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Technical Note

Enhancement of the critical heat flux in saturated pool boiling of water by nanoparticle-coating and a honeycomb porous plate

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A B S T R A C T

Various surface modifications of the boiling surface, e.g., integrated surface structures, such as channels and micro-pin fins, and the coating of a micro-porous layer using sintered metal powders and nanoparticle deposition onto the heat transfer surface, have been proven to effectively enhance the critical heat flux (CHF) in saturated pool boiling. In particular, novel methods involving nanofluids have gained a great deal of attention because the CHF for the use of nano-fluids is increased drastically, by up to approximately three times compared to that of pure water. CHF enhancement using nanofluids is related to surface wettability, surface roughness, and capillary wicking performance due to nanoparticle deposition on the heated surface. Several studies have proposed the use of nanofluids to enhance the in-vessel retention (IVR) capability in the severe accident management strategy implemented at certain light-water reactors. Systems using nanofluids for IVR must be applicable to large-scale systems, i.e., sufficiently large heated surfaces compared to the characteristic length of boiling (capillary length). However, as for the effect of the size of heater with nanoparticle deposition, it was revealed that the CHF tends to be decreased with the increased heater size. On the other hand, the CHF in saturated pool boiling of water using a honeycomb porous plate was shown experimentally to become approximately twice that of a plain surface with a heated surface diameter of 30 mm, which is comparatively large. The enhancement is considered to result from the capillary supply of liquid onto the heated surface through the microstructure and the release of vapor generated through the channels.

In the present paper, in order to enhance the CHF on a large heated surface, the effects of a honeycomb porous plate and/or nanoparticle deposited heat transfer surface on the CHF were investigated experimentally. As a result, the CHF was enhanced greatly by the attachment of a honeycomb porous plate to the modified heated surface by nanoparticle deposition, even in the case of a large heated surface. Under the best performing surface modifications, the CHF for 10-mm-, 30-mm- and 50-mm-diameter surfaces was enhanced up to 3.1, 2.3, and 2.2 MW/m^2, respectively.

1. Introduction

One strategy for severe accidents, such as loss of coolant accidents (LOCA), is in-vessel retention (IVR) of corium debris [1]. The IVR consists of external cooling of the reactor vessel in order to remove decay heat from the molten core through the lower head of the vessel. However, the heat removal is limited by the occurrence of critical heat flux (CHF) at the outer surface of the reactor vessel. Therefore, in order to enhance the capability of the IVR in the severe accident of the light-water reactors, methods to increase the CHF should be considered.

Various modifications of the boiling surface, e.g., integrated surface structures, such as channels and micro-pin fins, and the coating of a micro-porous layer using sintered metal powders and nanoparticle deposition onto the heat transfer surface, have been proven to effectively enhance the CHF in saturated pool boiling [2–6].

Several researchers have offered novel structures of the porous media in which the liquid and vapor flow paths will be separated [7–12]. The CHF has been enhanced significantly up to approximately twice that of a plain surface with a heated surface diameter of 30 mm using a honeycomb porous plate [11]. Moreover, the effect of the channel width on the CHF in the saturated pool boiling has been investigated experimentally [12].

You et al. [6] introduced a novel method to enhance the CHF of pool boiling using nanofluids. The CHF was increased drastically up

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to approximately three times (1.68 MW/m^2) compared to that of pure water. The drastic enhancement in the CHF obtained by using nanofluids is of particular interest [13,14]. The CHF enhancement obtained by using nanofluids is related to the surface wettability, surface roughness, and capillary wicking performance due to nanoparticle deposition on the heated surface [15].

Based on the studies mentioned above, the mechanism of the CHF enhancement can be explained by the capillary suction effect, the extended surface area effect, the liquid supply caused by the hydrodynamic effect, and the wettability of the heated surface.

There are several ways to enhance the CHF. However, approaches for increasing the IVR capability must be simple and installable at low cost. The use of nanofluids has been proposed in order to enhance the IVR capability in severe accident management strategies for advanced light-water reactors [16,17]. The strategy of using nanofluid for IVR should be applicable to a large heated surface compared to a characteristic length of boiling (capillary length). However, for Al_2O_3 nanoparticle-coated flat heaters, the CHF tends to be decrease with an increase in heater size [18]. On the other hand, as stated above, the CHF using a honeycomb porous plate was shown experimentally to be approximately twice that of a plain surface having a heated surface diameter of 30 mm [11,12], which is comparatively large. The enhancement is considered to result from the capillary supply of liquid onto the heated surface and the release of generated vapor through the channels.

In the present paper, in order to succeed in heat removal from a large heated surface with high heat flux, we focused on the use of a honeycomb porous plate and nanofluid. Therefore, the CHF in a saturated pool boiling of water was investigated experimentally using a honeycomb porous plate and/or nanoparticle deposited heat transfer surface. As a result, the CHF was greatly enhanced under the attachment of a honeycomb porous plate on the modified heated surface by nanoparticle deposition.

2. Experimental apparatus and procedure

2.1. Experimental apparatus

A schematic diagram of the pool boiling test facility is shown in Fig. 1. The main vessel is made of Pyrex glass and has an inner diameter of 87 mm and a height of 500 mm. The pool container was filled with distilled water to a height of approximately 60 mm above the heated surface. The heat flux was supplied to the boiling surface through a copper cylinder using a cartridge electric heater, which was inserted into the copper cylinder and was controlled by an AC voltage regulator. The heat loss from the sides and bottom of the copper cylinder was reduced using a ceramic fiber insulation material.

The top horizontal surface of a copper cylinder with diameters of 10 mm, 30 mm, and 50 mm is smooth and is used as the heat transfer surface in the experiments. Three sheathed thermocouples with an outer diameter of 0.5 mm were inserted horizontally to the centerline of the copper cylinder. The thermocouples (TC1, TC2 and TC3 shown in Fig. 1) in the copper cylinder were set apart axially by 5.0 mm. The closest thermocouple was located 10.0 mm below the boiling surface. These thermocouples were calibrated using a

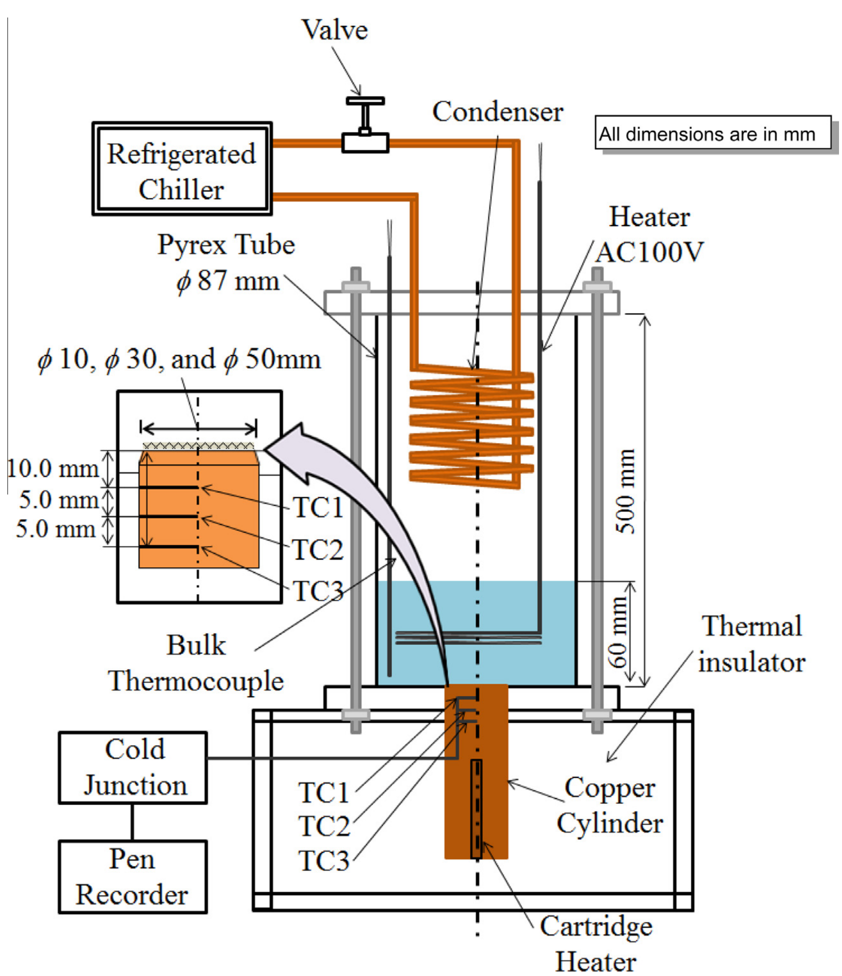

Fig. 1. Schematic diagram of the experimental apparatus.