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Research Paper

Enhancement of critical heat flux using spherical porous bodies in saturated pool boiling of nanofluid

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HIGHLIGHTS

- CHF is enhanced by a nanofluid and spherical porous bodies.
- The proposed method can improve CHF of heated surface with curvature.
- Dryout was restricted by spherical porous body in a saturated boiling pool of nanofluid.
- Liquid was supplied by spherical porous bodies to the nanoparticle-deposited layer.

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ABSTRACT

One strategy to address severe nuclear accidents is the in-vessel retention (IVR) of corium debris. IVR consists of the external cooling of the reactor vessel to remove the decay heat from the molten core through the lower head of the vessel. However, heat removal is limited by the occurrence of the critical heat flux (CHF) condition at the outer surface of the reactor vessel. Therefore, we propose a CHF enhancement technique in a saturated pool boiling by the attachment of a honeycomb porous plate (HPP) on the heated surface. However, the reactor vessel on which to install the HPP exhibits curvature, so the key to realizing IVR depends on the placement of the HPP on the curved surface of the reactor vessel. Accordingly, we propose an approach using porous cellulose beads and a nanofluid. Consequently, for the combination of the nanofluid (TiO_2, 0.1 vol%) and spherical porous bodies, the CHF is demonstrated to be enhanced by up to a maximum factor of two compared to that of a plain surface of distilled water.

1. Introduction

It is a great challenge to ensure the safety of nuclear power plants during severe accidents. One of the major concerns is the overheating of the reactor core, which may potentially create a nuclear crisis if the cooling of the core fails. In-vessel retention (IVR) is a method that is gaining attention for heat removal in core-melt accidents. It consists of the external water cooling of the reactor vessel to remove decay heat from the molten core through the lower head of the vessel. Unfortunately, heat removal by a boiling substance is limited by the critical heat flux (CHF) where the heat transfer rate drops drastically. The enhancement of the CHF is a great concern for increasing the capability of IVR, which will be implemented in many light water reactors [1–4].

Numerous studies have proposed novel methods for improving the CHF in a pool boiling under saturated atmospheric conditions [5]. Table 1 summarizes studies on CHF enhancement of flat heaters in saturated pool boiling for water and water based nanofluid under atmospheric pressure condition. $q_{CHF,max}$ and $q_{CHF,p}$ indicate the critical heat flux of flat heater with and without surface modification, respectively. As shown in Table 1, there exist surface modifications such as the coating of a heat transfer surface by a porous layer, integrated surface structures such as channels, fins, and nanotubes, which have shown a significant enhancement in the CHF.

Based on recent developments in nanotechnology, the use of a nanofluid instead of pure water has shown promising results in enhancing the CHF. The pioneer of this novel method was suggested by You et al. (2003) [6]. They reported that the CHF can be enhanced by a factor of

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Nomenclature

A	area of heater surface [m^2]
I	current [A]
λ	thermal conductivity [W/(mK)]
h	heat transfer coefficient [$\mathrm{W/(m^2K)}$]
q“	heat flux [$\mathrm{W/m^2}$]
q_{CHF}	critical heat flux [$\mathrm{W/m^2}$]
S	contact area ratio [-]
T	temperature [K]
T_{sat}	saturated temperature of water [K]
V	voltage [V]
Δx_1	length of one side of heater [m]
Δx_2	length of other side of heater [m]

Greek symbols

ρ	density [$\mathrm{kg/m^3}$]
γ	thermal activity [$\mathrm{m}\cdot\frac{\mathrm{J}}{\mathrm{m^2K\cdot S^{0.5}}}$]

Subscripts

sat	saturation

about two compared to that of pure water with a low concentration of $\mathrm{Al_2O_3}$/water nanofluid varying from 0 to 0.05 g/L. Kwark et al. (2012) [7] conducted an experiment using a low water/alumina nanoparticle concentration (≤1 g/L) and found that there was no further CHF enhancement with concentrations higher than 0.025 g/L. Nanoparticles deposited on the heated surface during vigorous boiling offer a good wettability and capillarity [8]. Therefore, it can retard the spreading of the dry region and, as a result, increase the CHF.

In contrast, the CHF enhancement of a flat heater using a honeycomb porous plate (HPP) has also been experimentally shown to be more than approximately twice that of the plain surface under atmospheric and saturated pool boiling conditions [9–14]. This is attributed to the HPP, which provides an automatic liquid supply because of the capillary action and the reduction in the vapor escape flow resistance because of the separation of the liquid and vapor flow paths. By the enhancement of the CHF to improve the capability of the IVR by integrating these two elements, the HPP attachment and nanofluid as a working fluid have been proven. However, the reactor vessel on which to install the HPP has curvature, so the key to realizing IVR depends on the placement of HPPs on the curved surface of the reactor vessel.

2. Proposed method for improving chf of heated surface with curvature

In order to address the issue stated above, we propose a method using spherical porous bodies fixed by a stretchable metal net, which can guarantee contact with the curved heat transfer surface, as shown in Fig. 1. Fig. 1 shows a schematic of our idea for installing porous bodies on the curved heated surface. The spherical porous body can deform to keep contact with the heated surface having curvature. Note that the size and installation pitch of the spherical porous body are significantly different from those used in the present study.

Therefore, the main objective of this study is to investigate the effect of spherical porous bodies on the CHF in a boiling pool of nanofluid.

3. Experimental apparatus and procedure

3.1. Experimental apparatus

Schematics of the pool boiling apparatus are illustrated in Fig. 2. Fig. 2(a) presents a conventional pool boiling experimental apparatus incorporating a copper block heater, while Fig. 2(b) presents the experimental setup in which an ITO heater is used to measure the temperature distribution of the heated surface with a high-speed IR camera. The main vessel, which is made of Pyrex glass, has an inner diameter of 87 mm and height of 500 mm. The pool container was filled with distilled water or a nanofluid to a height of approximately 60 mm above the heated surface.

3.2. Copper block heater

The heat flux was supplied to the boiling surface through a copper cylinder using a cartridge electric heater, which was inserted into the bottom of the copper cylinder, and the cartridge heaters were 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 the copper cylinder with a diameter of 30 mm was smooth and was used as the heat transfer surface in the experiment. Three sheathed thermocouples with an outer diameter of 1 mm were inserted horizontally into the centerline of the copper cylinder.

The thermocouples (TC1, TC2, and TC3 shown in Fig. 2(a)) in the copper cylinder were set axially apart by 5 mm. The closest thermocouple was located 10-mm below the boiling surface. These thermocouples were calibrated using a platinum resistance thermometer. The wall temperature and wall heat flux were calculated by applying Fourier's Law, where the thermal conductivity of the copper was evaluated at the arithmetic averaged temperature of TC1, TC2, and TC3, and the linearity of the data was confirmed.

3.3. ITO heater

Fig. 2(b) depicts the ITO heater used in the present study. This device was fabricated by vacuum-depositing a 250-nm-thick ITO film on a sapphire substrate (1 × 40 × 40 mm). The heating area of the ITO unit was 20 × 20 mm. The heater was installed with the ITO film facing upward and, in order to improve wettability, the film was coated with a 100-nm-thick layer of $\mathrm{TiO_2}$ because ITO is hydrophobic. Cr (30-nm-thick) and Au (200-nm-thick) electrodes were deposited sequentially on the sapphire substrate and connected to an AC power supply to control the heat flux at the surface. An AC supply was used rather than DC because it was found that the ITO heater installed facing upward, to be in contact with the water and heated by a DC power supply, was often damaged as a result of electrochemical reactions. The heating cycle frequency of the AC power supply had to be as high as possible to not affect the primary bubble generation. Thus, in the present study, the heating frequency was set to 1000 Hz based on a consideration of the frequency of the primary bubble detachment. Taking into account the thermal activity value, $\gamma = \delta\sqrt{\rho C_p k}$ [15], a thickness of 1 mm was selected for the sapphire glass (giving $\gamma = 9.3$) so that the heating conditions would be as close as possible to those associated with copper block heating. Moreover, the effect of the ITO heater and copper cylinder heater on CHF was considered experimentally. As a result, it is confirmed that the difference of the CHF in the two kinds of heaters was not so large.

The temperature distribution on the heated ITO surface was