



# Role of nanoparticles on boiling heat transfer performance of ethylene glycol aqueous solution based graphene nanosheets nanofluid



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## ABSTRACT

As the ethylene glycol aqueous solution (EG/DW) with a volume fraction of 60:40% (the ratio of ethylene glycol (EG) and deionized water (DW)) was widely used as an antifreeze solution, pool boiling heat transfer (BHT) characteristics including boiling heat transfer coefficient (HTC) and critical heat flux (CHF) of EG/DW based graphene nanosheets (GNs) nanofluids are experimentally investigated under atmospheric pressure. The influence of heat flux and nanoparticles mass fraction on the boiling heat transfer has been measured and discussed. Boiling curves were obtained for the nanofluids compared with the baseline case of EG/DW. It was shown that for low concentration (i.e., mass fraction up to 0.02%) GNs-EG/DW nanofluids, the boiling performance of the EG/DW had been obviously enhanced by adding GNs nanoparticles, which was resulted from the enhancement of surface wettability caused by nanoparticles deposition. However, further loading GNs in EG/DW reduced the BHT capability of EG/DW, results from the GNs sedimentation and subsequent blockage of the nucleation sites. At the small concentration less than 0.02%, the CHF rapidly increases with increasing nanoparticle concentration. However, the CHF magnitude is almost the same for GNs-EG/DW nanofluids with concentration beyond the critical concentration.

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## 1. Introduction

Since heat transfer phenomena widely exist in nature and the requirement for heat transfer is becoming stricter and stricter, many investigations focus on enhancement [1–3] or reduction [4] of heat transfer. Among many heat transfer forms (heat conduction [5], convection [6], and radiation [7]), BHT is the most effective convective heat transfer form as its huge potential for thermophoresis in a rather low temperature difference. It is fairly a short time between the conception of “nanofluids” put forward in 1995 [8] and the publications of BHT performance of nanofluids reported in the year of 2003 [9,10], which shows a strongly urgent requirement for efficient BHT medium in thermal engineering, i.e., electrical engineering, fluid mechanical engineering, refrigeration engineering and vehicle engineering.

Sheikhhahai et al. [11] stated that the addition of nanoparticles into base fluids was an effective method for BHT augmentation. They also made a strategic vision to combine BHT with an active method for intensified augmentation. Rana et al. [12] performed an experimental study on the subcooled flow boiling of ZnO–water

nanofluids. Results show that adding nanoparticles can increase the maximum bubble diameter and decrease the bubble density. Literatures about enhancement of heat transfer coefficient and critical heat flux were widely published. Soltani et al. [13] investigated the pool boiling heat transfer of non-Newtonian nanofluids. With increasing the concentration of carboxy methyl cellulose in water, the heat transfer was weakened. While with the presence of nanoparticles, the heat transfer was enhanced. Liu et al. [14] experimentally studied the nucleate BHT of CuO–H<sub>2</sub>O nanofluids at various operating pressures and nanoparticle mass concentrations. They concluded that the HTC and the CHF increase slowly with the increase of nanoparticle mass concentration when lower than 1.0 wt.%. Heris [15] studied the influence of low concentration ethylene glycol–water based CuO nanofluids on pool boiling, finding an enhancement about 55% of HTC. In the experimental investigation of Kim et al. [16], they compared flow BHT in water-based nanofluids with different nanoparticles. Flow boiling CHF was enhanced on various degrees depending on nanoparticle materials and operating conditions. An attempt had been made to study the interactions between the concentration and the heater surface giving due consideration to the transient nature of the boiling process by Harish et al. [17]. It was indicated that the Al<sub>2</sub>O<sub>3</sub>–H<sub>2</sub>O nanofluid resulted in a better performance compared to the base fluid on a rough heater. However, it also showed a deteriorated boiling

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performance on a smooth heater surface and the percentage of deterioration clearly increases with increasing the nanoparticle concentration. In the study of Zhang et al. [18], a porous surface had been recognized as an efficient medium to increase the boiling performance in a nucleate boiling regime, and a significantly enhanced pool BHT was observed in a submicron regime through three dimensionally interconnected hybrid pores. At a lower heat flux regime (20–40 kW/m<sup>2</sup>), the HTC enhancement was 200% and the HTC augment within the range of 40–100 kW/m<sup>2</sup> was 75% when compared to that of the plain surface. Bang and Chang [19] investigated the pool boiling heat transfer performance of Al<sub>2</sub>O<sub>3</sub>–water nanofluids on a plain surface. They found that CHF had been enhanced both in horizontal and vertical pool boiling, and the Rohsenow correlation could predict the heat transfer performance. Park and Jung [20] investigated the effect of carbon nanotubes on nucleate BHT in R22 and water with the addition of 1.0 vol.% carbon nanotubes, and the nucleate BHT was enhanced up to 28.7% at a low heat flux. Peng et al. [21] investigated the heat transfer characteristics of R113 based CuO nanofluids. A maximum enhancement of HTC about 29.7% was found compared with pure refrigerant and a heat transfer correlation for nanofluids was proposed within the deviation of ±20%.

Ideally, the nanoparticle in a fluid itself can be used as the direct enhancement medium of BHT, which not only can simplify the infrastructure and reduce operation temperature for the heat exchangers, but also can improve the energy conversion efficiency and reliability. However, the nanofluid is not always an efficient direct enhancement medium of BHT. Many literatures [22–26] reported nanofluids as deterioration media of BHT. Almost all investigations about pool BHT performance of nanofluids have expressed varying degrees of nanoparticles deposition on heater surface, then the surface wettability was improved and significant enhancement was made in CHF at the expense of deteriorative BHT coefficient.

Much more than this, Kim et al. [27] found the pool boiling of pure water on the nanoparticle-coated heater sufficiently achieved the CHF enhancement of nanofluids. They attributed the CHF enhancement in pool boiling of nanofluids to the coating of nanoparticles on heating surface. Rana et al. [28] studied the flow boiling of water and ZnO–water nanofluids as a function of nanoparticle concentrations (0.001–0.01 vol.%) in a horizontal annulus, finding that the void fraction reduced with the increase of nanoparticle concentration. As mentioned above, the results can be explained through the fact that with the increase of nanoparticle concentrations, convective heat transfer increases and less energy is available at the heater surface for bubble nucleation due to plugging of nucleation cavities by nanoparticles. Transient pool boiling experiments were performed by quenching of stainless steel spheres in dilute aqueous nanofluids in the presence of GNs oxide nanosheets at various concentrations (by weight) up to 0.1 wt.% by Fan et al. [29]. In their work, the increase of both nucleation site density and liquid agitation intensity as a result of the presence of porous structures at relatively high concentrations was recognized to be responsible for the enhanced CHF.

It is believed that both the deposited nanoparticles on heater surface and the suspended nanoparticles into the base fluid could strongly affect the BHT performance. The reasons for enhancement or deterioration of the BHT coefficient in nanofluids were detailed discussed by Vafaei and Borca-Tasciuc [30], including the effects of substrate material, thermal conductivity of the deposition layer, the heat flux range, surface roughness, nucleation site density, and wettability.

It is widely convinced that BHT characteristics of nanofluids relate to many factors such as the material of the base liquid and heater surface, concentration and properties of nanoparticles (size, shape, kind, coating, etc.), and physical conditions including

temperature, pressure, heat flux, specific heat capacity, etc. However, the limited reliable experimental data and theoretical models impose restrictions on the understanding of the BHT mechanism in this interdisciplinary field. To the best of our knowledge, literature about boiling performance of GNs-EG/DW nanofluid has not been reported anywhere. Herein, we focus on the experimental results of BHT of 60:40 vol.% ethylene glycol aqueous solution based GNs nanofluids under atmospheric pressure. Experimental investigations were carried out to found out the most applicable GNs concentration for 60:40 vol.% ethylene glycol aqueous solutions.

## 2. Experiment

### 2.1. Nanofluids preparation

Few-layer GNs powders with thickness and layers of 0.335–3.35 nm and 1–10 were supplied by School of Materials Science and Engineering of Harbin Institute of Technology. It was prepared by the principle of metal magnesium burning in carbon dioxide and generating GNs, which was announced by the patent applicants [31]. The first picture in Fig. 1 shows a scanning electron microscopy (SEM) image of the nanoparticle, indicating that the GNs is a two-dimensional structure of thin plate shape consisting of several individual diameters from 10 to 20 μm, and the semi-transparency of the GNs particles also indicates their infinitesimally small thickness. By using a sensitive electronic balance (BSA423S, Sartorius Scientific Instruments Co., Ltd., Germany) with an accuracy of 1 mg, nanoparticle sample preparation was carried out. In order to manufacture a stable nano-suspension, properly proportioned DW and EG were adequately mixed as base fluid. Nanoparticles were dispersed into a constant volume (200 mL) of ethylene glycol aqueous solution with different mass concentrations (0.005%, 0.01%, 0.02%, 0.05%, and 0.1%, respectively). An ultrasonic cell crusher (Biosafe 900–92, Safer Co., Ltd., China) with an amplitude amplifier pole diameter of 6 mm, a working frequency of 20–25 kHz and ultrasonic power of 900 W was used to break down the large agglomeration. Both the ultrasound time and pausing time were set to 2 s. To ensure the stability of nanofluids, samples were magnetic stirred for 36 h and ultrasonic oscillated for 4 h. None surfactant was used in present study since it has a significant influence on the surface tension which will affect the boiling process. SEM images of dispersed graphene nanoparticles marked nanoparticle concentrations were shown in Fig. 1, which also ensured that the nanoparticles were broken down to a considerable extent. There was no visible sedimentation after 12 h in Fig. 2, thus the stability and reliability of nanofluids for present experimental study were confirmed.

As the graphene is added in a form of nanosheets, it is scarcely possible to break them into nanosize in all dimensions. Here we called this fluid as “nanofluid” due to the thickness of the graphene is in the range of 0.335–3.35 nm and considering as a one-dimensional nanosized material. Nanofluids contain one-dimensional nanosized particles are far from being rare [32,33].

### 2.2. Experimental setup

A hot wire method was designed to conduct a simple boiling experiment. Fig. 3 shows the schematic of the boiling test devices including a reagent bottle, heating system, cooling system and data acquisition system. A heater wire was submerged into a 200 mL reagent bottle containing the test nanofluid. The bottle was surrounded by an isothermal oil bath at the saturation temperature of the test nanofluid. On the other hand, the oil bath also could pre-heat the working fluid close to its boiling temperature. Before

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