International Journal of Heat and Mass Transfer 53 (2010) 4579–4587

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Nanocoating characterization in pool boiling heat transfer of pure water

Sang M. Kwark, Gilberto Moreno, Ratan Kumar, Hyejin Moon, Seung M. You *

Mechanical and Aerospace Engineering Department, The University of Texas at Arlington, 500 W. First Street, Arlington, TX 76019, USA

ARTICLE INFO

Article history:
Received 20 October 2009
Received in revised form 15 June 2010
Accepted 15 June 2010
Available online 16 July 2010

Keywords:
Nanocoating
Wettability
Critical heat flux
Boiling heat transfer

ABSTRACT

The pool boiling behavior of nanoparticle coated surfaces is experimentally studied in pure water. Nanoparticle coatings were created during nanofluid pool boiling experiments (Al_2O_3–water/ethanol). The nanocoatings developed can significantly enhance the critical heat flux. Ethanol nanofluids created more uniform nanocoatings which outperformed nanocoatings created in water nanofluids. The wetting and wicking characteristics of the nanocoatings are investigated through contact angle measurements and by conducting a dip test. A linear relationship between the CHF enhancement and the quasi-static contact angles of the nanocoatings was revealed. Additionally, a mechanism potentially responsible for nanocoating CHF enhancement is identified.

1. Introduction

Two phase heat transfer is highly efficient mode of heat dissipation but its implementation can be restricted as a result of the critical heat flux (CHF) phenomenon. CHF essentially limits the heat flux dissipation potential of two phase (boiling) heat transfer and exceeding this CHF limit may result in component damage. To increase the viability of two phase heat transfer, extensive research has been dedicated to develop methods to enhance CHF. One such method consists of dispersing nanoparticles in a liquid to create solutions called nanofluids. Although the CHF enhancement of nanofluids has been confirmed by extensive research at various laboratories, the mechanisms behind the enhancement are not fully understood.

The increasing amount of research into nanofluid boiling has provided a better understanding into the effects of nanofluids on boiling performance and specifically their effect on boiling heat transfer (BHT) and critical heat flux (CHF). Although there are studies which report that nanofluids enhance boiling heat transfer (BHT), such as those of Wen and Ding [1] who reported a 40% increase in the BHT; the majority of the research seems to indicate that nanofluids can either degrade or have no effect on BHT. Such is the case with studies by Das et al. [2] and Bang and Chang [3] who conducted pool boiling experiments using alumina–water nanofluids and found them to decrease BHT. In these studies, the degradation is attributed to either a "smoothening" of the heater surface as nanoparticles collect in surface cavities or an increase in the thermal resistance as nanoparticles form a thin layer on the heater. Similarly, other studies [4–7] have also reported that nanofluids either have no effect or degrade BHT.

Therefore, the only benefit that the nanofluids provide, to boiling heat transfer, is an ability to significantly increase CHF. You et al.'s [7] initial study reporting a 200% CHF enhancement using alumina–water nanofluids was quickly followed by a similar study by Vassallo et al. [4] who also reported significant CHF enhancement using silica–water nanofluids. Ever since these initial findings were first reported, many other studies have also reported CHF enhancement using nanofluids composed of various nanoparticles types and base fluids [3–10]. Thus, extensive amount of research has confirmed that nanofluids can enhance CHF; however, the mechanisms responsible for the enhancement remain relatively unknown.

A recent study by Kim et al. [6] found that the nanoparticle film formed on the heater surface, during nanofluid boiling experiments, increases the wettability (i.e. lower static contact angles) of the surface. Furthermore, they found a strong relationship between the CHF enhancement and the wettability of the surface. Kim and Kim [9] also obtained significant CHF enhancement using nanofluids (titania/alumina–water) with wire heaters. They further investigated the effect of the nanoparticle coating developed during the nanofluid experiments and revealed that the heater's surface modification due to nanoparticle deposition can bring about CHF enhancement of around ~160% in pure water. Moreover, they reported that the nanocoated surface tested in pure water exhibited higher CHF than that of the uncoated surface tested in nanofluids. Coursey and Kim [11] investigated the effect of the surface wettability in pool BHT using alumina–water/ethanol nanofluids on various surfaces (glass, gold, copper, and oxidized copper). They reported that the CHF enhancement rate of the nanofluids is

* Corresponding author.
E-mail address: you@uta.edu (S.M. You).

0017-9310/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.ijheatmasstransfer.2010.06.035

Nomenclature

BHT	boiling heat transfer
CHF	critical heat flux
d_d	bubble departure diameter (m)
f	bubble release frequency (1/s)
h	heat transfer coefficient (W/(m^2 K))
q''	heat flux (kW/m^2)
T	temperature (°C)
T_{sat}	wall superheat ($T_w - T_{sat}(P_{sys})$)
Greek symbols	
ρ	density (kg/m^3)
σ	surface tension (N/m)
θ	contact angle (°)
Subscripts	
d	diameter
g	vapor
l	liquid
sat	saturated conditions
w	wall, heater surface

dependent on the wetting characteristics between the surface and the working fluid. Noticeable CHF enhancement (~40%) was observed in the poorer wetting configuration (e.g. alumina–water on polished copper), whereas better wetting systems showed less improvement (e.g. alumina–ethanol on glass and gold).

Prior studies have investigated the effect of surface wettability on boiling heat transfer. Various techniques to modify surface wetting characteristics have been considered including oxidation, plating, and UV irradiation. Liaw and Dhir [12] investigated the effect of thermal oxide layer growth on CHF. Using water as the fluid, this process decreased static contact angles from 90° to 14° producing a significant ~90% CHF enhancement. Tachibana et al. [13] reported that an aluminum heater produces higher CHF as compared to stainless steel, nickel, copper, and lead heaters. It was further reported that an aluminum plated stainless steel heater can produce CHF values similar to those of the solid aluminum heater indicating that surface conditions influence CHF. The superior performance of aluminum surfaces was attributed the "good affinity" for water due to the native aluminum oxide film that developed soon after initiation of boiling and spread gradually over the entire surface. Takata et al. [14] generated a superhydrophilic surface by exposing a TiO_2 surface to UV irradiation. The superhydrophilic surfaces created were reported to produce CHF values two times greater than those of the uncoated surface. Realizing that surface wettability characteristics can influence CHF, Kandlikar [15] proposed a pool boiling CHF correlation which included the effect of surface wettability (i.e. static contact angle).

It is now widely accepted that nanofluids enhance CHF through the formation of a nanoparticle coating, on the heater's surface, which alters surface wetting characteristics. Therefore, the focus of this study is on the nanoparticle coatings (nanocoatings) and their ability to enhance CHF. This was accomplished by artificially generating various nanoparticle coatings by means of varying nanofluid boiling parameters including the heat flux, boiling duration, and nanoparticle concentration. In this manner, a number of nanocoatings were created of varying thicknesses and structures. The performance of these nanocoatings created was then evaluated through pool boiling experiments conducted in deionized-distilled water at atmospheric pressure. Finally, the wettability of the coatings was quantified via contact angle measurements. These results were then used to in conjunction with SEM images, surface profile measurements, and boiling performance to further understand the nanocoatings ability to enhance CHF.

2. Nanofluid preparation

The Al_2O_3 nanofluids were prepared by weighing the appropriate quantities of nanoparticles using an Acculab VI-1 mg precision balance and then dispersing them into 500 ml of deionized-distilled water. This nanoparticle solution is then subjected to an ultrasonic bath for 2 h using a Cole Palmer Ultrasonic Cleaner Model 08849. The 500 ml of nanofluid is then added to 3 L of distilled water to make a total of 3.5 L. These 3.5 L of nanofluid were used as a working fluid for the pool boiling experiments. The preparation procedures, for Al_2O_3–ethanol nanofluids, were identical to those used to prepare the water-based nanofluids.

In solution, the particle size distribution was characterized using Nanotrack particle size analyzer, Microtrac Inc. The volume weighted average particle size was measured to be 139 nm ± 100 nm for the Al_2O_3–water nanofluids. To determine colloidal stability of the nanofluids, the isoelectric point (IEP) is considered since IEP is known as a critical indicator for the particle agglomeration and setting in colloids [1,6]. The measured pH value of Al_2O_3–water nanofluids was 6.3 and it is away from ~9, the known unstable IEP value of Al_2O_3 particles. Therefore, it is assumed that the nanofluids used in present study are colloidally stable. It is assumed that dispersed nanoparticle sizes and stability of Al_2O_3–ethanol nanofluids are similar with the water-based nanofluids.

3. Experimental apparatus and procedure

3.1. Test vessel

A schematic of the test vessel used for the pool boiling tests is shown in Fig. 1(a). The internal dimensions of the apparatus are 20 cm (wide) × 20 cm (high) × 17 cm (depth). The test vessel has two reinforced glass windows on the front and back. Two half-inch diameter (1000 W) cartridge heaters were mounted in the vessel and used for heating and degassing processes. Band heaters were externally attached to the test vessel and used to maintain constant working fluid temperatures during experiments. Two valves are connected to the vessel, one on the top (degassing) and one at the bottom (draining). The top valve is connected to an external condenser to minimize loss of the working fluid during the degassing procedures. T-type thermocouples are used to measure liquid, vapor, and test heater temperatures. A pressure transducer (Omega PX202) attached to top plate is used to measure the system pressure.

3.2. Test heater

A schematic of the heater assembly used for the pool boiling tests is shown in Fig. 1(b). The test heater consists of a square copper block, a heating element, lexan substrate, epoxy, and wires. The 1 cm × 1 cm resistor (20 Ω) is soldered to the copper block (1 cm × 1 cm × 0.3 cm). The copper block and resistor assembly are then placed in a polycarbonate substrate, copper side up. 3 M® 1838 Scotch-Weld Epoxy is then distributed around the