Measurements of Nuclear Heating Rate and Neutron Flux in HANARO CN Hole for Designing the Moderator Cell of Cold Neutron Source

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Abstract

The design of the cold neutron source(CNS) facility for HANARO, a 30 MW research reactor, is in progress. In order to measure the nuclear heating rate and thermal neutron flux in the CN hole of HANARO, a calorimeter based on the concept of the heat flow calorimeter is designed and constructed. The calorimeter sensor consists of a cylindrical Al sample, Al container, Al pipe for the neutron flux measurement, two thermocouples and an electric heater for the calibration. The sample is separated by an air gap from the Al container surrounded by an air containing Al sleeve. The heat transfer of the calorimeter under the irradiation condition is simulated by the calibration experiment of the electric heating for the sample. Thereupon, the relationship between the temperature difference and the heating power is predetermined. By using the calibration curve and the temperature measurements, the nuclear heating rates in the CN hole at the reactor powers of 1, 4 and 8 MW are determined. The measured nuclear heating rate per unit mass of the Al sample at an 8 MW reactor power is 0.143 W/g, from which, the heating rate at 30 MW is expected to be 0.494 W/g. The thermal neutron flux at an 8 MW reactor power measured by the Co-wire activation method is 2.314×10^{13} n/cm^{2}sec, from which, the flux at 30 MW is expected to be 7.450×10^{13} n/cm^{2}sec. These values are very useful for designing the moderator cell of the cold neutron source of HANARO.

1. Introduction

The heat removal capacity of the moderator cell is essential information for a cold neutron source design. In order to determine the capacity of this refrigerator, we must know the nuclear heating rate at the CN hole of HANARO. Nearly all the energy absorbed in a material placed in the radiation field of a research reactor appears in the form of a heat. This nuclear heating in research reactors arises from the interactions with gamma-rays, fast and thermal neutrons. The heating rate can be determined by the calorimetry, the ionization chambers and the chemical dosimeters. Ionization chambers require precise calibration, and the materials that may be used are much more limited than in calorimeters, while they are more sensitive, and they can give an instantaneous, continuous measure of the absorbed dose rate. Chemical dosimeters have no lead wires into the reactor, but they are not suitable for obtaining the gamma-ray dose rate in structural materials [1].

Calorimetric dosimeters have various advantages for high-dose applications. The operation of the calorimeter is possible by measuring the total amount of energy that is deposited as heat in a thermally isolated mass. The measurement of the temperature rise in a calorimetric dosimeter provides a direct measurement of the full energy imparted to matter by radiation. The thermocouples and the thermistors are sufficiently sensitive and small enough to measure the temperature change with sufficient accuracy and precision [2].

In this work, we measured the nuclear heating rate at the CN hole of HANARO by using the calorimetric method. We have designed and constructed a calorimeter, and measured the

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nuclear heating rate at CN hole with it. In addition to the measurement of the nuclear heating rate, the thermal neutron flux in the CN hole, which is one of the important parameters in the design of the cold neutron source, was measured by the cobalt wire activation method. The measurements will be very useful for designing the moderator cell of the cold neutron source of HANARO.

2. Heating Rate Measurement by Calorimetry

In an adiabatic calorimeter, it is necessary to keep no heat exchange and to measure the temperature as a function of the time. In that case, the absorbed power can be easily and exactly obtained. But, the inner volume of the calorimeter must be evacuated in order to obtain a good thermal insulation below 10^{-2}~10^{-3} Torr [3,4]. Below 10^{-5} Torr, the conduction heat transfer in air may be negligible. For the case of the CN vertical hole of HANARO, the length from the top of the D_2O reflector tank to the upper part of the water storage tank where the vacuum pump is installed is about 11 m. So, a great deal of effort may be needed to apply the adiabatic calorimeter to HANARO because of a difficulty in maintaining the vacuum. Additionally, the sample temperature of the adiabatic calorimeter can be infinitely increased even if the heating power is small. The calorimeter must be loaded during the reactor power operation with maintaining the vacuum, and only instantaneous measurements at a low reactor power are possible. Therefore, the concept of a heat flow calorimeter was introduced to measure the heating rate of the CN hole of HANARO.

The temperature of the radiation absorber in a calorimeter is determined by the absorbed energy and heat transfer between the absorber and its environment. Assuming a good thermal conductivity of the sample and the small heat transfer coefficient, in equilibrium condition of steady state, the power integrated over the volume of the sample, P become

$$P = hs(T_s - T_e), \text{ or } T_s - T_e = \frac{P}{hs}, \qquad (1)$$

where, h is the heat transfer coefficient of the medium, s is the outside surface of the sample, T_s is the temperature of the sample surface, and T_e is the temperature of the surrounding shell. From the above equation, if the surface temperature is uniform, and if the thermal resistance, $1/hs$ is known, the power can be obtained by measuring the equilibrium temperature difference $(T_s - T_e)$ [3]. It is necessary to know the thermal resistance in order to obtain the heating rate, and it may be determined by the calculation. But, it is preferable to simulate the dose rate by the thermal heating produced in the sample by the Joule effect [5].

3. Experimental Setup

The heating rate measurement facility at the CN hole of HANARO was designed to be applicable for heating rate measurements in other vertical irradiation holes of HANARO. The facility is composed of a calorimeter sensor, an air containing aluminum sleeve for fitting the sensor to the CN hole, aluminum weight and a lead wire assembly.

Figure 1 shows the detailed layout of the sensor part of the calorimeter for measuring the nuclear heating rate at the CN hole of HANARO. The outer diameter of the sensor is 56 mm. The calorimeter sensor consists of a cylindrical Al sample, Al container, Al pipe for positioning the neutron flux monitor, two thermocouples and the electric heater for a calibration. The sample is separated by an air gap from the Al container surrounded by an air containing Al sleeve. The longitudinal center of Al sample is equal to the center of reactor core. The calibration heater allows one to determine the thermal resistivity in eq. (1), and this calibration gives a simulation of the heat transfer of the calorimeter over the temperature range and under the irradiation condition.

The cylindrical sample was made of Al6061, and its diameter and length was 19.3 and 49.9 mm, respectively. The reduced sample mass including the aluminum volt for sample fixing and the electrical heater for calibration is 39.345 g. The expected heating rate of the sample with that mass is about 20 W at the reactor power of 30 MW.

The outer diameter of the aluminum pipe for neutron flux measurement is 12 mm. The cobalt wire sample is dropped through this pipe. After irradiation, it is withdrawn, and its activity is measured with calibrated HPGe detector system in order to obtain the neutron flux. AlN detector developed in another project was included for the irradiation experiment.

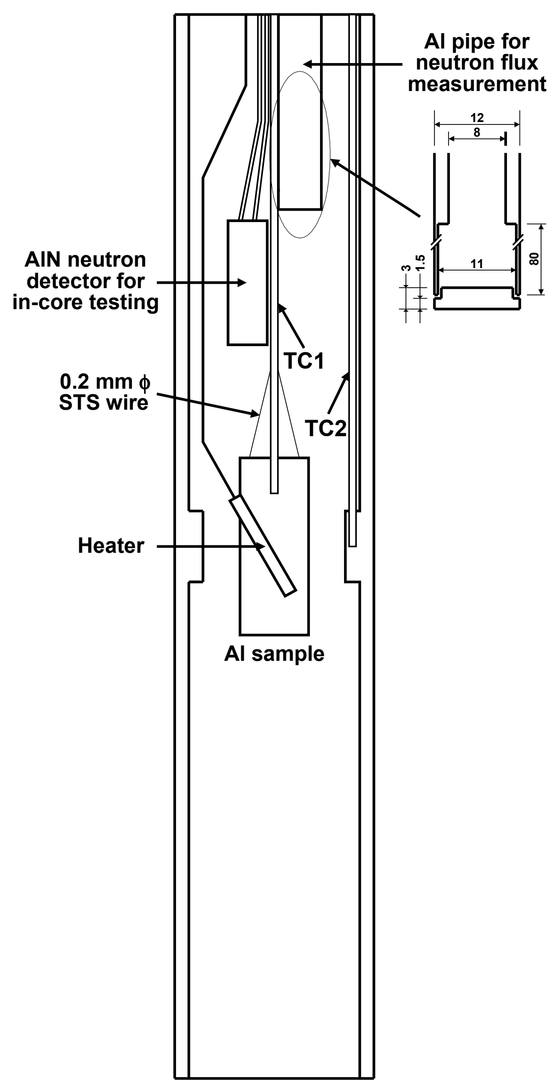

Fig. 1. Detailed layout of the sensor part of calorimeter.

4. Calibration Experiment

Fabricated facility for the heating rate measurement was installed at the CN hole of HANARO, and the calibration experiments were performed. The temperatures of the sample and container were measured with a variation of the electric power supplied to the heater loaded in the sample. The maximum temperature of the aluminum sample was 385 ℃ at the electric power of 20 W. The temperature change of the container was several ℃ in the whole power range.

Figure 2 shows the whole trends of the temperature changes of the Al sample and the container in the calibration experiment for the high electric power range. In a heat flow calorimeter like this experiment, the sample temperature changes approximately exponentially with time after constant heat input [6,7,8]. The saturated temperatures of the sample and container were found by the fitting curve with an exponential growth function for the measured temperature.

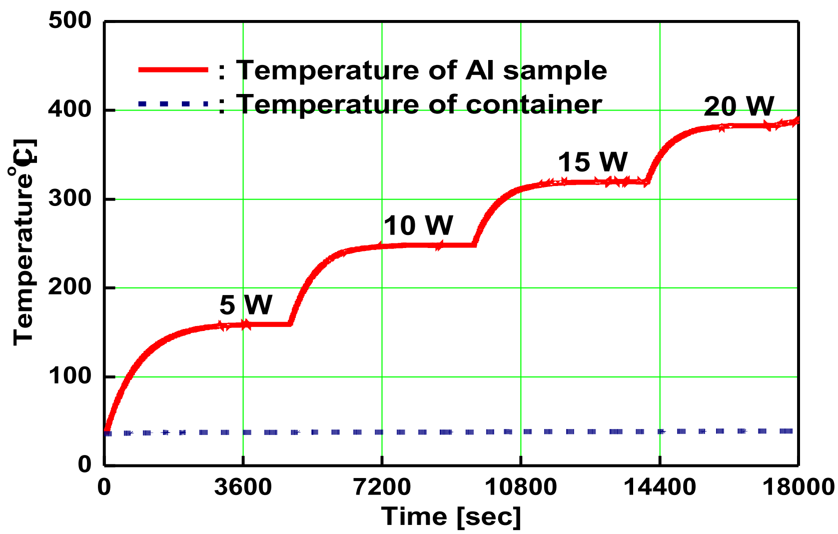

Fig. 2. Whole trends of the temperature changes of Al sample and container in the calibration experiment for the high electric power range.

From this calibration experiment, the relationship between the power supplied to the heater and the temperature difference was determined, and figure 3 represents the result of the calibration experiment. In the figure, the solid line is fitting to the measurements with 2nd order polynomial. The calibration curve is not linear because the convective and radiative heat transfers are increased in high sample temperature range [9].

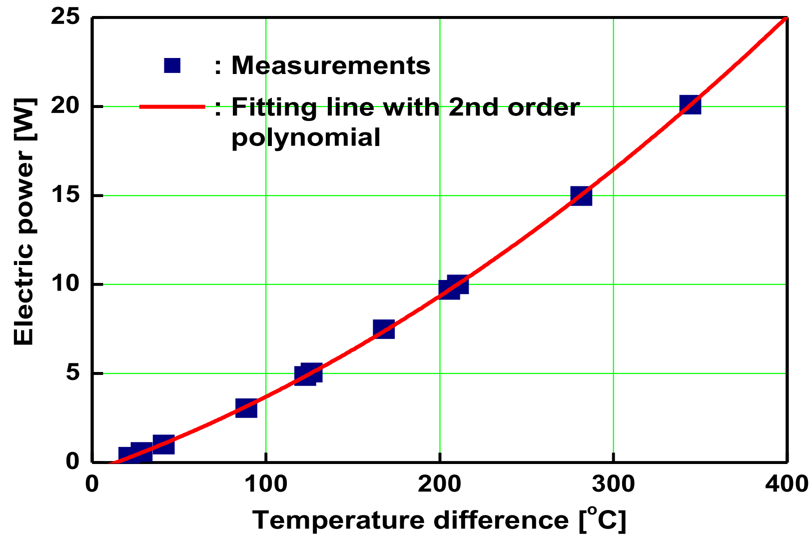

Fig. 3. The result of the calibration experiment.

3. Results

After the calibration experiment, the nuclear heating rates at the CN hole were measured at three reactor powers of 1, 4 and 8 MW. The data reduction method in these experiments was almost the same as in the calibration experiment. Simultaneously with the heating rate measurements, the cobalt wire irradiations were performed at the reactor powers of 1 and 8 MW for the neutron flux measurements. The activities of the withdrawn cobalt samples were measured using the HPGe detector system. The diameter of the cobalt wire was 0.05 mm, and its self-shielding effect was negligible.

The nuclear heating rates per unit sample mass measured at three reactor powers are shown in Table 1.

Table 1. Measured nuclear heating rates at CN hole of HANARO.

Reactor power [MW]	Container temperature [℃]	Sample temperature [℃]	Temperature difference [℃]	Nuclear heating rate at sample [W]	Heating rate per sample unit mass [W/g]
1.18	31.167	63.284	32.118	0.697	0.018±0.00068
4.20	37.051	122.592	85.540	3.000	0.076±0.0023
8.48	40.158	177.220	137.062	5.618	0.143±0.0041

Uncertainty of the measurements is within 3.8%, and the uncertainty in the temperature measurement is a main contribution. The thermocouples have some thermal insulation between them and the sample. Power from the radiation interaction is generated in the thermocouple, and this power leaks to the sample and also leaks through the thermocouple lead wire. For an instrument like this experiment, it can be considered that the thermocouple reading agrees with the true temperature of the sample to within 1% [10]. The measured nuclear heating rate per unit mass of the Al sample at an 8 MW reactor power is 0.143 W/g, from which, the heating rate at 30 MW_{th} is expected to be 0.494 W/g. This value is very useful for designing the moderator cell of the cold neutron source of HANARO.

The neutron flux at the CN hole measured at an 8 MW reactor power by the cobalt wire activation method is 2.314×10^{13} n/cm^{2}sec, from which, the neutron flux at 30 MW_{th} is expected to be 7.450×10^{13} n/cm^{2}sec. The neutron flux is Westcott flux which was deduced by dividing the saturated activity per cobalt nuclei by a 2200 m/sec radiative capture cross-section. Therefore, they may be overestimated by about several percents due to the effects of the epithermal and fast neutrons. This can be compensated for by the cadmium ratio which could be determined by calculation with a proper code like MCNP.

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