International Communications in Heat and Mass Transfer 77 (2016) 155–158

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Improvement of water wetting capability of copper wire braids by surface modification approaches☆

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ARTICLE INFO

Available online 16 August 2016

Keywords:
Wettability
Surface modification
Capillary rise measurements
Laplace-Young equation

ABSTRACT

This study investigated the wettability enchancement of copper wire braids and copper plates by surface modification methods. Two different surface modification methods are applied to form nano structures on surfaces, resulting in superhydrophilic wettability. To examine the wetting capability of the modified samples, the capillary rise measurement for copper plates and copper wire braids was chosen as the performance index in this study. The experimental data of the capillary rise measurements between two parallel plain-copper plates show a good agreement with the Laplace-Young equation. As for the braided copper wires with superhydrophilic wettability, the experimental results have stronger capillarity than that of the plain ones.

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1. Introduction

Heat transfer is an important mechanism in many industrial applications, a classic example is the heat pipes in consumer electric cooling systems [1–3]. Nowadays, with the more compact consumer electronics, the available space in the system is limited. Therefore, ultra-thin heat pipes (thickness lower than 2 mm) draw more attentions than ever before. On the other hand, surface wettability is one of the key factors for enhancing two-phase heat transfer [4–6]. Various levels of surface wettability from superhydrophilic to superhydrophobic can be accomplished by different surface modification techniques. Such techniques are also applied in the heat pipes to fabricate the wick structures which include sintered metal powder, mesh, and grooved wicks. These important microstructures in the heat pipes provide capillarity for working fluid to exert force on. Liou et al. [7] fabricated a flat-plate heat pipe with sintered multi-layer copper-mesh wick and measured its evaporation resistance. The results show that the finer mesh screen can reach smaller evaporation resistance. Based on Liou's work, Wong et al. [8] fabricated sintered-copper-powder-mesh wicks and homogeneous copper-powder wicks in flat-plate heat pipes for the same test. The results show that the minimal values of the evaporation resistance was about the same as that of multi-layer copper-mesh wick in Ref. 7.

Many plants and animals in their natural state were found to have some special surface properties on parts of their body. In addition to the well-known water repellent lotus leaf effect [9] and petal effect [10] of plants, some animals also have interesting mechanisms to interact with water [11–13]. For instance, Cribellate spider's silk is capable of collecting water from air. Zheng et al. [14] found that there are two mechanisms involved in the collection process, the surface wettability induced surface energy gradient and the curvature gradient induced difference in Laplace pressure between spindle-knots and joints. Dong et al. [15] investigated the effect of surface hydrophilicity on water transport behavior of dual-layer electrospun nanofibers mats. They found that with a large quantity of nanochannels, the porous polystyrene nanofibers exhibit a stronger capillary effect than the solid polystyrene nanofibers. Applying surface modification on the polystyrene nanofibers can further enhance the capillary motion.

Inspired by these literatures, the feasibility of applying the surface modification techniques on the copper wire braids to improve the capillarity is to be investigated in this study. The capillary motion between two copper plates (thickness = 0.3 mm) and braided copper wires (thickness = 0.5 mm) will be compared. The measurements of capillary rise between two parallel plain copper plates will be conducted as performance index. The measured data are then compared with a theoretical equation, the well-known Laplace-Young equation, as a benchmark test. The copper surfaces after surface modification treatments will become superhydrophilic for enhanced capillary motion. Therefore, the measurements of capillary rise using surface-modified superhydrophilic copper plates are conducted to compare the differences between superhydrophilic and plain surfaces. Second, for the copper wire braids, the capillary rise measurement is not applicable because of the through holes on the copper wire braids surfaces. Thus, the wetted heights on the copper wire braids by inserting into water and the weight changes before and after the experiment are measured.

☆ Communicated by H. Yoshida and S. Maruyama.
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http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.08.012
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2. Experimental

2.1. Preparation of superhydrophilic surfaces

For the plain copper plates, the measured water contact angles are approximately 95° with a variation of 2°. The water contact angles were measured using a contact angle goniometer (Model 100SB, Sindatek Instruments Co., Ltd., Taiwan) with a sessile drop volume of 2μl. The nanostructured thin film on copper wire braids and plates with superhydrophilic wettability were prepared using two different surface modification techniques for comparison. The first one is the sol-gel surface modification approach [16] which is a silica-based coating method to establish various levels of surface wettability from superhydrophilic to superhydrophobic on copper materials (includes plates and wire braids). The SiO_2 particles with 40 nm in diameter are used in the sol-gel surface modification approach. Hereafter it will be referred to as SiO_2 method for short. The dip rate for dip coating is fixed to be 1.1 cm/min. The other method is a chemical-oxidation-based CuO fabrication process. The nanostructured CuO films are formed by immersing copper materials into a 95 °C alkaline solution for 10 min where the solution composed of $NaClO_2$, NaOH, $Na_3PO_4 \cdot 12H_2O$, and DI water (3.75:5:10:100 wt.%) [17]. After 10 min, the color of the immersed copper material will become black and the solution will become light blue. Then the oxidized copper materials are put into an oven at 120 °C for 15 min to dry. The samples of modified copper surfaces with superhydrophilic wettability using the chemical-oxidation-based CuO fabrication process (hereafter it will be referred to as CuO method) are then ready for experiments.

The measured water contact angles of the modified copper surfaces by both SiO_2 and CuO methods are less than 10°, reaching the instrument detection limit of the instrument. The dimensions of the copper plates and wire braids are 100 mm (L) × 20 mm (W) × 0.3 mm (H) and 125 mm (L) × 1.5 mm (W) × 0.5 mm (H), respectively. The 192 copper wire braids used in this study have a wire diameter of 0.05 mm. All the experiments were conducted 3 times for repeatability.

2.2. Experimental apparatus setup

Fig. 1(a) illustrates the scheme of the experimental apparatus setup for capillary rise measurement between two copper plates. The independent variable in the experiments is the spacing between two copper plates. Three different copper plate sets were used in the measurements for comparison: plain copper plates, copper plates with SiO_2 method and copper plates with CuO method. Each set has two copper plates identical in size and were arranged in parallel and then inserted into DI water. Due to the capillary action, the liquid will elevate along the plates. After reaching steady state, the meniscus profiles and liquid elevation heights between the copper plates will no longer change. Then photos were captured by a camera for further analysis. The photos were analyzed by a self-programmed MATLAB (Math Works Inc., USA) to examine the meniscus profiles and the areas under the meniscus then calculate the mean heights of the capillary rise. The photos were then processed with binary process by setting a threshold value and the black and white regions in the processed pictures. When the spacing between two copper plates is given, the mean heights for capillary rise measurement between two copper plates can be calculated.

Fig. 1(b) illustrates the scheme of the experimental apparatus setup for capillary rise measurements on the copper wire braids. The copper wire braids were inserted 1 cm below water level. For easier observation during the measurement, few drops of blue ink were added into the DI water. After two minutes, the wetted heights of the wetted region on the copper wire braids were recorded. Before and after the measurements, the weight changes of the copper wire braids were also measured by an electric balance. Three different types of copper wire braids were used to conduct the measurements for comparison: plain copper wire braids, copper wire braids with SiO_2 method and copper wire braids with CuO method.

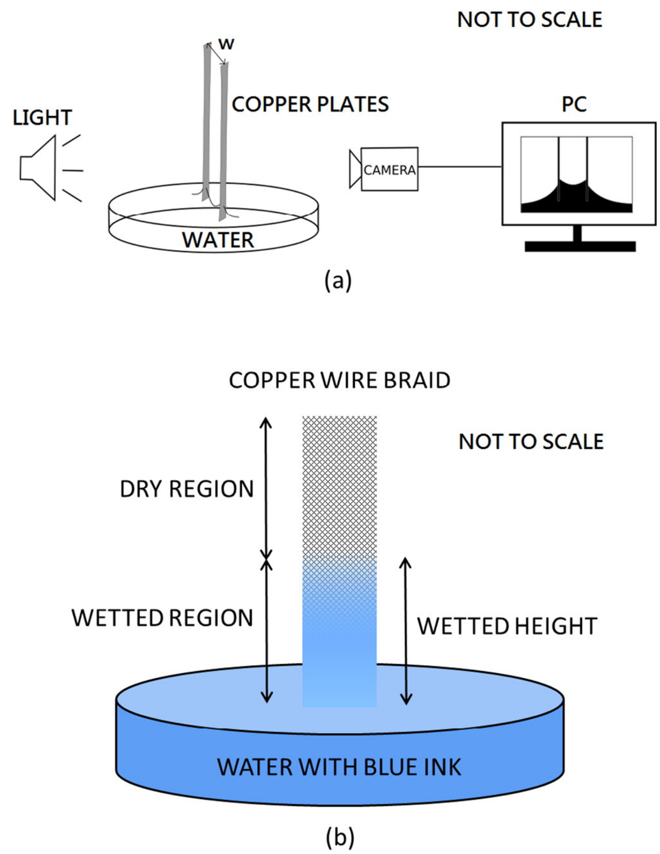

Fig. 1. The scheme of the experimental apparatus setup for (a) capillary rise measurement between two copper plates (b) wetted height measurement on the copper wire braid.

3. Results and discussion

3.1. Surface morphology of superhydrophilic surfaces

Fig. 2 shows the scanning electron microscopy (SEM) images for (a) plain copper plate, (b) plain copper wire braid, (c) copper plate with CuO method, (d) copper wire braid with CuO method, (e) copper plate with SiO_2 method, and (f) copper wire braid with SiO_2 method. In Fig. 2(c), there are many CuO microstructures in flower shapes generated on the copper plate, which is consistent with the results shown in ref. [17]. Fig. 2 (c–f) shows that the micro/nanostructures fabricated by these two surface modification techniques are very different. In Fig. 2 (c) and (d), although both of the copper materials fabricated by CuO method were using the same processes, the characteristic lengths of the microstructures on the copper plate are obviously larger than that on the copper wire braids. Each flower shape microstructures on the copper plate are around 10 μm in diameter. In contrast, the microstructures on the copper wire braids are down to 2 μm. One possible explanation is that the copper wire braids are not able to support such large microstructures on the curved surfaces and round edges. In addition, the copper surfaces by SiO_2 method show smoother and finer surfaces than CuO method because nanoparticles are used for fabricating nanostructures. Although the copper surfaces by different modification methods have different surface structures, both of the surfaces still have superhydrophilic wettability. The coarser copper surfaces fabricated by CuO method also imply that there are more voids created in the fabrication process that lead to differences in capillary rise height.

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