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Self-overcoming of the boiling condition by pressure increment in a water target irradiated by proton beam

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ABSTRACT

An experiment was conducted to examine and visualize the boiling phenomena inside a water target by irradiating it with a proton beam from MC-50 cyclotron. The boiling phenomena were recorded with a CMOS camera. While an increase of the fraction of the water vapor volume is generally considered to be normal when water is boiled by a proton beam, our experiment showed the opposite result. The volume expansion of the liquid water exceeded the compressibility of the initial air volume. A grid structure in front of the entrance window foil held the target volume constant. Therefore, the phenomena inside the target underwent an isochoric process, and the pressure inside the target was increased rapidly beyond the pressure at the boiling point. Consequently, there was no more bulk boiling in the Bragg-peak region in the target water. Our results show that the boiling of the water can be controlled by controlling the equilibrium pressure of the water target.

1. Introduction

The boiling of a water target by proton beam irradiation is considered a natural phenomenon that cannot be prevented except by increasing the initial pressure of the target above its boiling point. The phase change of the target material induced by irradiation with charged particles from an accelerator is an important issue to explore. However, there have not been enough experimental studies of this subject. One of the representative fields in which this issue occurs is radioisotope targets. In the case of a $H_2{}^{18}O$ liquid target for ^{18}F production, the phase change caused by boiling of the water during proton beam irradiation should be considered. The local boiling along the beam path through the water reduces the local density in this region. The density reduction in this region has an effect on the nuclear reaction cross-section, which is proportional to the target material density. Therefore, in the case of a high radioisotope production yield, the phase change of the water causes a negative effect on the production yield.

Heselius et al. have presented a photographic view of the water during irradiation [1]. The tested target had a double-foil entrance window structure. This structure had no additional substructures to hold the entrance foil against the inner pressure of the water target. As a result, the level of the water inside the target began to decrease when the proton beam irradiation began. The presented pictures also showed vapor bubbles generated along the proton beam path in the target water. Hur et al. have recorded the boiling phenomena of water with a video camera during irradiation [2]. This study also showed a decrease of the water level caused by boiling. The boiling of the water is caused not only by the energy dissipation of the proton beam, which raises the water temperature, but also by the radiation effect, which enhances the boiling. A thermodynamic study related to this effect caused by multiple mechanisms was made to investigate the tendency of the boiling flux, and an experimental study was planned [3].

The steam–water fraction, where the steam corresponds to the water vapor created by the power of the irradiating beam incident on the water and the water corresponds to the liquid water present before irradiation begins, was measured [4]. The results showed that this fraction was proportional to the beam power. After a time, the water reached a fully developed boiling condition and attained equilibrium with the cooling power, holding a steady water level.

Compared with other experiments that have been performed, our research was performed with a target of a different structure. The main difference was the structure of the beam entrance window foil. The target in this experiment has a grid support structure that could hold constant the inner volume of the water. This structure was first suggested by Barthart et al. [5]. The other experimental research targets that have been used have had no support structures. Therefore, it was possible for the volume of the

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water to change. This structural difference caused our experiment to yield different results.

2. Experimental apparatus and procedure

The experiment was conducted with the same experimental setup and procedure as our previous experimental research [6]. The proton beam used for irradiation had energy of 30 MeV and a beam intensity of 25 μA. The diameter of the beam was 10 mm.

The water target for the experimental study was fabricated to allow installation of a tempered glass window in the side wall. Through this window, the phenomena occurring in the water were recorded with a CMOS camera. Fig. 1 illustrates the structure of the target. Twelve J-type thermocouples were installed on the wall that faces the view window. The positions of the thermocouples are shown in Fig. 2. The bead junctions of these thermocouples did not protrude from the surfaces of the thermocouple mounts. At the same height as the side wall surface, the bead junctions were exposed to the water. At the bottom, there is another glass window. This window is for illuminating the inside of the target with light. A single entrance window foil with a grid support structure was used to hold the water inside the cavity of the target, which had a volume of 4.5 cc. The grid structure with a void fraction of 80% on the entrance window foil prevents the blowing of the foil at high inner pressure during proton beam irradiation of the target water. The target body, the grid structure, and the foil were all made of aluminum. The thickness of the window foil was 200 μm. During irradiation, the target body was cooled directly by water, but the window foil was cooled through strong contact with the grid structure, which was cooled by water.

Fig. 3 shows the experimental setup for the boiling visualization experiment. A pressure transducer was installed in the water injection line to measure the inner pressure of the target. The direct path between the target and the camera used for recording the boiling phenomena during proton beam irradiation was blocked with lead and paraffin bricks to reduce the effect of the

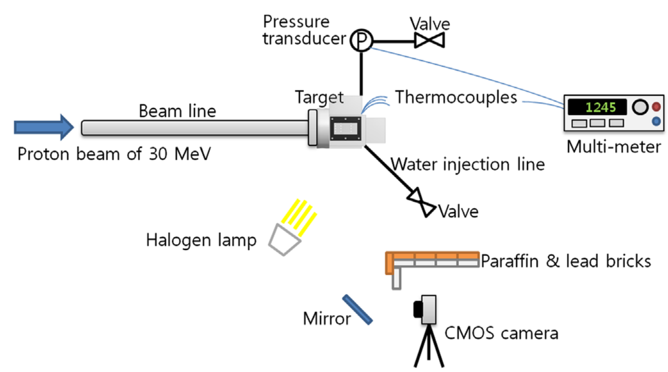

Fig. 3. Schematic diagram of the experimental setup.

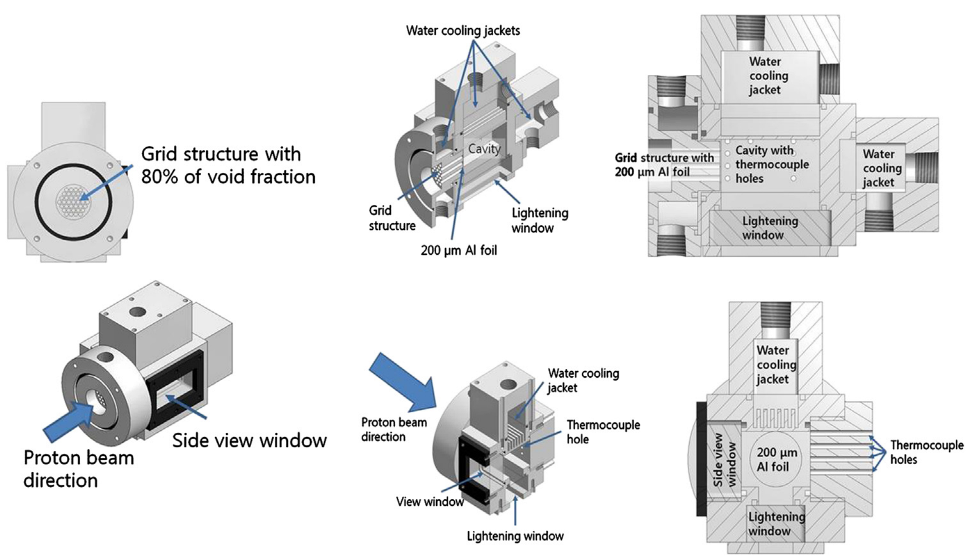

Fig. 1. Structural view of the water target.

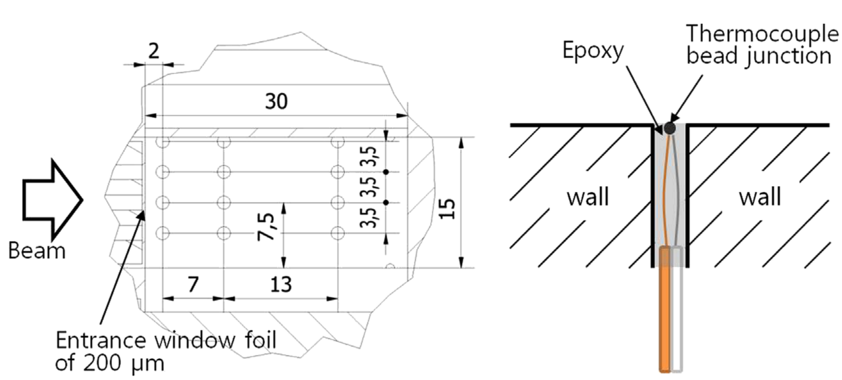

Fig. 2. Schematic view of the positions of the thermocouples and a diagram of an installed thermocouple.