



Research paper

Pool boiling enhancement using switchable polymers coating

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HIGHLIGHTS

- Experiments are performed to highlight the influence of thermo responsive polymers on nucleate boiling heat transfer.
- Thermo responsive polymers induce a change in wettability at a given temperature.
- An enhancement of heat transfer coefficient is observed with coated surfaces.

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ABSTRACT

In the present paper, experiments were performed to combine the advantages of hydrophilic and hydrophobic surfaces in pool boiling conditions. Hydrophobic surfaces easily initiate bubble nucleation while hydrophilic ones facilitate bubbles detachment. For this purpose, specific surfaces grafted with stimuli responsive polymers have been designed and tested. Switchable or thermo responsive polymers, specifically thermo responsive hydrogels, exhibit a drastic and discontinuous change of their physical properties with temperature moving to a total affinity for water to a total hydrophobic state around a narrow temperature (Lower Critical Solution Temperature). Around this specific temperature (LCST) the transition hydrophilic to hydrophobic will be totally reversible. Such polymers have thus the characteristic, when deposited on a flat surface, to induce a change in wettability of the sample at a given temperature. Physico-chemical techniques were used to obtain a coating switching near the saturation temperature of water at atmospheric pressure. It was found that the coated surfaces well perform and exhibit better thermal performances than the uncoated ones (average boiling enhancement about 20%). The present study constitutes a new approach of nucleation mechanism control and offer new perspectives for thermal applications.

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1. Introduction

For several decades, nucleate boiling, a very effective and performing heat transfer mechanism, has been widely applied in various scientific and engineering fields. So far, with the increasing demand of cooling ultra-high heat flux equipment and miniaturisation, several studies have been carried out to improve heat transfer performances by nucleation.

One of the most applied technologies consists in coating heated surfaces by using enhancement techniques as direct spraying,

chemical etching, electroplating, etc. Hence, modified surfaces have larger number of nucleation sites to promote boiling and thereby to improve heat transfer.

Different types of coating have already been investigated and exhibited interesting performances. Coatings are provided at micrometric or nanometric scales either by particle depositions [1,2], or by an artificial creation of cavities to generate controlled nucleation sites [3].

Recent studies show that the influential parameters to enhance heat transfer during pool boiling are bubbles size, emission frequency and nucleation sites density. Surface wettability is also involved by connecting the contribution of those different parameters. For example, hydrophilic surfaces make bubbles detachment easier. The bubble is created in an active cavity. When liquid moves towards the cavity, the gravity force stretches the bubble vertically.

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Nomenclature

h	heat transfer coefficient, $W/m^2 K$
I	current, A
q	heat flux density, W/m^2
S	surface area, m^2
T	temperature, K
V	voltage, V

Greek symbols

θ	contact angle at, degree or rad
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Subscripts

liq	liquid
vap	vapour, phobe refers to hydrophobic, phile refers to hydrophilic, s or sat saturation,
w	wall

Consequently, the latter phenomenon is intensified for hydrophilic surfaces [1]. However, for such surfaces, bubble diameter departure increases, due to the augmentation of bubble growth time [1]. On the contrary, hydrophobic surfaces promote vapour confinement which easily initiates bubble nucleation: bubble growth time is then smaller (compared to that of the hydrophilic case) but the detachment stage is reduced leading to bubbles coalescence and rapid occurrence of critical heat flux.

Few studies have tried to perform experiments combining complementary properties of hydrophilic and hydrophobic surfaces [4,5] on a same sample: for a given surface wettability, a partial coating showing the inverse wettability is added. Jo et al. [6] have both investigated experiments: a hydrophilic surface including hydrophobic sites and the inverse pattern. They observed a better enhancement of heat transfer and a more efficient heat removal for the hydrophilic surface including hydrophobic sites. The authors, notably, conclude that thermal performances of the surface are dependent on the size of hydrophobic sites and on the distance between each spot.

Sun et al. [7] have reported the first demonstration on thermal reversible switching behaviour between superhydrophilicity and superhydrophobicity. They use a thermo responsive polymer (this kind of polymer can modify wettability samples as a function of surface temperature, as it is explained more in details in Section 2) that exhibits, when deposited on a flat surface, a contact angle modification from 63.5° for a temperature of $25^\circ C$ – 93.2° at $40^\circ C$. Fu et al. [8] have developed a different approach based on a porous anodic aluminium oxide template with nominal pore sizes from 20 to 200 nm. The authors report a change in wettability due to the expansion and contraction of the grafted polymer.

Theoretically, better heat transfer will be obtained with a local modified surface, i.e., a surface whose wettability could only change on nucleation spots. Those initially hydrophobic sites would be transformed into hydrophilic sites during the nucleation beginning to make bubble growth easier.

In this study, specific surfaces called “switchable surfaces” have been especially designed to this aim. Those surfaces are able to reduce the waiting time between departures of successive bubbles. Thermo responsive polymers have been grafted on a stainless steel sample to induce a change in wettability near saturation temperature of water at atmospheric pressure. This modification is called a switch in this paper and the quantities involved switchable parameters. This technology of switchable polymers is well known in chemical applications but, according to our knowledge, has never been used for boiling enhancement.

2. Polymer surface characteristics

The swelling–shrinking behaviour of hydrogel polymers with temperature have been extensively described in literature. Numerous families of polymers exhibit such a behaviour, the most famous being polyNiPAAM (cf. Fig. 1), [9]. However there are other families of polymers which exhibit a similar behaviour in water versus temperature: hydroxyl alkyl cellulose (LCST: $56^\circ C$), polyalkyloxazoline (LCST: $70^\circ C$), polyvinylmethylether (LCST: $40^\circ C$), polyethyleneglycols (LCST: $100^\circ C$ – $150^\circ C$) depending on the molecular weight. All these polymers are commercially available.

The switch temperature has a very accurate value for polymers having the same crystalline arrangements. Thus, when polymer shrinks, a change in wettability is observed as the energetic level of the polymer is modified. The challenge is to find a polymer whose switch temperature was slightly higher than saturation temperature of the working fluid [10]. The polymer sequences are implemented on the surface tanks to a particular coating. This coating connects to the polymer extremity and generates a robust and perfectly regular layer.

Polymers size is smaller than the critical radius of a vapour bubble (a few thousand nanometers). Thus, coating will not change the topography of the surface and the dynamic of bubble formation during boiling (cf. Fig. 2).

The polymer is hydrophilic when it is expanded and hydrophobic when it is contracted. Before nucleation, the wall is superheated and the wall temperature becomes higher than the switch temperature, the polymer contracts, so that the surface becomes hydrophobic and bubbles form easily. This occurrence implies that the temperature at the liquid vapour interface and particularly near the triple line is equal to the saturation temperature.

During the bubble growth, in the micro region near the triple line, there is a strong evaporation leading to an enhanced conductive heat flow in the liquid layer and finally to a very fast decrease of surface temperature. Thus this surface becomes hydrophilic locally, near the triple line. The contact angle is now decreased. Moreover, the liquid is now able to shear the base of the bubble allowing its rapid departure. The rewetting of the surface makes the temperature increasing again over the switch temperature value leading to a new cycle of bubble growth.

3. Pool boiling experiments

3.1. Experimental apparatus

The experimental setup is shown in Fig. 3. The layout is designed to study the pool boiling heat transfer in a horizontal position with stainless steel or coated surfaces. The main components are a test foil heater (1), a boiling vessel (2), a sample holder (3) and a thermostat (4). The tested surface is made of $20\ \mu m$ -thick stainless steel strips, and its $100\ mm \times 5\ mm$ faces are brazed between two

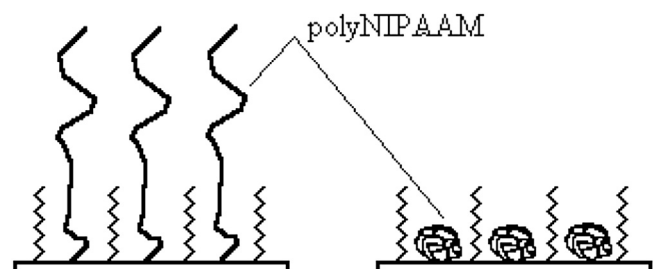


Fig. 1. Switchable polymers sequences on a surface.

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