on the silicon ingot surface. The boiling disturbs the uniformity of the neutron flux, which directly affects the silicon quality. A thermal-hydraulic analysis using a CFD code and a measurement were carried out to examine the temperature distribution of Si ingot during an irradiation. In a comparison these two results agreed well with each other.

2. Computational Model

Figure. 1 shows a detail of an irradiation can of 6 inch diameter Si ingot, which rotates by 15 rpm for radial uniformity. It has a floater with a helical groove on its surface, which is expected to have a pumping effect. Three different CFD cases are created. Those are a natural convection with rotation case(case-I) to examine the temperature distribution of a Si ingot during irradiation, a natural convection case(case-II) to find out the rotation effect on a cooling, and a rotation case(case-III) to evaluate the pumping effect of a helical groove.

Only a half-quarter of the geometry in the radial direction is considered as a computational domain, because the shape of the irradiation can with a Si ingot is axi-symmetric and cyclic by 45°. The geometry is so complex that it is divided into a solid part and a fluid part to generate a mesh respectively, and then the meshes are re-united again. Fig. 2 shows a computational mesh. The axial distributions of the nuclear heating rate for a unit volume of each part calculated by MCNP code[2] are applied to the CFD model as a function of the axial length using a user subroutine. The Boussinesq model is used to simulate a natural convection.

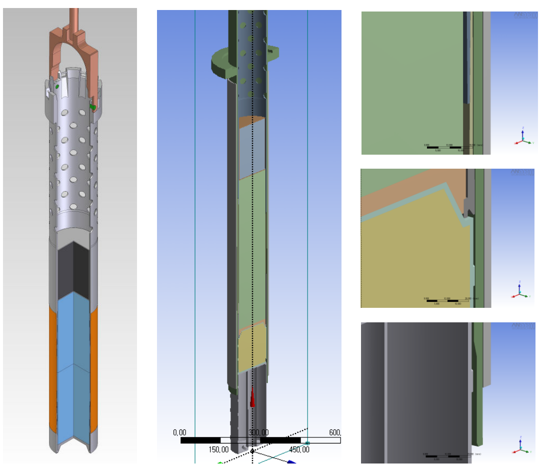


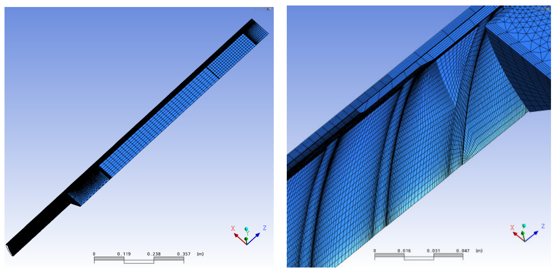
Figure 1. Geometry of an irradiation can with a Si ingot

3. Results and Discussion

3.1 The Temperature Distribution of Irradiation Can

The axial temperature distribution of Si ingot during the irradiation for the case-I is shown in Fig.3. The temperature of Si ingot increases from the lower side to the upper side. The maximum surface temperature of 143°C is appearing near the upper side of a Si ingot. The temperature of the Si ingot center rises a little more. The hydro static pressure around the NTD system is over 2 bar. Because the ONB(Onset of Nucleate Boiling) temperature at this pressure condition is estimated about 120°C, it seems that a boiling may occur at more than a half of the Si ingot surface above 120°C as shown in Fig. 3

According to the results of case-I, the flow velocity through the gap is between 4.15cm/s and 1.53cm/s.



(a) overview (b) near a helical groove
Figure 2. Computational mesh

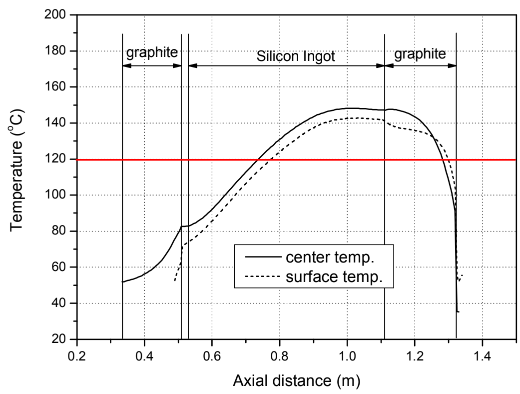


Figure 3. Axial temperature distribution of Si ingot

Table 1. Summary of CFD analysis results

Max. temp. of silicon ingot center	148.5 °C
Max. temp. of silicon ingot surface	143.0 °C
Mass flow rate by natural circulation	28 g/s
Avg. coolant temp of outlet	125.1 °C
Avg. velocity of coolant	0.0415 m/s (max) 0.0153 m/s (min)

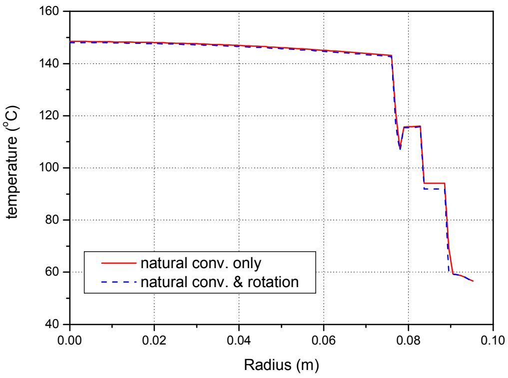


Figure 4. Comparison of temperature distribution in radial direction of NTD system for two cases

A mass flow rate by natural circulation is about 28 g/s at most, which is too small to cool a Si ingot to below the saturation temperature. The average temperature of exit flow from the gap is estimated at about 125.1°C. Some of the main results are summarized in table 1.

3.2 The Heat Transfer Enhancement by Rotation

During the irradiation process the Si ingot contained in a cylindrical can rotates by 15 rpm, which is expected to contribute to a cooling, to make the Si ingot have a uniform resistivity in the radial direction. The cooling enhancement of the Si ingot by a rotation can be found by comparing the results of case-I and case-II. Figure 4 shows that there is little difference, enough to ignore, between them. It seems that rotation by 15rpm is too slow to increase the cooling rate.

3.3 The Pumping Effect of a Helical Groove

The case-III is concerned only about the fluid region of NTD system to examine a pumping power of helical groove. No heat source and No natural convection are assumed. Table 2 shows the mass flow rate of each case. Although 4 g/s by the helical groove is about 14% of the total flow rate 28 g/s, the portion of the helical groove contribution to the flow rate can be ignored because there is no difference of flow rate between case-I and case-II, which means the natural circulation is the most dominant driving force to create a flow in the water gap between the cylindrical can and the Si ingot.

3.4 Measurement of Si Ingot Temperature and Comparison to the CFD Results

An experiment to measure the temperature of a Si ingot during irradiation was done. A schematic to describe a loading position of the Si ingot and an installation of temperature sensing papers is shown in Fig. 5. Although the Si ingot in the experiment was

Table 2 Pumping effect of helical groove

Cases	Mass flow rate
case-I	28 g/s
case-II	28 g/s
case-III	4 g/s

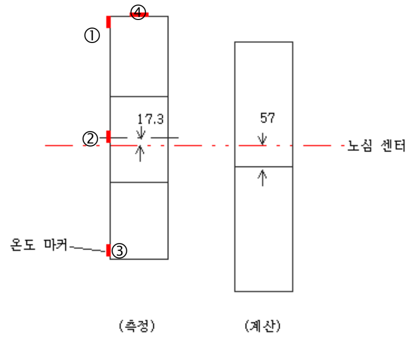


Figure 5. Schematic of a Si ingot installation and an attachment location of temperature marking stickers

Table 3. Comparison of measurement and CFD analysis

position	①	②	③	④
measurement	> 120°C	> 120°C	~ 75°C	> 140°C
calculation	145°C	130°C	75°C	147°C

shifted by up 64.3mm more so than that of CFD model, the measured temperatures show a good agreement with the CFD calculation results as shown in table 3.

During irradiation, the temperatures of a silicon ingot are predicted to reach 148.5°C at the center and 143°C at the surface. At this surface temperature boiling could occur on the silicon ingot surface. From the measured quality of the ingot after irradiation, however, the evidence of bulk boiling, for example, flux depression, was not found. And also, no vapor was observed at the NTD-Si site.

4. Conclusions

The results of this study can be summarized as follows:

1) Based on the analysis and the experiment, a measure to keep the ingot surface temperature below the saturation temperature should be found even though the current system worked fine.
2) The rotation of the silicon ingot does not help enhance heat transfer. The pumping effect by a helical groove can not be expected because of its too small volume.
3) The temperature prediction of the silicon ingot during irradiation by the CFD analysis agrees well with the measurement.

REFERENCES

[1] H. S. Kim et al, "Design of a Neutron Screen for 6-inch Neutron Transmutation Doping in HANARO," Nuclear Engineering and Technology, Vol. 38, No. 7, pp. 675-680, 2006.
[2] H. S. Kim, "Nuclear heating rate in 6-inch silicon ingot," personal communication, 2006.
[3] S. J. Park, "Temperature measurement of 6-inch silicon ingot during irradiation process," a brief note, 2006.