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Technical Note

Boiling heat transfer characteristics of ethylene glycol and water mixture based ZnO nanofluids in a cylindrical vessel

Yurong He *, Haoran Li, Yanwei Hu, Xinzhi Wang, Jiaqi Zhu

Harbin Institute of Technology, Harbin 150001, China

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ABSTRACT

Pool boiling heat transfer characteristics including boiling heat transfer coefficient (HTC) and critical heat flux (CHF) of ethylene glycol (EG) and deionized water (DW) mixtures based ZnO nanofluids are experimentally investigated in a cylindrical vessel under atmospheric pressure. As the heat flux goes on, the boiling HTC of nanofluids increases in an obvious way for the natural convective region while gradually increases in the nucleate boiling region. In addition, a significant enhancement of CHF between nanofluids and their respective base fluids is observed. The HTC and CHF are enhanced due to the surface wettability reduction and nanoparticle coating on heater surface. Results also show that only the nanofluids with ZnO mass fraction less than ~7.25% could enhance the boiling heat transfer capability of vol.% = 85% EG aqueous solution.

1. Introduction

Boiling heat transfer, as a kind of convection heat transfer with phase transition, is one of the most important and efficient heat exchanging modes for thermal engineering. However, boiling performance of traditional fluids is severely limited by their dissatisfactory CHF values. Once heat flux reaches the CHF, the temperature of the heater rapidly increases in a relatively short period, followed by serious erosion due to superheating. It seriously restricts the safety, economy, reliability and process capability of heat exchangers. For a conventional heat transfer medium, CHF inevitably occurs in the course of boiling heat transfer. Even worse, it is extremely complex, difficult to troubleshoot, unpredictable and irreparable. Recently, a lot of effective methods beneficial for boiling heat transfer have been validated to prevent heater failure during boiling, e.g., covering heater surface with three-dimensional foam [1], making nanofluid pass a nonlinearly permeable stretching/shrinking sheet [2] and enhancing thermal conductivity of nanofluids [3], etc.

Researchers have tried to enhance the boiling heat transfer capability via two routes including increasing the boiling HTC and/or CHF values. The increasing amount of researches on nanofluid boiling has provided a better understanding of the effects of nanoparticles on boiling performance [4,5], and a considerable enhancement of boiling heat transfer has been discovered. As frost growth is more likely generated in cold regions [6], EG or its aqueous solution are widely used as working media. Kole and Dey [7] researched pool boiling characteristics of ZnO-EG nanofluids without surfactants and prepared through long duration sonication, showing a significant enhancement (~22%) in HTC for nanofluids with a volume fraction of 1.6%. That may illustrate that a well dispersed ZnO-EG nanofluid could serve as an effective refrigerating fluid. The work about EG/H_2O based nanofluids exhibiting significant HTC enhancement is far from being rare, such as Al_2O_3 [8] and CuO [9] nanofluids. Additionally, much work has been done to ascertain the CHF values of nanofluids. Sheikhbahai et al. [10] experimentally investigated the pool boiling of Fe_3O_4/EG/H_2O nanofluid in an electric field, and the maximum CHF enhancement of ~100% was obtained for 0.1% (by volume) nanofluid. The boiling performance investigations for CuO [11], SiC [12], ZnO [13,14], Al_2O_3 [15,16] and carbon nanotube (CNT) [17] nanofluid also showed obvious CHF enhancement even in a lower nanoparticle concentration.

The review of Cheng and Liu [18] presented that the boiling characteristics of nanofluids were strongly affected by their own physical properties, but the lack of reliable experimental data and quite contradictive results had been limiting the understanding of the boiling heat transfer mechanism in this emerging field. Plenty of work has been done on boiling heat transfer, but few literatures reported the investigation of ZnO-EG/DW nanofluids. What's more, as ethylene glycol aqueous solution is considered as the most common water-based antifreeze solution, the current work focuses on an experimental study of the boiling performance

* Corresponding author. Tel.: +86 0451 86413233.
E-mail address: rong@hit.edu.cn (Y. He).

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of ethylene glycol aqueous solution based ZnO nanofluid under atmospheric pressure. Experiments are designed to answer whether boiling heat transfer parameters of nanofluids are affected by applying different concentrations of the ethylene glycol aqueous solution as well as concentrations of nanoparticles. It guides the reader through different perspectives to investigate the boiling heat transfer of nanofluids.

2. Experiment

2.1. Nanofluids preparation

The nanofluids preparation process is similar to that of our previous work [19], the only difference is that the volume of base fluids in this work is 200 mL, which is coincident with the capacity of the boiling container.

2.2. Experimental setup

A device consists of a heating system, a reagent bottle, a cooling system and a data acquisition system was used to conduct the experiment. The installation and operating instructions, experimental principle and uncertainties analysis had been illustrated in our previous work [20] in detail. What deserves special mention is that the heater wire used in this work is Ni–Cr wire with a diameter of 0.5 mm and a length of ~5 cm.

3. Results and discussion

3.1. Boiling correlation analysis for water

To verify the reliability and repeatability of the test apparatus, boiling heat transfer characteristics of DW were first measured three consecutive times. Presented data is the mean value of the three tests. Fig. 1 shows the boiling curve for DW at saturated temperatures and local atmospheric pressures. Isolated bubbles firstly generate around a superheat of 6 °C and the mean CHF value is 964 ± 33 kW/m^2. The boiling curves show a good agreement with the curve fitting of Rohsenow's correlation [21] with a surface constant of 0.015.

3.2. Boiling curves for ZnO-EG/DW nanofluids and EG/DW mixtures

Comparison of experimental results of heat flux vs. superheat between nanofluids and base fluids are shown in Fig. 2(a). It can be clearly seen that the boiling performance of base fluids is enhanced by adding ZnO nanoparticles as the boiling curves shift slightly to the left. Additionally, the heat flux increases slightly with increasing the superheat in natural convection region, while it increases rapidly in the nucleation boiling region. At the beginning of this region, isolated bubbles are generated, and heat is mainly transferred from heater surface to liquid. As heat flux increases, more nucleation sites become active and bubbles coalesce, mix, and ascend as merged jets or columns of vapour before the heat flux is up to CHF [22]. Eventually, the boiling HTC rapidly decreases, which implies the achievement of criticality. Further increasing heat flux will cause the generation of a fair amount of white smoke and it is hardly to record the voltage and current across heater wire. On the other hand, the 75EG/25DW (i.e. volume ratio of EG and DW is 75:25) based ZnO nanofluid firstly gets into the nucleate boiling region from the free convection region, following by 85EG/15DW (i.e. volume ratio of EG and DW is 85:15) and 95EG/5DW (i.e. volume ratio of EG and DW is 95:15) based ZnO nanofluid, respectively. For ZnO-EG/DW nanofluid with a mass fraction of 5.25%, heat flux increases with the decreasing of EG in a constant volume of base fluid. Similar results for base fluids confirmed the fact that the enhancement of heat transfer capability is partly caused by the better thermal conductivity of DW. EG/DW with more water possesses higher thermal conductivity. Fig. 2(b) depicts the boiling HTC distribution as a function of heat flux in natural convection and nucleate boiling regions for nanofluids and base fluids. It clearly shows that the addition of ZnO nanoparticles to EG/DW enhances the boiling HTC of the ZnO-EG nanofluid. A maximum enhancement of 2.28 kW/(m^2 K) in boiling HTC is observed for the ZnO-85EG/15DW nanofluid.

Pioro et al. [23] has stated that boiling mechanisms are dependent on the surface wettability. The relative wettability of a liquid can be quantified by the surface tension and contact angle of the liquid in contact with a same substrate. A Surface Tensionmeter (BZY-2, Hengping Instrument & Meter Factory, China) with a precision of ±0.1 mN/m was used under ambient pressure and temperature, and each fluid was tested for 5 times. The average surface tension values for 75EG/25DW, 85EG/15DW and 95EG/5DW respectively are 51.8, 50.2 and 48.5 mN/m and those for their ZnO nanofluid are 51.3, 49.8 and 48.2 mN/m. As a result, the surface tension of base fluids slightly decreases as the presence of nanoparticles. Thus, during nucleate boiling, critical radius of the bubbles of EG/DW is improved and more nucleation sites on the heated surface will be activated, so the boiling HTC will be enhanced [8]. A Contact Angle Meter (JCY-2, Fangrui Instrument Co., Ltd., China) was used to measure the static equilibrium contact angle of nanofluids and base fluids. A 3 μL-volume liquid droplet was placed on an electronic microscope slides. The contact angle for 75EG/25DW, 85EG/15DW and 95EG/5DW without PVP are 35.3°, 39.9° and 47.0° and those for EG/DW solutions with PVP

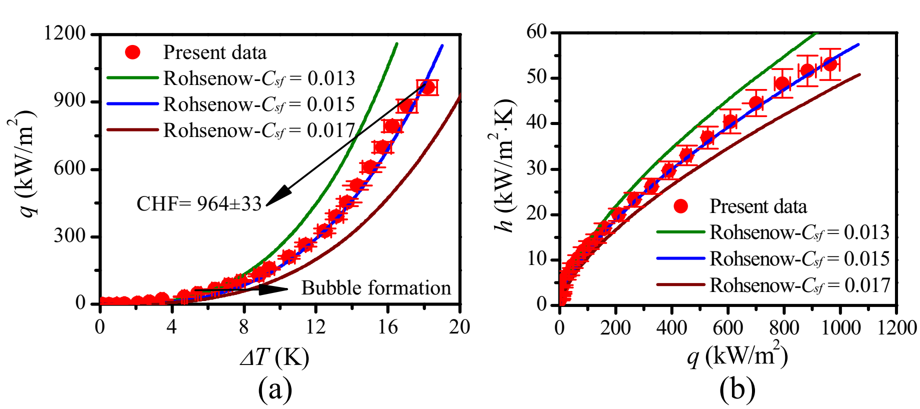

Fig. 1. Boiling curves for DW at saturated temperatures and atmospheric pressures. (a) Heat flux vs. superheat and (b) HTC vs. heat flux.