A hybrid surface modification method on copper wire braids for enhancing thermal performance of ultra-thin heat pipes

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Abstract. Copper is the most widely used material in heat pipe manufacturing. Since the capability of wick structures inside a heat pipe will dominate its thermal performance, in this study, we introduce a hybrid surface modification method on the copper wire braids being inserted as wick structure into an ultra-thin heat pipe. The hybrid method is the combination of a chemical-oxidation-based method and a sol-gel method with nanoparticles being dip-coated onto the braid. The experimental data shows that braids under hybrid treatment perform higher water rising speed than the oxidized braids while owning higher water net weight than those braids being only dip-coated with nanoparticle.

1. Introduction
Delivering heat at high rates over considerable distance with extremely small temperature drop, the heat pipe is a both smart and effective thermal management solution with simple construction and without any external pumping power. Figure 1 displays the basic working principle of the heat pipe. A heat pipe has wick structure on the inner surface and a small amount of working fluid delivering thermal energy at saturated state. It is composed of three sections: evaporator, where fluid absorbs heat and vaporizes; condenser, where vapor rejects heat and condenses; and an adiabatic section in which liquid and vapor flow in opposite direction back to evaporator and condenser, respectively.

Figure 1. Basic working principle of the heat pipe
Classic examples for heat pipe application are in the market of consumer electronics [1-4]. As high performance and downsizing having been prerequisites in this market in recent years, ultra-thin heat pipes (thickness lower than 2mm) or flat plate heat pipes are attracting more and more attention [5-8]. In this study, we introduce a hybrid surface modification method for the copper mesh being inserted as wick structure into ultra-thin heat pipes.

2. Experimental process

2.1. Preparation of surface modification

The hybrid treated copper wire braid in the experiment undergoes a chemical-oxidation-based process [9-11] and then being dip-coated out of a sol-gel solution containing SiO$_2$ nanoparticles [12, 13].

2.1.1. Chemical-oxidation-based process

Under this process, thenanostructuredCuO films are formed by immersing copper materials into a hot alkaline solution composed of NaClO$_2$, NaOH, Na$_3$PO$_4$·12H$_2$O and DI water [14]. After 6 min, the color of the immersed copper material will become black and the solution will become apparently light blue because of the presence of Cu(H$_2$O)$_6^{2+}$ ions.

2.1.2. Sol-gel method

This process of surface modification is a coating method also for transforming surface wettability from superhydrophilic to superhydrophobic on copper materials [15]. The SiO$_2$ particles with 40 nm in diameter are mixed in the sol-gel solution. Since the dip-coating speed has a great influence on surface property after modification, two specific values of dip coating speed are set in the experiment, which are 3cm/min and 10cm/min.

2.2. Copper wire braid settlement

Following the same settlement introduced by Hsu et al. [16], figure 2 shows the definition of wetted height. The total length of a single copper wire braid is 11.0cm and all the braids are stuck at its top endonto a metal ring hanging with the same level on a plastic plate. 5 braids are weighed together at a time after immersing its bottom end into water for 75 seconds.

![Figure 2. The scheme of the experimental setup for wetted height measurement on the copper wire braid](image)

2.3. Wetted height observation

The black colour of the oxidized copper surface blurred the water boundary on the braid. To tackle with this issue, Tang et al. introduced an IR thermal imaging method [17]. Due to the distinct difference in infrared emissivity between braid material and water, different temperature distributions were clearly displayed in IR thermal images. Figure 3 demonstrates the sequential images captured by IR camera.
3. Results and discussion

3.1. SEM images of surface modification

In figure 4, the scanning electron microscopy (SEM) images are shown for the 4 different kind of copper wire braids, which are (a) plain, (b) dip-coated with SiO$_2$ nanoparticles, (c) oxidized in hot alkaline solution, and (d) hybrid treated. The first three photos are cited from those shown in ref. [16] and the fine flake-shaped structure of CuO can be seen in figure 4(c), which is consistent with results shown in ref. [14]. The hybrid structure in figure 4(d) can be found remarkably straightforward “hybrid”.

However, the individual SiO$_2$ nanoparticles could not be easily observed in figure 4 for its scale being too small. Although the copper surfaces made by different modification method have different surface structures, copper surfaces in figure 4(b), figure 4(c) and figure 4(d) are all found to be superhydrophilic, which is experimentally proved being helpful for enhancing the wetted height. The coarser surface made by chemical-oxidation-based method implies that there are voids created in the modification process which is also found leading to an enhancement in water net weight.

3.2. Water net weight

The experimental data of weight measured are shown in Table 1. For the sake of conciseness, the calculated standard deviations of those measured weight data are not shown in the table since it is almost an order smaller than the max error of the scale, which is 0.01 gram, stated by the manufacturer.

Water net weight of a copper wire braid would refer to the capability of working fluid transportation by wick structure in heat pipes. Oxidized copper wire braid is found having higher porosity on the surface, which could lead to the result of higher water net weight than the dip-coated braids. After 75
seconds the bottom end being touched and immersed into water, as all the samples are supposed to be fully wetted, those braids underwent oxidation process are showing obviously higher water net weight than those braids being only dip-coated.

Table 1. Measured weight changes for copper wire braids under various surface treatment

|                     | Dip-coated (10 cm/min) | Hybrid (10 cm/min) | Dip-coated (3 cm/min) | Hybrid (3 cm/min) | Oxidized |
|---------------------|------------------------|--------------------|-----------------------|-------------------|----------|
| Dry weight (g)      | 26.96                  | 26.95              | 26.93                 | 27.01             | 26.94    |
| Gross weight (g)    | 27.22                  | 27.25              | 27.19                 | 27.31             | 27.25    |
| Water weight (g)    | 0.26                   | 0.30               | 0.26                  | 0.30              | 0.30     |

3.3. Water rising speed

The detailed wetted height measurement is as the following. First, count the vertical black-pixel-number in each IR image with software and find the ratio between this black-pixel-number to that of a wire braid with full wetted height. Multiply the ratio obtained above by the actual full length of the copper wire braid and so comes the actual wetted height.

The water rising speed can be clearly compared among copper wire braids under different surface modification process. It is conspicuous that curves with larger slope have higher water rising speed. As shown in figure 5, dip-coated braids share higher water rising speed than others; meanwhile, the hybrid treated braids have noticeable higher value in wetted height as well as in water rising speed than the oxidized copper wire braids.

![Figure 5](image_url)

Figure 5. Wetted height against time elapsed for copper wire braids under various surface treatment.

The dip-coating speed in each method is declared within parentheses

4. Conclusion

In conclusion, the feasibility of the copper wire braids applied with hybrid surface modification techniques to improve the performance of wick structure in an ultra-thin heat pipe was experimentally investigated. The hybrid surface modification method is introduced to fabricate a hybrid surface structure and from the SEM results, it is shown that the hybrid surface processed by the two methods share the two distinct surface properties. The flake-shaped CuO structure may refer to a higher surface porosity and the area covered by the SiO$_2$ nanoparticles retains a superhydrophilic surface property.

The hybrid treated copper wire braids perform higher water rising speed than the oxidized copper wire braids while owning higher water net weight than those braids being only dip-coated and this fact indicates that this hybrid surface modification method on copper wire braids could lead to a superior thermal performance of those ultra-thin heat pipes containing the braid-like wick structure inside.
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