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Wall-temperature distributions of nucleate pool boiling surfaces vs. boiling curves: A new approach

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ABSTRACT

Boiling is one of the most effective heat transfer mechanisms and has a great potential in applications where superior thermal energy management capability is required. During nucleate boiling the fluid vaporises on a surface heated above the fluid's saturation temperature and the latent heat of vaporisation allows dissipating large heat flux. The boiling performance is usually represented by a boiling curve that plots the spatio-temporal averaged heat flux versus the wall superheat. Here, we show a new approach to evaluating the process on the basis of wall-temperature distributions, calculated from spatio-temporal thermographs of the boiling surface. Instead of a single data point on the boiling curve, the presented distributions provide spectra of information, such as the maximum, minimum and mean wall superheat and the standard deviation of the wall temperature. These parameters are all associated with the nucleation frequencies and the nucleation site densities. The experimental results from various state-of-the-art surfaces suggest that the distributions reveal the stability of the boiling process, which opens a new path towards a better understanding and the development of heat transfer technology.

1. Introduction

Boiling is a part of our everyday life and is one of the most effective, technically controllable heat transfer mechanisms. Constant desire to enhance heat transfer during boiling has led to incorporation of various research fields, which made it a highly multidisciplinary field of research. Future development demands for better understanding and new approaches in boiling heat transfer.

During nucleate boiling the liquid undergoes a liquid–vapour phase change at the heated surface and the quantity of heat flux transmitted from the surface (q) increases as the temperature difference between the surface and the working fluid (ΔT) increases until a critical heat flux (CHF) is reached. Any further increase of q beyond that limit leads to film boiling, which results in a large increase of ΔT and usually leads to burnout of the boiling surface. The main advantages of nucleate boiling are the high heat flux rates, a constant fluid temperature during the phase change and a relatively low ΔT (<50 K), which makes this process suitable for cooling delicate high-heat-flux applications where 1 MW m^{-2} is easily exceeded (e.g., nuclear-fuel claddings [1] and electronics [2,3]). Researchers already developed various surface [4–6] and fluid [7] modification techniques to enhance heat transfer (e.g. to increase the CHF and lower the ΔT). So-called biphilic surfaces, made of hydrophobic (water-repellent) and hydrophilic (water-loving) networks, have recently shown dramatic improvements [8–11]. A hydrophobic surface promotes nucleation and lowers the temperature of the onset of boiling, while a hydrophilic surface increases the suction of the liquid and consequently increases the CHF. However, the development of a biphilic surface for optimal boiling performance is still under investigation.

Boiling heat transfer performance used to be represented by a boiling curve [12] that plots the heat flux versus ΔT and highlights the different boiling regimes. For nucleate boiling the curve contains information about the temperature of the onset of nucleate boiling, CHF, and the heat transfer coefficient (the ratio between q and ΔT) for every measured point. Unfortunately, such a boiling curve lacks some of the key boiling parameters, like the distribution and density of the active nucleation sites, the size of the bubble contact areas and the bubble nucleation frequencies – parameters that are also discussed in many mechanistic models [13–16] and empirical correlations [17–22].

The development of new, 5th-generation, boiling heat transfer technology requires not only an improvement in the heat transfer surfaces [8,23–25] and the incorporation of better measurement techniques [26], but also new analysis approaches to overcome the limitations of the spatio-temporal, averaged data presented

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in the boiling curves. We present the novel approach of studying boiling heat transfer phenomena through wall-temperature probability density distributions. Distributions were calculated from high-speed infrared thermographs obtained during saturated nucleate pool boiling on various surfaces with uniform wettability and different state-of-the-art biphilic surfaces. This work presents an alternative to currently established boiling curves and is a necessary step forward towards better understanding of boiling phenomena and future progress in phase-change heat transfer.

2. Materials and methods

2.1. Fabrication and characterisation of boiling surfaces

To achieve a variety boiling performances, we created hydrophobic (HPO), superhydrophilic (SHPI), and patterned laser-processed biphilic (BPI) surfaces on a stainless-steel (SS) base. Stainless-steel foils were first coated with custom hydrophobic paint made of polydimethylsiloxane (PDMS) and the PDMS-coated fumed silica. After the air-spraying and thermal curing (30 min at 230 °C), the coated stainless-steel foils became highly hydrophobic with static water contact angles greater than 137° as shown in Fig. 1b. The thickness of the coating was 1 μm. Proper thermal treatment at temperatures over 500 °C turned the surface superhydrophilic with contact angles below 1°. Based on this, we created three differently patterned biphilic (BPI) surfaces. Each biphilic surface is a combination of hydrophilic network and evenly distributed hydrophobic square-shaped spots. The spots were differently sized for each surface: $2 \times 2\,\text{mm}^2$ (BPI_2); $1 \times 1\,\text{mm}^2$ (BPI_1); and $0.25 \times 0.25\,\text{mm}^2$ ($\text{BPI}_{0.25}$). The pitch between spots was 4 mm, 3 mm, and 1.5 mm, respectively. To produce such patterns, we used a pulsed Nd:YAG laser with a 2-μm scanning resolution, pulse energy of 1.0 mJ, a pulse duration of 340 ns and a spot size of 50 μm.

Atomic force microscopy (AFM) revealed a hierarchically structured hydrophobic coating that is micro-porous and covered with spherical, fumed-silica nanoparticles, as shown in Fig. 1b. Fourier-transform infrared spectroscopy (FTIR) also confirmed the presence of non-polar $–\text{CH}_3$ groups on the surface [9]. The combination of a hierarchical structure and non-polar groups resulted in a highly hydrophobic surface [27,28]. After the thermal treatment the surface remains nano-porous, but its micro-roughness changes (see Fig. 1c). The –CH3 groups are oxidised and silicon carbide is partially formed. This causes the transition from hydrophobic to super-hydrophilic. The fabrication procedure and the surface characterisation results are presented in detail in Ref. [9].

2.2. Pool boiling setup

The setup for saturated pool boiling experiments is similar to the one used in our previous work [9]. It consists of a $170 \times 100 \times 100\,\text{mm}^3$ pool-boiling chamber made of

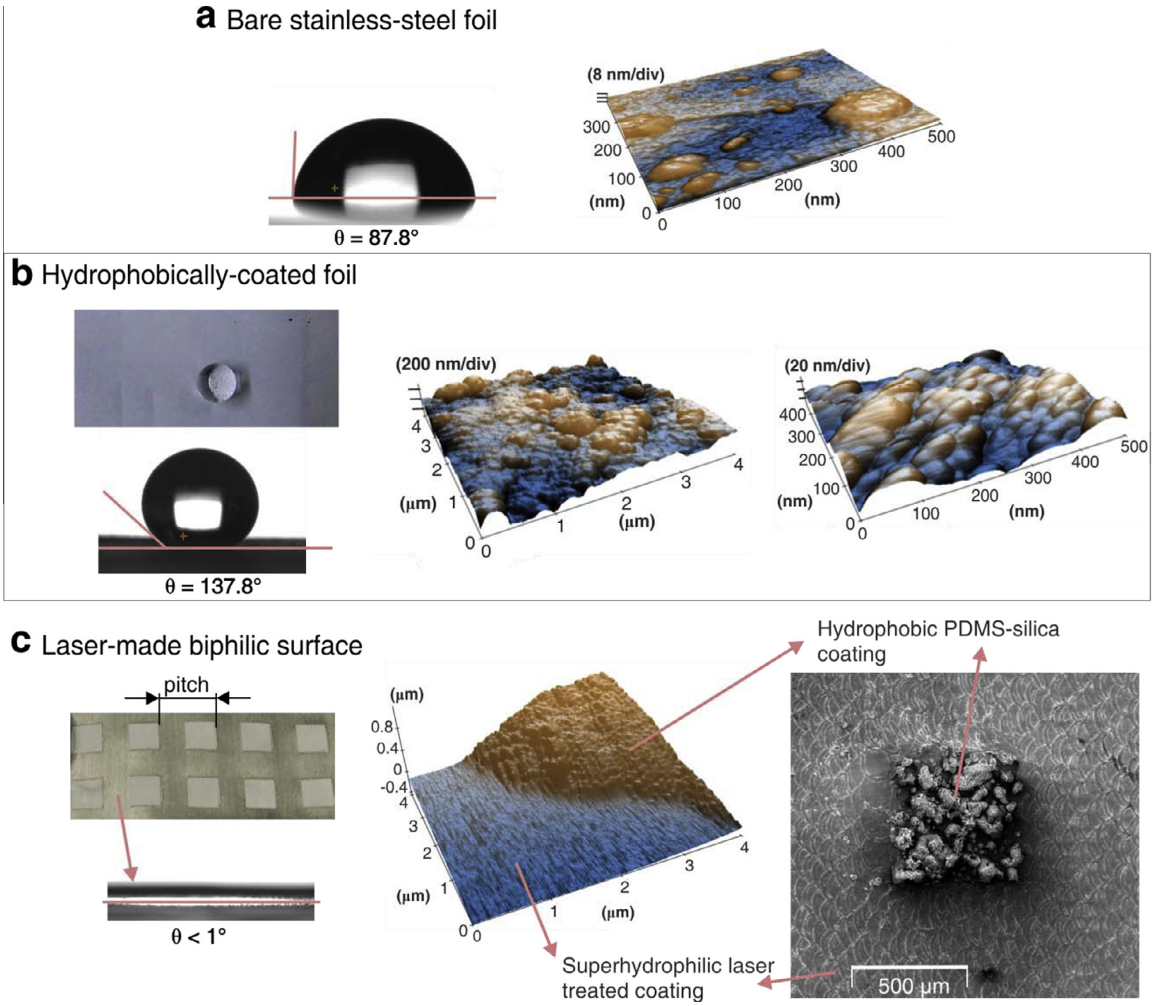

Fig. 1. Characterisation of boiling surfaces. (a) Contact angle (CA) and atomic force microscopy (AFM) of bare stainless steel; (b) CA and AFM of hydrophobically coated foil (spherical particles with sizes of 10–50 nm on the surface correspond to the primary particle size of the fumed silica); and (c) CA, AFM and scanning electron microscopy (SEM) of the laser-made biphilic surface.