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Effect of honeycomb porous plate on critical heat flux in saturated pool boiling of artificial seawater

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ABSTRACT

During a severe nuclear power plant accident, the integrity of the reactor pressure vessel must be assured. In response to a possible fuel meltdown, operators of the current generation of nuclear power plants are likely to inject water into the reactor pressure vessel cavity to cool down the reactor vessel wall, preserving its integrity and avoiding leakage of radioactive material. This study considers the use of seawater to flood a reactor pressure vessel cavity combined with the attachment of a honeycomb porous plate (HPP) on the vessel outer wall as a way to improve the safety margins for in-vessel retention of fuel. In long-duration experiments, saturated pool boiling of artificial seawater was performed with an upward-facing plain copper heated surface 30 mm in diameter. The resulting value for critical heat flux (CHF) was 1.6 MW/m^2 at atmospheric pressure, a value significantly higher than the CHF obtained when the working fluid was distilled water (1.0 MW/m^2). It was verified that sea-salt deposits could greatly improve surface wettability and capillarity, enhancing the CHF. The combination of artificial seawater and an HPP attached to the heated surface improved the boiling heat transfer coefficient and increased the CHF up to 110% (2.1 MW/m^2) as compared to distilled water on a bare surface. After the artificial seawater experiments, most of the wall micropores of the HPP were clogged due to sea-salt aggregation on the HPP top and bottom surfaces. Thus, the CHF enhancement observed in this case was attributed mainly to the separation of liquid and vapor phases provided by the HPP channel structure and improvement of surface wettability and capillarity by sea-salt deposition.

1. Introduction

Increasing safety is vital for the future of nuclear power plants, so great effort has been invested in making accident management techniques more reliable for the next generation of nuclear reactors [1]. A potential scenario for severe nuclear accidents is reactor core meltdown, during which core debris relocates to the lower head of the reactor pressure vessel (RPV) and threatens its integrity. In-vessel retention (IVR) is a set of strategies that aims to confine this debris and control RPV damage. Next-generation nuclear reactors are built to allow flooding of the vessel cavity with water to remove core decay heat through the external wall of the RPV, avoiding its structural failure and release of radioactive material.

Various methods have been proposed for enhancing IVR performance and reliability, including using nanofluids [2–5] or surfactant solutions [6–8] instead of water and modifying the RPV outer wall [9–14]. Mori et al. [15] proposed a combination of two approaches, the adoption of TiO_2 nanofluid as coolant and the attachment of a honeycomb porous plate (HPP) to the RPV outer wall to improve the critical heat flux (CHF). They found that the CHF increased when using the nanofluid concentrations tested (0 vol%, 0.001 vol%, and 0.1 vol%), with a CHF of 3.2 MW/m^2 for 0.1 vol% nanofluid with an HPP attached to the surface. This CHF was more than three times the CHF of pure water on the same surface without the HPP (1.0 MW/m^2).

Due to a shortage of freshwater, seawater was employed during the 2011 accident at the Fukushima Daiichi Nuclear Power Plant. This event raised the question of whether seawater can be employed as coolant during IVR efforts. If its viability is proven, seawater could represent a simple and economically attractive alternative compared with other methods.

Raghupathi and Kandlikar [16] investigated artificial seawater pool boiling on a 10 mm x 10 mm copper boiling surface and compared the results to those for distilled water. They found the CHF of seawater to be 52% higher than that of distilled water. They also studied the effect of scale formation during extended periods of time at an approximately constant heat flux. To this end, they

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Nomenclature

q	heat flux (W/m^2)
h	boiling heat transfer coefficient (W/(m^2 K))
T	temperature (K)
d_1	diameter of heat transfer surface (m)
d_2	diameter of copper block upper body (m)
d_{ch}	honeycomb porous plate channel width (m)
k	thermal conductivity (W/(m K))
c_{pl}	specific heat of liquid (J/(kg K))
H_{lg}	latent heat of evaporation (J/kg)
C_{sf}	Rohsenow correlation constant
g	gravitational acceleration (m/s^2)

Greek characters

δ_h	height of the honeycomb porous plate (m)
δ_w	width of the honeycomb porous plate wall (m)
ρ	density (kg/m^3)
μ	viscosity (N s/m^2)
σ	surface tension (N/m)

Subscripts

l	liquid
v	vapor
w	wall
i	thermocouple number
sat	saturation
CHF	critical heat flux

developed a passive method using stainless steel beads to remove scale from the boiling surface during the experiment. Without the beads, the wall superheat increased from 27 K to 34 K during the boiling experiment. Adding the beads resulted in significantly lower wall superheat, which decreased from 16.6 K at the beginning of the experiment to 12.0 K at the end. From these experiments, they concluded that additional nucleation sites and increased thermal resistance due to scale formation were responsible for the higher CHF and wall superheat observed for artificial seawater.

Uesawa et al. [17] performed experiments for nucleate pool boiling of distilled water, solutions of NaCl (3.5 wt%, 7 wt%, and 10 wt%), artificial seawater (3.5 wt%, 7 wt%, and 10 wt%), and real seawater on a 10 mm × 10 mm copper printed circuit board surface. Similar CHF values were found for distilled water (0.92 MW/m^2), NaCl solutions (0.95 MW/m^2), real seawater (0.95 MW/m^2), and artificial seawater with a concentration of 3.5 wt% (0.96 MW/m^2). The accumulation of deposits was only observed for artificial seawater with concentrations of 7 wt% and 10 wt%, which produced CHFs of 0.60 MW/m^2 and 0.12 MW/m^2, respectively. Moreover, the layer of salt deposited during the experiment on the boiling surface was verified to be mainly composed of $CaSO_4$.

The present study focused on clarifying the effect of an HPP on the CHF in saturated pool boiling of seawater, which represents the first step toward investigating whether IVR can be improved by combining an HPP attached to the outer wall of the RPV with the use of seawater to flood the vessel cavity. If feasible, both options are economically attractive and easily applied in comparison with other IVR alternatives.

2. Experimental apparatus and procedures

2.1. Experimental apparatus

Fig. 1 is a schematic of the experimental apparatus, which was housed in a cylindrical Pyrex glass vessel with a height of 500 mm and inner diameter of 87 mm. Inside the glass vessel was a condenser to keep the working fluid volume constant, a pre-heating element of 25 Ω resistance to degas the working fluid, and a K-type thermocouple to monitor the fluid bulk temperature.

The boiling surface was a circular upward-facing plain copper surface 30 mm in diameter. It was the top of a copper block which had seven cartridge heaters (13.7 Ω) at the bottom. Except for boiling surface which is referred to heated surface in the following, the copper block was covered with fiberglass insulation to avoid heat losses as much as possible. The upper part of the copper block body was a cylinder 32 mm in diameter, and it had four thermocouples (TC1, TC2, TC3, and TC4), spaced 5 mm apart and inserted in its central axis. Fig. 1 also shows a detailed sketch of the copper block. Outputs from TCs were recorded at a sample frequency of 1 Hz during the experiment.

2.2. Honeycomb porous plate

The HPP used in this experiment was a ceramic grid structure, made of *$CaOAl_2O_3$ (30–50 wt%), fused SiO_2 (40–60 wt%) and TiO_2 (5–20 wt%)*, with 200 cells/inch^2. Fig. 2 shows the structural design and dimensions of the HPP. Its porous walls had height δ_h of 1 mm and thickness δ_w of 0.4 mm; the walls had capillary pores with median radius of 0.13 μm and porosity of 24.8% and square-shaped channels (cells) with side width d_{ch} of 1.3 mm. These channels provided a path for vapor to leave the heated surface.

The CHF enhancement capability of an HPP lies in two main mechanisms: (1) the capillary action provided by the micropores in its walls, which draws the fluid toward the boiling surface, and (2) the separation of fluid and vapor flow paths in the channels. The vapor leaves the heated surface at the center of the channels and the liquid is pulled toward the surface by gravity at the channel edges. The performance and CHF enhancement capabilities of the HPP employed here were extensively studied by Mori et al. [18,19].

No adhesive was used to fix the HPP to the surface; instead, it was attached by pressing it against the surface with stainless steel wires. Fig. 3 shows the boiling surface with and without the HPP installed.

2.3. Working fluid

The artificial seawater was prepared by adding 35 g of Red Sea Salt from Red Sea Aquatics, Ltd., to 1 L of distilled water. The resulting artificial seawater had a concentration of salts and composition close to the average values found in real seawater [20], as shown by the elemental comparison presented in Table 1.

2.4. Experimental procedures

To prepare the boiling surface, it was polished with 2000-grit abrasive paper and cleaned with acetone. The vessel was filled with working fluid to a level 60 mm above the boiling surface. The working fluid was heated and maintained at its saturation temperature for 40 min to degas it. The pre-heater used to degas the liquid had a surface area of 0.014 m^2 and resistance of 25.0