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An experimental investigation on wettability effects of nanoparticles in pool boiling of a nanofluid

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ABSTRACT

Wettability effects of nanoparticles on pool boiling heat transfer of a nanofluid are investigated experimentally for the first time in this paper. The mechanism on wettability effects of nanoparticles in pool boiling is revealed by a visualization study of bubble dynamics in the nanofluid, and by analyzing the morphology of nanoparticle deposition layers on the heater surface as well as residue patterns after nanofluid droplets evaporation on a glass surface. The enhancement and deterioration of boiling heat transfer of nanofluids as compared with their base fluid are attributed to different wettabilities of nanoparticles, resulting in different bubble behaviors and different morphologies of nanoparticle deposition layers. It is found that (i) nanofluids containing *moderately hydrophilic* nanoparticles enhance boiling heat transfer at fully-developed nucleate boiling regime with a significant increase in critical heat flux, and (ii) nanofluids containing *strongly hydrophilic* nanoparticles do not enhance nucleate boiling heat transfer, and the *strongly hydrophilic* nanoparticle deposition layer deteriorates boiling heat transfer coefficient.

1. Introduction

Boiling heat transfer of a nanofluid is a very complex phenomenon, possessing many characteristics different from those of its base fluid [1,2]. The nucleate boiling heat transfer coefficient of a nanofluid has been reported to increase [3,4], decrease [5,6] or remain unchanged relative to its base fluid [7]. In early dates, the enhancement of convective heat transfer coefficient of a nanofluid compared with its base fluid [8] has been attributed to the increase in thermal conductivities and Brownian motion of nanoparticles [9]. Sonltani et al. [10] suggested that the increase in thermal conductivity of a stable nanofluid resulted in an increase of heat conduction in the microlayer, thus increasing nucleate boiling heat transfer of a nanofluid. However, since the enhancement of nucleate boiling heat transfer coefficient was much larger than the enhancement in thermal conductivity, Wen et al. [3] concluded that the enhancement of nucleate boiling heat transfer of a nanofluid could not be attributed only to the increase in its thermal conductivity.

In recent years, the following two school of thoughts on the enhanced boiling heat transfer mechanism of a nanofluid have emerged:

(i) Formation of a deposition layer on the heater surface during boiling of a nanofluid.

According to the nanoparticle deposition theory proposed by Kim et al. [11] and confirmed by Kwark et al. [12], if nanoparticles were confined in the microlayer under bubbles, these nanoparticles would deposit on the heater surface after dryout of the microlayer. Kim et al. [13] suggested that nanoparticles deposited on heater surfaces during boiling of nanofluids could enhance wettability of heater surface, thus possibly decreasing active nucleate density and increasing critical heat flux. Narayan et al. [14] proposed that the enhancement or deterioration in nucleate boiling heat transfer coefficient of a nanofluid depended on the ratio of heater surface's roughness to the nanoparticles' average diameter. However, the nanoparticle deposition layer on a heater surface could result in additional thermal resistance between fluid and heater surface [12,15], thus deteriorating boiling heat transfer coefficient. Vafaei et al. [1] noted that nanoparticles might deposit on the heater surface in agglomerate form. However, it has also been reported that nanoparticles did not deposit on the heater sur-

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face [16], or deposited on the heater surface irregularly [17] during nucleate boiling of nanofluids.

(ii) Reduction of bubble size in a nanofluid

Vafaei et al. [18] found that suspended nanoparticles could decrease surface tension of nanofluids, which could reduce radius of bubbles in nucleate boiling of nanofluids, and thus enhancing nucleate boiling heat transfer rate. Tu et al. [19] observed that vapor bubbles in pool boiling of water-based Al_2O_3 nanoparticle suspensions were smaller than those that in boiling of pure water. By investigating gas bubble behaviors in nanofluids [20–22], Vafaei et al. [23] proposed that the structural disjoint pressure (resulting from nanoparticles confined in the microlayer under vapor bubbles) could also affect vapor bubbles behavior in boiling of nanofluids. Xu et al. [24] found that vapor bubbles in flow boiling of nanofluids containing γ-Al_2O_3 nanoparticles were smaller than those in boiling of pure water due to the structural disjoint pressure in the microlayers of bubbles. They suggested that the structural disjoint pressure enhanced bubble departure, causing smaller bubbles in flow boiling of nanofluids.

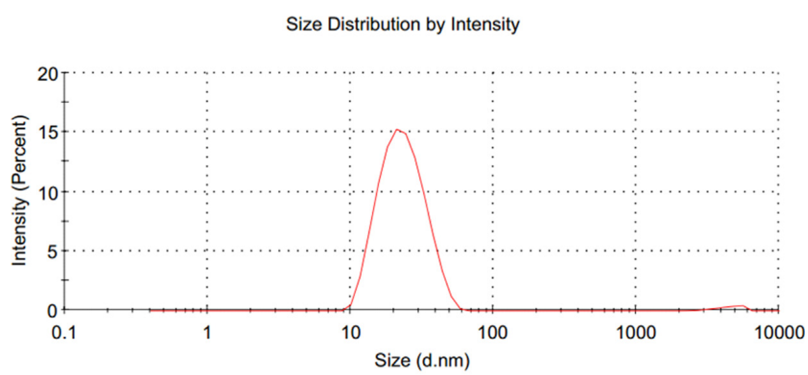
In this paper, we propose that (i) the wettability of nanoparticles can affect the surface roughness of the heater surface, and nanoparticles with suitable wettability can reduce the amount of their deposition on the surface. This speculation is confirmed by our experiments on drying patterns of nanofluid droplets in Section 2.2 with the assistance from drying pattern deposition theories [25–28]. Furthermore, morphologies of nanoparticle deposition layers are studied to examine wettability effects of nanoparticles on modification of the heater surface in Section 2.3.3; (ii) vapor bubble coalescence can be controlled by changing the wettability of nanoparticles based on the pioneering work on gas bubble stabilized by solid particles [29,30]. This proposal is verified by direct observation of bubble size in our experiments on pool boiling of nanofluids with nanoparticles having different wettabilities in Section 2.3.2.

Based on these experimental results, we can conclude that wettability of nanoparticles can affect nucleate boiling heat transfer coefficient of a nanofluid through influencing bubbles size and altering morphology of nanoparticle deposition layers on heater surfaces. As far as we are aware, this is the first time that wettability effects of nanoparticles on bubbles behavior in boiling of nanofluids and on morphologies of nanoparticle deposition layers are investigated.

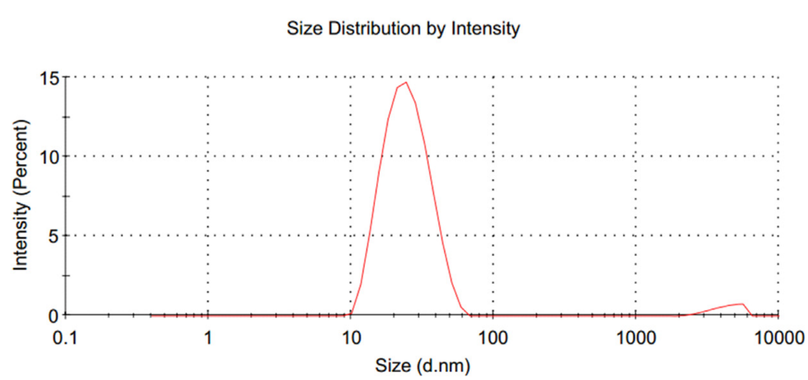
2. Experimental investigations

2.1. Nanoparticles preparation and contact angle measurement of nanoparticles

A two-step method was used to synthesis silica nanoparticles with different wettabilities. In the first step, silica nanoparticles were synthesized by the method given by Stober et al. [31]. Then, surfaces of silica nanoparticles were modified by different silanes, and wettabilities of silica nanoparticles were changed, depending on the wettability of the silane. In the following, silica nanoparticles with surface modification by sulfo groups will be called *strongly hydrophilic* while those with surface modification by polyethylene glycol groups will be called *moderately hydrophilic*. The mass ratio of reacting silane and nanoparticles was 1:1. Because surfactant could affect boiling experiments of nanofluids [4,32] and sessile nanofluid droplet evaporation experiments [27,33],



(a) Size distribution of *strongly hydrophilic* nanoparticles



(b) Size distribution of *moderately hydrophilic* nanoparticles

Fig. 1. Size distribution of nanoparticles in suspensions measured by DLS.