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Electron beam irradiation effect on critical heat flux in downward-facing flow boiling

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ABSTRACT

In previous research on nuclear reactors, the effect of irradiation on heat transfer has rarely been studied. We investigated the electron beam irradiation effect on downward-facing flow boiling heat transfer and critical heat flux. All the critical heat flux values in flow boiling decreased after irradiation, particularly at low doses, whereas heat transfer coefficient almost remained the same. Low dose electron beam irradiation substantially increased the nucleation sites on the heated copper surface, and the critical heat flux was inversely related to the nucleation site density in downward-facing flow boiling.

1. Introduction

Various types of radiations are emitted in nuclear reactors, namely, neutron, alpha, beta, and gamma radiations. Many studies have shown that these radiations can change the mechanical properties of metallic materials, such as hardness, embrittlement, and susceptibility to environmentally induced cracking [1,2]. For convenience, most previous experimental studies on the heat transfer and critical heat flux (CHF) related to nuclear reactors have been conducted using an electric heater without any irradiation. Therefore, the effect of irradiation on heat transfer and CHF has not received sufficient attention.

Some researchers have found that gamma-ray irradiation can significantly increase the surface wettability of metals and oxides [3,4]. This increase is assumed to be caused by oxygen vacancies produced on the surface because of cathodic and anodic reactions. Many studies have shown that the CHF in pool boiling is related to surface wettability [5–10]. Based on these studies, Okamoto et al. [11] performed a pool boiling experiment using a gamma-ray-irradiated SUS304 foil with a plasma-oxidized surface and obtained a CHF enhancement of ~20%.

Advanced pressurized water reactors are designed to confine the molten corium inside the reactor pressure vessel (RPV) by cooling the outer bottom wall surface of the RPV during a severe accident. This process is known as in-vessel retention (IVR) [12]. During the IVR process, the RPV bottom wall is exposed to very high temperatures and radiation. For the IVR strategy to succeed, the CHF for the outer surface of the RPV should not be reached during the cooling process.

In this study, we present the investigation of the electron beam irradiation effect on metal surface wettability and heat transfer in saturated, downward-facing flow boiling considering the IVR condition. To investigate the heat transfer characteristics on irradiated surfaces in downward-facing boiling, copper surfaces were irradiated by electron beams having a certain irradiation dose, and soon after, flow boiling experiments were performed. Different irradiation doses in the range of 30–3000 kGy were applied to investigate the dose effect. It was found that copper surface wettability increases significantly after irradiation. However, all the CHF values decrease after irradiation, particularly when the irradiation dose is low, whereas heat transfer coefficient does not show significant change. By carrying out high-speed imaging, we observed that a large number of nucleation sites are generated after the low dose irradiation. The substantial increase in the nucleation sites might have reduced the water supply to the boiling surface, leading to a decrease in the CHF. This observation reveals that an inverse relationship exists between CHF and nucleation site density in flow boiling. This relationship should not be ignored in studies on flow boiling heat transfer in nuclear reactors.

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2. Experimental apparatus

2.1. Electron beam irradiation facility

In this study, electron beam irradiation and flow boiling experiments were both performed at the Takasaki Advanced Radiation Institute of Japan. The schematic layout of the electron beam irradiation facility is shown in Fig. 1. Electrons emitted from heated filaments were accelerated through a vacuum tube by providing a high voltage; the electrons then passed through a metallic window to irradiate the copper surface. A beam scanner was placed before the window to expand the irradiation area. The irradiation parameters are listed in Table 1.

2.2. Flow loop and test section

The flow-boiling experimental loop is shown in Fig. 2. A pump was installed near the downstream tank to drive the flow. The water flow rate was varied by changing the pump speed. The flow rate was measured by an electromagnetic flowmeter. Distilled water was used as the working fluid. Water entered the flow channel from the upstream tank. The flow channel cross section was 40 mm (width) × 10 mm (height), and it was made of polycarbonate transparent glass for visualization purposes. The total length of the flow channel was 980 mm. The test section was installed through a flange from the upper surface of the rectangular flow channel to achieve downward-facing boiling. During the experiment, a high-speed camera was used to observe and record the boiling phenomena from the bottom of the flow channel. The flow boiling experiment was performed under saturated and atmospheric pressure conditions. Before the experiment, the water in the loop was heated up to 100 °C under atmospheric pressure using the pre-heater in the downstream tank.

Fig. 3 shows the structure of the test section. Copper was used as the heating material because of its high thermal conductivity. The copper block was insulated using polyether ether ketone. Electric cartridge heaters were used to heat the copper block. The copper boiling surface area was 30 mm × 30 mm. During the experiment, the heat flux, which could be changed by changing the input voltage, was increased stepwise until CHF occurred. Three K-type thermocouples were installed along the centerline of the copper block. The distance between each thermocouple was 3 mm. The distance between the boiling surface and the bottommost thermocouple was also 3 mm. Therefore, we could calculate the heat flux according to Fourier's law. Two identical test sections (A and B) were manufactured and used in the whole experiments to check the repeatability. Before the boiling surface was irradiated, it was polished using sandpaper (type P1200) and cleaned, first with acetone and then with distilled water. All the experiments were performed at a flow rate of 320 kg/(m^2 s).

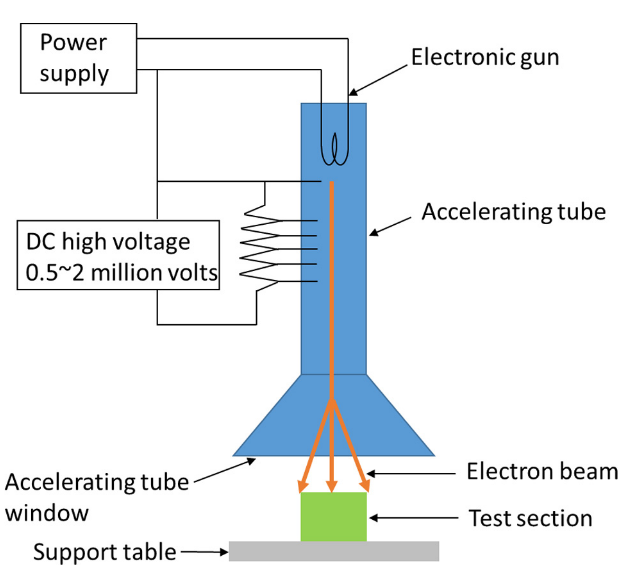

Fig. 1. Schematic diagram of electron beam irradiation facility.

Table 1
Parameters for electron beam irradiation.

Accelerating voltage	Electronic current	Sweep speed	Dose rate
2 MeV	1 mA	200 Hz (5 ms)	~1.5 kGy/s

3. Experimental procedure and results

Before each irradiation, the copper surface was first cleaned by sand paper (P1200), then acetone, and finally distilled water. Next, the test section was quickly installed on to the support table to be irradiated. Shortly after the electron beam irradiation, droplet tests were performed to test whether electron beam irradiation could increase the surface wettability of copper or not. Fig. 4 shows the contact angle changes before and after the copper surface was irradiated by different doses. It was found that the static contact angle decreased, implying an increase in the surface wettability as the irradiation dose increased. The static contact angle became quite small when the irradiation dose was increased beyond 1000 kGy.

After the water droplet test, the test section was installed on the flow channel immediately to perform the saturated flow boiling experiment. Two identical test sections (A and B) were used in all the experiments. Test section A was irradiated at 300, 1000, and 3000 kGy. Test section B was irradiated at 30, 100, 300, and 1000 kGy. Before the irradiation experiment, a non-irradiation experiment was performed for comparison. The boiling curves for the non-irradiation and irradiation experiments are shown in Fig. 5. The arrows refer to the occurrence of CHF. Unexpectedly, all the CHF values decrease after irradiation, whereas the heat transfer coefficient almost remains the same at the same heat flux. For test section A, the CHF values decrease by 82%, 61%, and 23% at 300, 1000, and 3000 kGy, respectively. The CHF value at 300 kGy is 0.14 MW/m^2, which is very low. For test section B, the CHF values decrease by 62%, 70%, 46%, and 46% at 30, 100, 300, and 1000 kGy, respectively, compared to the CHF values for the non-irradiated surface. We checked the surface wettability again by dropping a water droplet on the boiling surface using a syringe just after the flow boiling experiment. It is found that irradiation effect on surface wettability was disappeared even for the highest irradiation dose condition.

The abovementioned experimental results were unexpected. In this regard, two main concerns need to be addressed. First, why do the CHF values decrease with the irradiation even when wettability increases? Second, why is the decrease in the CHF larger for a lower dose irradiation? High-speed images of the boiling phenomena were evaluated to investigate these concerns. Fig. 6 shows the boiling snapshots of the four cases for test section A at approximately the same heat flux, which is lower than the CHF. As can be seen from Fig. 6(b), many tiny bubbles are observed on the surface, implying that the nucleation site density for the 300 kGy irradiation is larger than that for the other cases. For the 1000 kGy irradiation, it seems that the number of bubbles is similar to that for the non-irradiation condition and 3000 kGy irradiation. The number of nucleation sites actually increases because of some tiny nucleation sites generated in some small areas (Fig. 6(c)). In the same way, we compared the boiling images for the non-