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Rapid cooling of a high-temperature block by the attachment of a honeycomb porous plate on a nanoparticle-deposited surface

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HIGHLIGHTS

- Quenching period was reduced significantly by the honeycomb porous plate (HPP).
- The wettability and capillarity is important for reduction of quenching period.
- The combination of HPP and NPDS was the best to enhance quenching performance.

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ABSTRACT

One strategy for dealing with severe accidents is in-vessel retention (IVR) of corium debris. In-vessel retention consists of external cooling of the reactor vessel in order to remove decay heat from the molten core by lower head of the vessel. In this system, it is important to establish techniques to (1) cool the high-temperature reactor vessel in order to change the boiling regime from film boiling to nucleate boiling as soon as possible, because the heat transfer coefficient for film boiling is very low, and (2) enhance the critical heat flux (CHF), because heat removal is limited by the occurrence of the CHF condition at the outer surface of the reactor vessel. Furthermore, approaches for increasing the IVR capability must be simple and installable at low cost. Regarding (2) CHF enhancement, we have demonstrated CHF enhancement of a large heated surface by a honeycomb porous plate (HPP) in saturated pool boiling of distilled water.

In the present paper, we focus on the quenching behavior of a honeycomb porous plate on a nanoparticle-deposited surface. As a result, the quenching period was significantly reduced by approximately 22% as compared to the case of bare surface (without surface modification) due to the combination of nanoparticle deposition and a honeycomb porous plate.

1. Introduction

One strategy for dealing with severe accidents is in-vessel retention (IVR) of corium debris [1]. In-vessel retention consists of external cooling of the reactor vessel in order to remove decay heat from the molten core by lowering the head of the vessel. In this system, the establishment of techniques by which (1) to cool the high-temperature reactor vessel in order to change the boiling regime from film boiling to nucleate boiling as soon as possible because the heat transfer coefficient for film boiling is very low and (2) to enhance the critical heat flux (CHF) because heat removal is limited by the occurrence of the CHF condition at the outer surface of the reactor vessel is important. Furthermore, approaches for increasing the IVR capability must be simple and installable at low cost.

Regarding (2) CHF enhancement, we have demonstrated CHF enhancement of a large heated surface by a honeycomb porous plate (HPP) in saturated pool boiling of distilled water [2–8]. The CHF has been enhanced experimentally by more than approximately twice that of a bare surface (approximately 2.0–2.5 MW/m^2) with a diameter of 30 mm [8]. Moreover, for a HPP attached to a 50-mm-diameter nanoparticle-deposited surface regarded as an infinite surface [9], the CHF was enhanced up to 2.2 times (2.2 MW/m^2) [5], as compared to a bare surface. Regarding (1) enhancement of transition from film boiling to nucleate boiling, several interesting approach for improving quenching behavior have been proposed [10–18]. In the present paper, we focus on the quenching behavior by the surface modification, especially, a HPP. As a result, the quenching period was significantly reduced by the combination of nanoparticle deposition and a HPP.

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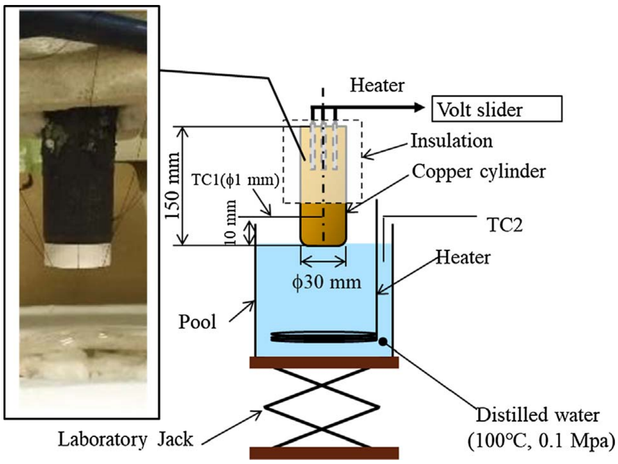


Fig. 1. Schematic diagram of the experimental apparatus.

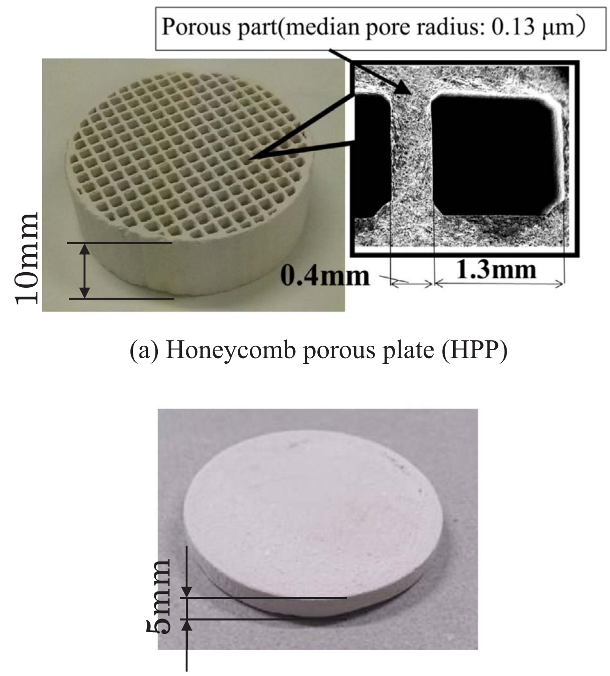
2. Experimental apparatus and procedure

A schematic diagram of the quenching test facility is shown in Fig. 1. The diameter and height of the test vertical rod were 30 mm and 150 mm, respectively. A sheathed Type K thermocouple (TC1) with an outer diameter of 1.0 mm was located 10.0 mm above the heat transfer surface and was inserted horizontally along the centerline of the copper cylinder. During the quenching experiments, the time varying outputs from the thermocouples were recorded on a digital recorder at a sampling frequency of 100 Hz. The pool was filled with approximately 4 L of distilled water, and the temperature of the pool was controlled to saturated conditions using a 0.5-kW immersion heater installed in the pool. The position of the water surface was adjusted by moving the laboratory jack as shown in Fig. 1.

The TiO_2 nanoparticles (Aero-sil Corporation, Aeroxide TiO_2 P 25) were selected as the test nanoparticles to prepare the nanoparticle-deposited surface. The average particle diameter supplied by the manufacturer was approximately 21 nm. For preparation of a nanoparticle-deposited surface (shown in Fig. 2), 4 L of water based nanofluid (0.1 vol%) was stirred for at least four hours using an ultrasonic bath. The nanoparticle-deposited surface was produced as follows. The copper block was heated to approximately 360 °C and immersed in nanofluid of 0.1 vol% to 1 mm from the heat transfer surface to the upper side, and then cooled to the saturation temperature only once. The vessel was then cleaned and refilled with distilled water.

Fig. 3 show the HPP and solid porous plate (PP) used in the present study [8], and a micrograph of HPP's structure is shown on the right-hand side of the figure (a). The HPP, which is commercially available, is used as a filter for purifying exhaust gases from combustion engines.

Fig. 2. Nanoparticle-deposited surface (NPDS).



(a) Honeycomb porous plate (HPP)

(b) Porous plate (PP)

Fig. 3. Tested porous plate.

The constitutive ingredients are $CaOAl_2O_3$ (30–50 wt%), fused SiO_2 (40–60 wt%), and TiO_2 (5–20 wt%). The cell width $d_{V'}$, the wall thickness δ_S of the grid, the aperture ratio, and the height of the HPP δ_h are 1.3 mm, 0.4 mm, 0.55, and 10 mm, respectively, as shown in Fig. 3(a). On the other hand, height of PP is 5 mm, the constitutive ingredients of PP are completely same with a HPP. The HPP and PP were pressed against the bottom of the boiling surface by stainless steel wire of 0.3 mm in diameter. No thermally conductive grease was used between these porous materials and the heated surface. The pore radius distribution of the HPP was measured by mercury penetration porosimetry, and it was peaked at approximately 0.17 μm. The median pore radius, the average pore radius, and the porosity of the HPP obtained by porosimetry are 0.13 μm, 0.037 μm, and 24.8%, respectively.

The experimental procedure is as follows. First, the copper rod was heated so that the temperature of TC1 was approximately 360 °C or 600 °C. The pool container with saturated water was then moved upward by a jack so that the water surface contacted the heat transfer surface. Heating of the copper block was stopped just as the water and heater surface came into contact. During the quenching experiment, the water level was adjusted manually to 1 mm from the heat transfer surface to the upper side.

The quench experiments were performed using a bare surface (BS) without any modification and four types of heat transfer surface with modifications: a PP attached to a bare surface (PP), a HPP attached to a bare surface (HPP), a nanoparticle-deposited surface on a bare surface (NPDS), and a HPP attached to a nanoparticle-deposited surface (NPDS + HPP) (see Table 1).

Table 1
Abbreviations on experimental conditions.

BS	A bare surface (BS) without any modification
PP	A porous plate (PP) attached to a bare surface (BS)
HPP	A honeycomb porous plate (HPP) attached to a bare surface (BS)
NPDS	A nanoparticle-deposited surface on a bare surface (BS)
NPDS + HPP	A HPP attached to a nanoparticle-deposited surface (NPDS)