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Research Paper

Influence of orientation and roughness of heater surface on critical heat flux and pool boiling heat transfer coefficient of nanofluid

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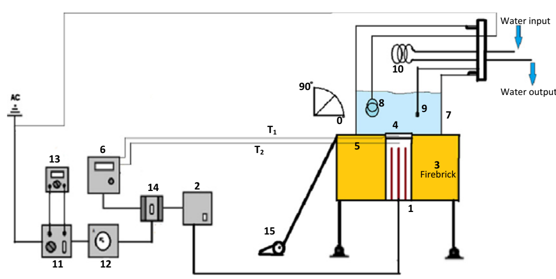
HIGHLIGHTS

- Pool boiling of silica nanofluid over an inclined surface was investigated.
- Heater orientation has a dramatic effect on pool boiling of nanofluid.
- Effect of initial roughness of surface on characteristics of boiling was studied.
- Boiling heat transfer was enhanced over a nanocoated surface.

GRAPHICAL ABSTRACT



Experimental setup:
1-Cartridge heaters, 2-on/off switch, 3-Copper block and firebrick, 4-Heater surface, 5-Thermocouples, 6-Thermostat, 7-Boiling vessel, 8-Pre-heater, 9-Thermometer, 10-Condenser, 11-Dimmer, 12-Ampere meter, 13-Voltmeter, 14-Contactor, 15-A mechanical device to incline the heater.

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ABSTRACT

Pool boiling of SiO_2/water nanofluid over a copper flat plate heater at various inclinations of the heater surface was investigated experimentally. In this work, the effect of heater surface orientation on changes in surface roughness and on the characteristics of nanofluid boiling was studied. We examined pool boiling of silica nanofluid at various concentrations (<0.1 vol.%) and various heater orientations from a horizontal state (0°) to a vertical state (90°). The results showed that in nanofluid boiling, increasing the inclination angle of the heater surface from 0° to 90° increases the critical heat flux (CHF) and decreases the boiling heat transfer coefficient (BHTC), while in boiling DI water, both for CHF and BHTC, decreases with the angle of the heater surface. Atomic force microscope images from the heater surface which has been boiled in nanofluids illustrated that surface roughness varies with the orientation of the surface. It was found that deposition of nanoparticles and bubble movements have important effects on nanofluid boiling over inclined surface. In addition, the performance of the boiling of DI water on a nanocoated surface was examined. The results showed that CHF and BHTC increase in comparison with the boiling of DI water on a bare heater.

1. Introduction

Nucleate boiling plays a basic role in many types of heat transfer equipment. In industrial heat transfer equipment such as cooling nuclear reactors and electronic chips, boilers, etc., achieving the highest heat transfer rate is of great significance [1]. Since critical heat flux (CHF) limits heat transfer, CHF enhancement has been the purpose of many recent studies. Using nanofluid is a new way to improve the boiling heat transfer coefficient (BHTC) and CHF. You et al. [2] surveyed CHF enhancement by using Al_2O_3-water nanofluid, and reported a 200% increase in comparison with pure water. Several researchers later used different nanofluids in boiling experiments. Kim et al. [3] observed that

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Nomenclature

BHTC	boiling heat transfer coefficient
CHF	critical heat flux
C_p	specific heat (J/kg k)
C_{sf}	fluid-surface combination coefficient
H	heat transfer coefficient
h_{fg}	latent heat of vaporization (J/kg)
q''	heat flux (kW/m^2)
Pr	Prandtl number
T	temperature (°C)
V	voltage
I	ampere
A	area of boiling surface
ΔT	wall super heat (°C)
Greek symbols	
ρ	density (kg/m^3)
σ	surface tension (N/m)
θ	inclination angle (°)
α	static contact angle

the CHF of low concentration nanofluid (<0.1 vol.%) in pool boiling increased with the concentration, and in high levels afterwards, it remained constant. Kim et al. [4] clarified that nanoparticles deposited on heater surfaces during nanofluid pool boiling led to his suggesting a hypothesis for the decomposition of nanoparticles. The nanocoated layer improves surface wettability by reducing the static contact angle on surfaces which have been boiled in nanofluid compared with surface boiled in pure water. Kwark et al. [5] studied nucleate boiling of low concentrations of Al_2O_3, CuO and diamond nanofluids over a flat plate to determine the mechanism of adhering nanoparticles on heater surfaces by experimental means. They compared the nanoparticle coatings formed when boiling on the heater with nanoparticle coatings formed when caused by gravity, natural convection and electric field. They reported that only the layer of nanoparticles formed during the boiling process has significant effects on CHF. Shahmoradi et al. [6] found that using alumina nanofluid (<0.1 vol.%) in pool boiling on a flat plate heater enhanced CHF and deteriorated BHTC. In their work, AFM images of heater surfaces before and after nanofluid boiling showed that the deposition of nanoparticles on the surface increased the roughness and CHF consequently. However increasing the thickness of the nanolayer enhances thermal resistance and deteriorates the heat transfer coefficient. It can be seen that some of the results obtained in nanofluid pool boiling are controversial.

Most researchers considered some of the parameters involved in pool boiling of nanofluids such as nanoparticle concentration, nanoparticle material and size, heater characteristics and size, system pressure, using of additive, etc. [7]. Another parameter which affects the boiling mechanism is heater orientation, which plays an essential role in the formation, growth and movement of bubbles over the surface of the heater. Pool boiling of dilute CuO/water on the surface of a horizontal cylindrical heater was investigated by Sarafraz and Hormozi [8]. They focused on the region of nucleate boiling of nanofluid. They observed that the deterioration of the BHTC of nanofluids for all concentrations (<0.4 wt.%) while using the surfactants helps improve the heat transfer coefficients of nanofluid due to decreases in surface tension. They also reported that the roughness of the heating section and the number of nucleation sites were reduced when the concentration of nanofluid filled the micro-cavities of the surface with nanoparticles during boiling. A recent study of the effect of surface on boiling heat transfer is Wen et al.'s work [9]. They observed that boiling heat transfer is dependent upon the relative size between nanoparticles and the heating surface and their interactions. Researchers have accurately studied some important parameters that can be affected surface roughness and the boiling heat transfer of nanofluids, but they did not investigate the effect of orientation of heating surfaces on changes in surface roughness and the boiling behavior of nanofluid. In addition, their experiments were carried out in low heat fluxes below CHF.

Practically speaking, boiling surfaces can occur at various orientations such as boiler walls, tubes and curved walls of vessels involving boiling. In these cases, the orientation of surface affects boiling mechanisms [10,11]. Most previous studies that investigated this parameter used common fluids [12–15], not nanofluids.

Narayan et al. [16] have studied the effects of surface orientation on alumina nanofluid pool boiling performance and mechanisms. Their experimental set up was a tubular heater (diameter 33 mm and length 170 mm) at various inclination (0°,45° and 90°) when the range of heat flux was 10–70 kW/m^2, lower than CHF. Their results showed that maximum BHTC occurred at horizontal configurations of heaters.

Kwark et al. [17] have performed water pool boiling experiments over alumina nanoparticle coated heaters in order to observe the effects of nanocoated heaters, pressure, size and orientations of heaters on CHF and BHTC. They indicated that in lower heat fluxes (≤100 kW/m^2), when heater orientation varies from 0° to 180°, BHTC increases. In higher heat fluxes, increase in the inclination angle of the heater does not have an appreciable effect on BHTC. In addition, they concluded that CHF significantly increases when heater orientations are beyond 90°, although CHF almost remained constant for lower inclination angles. The capacity of graphene-oxide in CHF enhancement during external reactor vessel cooling (ERVC) was investigated by Park et al. [18]. Their experimental results showed that CHF was enhanced about 40% and 200% at vertical and horizontal orientations of thin-wire heater, respectively.

Real applications of surface boiling at various orientations, and the lack of studies of nanofluid boiling over inclined flat plates for realizing the effects of heater orientation on CHF and BHTC, motivated this work. Some of these studies were carried out in low heat fluxes (below CHF). The present study investigates the effect of heater orientation on characteristics of pool boiling of silica/water nanofluid. In this manner, some important questions will be answered: can the orientation of the heater surface affect conditions which influence nanoparticles deposition on the heater surface and roughness of surface? What are the variations of the CHF and BHTC of nanofluid at various inclination angles of heater surfaces? For these purposes, nanofluid boiling at different concentrations was carried out over a flat plate heater at various inclination angles. Boiling curves were then analyzed up to CHF. AFM analysis is used to characterize surface roughness before and after the boiling processes. In order to investigate the effect of the initial roughness of the surface on the performance of boiling, a series of experiments utilizing different surfaces (sanded and polished) under the nanofluid boiling were designed and AFM images were analyzed.