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# An experimental study of the accelerated quenching rate and enhanced pool boiling heat transfer on rodlets with a superhydrophilic surface in subcooled water

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## ABSTRACT

Pool boiling heat transfer during quenching in subcooled water at atmospheric pressure was investigated on stainless steel rodlets with a superhydrophilic surface. It was shown that both the surface superhydrophilicity and degree of subcooling can accelerate significantly the quenching process. Under saturated condition, the quenching time is reduced by 50% for the superhydrophilic surface in comparison to the untreated one, due to the remarkable heat transfer enhancement with the critical heat flux being increased by 128%. The increase of the degree of subcooling can further reduce the quenching time. Frequent and intensive liquid-vapor interface fluctuations were observed visually during the initial phase of quenching for both saturated and subcooled conditions, indicating the absence of stable film boiling regime even though film-boiling-like boiling curves were obtained for the subcooled cases. Through visualized observations, the quench front was found to propagate upwards from the bottom of both the untreated and superhydrophilic rodlets. The propagation velocity could be accelerated noticeably with increasing the degree of subcooling. In addition, good durability and stability of the superhydrophilicity were exhibited by consecutive quenching tests up to 100 times.

## 1. Introduction

Quenching is an efficient approach to realization of rapid cooling, which has long been used in various applications. For example, in steelmaking industry the properties of steel products depend strongly on the quench cooling procedure. In water-cooled reactors, quenching occurs when the emergency cooling water is injected into the reactor core to cool down the nuclear fuel rods after a loss of coolant accident. The rate of quenching does not only affect the quality control of steel products, but also determines the safety threshold of nuclear reactors [1]. A quenching process usually starts with film boiling because of the very high initial superheat. As quenching proceeds, the vapor film will collapse to lead to transition boiling and nucleate boiling that occur in sequence. To achieve acceleration of quenching, premature collapse of the vapor film as well as enhancement of transition and nucleate boiling heat transfer are desired [2].

Boiling heat transfer performance could be affected significantly by surface properties, e.g., thermal conductivity, roughness, wettability, etc. Among these properties, surface wettability has a clear influence on boiling heat transfer from the thermodynamic point of view. According to the Wenzel's wetting theory for rough surfaces [3], surface wettability can be improved by either increasing the surface roughness or surface energy. Recently, various surface roughness-enhanced schemes, such as deposition of nanoparticles [4–10], surface oxidation [11–13], and micromachining [14,15], have been adopted to modify surface wettability, and its effects on boiling heat transfer performance during quenching has been studied experimentally. It has been found that better wettability is preferred to improve the rate of quenching by promoting the transition from film boiling to transition boiling as well as enhancing the critical heat flux (CHF). Superhydrophilic surfaces, as characterized by a near-zero static contact angle, have been exhibited to have a great potential in accelerating quenching [16,17]. In addition, ambient pressure and liquid subcooling have also been identified as the major factors influencing boiling heat transfer during quenching [18–23]. Numerous quenching experiments conducted in subcooled coolant have validated that increasing the degree of subcooling can reduce the duration of film boiling and improve the rate of quenching.

However, the quenching behaviors around a metallic rodlet in

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**Nomenclature**

| | |
|---|---|
| $c_p$ | specific heat capacity (J/kg K) |
| $D$ | diameter (m) |
| $k$ | thermal conductivity (W/mK) |
| $q''$ | heat flux (W/m$^2$) |
| $r$ | radial coordinate component (m) |
| $R$ | radius (m) |
| $t$ | time (s) |
| $T$ | temperature (°C) |
| $u$ | velocity (m/s) |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | thermal diffusivity (m$^2$/s) |
| $\delta$ | thickness (μm) |
| ρ | density (kg/m$^3$) |

*Subscripts*

| | |
|---|---|
| c | center |
| cl | coating layer |
| s | surface |
| sat | saturation |
| sub | subcooling |

subcooled condition, mimicking a fuel rod in light water reactors, and the coupling effect of surface wettability and liquid subcooling in quenching (and boiling) have not been fully addressed. In this paper, the accelerated quenching of stainless steel rodlets with a superhydrophilic surface in subcooled water was studied in comparison to the untreated hydrophilic surface. The effects of degree of subcooling of water were also investigated parametrically. The enhanced pool boiling heat transfer during quenching, along with the accelerated propagation of the quench front, was characterized through visualized observations.

## 2. Experimental

### 2.1. Surface preparation and experimental procedure

The surface wettability of cylindrical rodlet samples made of stainless steel 316L was modified by employing the spray coating method, as proposed by Vakarelski et al. [24]. A thin layer of silica nanoparticles was deposited on the stainless steel surface, thus creating a superhydrophilic surface through the increase in both surface roughness and surface energy [3]. The untreated and superhydrophilic surfaces were both subjected to a series of characterizations on their morphology, roughness, and wettability. As shown in Fig. 1, the layer of nanoparticles (with the cluster size ranging from ~50 nm to ~200 nm) is clearly seen in the scanning electron microscope (SEM) image on the superhydrophilic surface. The roughness profiles and the atomic force microscope (AFM) images indicate that the surface roughness was enhanced due to the presence of the coating layer. The ten-point mean roughness was found to increase from 0.510 ± 0.090 μm (untreated surface) to 0.629 ± 0.112 μm (superhydrophilic surface). The thickness of the coating layer of silica nanoparticles was found to be ~1 μm, as demonstrated in Fig. 1b, where an AFM image was taken near the boundary of a coating layer on a modified surface. It should be noted that the AFM imaging was performed on flat plate samples, instead of rodlet samples, made of the same material and with the same surface finish/modification. However, the static contact angles were measured directly on the untreated and superhydrophilic rodlet samples using sessile drop method with deionized water drops of a volume of ~3 μL at room temperature. The measurements were carried out on a goniometer equipped with a CCD camera (JC2000D1, Zhongchen Co. Ltd., China), and the tangent method was adopted to extract the contact angles. The untreated surface was shown to be hydrophilic with a static contact angle of ~41° (Fig. 1a), which reduces drastically to 0° for the modified surface (Fig. 1b), confirming the achievement of surface superhydrophilicity. Details regarding the surface preparation and characterization can be found in our previous work [22].

As shown in Fig. 2, the quenching test setup mainly consists of a radiative furnace (MTF 10/25/130, Carbolite Co. Ltd., UK), an electric motor driven slide track (LEFS16AB-200B-R16N, SMS Co. Ltd., Japan), a quench pool made of quartz glass to allow for direct visualization, a plate heater (c-mag HS10, IKA Co. Ltd., Germany), a high-speed camera (GX-1, NAC Co. Ltd., Japan), and a data acquisition system (Agilent 34972A, Agilent Co. Ltd., USA). The detailed description of the apparatus can be referred to our previous work [16]. A schematic drawing of the rodlet sample, which has a diameter of 10 mm and a length of 50 mm, is shown in Fig. 2a. Along the central axis of the rodlet, a semi-through hole of 1.5 mm in diameter and 25 mm in depth was drilled. A

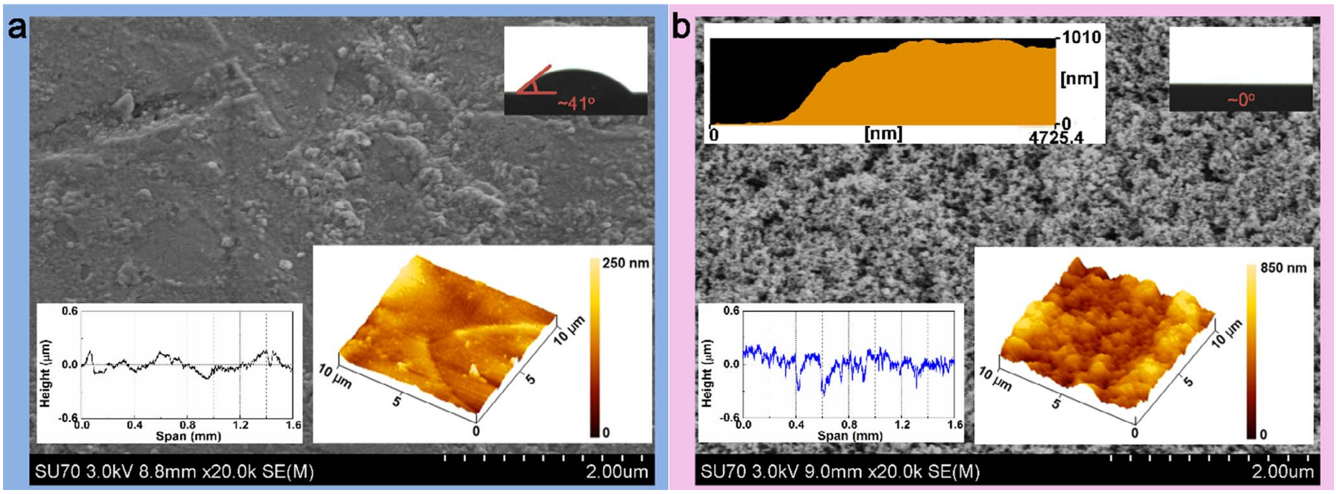

**Fig. 1.** Microscopic characterization by SEM imaging on the (a) untreated and (b) superhydrophilic surfaces, with the upper right insets illustrating the static contact angle on the two-types of rodlet samples (lateral view) and the lower insets showing the surface roughness measured by a profilometer (left) and three-dimensional surface morphology measured by AFM imaging (right). The upper left inset in (b) indicates the nominal thickness of the coating layer, as measured by AFM imaging as well.