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Modification of sandblasted plate heaters using nanofluids to enhance pool boiling critical heat flux

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ABSTRACT

Nanofluids are colloidal dispersions of nanoparticles in homogenous base fluids. Previous studies have shown that nanofluids can increase pool boiling critical heat flux (CHF) by forming a porous deposition on the heated surface. However, questions remain whether nanoparticles can further enhance the CHF on a passively engineered heat transfer surface, such as a sandblasted metal plate. In this study, three water-based nanofluids (diamond, zinc oxide and alumina) were used to modify sandblasted stainless steel 316 plate heaters via boiling induced deposition. The pool boiling CHF of these pre-coated heaters increased by up to 35% with respect to that of the bare, sandblasted heaters. The enhancements are highest for alumina and zinc oxide nanofluids. Detailed surface characterization of these pre-coated heaters showed different surface morphology depending on the type of nanofluids used. Additionally, the deposited nanoparticles layers were found to alter the wettability of the heaters. Contact angle measurement provided quantitative data to determine possible CHF enhancement based on existing correlations.

1. Introduction

Nanofluids are colloidal dispersions of nanoparticles in common base fluids. Materials used for nanoparticles include chemically stable metals (e.g., gold, silver, copper), metal oxides (e.g., alumina, zirconia, silica, and titania) and carbon in various forms (e.g., diamond, graphite, and carbon nanotubes). Base fluids used for nanofluids include water, refrigerants, ethanol, and ethylene glycol. Nanoparticles can remain dispersed without significant agglomeration by controlling their surface properties through pH and use of surfactants. It has also been found that nanofluids can remain stable over a long period of time with little erosion and gravitational settlement [1].

One of the most intriguing features of nanofluids is their ability to enhance the critical heat flux (CHF) significantly. CHF increases of up to 200% are obtained at relatively low nanoparticle concentrations, typically less than 0.1 vol% (You et al. [2] and Kim et al. [3]). Other researchers, Vassallo et al [4], Tu et al. [5], Kim and Kim [6], Moreno Jr. et al. [7], Bang and Chang [8], Milanova et al. [9], Jackson et al. [10] and Wen and Ding [11], have also measured CHF enhancement of varying magnitudes with different nanoparticle materials and a wide range of concentrations. However, there is still no consensus on the boiling heat transfer rate of nanofluids. A summary of these studies is provided in Table 1.

Another common finding in most of these studies is the formation of a porous layer on the heater due to nanoparticle deposition during boiling. For example, nanoparticle depositions on heater surfaces are reported by Bang and Chang [8] and Kim et al. [12]. Also, Liu and Qui [13] reported a thin sorption layer on the heated surface when a nanofluid jet impinges on the surface. The deposition of nanoparticles was found to change the morphology and properties (e.g., roughness and wettability) of the heater surface. Since the thermophysical properties (surface tension, thermal conductivity, viscosity, evaporation heat, specific heat, and density) of low volume concentration nanofluids are similar to those of pure water, these changes in surface morphology and properties are believed to be the main mechanism for the CHF enhancement of nanofluids.

While surface modification to enhance CHF and heat transfer is well known, the use of nanofluid boiling deposition is relatively new because research in nanofluids has only captured wide interests in the last decade. Nanofluids have also consistently shown significant CHF enhancements, however, questions remain whether nanoparticles can further increase the CHF on an already enhanced heat transfer surface, such as a sandblasted metal plate.

It should be noted that sandblasted surfaces have been shown in previous studies to enhance heat transfer compared to polished surfaces. For example, Jacob and Fritz [14] (as cited in Collier and Thome [15]) was one of the first researchers to measure enhanced boiling heat transfer and CHF for sandblasted and other treated surfaces. Fagerholm et al. [16] measured boiling heat transfer of

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Nomenclature

A	surface area (m^2)
C	constant in Eq. (2)
g	gravitational acceleration (m/s^2)
h_{fg}	latent heat of vaporization (J/kg)
I	current (A)
q''	heat flux (W/m^2)
r	electrical resistance (ohm)
T	temperature (°C)
V	voltage (V)

Greek symbols

α	temperature coefficient of resistance ($°C^{-1}$)
κ	constant in Eq. (4)
Φ	angle of heater orientation (°)
ρ	density (kg/m^3)
σ	surface tension (N/m)
θ	contact angle (°)

Subscripts

CHF	critical heat flux
f	fluid
g	gas
o	initial
w	wall

Table 1
Summary of effect of nanofluids on critical heat flux and boiling heat transfer rate reported in the literature.

Reference	Nanofluid	Maximum CHF enhancement (%)	Heat transfer rate
You et al. [2]	Al_2O_3 in water	200	Unchanged
Kim et al. [3]	TiO_2 in water	200	Not reported
Vassallo et al. [4]	SiO_2 in water	60	Unchanged
Tu et al. [5]	Al_2O_3 in water	67	Enhanced
Kim and Kim [6]	TiO_2 in water	50	Not reported
Moreno Jr. et al. [7]	Al_2O_3, ZnO in water Al_2O_3 in ethylene glycol	200	Unchanged
Bang and Chang [8]	Al_2O_3 in water	50	Deteriorated
Milanova et al. [9]	SiO_2, CeO_2, Al_2O_3	170	Unchanged
Jackson et al. [10]	Au (3 nm) in water	175	Deteriorated
Wen and Ding [11]	Al_2O_3 in water	40	Enhanced
Kim et al. [12]	Al_2O_3, SiO_2, ZrO_2 in water	80	Deteriorated

plain and porous tube (sandblasted and other coating) in falling film flow using R114 and found that the heat transfer coefficient of the modified surface was up to 10 times higher than that of the smooth tube. Frieser and Reeber [17] also found that sandblasted, and sandblasted/etched silicon surface have higher heat transfer due to higher nucleation rate compared to that of a polished surface. Trepp and Hoffmann [18] showed that surface treated by sandblasting and then galvanizing has higher heat transfer rate in liquid nitrogen compare to that of a smooth surface. They also observed that the treated surface have a lot of smaller bubbles generated at much higher frequency compared to a smooth surface. However, Cieslinski [19] compared boiling curve of a sandblasted stainless steel tubes to that of a smooth tube but found no CHF enhancement.

This experimental study is an attempt to elucidate the merits of using nanofluids to enhance CHF of sandblasted surfaces. In this study, three nanofluids (diamond, zinc oxide and alumina) were used to pre-treat sandblasted plates via boiling enhanced deposition. These modified heater surfaces were then used to measure CHF in water to determine pool boiling CHF enhancement compared to that of bare sandblasted plate heaters. Finally, detailed characterizations of the modified surfaces provided insights to the possible CHF enhancement mechanism.

2. Experiments

2.1. Pool boiling facility

A pool boiling facility was used to perform the coating of the plate heater and to measure the CHF of water on the coated heaters. The schematic of the facility is depicted in Fig. 1. Here, a glass test cell of dimensions 10.2 cm × 15.2 cm × 20.3 cm sits in the middle of an isothermal bath equipped with an electric heater. The test cell contains either deionized water or nanofluid, preheated in a microwave before each test.

The constant fluid temperature in the test cell is maintained by using an isothermal bath. In addition, a reflux condenser on top of the test cell prevents fluid loss due to evaporation. The heater is immersed in the liquid in the test cell and connected to two copper electrodes of approximately 0.5″ in diameter. In series with the heater is a shunt resistor (100 mV × 800 A), which determines the electric current in the system. The accuracy of the shunt used was 0.25% over its entire working range of 800 A. Heating up of the shunt was considered negligible since the maximum current through the system was 300 A in all experiments, which is far below the rated current for the shunt. In addition, the current measured by the shunt was verified by the digital current readout from the power supply. Power is supplied to the heater via a DC power supply (20 V × 500 A). The two voltage taps measure the voltages across the heater and the shunt resistor. Two K-type thermocouples are used to measure the temperatures of the fluids in the isothermal bath and in the test cell. All data are collected using a Data Acquisition System (DAQ).

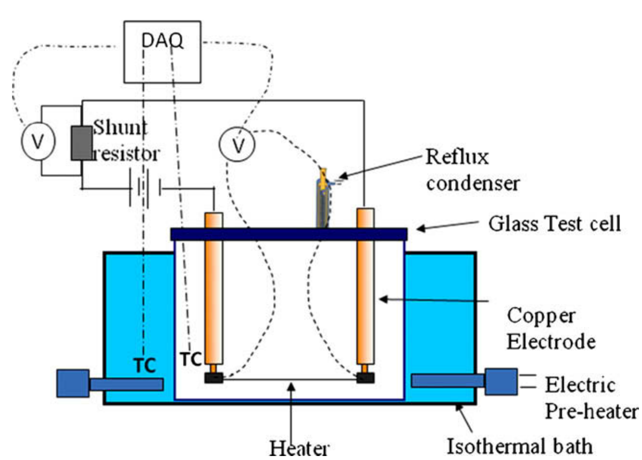

Fig. 1. Schematic diagram of pool boiling CHF facility.