



The effect of concentration on transient pool boiling heat transfer of graphene-based aqueous nanofluids



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ARTICLE INFO

Article history:

Received 28 May 2014

Received in revised form

30 December 2014

Accepted 12 January 2015

Available online

Keywords:

Pool boiling

Quenching

Nanofluids

Graphene oxide

Surface roughness

Surface wettability

ABSTRACT

Transient pool boiling experiments were performed by quenching of stainless steel spheres in dilute aqueous nanofluids in the presence of graphene oxide nanosheets (GONs) at various concentrations (by weight) up to 0.1 wt.%. All the experiments were performed for saturated boiling at atmospheric pressure. Quenching and boiling curves were obtained for the nanofluids in comparison to the baseline case of pure water. It was shown that quenching is accelerated upon increasing the concentration of GONs. The enhanced boiling heat transfer by the nanofluids was interpreted in relation to the modified surface properties, including morphology, wettability, and roughness, on the quenched surfaces. Unlike the findings in available relevant studies that point to surface wettability change, however, the primary cause of critical heat flux (CHF) enhancement was observed to be related to the increased surface roughness serving as paths to facilitate solid–liquid contacts. The increases of both nucleation site density and liquid agitation intensity as a result of the presence of porous structures at relatively high concentrations were also found to be responsible for the enhanced CHF.

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1. Introduction

Pool boiling and its enhancement has long been a subject of interest to the heat transfer community [1]. During the last decade, a new dimension has been added to this traditional area by the inspiration of emerging nanotechnology. The adoption of nanofluids, i.e., engineered colloidal suspensions with highly-conductive nanoparticles, as a novel working fluid for pool boiling enhancement has attracted intensive attention [2–6]. A great number of experimental studies on this topic have revealed that the primary cause of pool boiling enhancement by nanofluids is linked to the modified surface properties due to deposition of nanoparticles during pool boiling [7–10]. This approach may thus be considered a passive means of surface modification toward pool boiling heat transfer and critical heat flux (CHF) enhancement. Owing to the passive nature of this approach, the modified surface properties, i.e., wettability, roughness, and porous structures, depend strongly on the material, size, shape, and concentration of the nanoparticles, and on the surfactants, if any, in suspensions and original boiling surface features as well.

Concurrent with the emergence of candidate nanoparticles for preparation of nanofluids, intensive efforts have been dedicated to exploiting and assessing their utilization in pool boiling enhancement [11]. Carbon nanomaterials, carbon nanotubes (CNTs) for example, have played the leading role due to their inherently high thermal conductivity and low density [12–14]. It is noted that the above-mentioned studies are examples where the quenching (transient cooling) technique featuring easy and rapid establishment of entire boiling curves were used in supplement to the widely adopted steady-state heating method [11–14]. More recently, focus has been moved onto a new comer to the existing family of carbon nanomaterials, i.e., graphene and its derivatives [15–23]. Remarkable CHF enhancement has been achieved using graphene-based nanofluids even at extremely dilute concentrations [15,21,22]. The primary cause has been directed to the unique surface modification, especially the significant wettability change toward hydrophilic state, as a result of graphene deposition that is associated with the two-dimensional planar shape of high aspect ratios. There is, however, so far in available literature a lack of careful examination on the effect of concentration of graphene-based nanofluids on their pool boiling behaviors.

This study aims at investigating experimentally pool boiling of dilute aqueous nanofluids in the presence of graphene oxide

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| Nomenclature | | V | volume, mm^3 |
|--------------|---|----------------------|--|
| A | area, mm^2 | <i>Greek symbols</i> | |
| Bi | Biot number | α | thermal diffusivity, m^2/s |
| c_p | specific heat, $\text{J}/\text{kg K}$ | δ | vapor film thickness, μm |
| D | diameter, mm | ϕ | concentration (by weight or volume) |
| g | gravitational acceleration, m/s^2 | μ | dynamic viscosity, $\text{N s}/\text{m}$ |
| h | heat transfer coefficient, $\text{W}/\text{m}^2 \text{K}$ | ν | kinematic viscosity, m^2/s |
| H | latent heat of evaporation, J/kg | ρ | density, kg/m^3 |
| Ja | Jakob number | <i>Subscripts</i> | |
| k | thermal conductivity, $\text{W}/\text{m K}$ | l | liquid |
| Nu | Nusselt number | MHF | minimum heat flux |
| q'' | heat flux, W/m^2 | sat | saturation |
| Ra | Rayleigh number | v | vapor |
| t | time, s | | |
| T | temperature, $^\circ\text{C}$ (or K) | | |

nanosheets (GONs) at various concentrations by means of the quenching technique. Interpretation of the experimental data is attempted in relation to characterization of the modified surface properties including morphology, wettability and roughness, in order to give insight into the underlying physical mechanisms of the observed phenomena. A heat transfer analysis is also performed to quantify the effect of concentration.

2. Experimental

2.1. Experimental setup and data reduction

Transient pool boiling experiments were performed on a compact quenching facility. As shown in Fig. 1, the key components included a tube furnace, an electric slider, a quench pool, and a plate heater. The tube furnace was arranged vertically on top of the rectangular pool vessel made of quartz glass with a top

opening. Polished stainless steel spheres, with a diameter of 10 mm, were employed as the quenching object. Being fixed on the computer-controlled slider through a brass tube, the sphere was allowed to move up and down vertically along a track. A sheathed type-K thermocouple (TC) was mounted in such a way that its bead was right attached to the center of the sphere. Details of assembly and specifications of the experimental setup have been reported elsewhere [24]. The quenching liquid, i.e., aqueous GON nanofluids in this study, was heated up to the saturation point (100°C at atmospheric pressure) by the heater placed underneath the pool, also allowing for degassing of the quenching liquid prior to experiments. It is noted that only saturated boiling was concerned in all experiments. A typical run of the quenching experiments begun with preheating of the sphere to 400°C while being suspended in the tube furnace, followed by descending the hot sphere to immerse quickly into the pool that triggers the quenching processes.

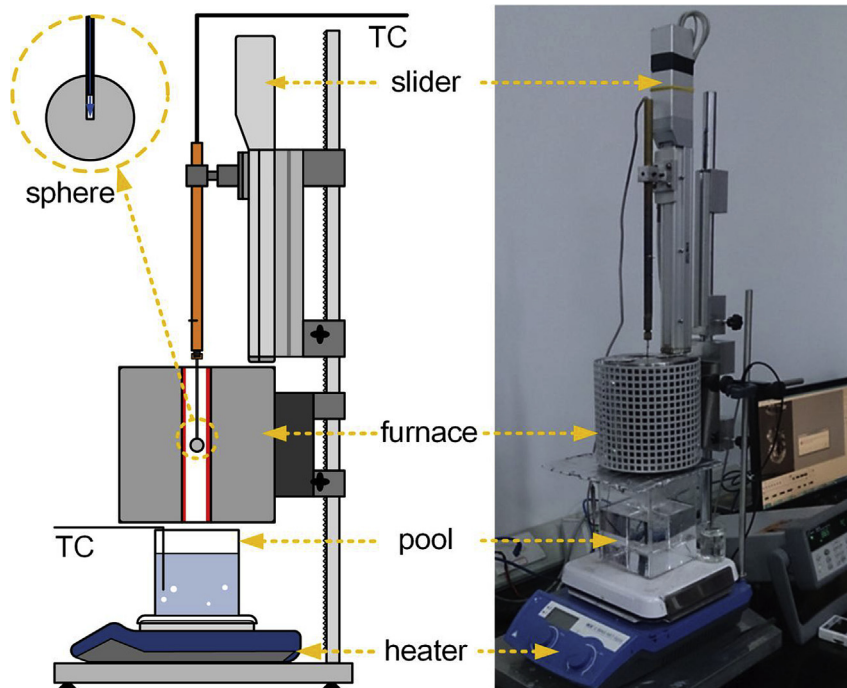


Fig. 1. Schematic diagram (left) and photograph (right) of the quenching facility.

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