



## Experimental investigation of pool boiling of Fe<sub>3</sub>O<sub>4</sub>/ethylene glycol–water nanofluid in electric field

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### ARTICLE INFO

#### Article history:

Received 26 March 2011

Received in revised form

6 October 2011

Accepted 6 October 2011

Available online 29 October 2011

#### Keywords:

Boiling

Nanofluid

Electrohydrodynamic

Heat transfer

Phase change

### ABSTRACT

Nucleate boiling and critical heat flux (CHF) of Fe<sub>3</sub>O<sub>4</sub>/ethylene glycol–water nanofluid at atmospheric pressure on a horizontal thin Ni–Cr wire were investigated. Fe<sub>3</sub>O<sub>4</sub> nanoparticles were dispersed in 50% (by volume) ethylene glycol/de-ionized water as base liquid in different concentrations (0.01–0.1% (by volume)). Experiments showed that boiling heat transfer coefficients deteriorate by increasing nanoparticle concentration in nanofluid. Addition of nanoparticles delays nucleate boiling incipience and increases CHF. Scanning Electron Microscope (SEM) graphs showed that porous layer of deposited nanoparticles formed on the heating surface boiled in nanofluid. The maximum CHF enhancement was obtained for 0.1% (by volume) nanofluid to be about 100%. Enhanced CHF was measured when previously boiled wire in nanofluid was used to boil the base fluid. Two different electrodes were used for applying electric field in the boiling nanofluids. Electric field applied in both configurations augmented boiling heat transfer coefficients while CHF remained almost unchanged.

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### 1. Introduction

Boiling is very effective and widespread heat transfer mechanism, due to its potential for removing large amounts of heat at low temperature differences. Boiling occurs in many engineering applications including boilers in power plants, evaporators in refrigeration systems, and nuclear reactors. Recent applications of boiling heat transfer in cooling of electronics show many promises [1]. Critical heat flux (CHF) is nucleate boiling limitation, causing an excessive increase in temperature at boiling surface. Both intensifying boiling heat transfer and delaying critical heat flux occurrence have attracted great interest. Nanofluid, a colloidal suspension in which solid nanoparticles are dispersed in base liquid have been considered a potential enhancement method for boiling heat transfer. Nanofluid boiling was investigated and the effect of type, size and concentration of nanoparticles on pool boiling behavior was addressed [2–7]. It is a common notion that addition of nanoparticles to the base fluid is an effective way to increase critical heat flux. Almost all nanofluid pool boiling studies have reported significant nanoparticle deposition on the heater surface, particularly close to CHF. Deposition of a layer of nanoparticles on heater surface during nucleate boiling improves surface wettability and makes significant increase in CHF [4,5,7–10]. In spite of the common notion about the increased CHF by addition of

nanoparticles to the base fluid, controversy has yet existed on the effect of addition of nanoparticles to the base liquid on boiling heat transfer enhancement (see Table 1).

Addition of nanoparticles to the base liquid is a passive method for boiling heat transfer augmentation and can be combined with an active method such as electrohydrodynamic (EHD) for intensified augmentation. Enhancing effect of electric field on boiling heat transfer and CHF has been known for over 50 years. In electrohydrodynamic technique, either DC or AC high-voltage (low-current) is applied in a dielectric fluid. EHD boiling heat transfer investigations have included experiments with a variety of geometric configurations and different dielectric cryogenics such as R-123, R-134a, liquid nitrogen and semi-dielectric liquids (e.g., highly pure water and ethanol) [11–14].

This paper reports experimental results of boiling heat transfer of Fe<sub>3</sub>O<sub>4</sub>/water–ethylene glycol nanofluid under electric field. Experiments were designed to answer whether boiling heat transfer parameters of nanofluids are affected by applying a high-voltage DC electric field or not.

### 2. Pool boiling experiment

#### 2.1. Preparation and characterization of nanofluid

Mixture of 50% by volume ethylene glycol in deionized water (DI) was used as the base liquid. Fe<sub>3</sub>O<sub>4</sub> nanoparticles

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### Nomenclature

$D$	Wire diameter, m
$E$	Field intensity, V/m
$F_e$	Electric body force, N
$I$	Current, A
$l$	Wire length, m
$q''$	Heat flux, W/m <sup>2</sup>
$R$	Wire resistance, $\Omega$
$R_0$	Wire resistance at reference temperature, $\Omega$
$T$	Wire Temperature, °C
$T_0$	Temperature of the boiling pool, °C
$V$	Electric potential across the wire, V

### Greek symbols

$\varepsilon$	Electric permittivity of liquid, F/m
$\rho$	Mass density, Kg/m <sup>3</sup>
$\rho_e$	Charge density, C/m <sup>3</sup>

(Sigma–Aldrich) smaller than 50 nm were dispersed in ethylene glycol. The proper amount of solid powder was weighed by an electronic scale accurate to  $\pm 0.0001$  g. Weighed nanoparticles were then added to ethylene glycol gradually under ultrasonic mixing for an hour. Sonication (using UP200S sonicator) continued for another hour to get stable nanofluid. Required amount of DI water was gradually added to nanofluid under vigorous agitation in 30 min period just before each experiment. No sedimentation at the bottom or clear layer at the top was observed after 8 h.

### 2.2. Experimental procedure

A schematic diagram of the experimental set up is shown in Fig. 1. The main test pool consisted of a cylindrical Pyrex glass 13 cm in diameter, 18 cm height. Two cm thick polyethylene cover was used on the top of the Pyrex glass to seal the test pool. The working fluid was pre-heated using a hot plate up to boiling temperature. The pool temperature was measured with a mercury thermometer with uncertainty of  $\pm 0.5^\circ$ . Experiments were carried out at boiling temperature and atmospheric pressure and Voltage and current were measured with DEC330F multimeters. The wire temperature

was calculated from measurement of the electrical resistance using the resistivity–temperature relation obtained for Ni–Cr wire (equation (1)).

$$\frac{R}{R_0} = (1 + 0.0004(T - T_0)) \quad (1)$$

In equation (1),  $R$  and  $R_0$ , are electrical resistances at temperatures  $T$  and  $T_0$ , respectively.

Electrical power was supplied to the wire and gradually increased by changing applied voltage in 0.2 V steps until CHF occurred. At CHF, resistance of the wire increased sharply and the wire glowed. Heat fluxes were calculated from the following equation:

$$q'' = \frac{VI}{\pi DI} \quad (2)$$

where  $V$ ,  $I$ ,  $D$ , and  $l$  are measured voltage across the heating wire, measured current passing the wire, diameter, and length of the wire, respectively.

Maximum uncertainties in current and voltage were 0.6% and 1%, respectively. Calculated uncertainties in heat flux, wire resistance and temperature are 4%, 2% and 15%, respectively.

### 2.3. Nanofluid pool boiling experiment

Fig. 2 shows heat flux versus temperature difference for different volume fractions of nanoparticles in the base liquid. Boiling curve shifts to the right by increasing the volume fraction of nanoparticles. This means that at a fixed heat flux, superheat temperature increases by volume fraction of nanoparticles. The maximum reduction of boiling heat transfer coefficient of nanofluids relative to the base fluid was about 18% in 0.1% (by volume) concentration. Partial reduction of superheat at lower heat fluxes (0.1–0.3 MW/m<sup>2</sup>) was due to nucleate boiling incipience. This phenomenon is known as temperature over-shoot and is characterized by a sudden decrease of excess temperature at the end of natural convection regime. After activation of nucleation sites and vapor bubbles formation, the superheat needed for the generation of following bubbles decreases. The departure of the bubbles also increases the convective motions in the boiling liquid, resulting in the cooling of the heater surface [14,15]. Temperature over-shoot

**Table 1**

A brief review of studies related to pool boiling of nanofluids.

Reference	Nanofluid (concentration)	Maximum CHF enhancement (%)	Heat transfer coefficient	Heater surface	Nanoparticle deposition on heater surface observation
Das et al. [2] (2003)	Al <sub>2</sub> O <sub>3</sub> in water (0.1–4 %v)	–	Deteriorated	Cartridge heater	Yes
You et al. [19] (2003)	Al <sub>2</sub> O <sub>3</sub> , SiO <sub>2</sub> in water ( $\leq 0.001\%$ w)	200	Unchanged	Copper block	–
Vassallo et al. [25] (2004)	SiO <sub>2</sub> in water (1.3%w)	200	Unchanged	Ni–Cr wire	Yes
Bang and Chang [17] (2005)	Al <sub>2</sub> O <sub>3</sub> in water (0–4 %v)	51	Deteriorated	Plane heater	Yes
Wen and Ding [26] (2005)	Al <sub>2</sub> O <sub>3</sub> in water (0.32–1.25%w)	–	Enhanced	Stainless steel disk	No
Kim et al. [5] (2007)	Al <sub>2</sub> O <sub>3</sub> , SiO <sub>2</sub> , ZrO <sub>2</sub> in water (0.0001–0.1%v)	80	Deteriorated	Stainless steel wire	Yes
Kim et al. [4] (2007)	Al <sub>2</sub> O <sub>3</sub> , TiO <sub>2</sub> in water (0.00001–0.1%v)	100	–	Ni–Cr wire	Yes
Chopkar et al. [16] (2008)	ZrO <sub>2</sub> in water (0.005–0.15%v)	–	Enhanced	Copper plate	Yes
Jackson [9] (2007)	Au in water (0.0003%v)	250	Deteriorated	Copper plate	Yes
Coursey and Kim [8] (2008)	Al <sub>2</sub> O <sub>3</sub> in water (0.026–1.02 %v)	37	Enhanced,	polished copper	Yes
	Al <sub>2</sub> O <sub>3</sub> in ethanol (0.001–10 %v)	25	Unchanged	and Glass surface	
Golbovic et al. [3] (2009)	Al <sub>2</sub> O <sub>3</sub> , BiO <sub>2</sub> in water (0–0.01%v)	50, 33 respectively	–	Ni–Cr wire	Yes
Park et al. [6] (2009)	CNTs in water (PVP as surfactant) (0.001–0.05%v)	200	Deteriorated	Copper block	Yes
Taylor and Phelan [7] (2009)	Al <sub>2</sub> O <sub>3</sub> in water (0.05–1%v)	–	Enhanced	Wire heater	Yes
Kwark et al. [10] (2010)	Diamond, Al <sub>2</sub> O <sub>3</sub> in water ( $\leq 1$ g/l)	80	Deteriorated	Flat heater	Yes
Truong et al. [27] (2010)	Diamond, Al <sub>2</sub> O <sub>3</sub> , ZnO <sub>2</sub> in water ( $\leq 0.1\%$ v)	35	Unchanged	Sandblasted plate heater	Yes

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