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On the quenching of stainless steel rods with a honeycomb porous plate on a nanoparticle deposited surface in saturated water

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ABSTRACT

Quenching of a stainless-steel rod with a porous ceramic structure, i.e. honeycomb porous plate (HPP), attached to its lower surface was investigated in distilled water under saturated conditions at atmospheric pressure. The experiments were performed on bare surface (BS) and on a TiO_2 nanoparticle-deposited surface (NPDS). When the HPP was attached, the quenching rate increased significantly on both tested surfaces. The quench time for the NPDS with the HPP was 28-times shorter than that for the bare stainless-steel surface. The results suggested that the combination of the HPP ability to transport water to the heat-transfer surface by capillary action, and the increase of surface roughness, capillarity and wettability properties by the deposited nanoparticle layer were responsible for the enhancement obtained.

1. Introduction

Quenching refers to the rapid cooling of a hot object by exposing it to a cooler liquid. When a liquid and a solid with a large temperature difference between them are brought into contact, a vapor film that prevents direct solid-liquid contact is formed, such regime is known as film boiling. As the temperature decreases due to heat transfer through this vapor film, it becomes unstable and the heat transfer rate increases significantly due to local solid-liquid contact. Eventually, the vapor film vanishes and transition to nucleate boiling occurs, which is the desire working condition since it provides the highest heat transfer rates.

One of the applications for the current study is on in-vessel retention (IVR) of pressurized water reactors (PWR), which is a countermeasure in the event of a severe accident accompanied by nuclear fuel meltdown. In this situation, IVR, which involves external cooling of the reactor pressure vessel (RPV) to remove the decay heat from the melting core, is employed in order to assure the confinement of the molten fuel in the RPV. Recently, this technique has attracted attention as a new accident management strategy [1].

When cooling the RPV, it is important to accelerate the transition from film boiling to nucleate boiling, a much more efficient boiling regime, in order to avoid the RPV structural failure. Numerous studies with this purpose have been reported. Fan et al. [2] modified the surface of stainless steel spheres to investigate the effect of surface wettability on the cooling rate in saturated water at atmospheric pressure. It was found that the cooling period of super-hydrophilic spheres were 7 s shorter than that of the original clean spheres due to reduced film boiling period. Kang et al. [3] found that the heat transfer coefficient was significantly increased by capillary wicking and the use of a completely wettable surface (contact angle near to 0) produced by oxidation to form nano-pins.

In addition, using metal spheres, Sher et al. [4] clarified the effect of factors such as the type of metal, sphere diameter, and degree of sub-cooling on quenching. Shahriari et al. [5] found that the vapor film disappeared at higher temperatures when a voltage was applied between the liquid and the heat-transfer surface.

Hsu et al. [6] compared quenching of stainless still 304 and zircaloy-702 spheres in natural seawater and de-ionized water. They suggested that the formation of the vapor film was inhibited in seawater by the zeta-potential effect and thus this fluid provided a much shorter quenching time. High speed camera images of the boiling phenomena on both spheres were used to support their conclusion.

Furthermore, studies have reported increasing in cooling rate by depositing a thin uniform layer of nanoparticles on the heat-transfer surface [7–10]. For example, Kim et al. [11] pointed out that deposition of a nanoparticle layer destabilizes the formation of a vapor film, thereby facilitating liquid-solid contact locally, resulting in rapid cooling.

Another important requirement for IVR is improving the critical heat flux (CHF). Mori et al. recently proposed a CHF enhancement technique that involves attaching an HPP, which has pores for supplying liquid by capillary action and cells through which the

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Nomenclature

BS	Bare Surface
CHF	Critical Heat Flux
NPDS	Nanoparticle Deposited Surface
HPP	Honeycomb Porous Plate
HSP	Honeycomb Solid Plate
PWR	Pressurized Water Reactors
RPV	Reactor Pressure Vessel
IVR	In-Vessel Retention
TC	Thermocouple
k	thermal conductivity (W/m·K)
c	specific heat (J/g·K)
T	temperature (K)
d_v	HPP channel width (m)
δ_s	HPP wall thickness (m)
δ_s	HPP height (m)
ρ	density (kg/m^3)

Subscripts

L	liquid
S	solid

vapor escapes from the heated surface [12–15]. They also showed that quenching could be enhanced by attaching an HPP to a copper cylinder [16].

However, to apply these methods to IVR, it is necessary to consider the physical properties of the high-temperature body itself. Moreover, the quenching enhancement mechanism is not yet fully understood. Therefore, in the present study, we performed experiments using a high-temperature rod made of stainless steel, whose properties are similar to those of a RPV, and examined the details of the boiling mechanism using a high-speed camera. The effect of an HPP attachment and a nanoparticle deposited surface (NPDS) on quenching of the stainless-steel rod in distilled water at saturation temperature were also studied. Although in a real IVR scenario the coolant is in subcooled condition, the experiments were conducted in saturated condition. Film boiling is not detected in subcooled condition. Thus, in order to analyze film boiling regime on different surface conditions, saturated quenching was evaluated. Furthermore, since subcooled quenching is known to have a better performance than that of saturated [17], the results presented here represent the worst possible scenario in an accident situation.

2. Experimental apparatus and procedure

2.1. Experimental apparatus

Fig. 1 shows a schematic diagram of the quenching test facility. The vertical SUS304 stainless steel test rod was 115 mm long and 40 mm in diameter. In order to reduce the edge effect on quenching, the corners of the rod close to its lower end were chamfered at R5 mm resulting in a test surface of 30 mm in diameter. The temperature of the rod at 10 mm from the heated surface was monitored through a K-type sheath thermocouple (TC1).

The pool container was made of Pyrex glass and filled with distilled water, which temperature was measured with another thermocouple (TC2). The liquid was maintained at its saturation temperature using a 0.5-kW immersion heater. To keep water level constant, the pool was connected to a water reservoir. It made possible injection of liquid at saturated temperature into the pool, keeping it completely filled during quenching. Before the experiment, the rod and the pool were carefully positioned so that, after the pool was filled, the heated surface was submerged 1 mm into

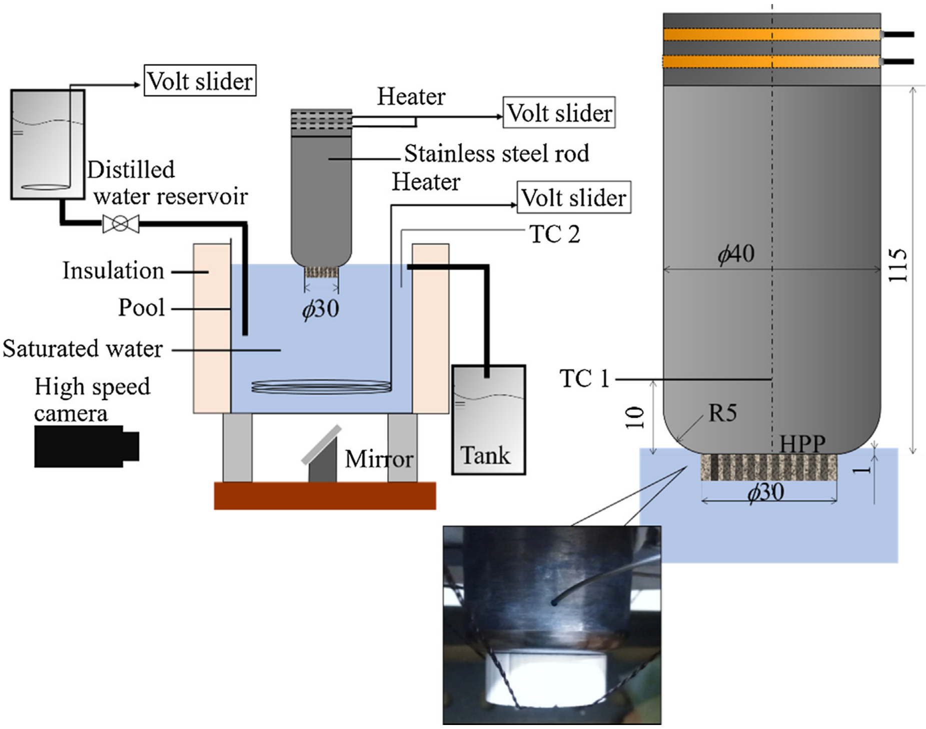

Fig. 1. Schematic diagram of the experimental apparatus. All dimensions are presented in millimeters.