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Pool boiling heat transfer enhancement with copper nanowire arrays

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HIGHLIGHTS

- We investigated the effect of nanowire arrays on pool boiling heat transfer enhancement.
- Nanowires with five different lengths were electroplated on bare copper surface.
- We studied the influence of the length of copper nanowire arrays on HTC and CHF of boiling.
- We explored the physics of the boiling mechanism on nanostructure surfaces.

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ABSTRACT

The pool boiling heat transfer on copper nanowire arrays has been experimentally studied. Five different copper nanowire arrays with various lengths (3 μm, 5 μm, 10 μm, 20 μm, and 30 μm) have been electroplated on bare smooth copper surfaces. Their pool boiling heat transfer performances were measured and compared with control surfaces. It is found that the integration of copper nanowire arrays on heating surface can effectively enhance the boiling heat transfer coefficient(HTC) as well as the critical heat flux(CHF). As the length of nanowires increases, more enhancements have been observed. This augment is due to the enhancement of the wettability and the number of the nucleation sites (defects).

1. Introduction

Boiling is the most efficient mode of heat transfer due to its inherent phase change nature. Hence, it is considered as one of the solutions capable for cooling electronic devices with extra-high heat flux in future.

Boiling heat transfer enhancement has been researched extensively over the last century. A detailed review has been provided by Pioro et al. [1]. One approach to enhance boiling heat transfer is to manipulate the topography of boiling surface. Several commercial products have proved that artificial surfaces, such as porous sintered coating (Union Carbide HIGH-FLUX), re-entrant grooves (Wielanderke AG GEWA-T), and tunneled surfaces formed by bending notched fins (Hitachi, THERMOEXCEL-E), can effectively raise the boiling Heat Transfer Coefficient (HTC) and the Critical Heat Flux (CHF) comparing with untreated bare smooth surfaces. This traditional enhancement was attributed to the increase of the liquid–solid contact area and the number of the nucleation sites in size of 10 μm.

Recently, researchers have noticed that the nanostructures can also improve the pool boiling heat transfer performance. In 2006, Ahn et al. [2] reported that the boiling surface integrated with vertically aligned multiwall carbon nanotubes (CNTs) can have an augment of CHF by 25–28% for PF-5060, compared with the control surfaces. Ujereh et al. [3] synthesized CNTs on copper and silicon surfaces and measured the pool boiling heat transfer performance in FC-72 experimentally. They found that the fully CNTs coated surfaces showed a noticeable decrease in the incipience superheat as well as a shift of the entire nucleation boiling region (about 2 °C) toward lower wall superheats. The similar conclusion has also been reported in Sathyamurthi et al.'s researches [4] for sub-cooled pool boiling. In their experiments, it was noticed that MWCNTs coated substrates yields higher wall heat fluxes under saturated and sub-cooled conditions compared with a bare silicon surface, while the enhancement heat flux was weakly dependent on the thickness of the MWCNTs. In 2009, Khanikar et al. [5] applied CNTs in micro-channels and the similar results had been observed.

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These researches provide an approach to enhance the boiling heat transfer performance by introducing CNTs on heating surfaces. However, the synthesis of CNTs on desired surfaces by chemical vapor deposition (CVD) requires high temperature environment (usually 500 °C–700 °C), which is not capable for applications in electronic devices. Recently, researchers found that other nanowires, such as copper, TiO_2, silicon, had similar effects on boiling heat transfer performance while the synthesis can be achieved in low temperatures. In 2008, Li et al. [6] deposited a copper nanowire layer on a substrate using electron-beam evaporation method. The pool boiling experiments showed that the deposition of copper nanorods on polished copper substrate brought more than 30% enhancement to the HTC. However, an apparent CHF rise was not observed in their experiments. While in Chen et al.'s work [7], both the HTC and the CHF enhancements had been reported by introducing copper nanowires as well as silicon nanowires on smooth silicon substrate. It is noticeable that their copper nanowires were synthesized by electroplating, which can be conducted at room temperature. Yao et al. [8] developed a new technique to directly grow Cu/Si nanowires with various heights. They obtained a heat flux of 134W/cm^2, which was 300% higher than a plain Si surface at the same wall superheat. Some other observations, such as Chen et al.'s [9], Im et al.'s [10] and Thiagarajan et al.'s [11], have also been published in last several years. Different nanowires have been integrated on boiling surfaces. Most of them have found that both the HTC and CHF had been improved by introducing nanowire arrays on bare smooth surfaces.

Though various experiments have proved the significant augment of boiling heat transfer performance using nanowire arrays, the mechanisms of such enhancement are still in debate. Several arguments have been proposed: 1) The wettability of the treated surface has been effectively improved. The contact angle decreases, which causes an increased CHF through the enhanced liquid spreading over the heated area. In the meantime, it also expands the contact area between solid and liquid. The fin effect reduces the interface temperature and hence shifts the boiling curve to the left side. 2) The abundant micro-sized cavities in the nanowire arrays defects can effectively trap air or vapor and serve as nucleation sites, which reduce the wall superheat. They also can provide sites for stable vapor formation at the top of the nanowire coating, which alters the critical distance between vapor columns on the heating surface and thus adjusts the critical instability wavelength. 3) The introducing of nanowires enhances the capillary pumping effect on solid surfaces, thereby delaying the dry out of the region under the vapor column.

According to these impacts, the effect of the length of nanowire arrays must affect the boiling heat transfer performance dramatically since some critical facts, such as wettability, number of defects and capillary pumping ability, all depend on the length. However, such researches have barely conducted and the pool boiling performance of nanowire array surfaces on the nanowire length is not revealed yet. This paper focuses on the preliminary experimental studies of the influence of the length of copper nanowire arrays on HTC and CHF of boiling and explores the physics of the boiling mechanism on nanostructure surfaces.

2. Experiment

2.1. Experimental setup

Fig. 1 shows the apparatus for the pool boiling heat transfer experiments. A copper heat transfer block (1 cm × 1 cm in cross section) embedded with a heater unit at the lower section was built and submerged in the test fluid (DI water), which was then heated up to its saturation temperature (100 °C) at 1 atm. The top surface, which was synthesized with copper nanowire array on, was directly contacted with test fluid, while the other surfaces were protected with ceramic fiber insulation materials from heat loss.

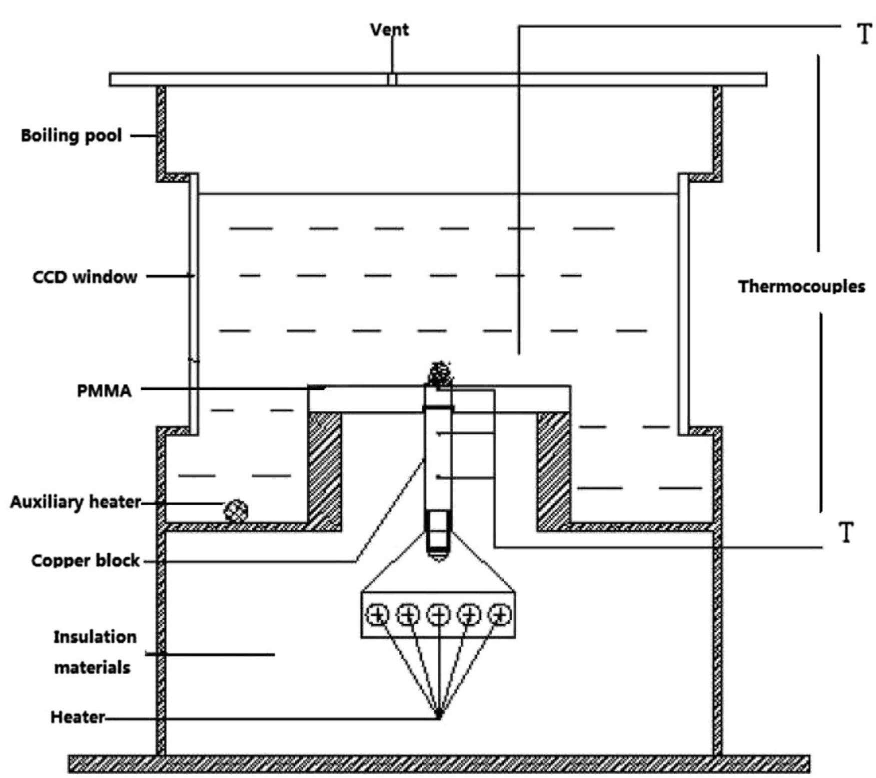

Fig. 1. Schematic of the experimental set-up.