



# Effect of nanoparticle deposit layer properties on pool boiling critical heat flux of water from a thin wire



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## ARTICLE INFO

### Article history:

Received 5 January 2011

Received in revised form 23 September 2013

Accepted 4 October 2013

Available online 1 November 2013

### Keywords:

Capillarity

Critical heat flux

Nanoparticle deposit

Thickness

Wettability

## ABSTRACT

Recent pool boiling heat transfer studies of nanofluids showed that nanoparticle deposit layer formed on a heater surface during nanofluid boiling can significantly increase critical heat flux (CHF). To identify the key parameter responsible for this observation, the effects of surface properties of the deposit layer on CHF of water were systemically studied, using various nanoparticle deposit layers applied to a thin wire heater by boiling in nanofluids. Different structures of nanoparticle deposits were obtained by controlling heat flux and time duration during nanofluid boiling. The deposit layers were quantitatively characterized using the surface parameters relevant to CHF phenomena, including wettability, capillarity and layer thickness. Performance of the nanoparticle deposits was then evaluated through pool boiling CHF experiments in distilled water. It was found that while wettability fails to interpret the CHF values on thin nanoparticle deposit wires, capillarity and thickness of the layers shows good correlations. It is supposed that nanoparticle deposit layer with a thickness increases pore volumes to hold liquid macrolayer and induces capillary liquid flow toward dry area underneath bubbles growing on a heater surface, thus effectively delaying occurrence of local dryout and subsequent overwhelming rise of surface temperature that is the dominant mechanism of CHF on a thin wire.

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## 1. Introduction

Limit of nucleate boiling heat transfer, the so-called critical heat flux (CHF), can be enhanced by modifying heater surfaces. Several prior studies have demonstrated the considerable effect of surface modification on nucleate boiling CHF. Berenson [1] obtained ~20% CHF enhancement in n-pentane by mechanically treating a heater surface to increase roughness. LITER and Kaviany [2] demonstrated increases in CHF up to ~300% for pool boiling of pentane using modulated porous-layer coatings of 200 μm-diameter spherical copper particles on heater surfaces. Kim et al. [3] reported the significantly enhanced CHF in saturated FC-72 on a microparticle-coated platinum wire. Honda [4] gives a summary of recent advances in enhancing boiling heat transfer and CHF by use of surface microstructures, including a sand-blasted and KOH treated surface, a dendritic sink, laser-drilled holes, re-entrant cavities, integrated surface structures (e.g., channels and fins) and the application of a porous-layer coating to the surface.

The prevailing focus of the previous studies for modifying boiling surfaces has been on optimization of surface structures at milli/microscale. On the other hand, the recent studies on

nano-engineered surfaces have been suggesting that there exists a huge room to significantly enhance CHF by modifying a heater surface at nanoscale. Ujereh et al. [5] studied the impact of the carbon nanotubes (CNT) coating on pool boiling performance. They found that coating the substrate surface with CNTs was highly effective at reducing the incipient superheat and greatly enhancing both the nucleate boiling heat transfer and CHF. Chen et al. [6] applied nanowire arrays made of Si and Cu to boiling surfaces, and achieved increases in both CHF and the HTC by more than 100%. Very lately, Im et al. [7] fabricated Cu nanowire arrays (300 nm in pitch and 200 nm in diameter) on a silicon substrate to generate a high performance boiling surface with application to high power electronic devices. Similar to the previous studies, they also demonstrated favorable effects of nanostructures on the CHF characteristics. While the milli/micro-scale surface modification gives attention to the building structures to promote heterogeneous nucleation of bubbles and circulation of micro-scale two-phase flow near the heater surface, nano-scale structures changes further fundamental interfacial properties between solid and liquid under thermally unbalanced condition. Kim et al. [8] actually demonstrated that the hybrid surface of micro-islands and nano-posts can intensify nucleate boiling CHF enhancement beyond the sole effect of micro-features. Thus, the nanostructures have a unique potential to further improve nucleate boiling CHF performance of

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## Nomenclature

$C_p$	heat capacity [J/kg-°C]
$h_{fg}$	latent heat of vaporization [kJ/kg]
$L$	characteristic length scale [m]
$L_c$	capillary rise of water [m]
$q''_{CHF}$	CHF value [kW/m <sup>2</sup> ]
$q''_{CHF,NF}$	nanofluid's CHF value [kW/m <sup>2</sup> ]
$q''_{CHF,Z}$	Zuber's CHF value [kW/m <sup>2</sup> ]
$q''_{max}$	applied maximum heat flux [kW/m <sup>2</sup> ]
$q''_{porous}$	heat flux gain due to porous layer [kW/m <sup>2</sup> ]
$R$	radius [m]
$R_c$	effective capillary radius for micro/nano-structured surface, $R_c$ [m]
$R'$	dimensionless radius ( $R' = R\sqrt{g(\rho_f - \rho_g)/\sigma}$ ) [ - ]

## Greek Letters

$\delta$	macrolayer thickness [m]
$\varepsilon$	porosity [ - ]
$\theta$	contact angle [degree]
$\rho$	density [kg/m <sup>3</sup> ]
$\sigma$	surface tension [N/m]
$\tau_d$	time to dry out the liquid macrolayer [sec]

## Subscripts

$f$	liquid phase
$g$	gas phase
$porous$	porous layer

a surface with micro-scale modification. However, there is still a lack of understanding about the nano-scale surface effects on nucleate boiling heat transfer and CHF.

In 2003, You et al. [9] initially demonstrated that the addition of nano-sized (1–100 nm) particles to base fluids, the so-called nanofluids, can significantly increase CHF up to 200% at relatively low nanoparticle concentrations, typically less than 0.1 vol%. However, any existing CHF correlation could not interpret the CHF increase observed in their experimental study. Such an abnormal CHF increase in pool boiling of nanofluids has been an intriguing but challenging topic in science as well as for industrial applications such as cooling of electronics and high density power dissipation systems. Several research groups thus have extensively investigated the characteristics and physical mechanism of CHF increase in nanofluids to utilize the fundamental finding as a technology [10–24]. As a result, a consensus has been established that the significant CHF increase in nanofluids is resulted from modification of a heater surface by nanoparticle deposition layer formed during nanofluid boiling, while the physical mechanism of the CHF increase is not well understood. It is now generally accepted that nanofluids significantly enhance CHF through the modification of the heater surface at nanoscale via the formation of a nanoparticle deposit layer which alters surface-liquid interfacial properties. Deposition of nanoparticles on a heater surface during nanofluid boiling can enable us to manufacture the micro/nanoscale surface structures in great vari-

ety, by controlling parameters of boiling process, including heat flux and time duration. Then, the parametric effects of surface properties with nanostructures on CHF can be extensively investigated using the various deposit layers prepared. Accordingly, such parametric studies can give some insight into the physical mechanism of the CHF increase on nanostructured surfaces.

The objective of this study is to identify key surface parameters of thin nanoparticle deposit layers responsible for such a high CHF enhancement. A number of titania nanoparticle deposit layers with different structures are prepared on a 0.2 mm-diameter NiCr wire heater by varying nanofluid boiling parameters including heat flux and boiling duration. The prepared layers are quantified using plausible surface-liquid interfacial properties associated with boiling CHF phenomenon, including wettability, capillarity and porous layer thickness. Pool boiling CHF performance of the nanoparticle layers is then evaluated in deionized water at atmospheric pressure. Then, the relations between the surface properties and CHF values on the nanoparticle deposit layers are examined in company with discussion of plausible physical mechanisms.

## 2. Experiments

### 2.1. Preparation of nanoparticle deposit layers

Nanoparticle deposit layers were prepared by boiling clean substrates in water-based titania (TiO<sub>2</sub>) nanofluids at the concentration of 0.01 vol%. The boiling for the preparation of the deposit layers were conducted with the pool boiling apparatus used for the main test in Section 2.3. The substrates were 0.2 mm diameter thin NiCr wires (80% Ni, 20% Cr). Titania-water nanofluids were prepared by dispersing dry nanoparticles into pure water by means of ultrasonic agitation for 3 h. The dry particles used were manufactured by Advanced Nano Product Corporation (Korea) using the sol-gel process, and the average particle diameter supplied by vendor was 47 nm. Fig. 1 shows the scanning electron microscope (SEM) images of the dry nanoparticles.

According to Asakura et al. [25], nanoparticle deposition on a surface during nucleate boiling is mainly influenced by heat flux of the heated surface, boiling time, concentration of nanoparticles, and pH of the suspension. In the present work, the heat flux and boiling time during nanofluid boiling were systemically controlled to prepare various features of nanoparticle deposit layers while the nanoparticle concentration and pH of nanofluids were fixed to be 0.01% of volume fraction and pH 7, respectively. Fig. 2 illustrates detail procedures of the nanofluid pre-boiling to obtain different characteristics of the nanoparticle deposits. First, with increasing heat flux

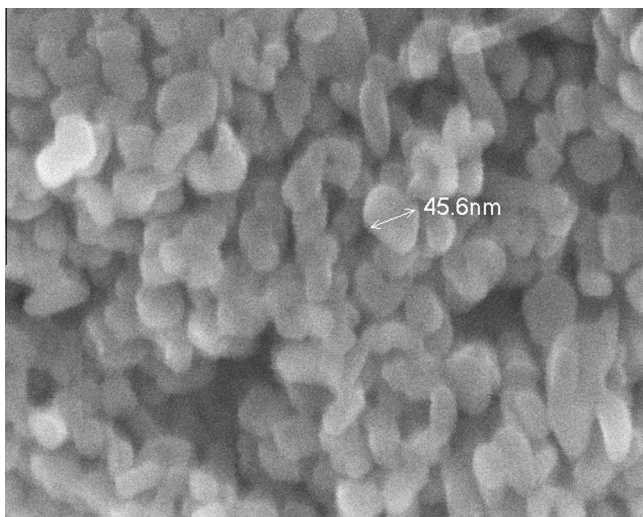


Fig. 1. SEM image of dry TiO<sub>2</sub> nanoparticles.

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