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Enhanced boiling heat transfer on binary surfaces

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ABSTRACT

A novel idea for the improvement of boiling heat transfer is that of a binary surface – where a non-boiling liquid coats sub-surface irregularities and aids in heat transfer to the primary working fluid. The threefold goal of this effort was to: (i) prepare durable, low-cost, scalable binary surfaces for boiling heat transfer enhancement, (ii) conduct pool boiling experiments on these surfaces, and (iii) derive the physical mechanisms perceived as responsible for the observed boiling enhancements. Accordingly, robust binary surfaces were prepared on copper using a facile, scalable bulk micro-manufacturing approach. These surfaces consist of numerous micro-/nano-cavities filled by a non-boiling liquid creating puddles around solid islands. Boiling experiments were carried out using a dielectric liquid, PF-5060, as the primary working fluid (the boiling liquid). It was observed that, compared to a smooth/plain copper surface, a binary copper surface, with water as the NBL, was able to simultaneously enhance the maximum heat flux limit by ~2.2 times and the average heat transfer coefficient by ~7.5 times. A maximum heat flux of 35.06 W/cm^2 was recorded, which is higher than the enhancements reported so far in literature for the pool boiling of PF-5060 on any enhanced surface. It was further found that decreasing the contact angle of the non-boiling liquid on the binary surface enhances both the heat transfer coefficient and the maximum heat flux limit.

1. Introduction

Heat transfer by boiling of a liquid has many practical applications such as in steam generation for electricity production, thermal desalination of brackish water, chemical processing, cooking, industrial heat exchangers, and thermal management of high heat flux electronics. Boiling heat transfer is preferable over single-phase heat transfer in realizing efficient and compact systems due to its ability to transfer substantial amounts of heat almost isothermally. For example, liquid-vapor phase change based thermal management solutions have gained prominence in recent years in high power-density electronics enabling complex functionality and compact form-factors.

To further extend the advantage of high heat flux dissipation capability associated with phase change, there has been a considerable focus on exploring ways to enhance boiling heat transfer. The efficiency of pool boiling heat transfer is usually gauged by (1) the maximum heat flux that can be dissipated, called the Critical Heat Flux (CHF) and (2) the temperature excess of the hot surface over the saturation temperature of the liquid required to initiate and sustain boiling. This temperature excess is called the surface superheat (ΔT_s). It is of utmost importance in many applications to have a low ΔT_s to maintain surface temperature within a narrow range. In other words, boiling heat transfer is highly efficient if the ratio of the dissipated heat flux to the ΔT_s at that heat flux, called the Heat Transfer Coefficient (HTC), is as large as possible.

Enhancement of boiling heat transfer is an active research field. Pursued solutions [1–56] include (1) random to physics-based modification of the surface features, (2) modifying the thermophysical properties of the boiling liquids, and (3) inducing oscillations in boiling liquids and surfaces. These efforts could be categorized as either (a) for promoting liquid re-wetting to the dry zones or (b) for aiding the removal of vapor bubbles from the surface. Some representative examples include micro-/nano-structures, pin fins and posts, carbon nanotubes, sintered particle walls, micro-channels, micro-dimples, metal and carbon foams, sintered wires and meshes, membranes and coatings, micro-bubbles, suspended micro-/nano-particles, and ultrasonic vibrations [2–56]. With recent advancements in micromachining and microfabrication, passive surface modifications have been pursued by most researchers. Considering the numerous publications available on boiling enhancements in recent years, an attempt was

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Nomenclature

A	projected boiling area (m^2)
I	current (A)
HTC	boiling heat transfer coefficient (W/m^2 K) or (W/cm^2 K)
Q	heat supplied to the heater (W)
Q_{loss}	heat loss from the set-up (W)
q“	heat flux (W/cm^2)
T_s	boiling surface temperature (°C)
T_{sat}	saturation temperature of the boiling liquid (°C)
ΔT_s	boiling surface superheat (°C)
V	voltage (V)

Abbreviations

AWG	American Wire Gauge
BiS	Binary Surface
BL	Boiling Liquid
CA	Contact Angle of a water (NBL) droplet
CHF	Critical Heat Flux
HTC	Heat Transfer Coefficient
NBL	Non-Boiling Liquid
PHF	Permissible Heat Flux
PS	Plain Surface
SEM	Scanning Electron Microscope
TFR	Thick Film Resistor
UOS	Ultra-Omniphilic Surface

made to include as many relevant references as possible in this paper and some reference articles are cited for further study e.g., [2,32,34].

Enhancement of boiling heat transfer on modified surfaces has been attributed to a variety of mechanisms, including increased bubble nucleation site density, improved contact line pinning, capillary wicking of the boiling liquid, improved surface thermal conductivity, and enhanced micro-convection. However, most micro-/nano-textured surfaces have been shown to improve nucleate boiling mainly for the lower heat flux regime compared to smooth surfaces. At higher heat fluxes, bubble departure characteristics were found to be degraded due to micro-/nano-structures providing extra anchoring of bubbles [2,32,34]. Hydrophobic surfaces and coatings were also used to improve vapor trapping and thus nucleation but led to lower CHF values than smooth surfaces due to their non-wetting characteristics [2,8–10,32,34].

Some researchers took advantage of evaporation momentum force on a bubble interface (which arises due to the difference in liquid and vapor densities at an evaporating interface [57]), or using bi-philic, bi-conductive, or bi-functional surfaces to facilitate separate and efficient vapor bubble removal passageways [9,58,59]. These surfaces were found to provide simultaneous enhancements in both CHF and HTC. However, researchers also identified some of the largest barriers to practical implementation of such enhanced surfaces as lack of durability, scalability, prohibitive manufacturing cost, and complexities associated with large-scale fabrication [9,32,58,59].

In summary, it can be concluded from published literature that it is advantageous to have surfaces that are capable of being continuously re-wetted and simultaneously providing passageways for efficient vapor bubble departure. To have practical use, these surfaces must also be durable, scalable, cost-effective, and easily manufactured. This effort pursued such surfaces and conducted boiling heat transfer experiments on these surfaces. The surface features and the outcomes of the experiments are described in the following sections.

2. Binary surfaces and their preparation

Binary Surfaces (BiS) comprising two distinct co-existing phases (a solid phase, and a liquid phase) were pursued in this work as an enhancement mechanism for boiling heat transfer. A diagrammatic representation is provided in Fig. 1. These surfaces were prepared in two stages. In the first stage, a bulk micro-manufacturing approach was implemented on plain copper surfaces to generate a highly wetting surface (an Ultra-Omniphilic Surface, or UOS) with many connected micro-/nano-cavities. The UOS strongly holds liquids due to capillary forces. Wetting on these surfaces is independent of the surface tension of the liquid and is a function of only the surface roughness. In the second stage, the UOS is saturated with a liquid to create a BiS. Therefore, a BiS will have both solid (islands; orange spots in Fig. 1) as well as liquid (puddles; white regions in Fig. 1) phases. This liquid situated in the micro-/nano-cavities is termed as the Non-Boiling Liquid (NBL) as it is selected to have a higher boiling point than the Boiling Liquid (BL) on the BiS. The BL and the NBL are chosen to be immiscible.

For the experiments, three 0.97 cm × 0.97 cm substrates were prepared from the same copper bar (of 99.99% purity); one Plain Surface (PS) and two UOS. A facile, scalable, three-step bulk micro-manufacturing approach was implemented to cost- and time-effectively prepare durable UOS (patent applied). The three steps of this approach to prepare the UOS are: (1) mechanical polishing in perpendicular directions using known grit SiC abrasive paper applying a known pressure force, (2) thermo-catalytic etching using 3:3:1 solution of water, ethyl alcohol, and hydrogen peroxide at 90 °C for 90 min, and (3) thermal gradation etching in the same solution for 12 h. Complete details of this approach are provided in Ref. [60]. The first step created micro-grooves, the second step created nano-cavities, and the third step created micro-cavities by enlarging the nano-cavities and formed new nano-cavities inside them. These surfaces demonstrated extreme wetting characteristics to hold the NBL and form the BiS.

A thorough characterization of these surfaces is available in Ref. [60] and the relevant information is provided here. Elemental analysis showed the resulting UOS to be copper (Fig. 2), which confirmed that the ultra-omniphilic effect is not due to any residue or coatings. The UOS appeared smooth at a macroscopic level but scanning electron microscope (SEM) images of the surfaces showed hierarchical surface roughness with nano-scale cavities inside the embryos of micro-scale cavities and connectivity of these cavities through micro-grooves (Fig. 2). This was found to result in a very strong capillary-induced wetting and spreading of numerous liquids with zero Contact Angle (CA) for many prepared surfaces.

All the liquids tested (water, FC-770, PF-5060, R-134a, R-254 fa, R-123, mineral oil, SAE 10, SAE 40, and glycerol) could wet these surfaces. However, since the pursued bulk micro-manufacturing approach is based on creating and/or utilizing the metallurgical defects of the original sample, it was observed that the wetting characteristics of liquids on these prepared surfaces were dependent on the state of the initial sample i.e., its location of cut in a large billet, the state of the metallurgical defects after the mechanical polishing step etc. Because of this nature of the process employed, the surfaces also contained non-uniform distribution