Applied Thermal Engineering 75 (2015) 908–917

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

# Condensation heat transfer enhancement by surface modification on a monolithic copper heat sink

Ding-Jun Huang [a, c, *], Tzong-Shyng Leu [b, c]

[a] Department of Materials Science & Engineering, National Cheng Kung University, Tainan 70101, Taiwan, ROC
[b] Department of Aeronautics & Astronautics, National Cheng Kung University, Tainan 70101, Taiwan, ROC
[c] Institute of Nanotechnology & Microsystems Engineering, National Cheng Kung University, Tainan 70101, Taiwan, ROC

## HIGHLIGHTS

- Superhydrophobic surface modification is applied to a monolithic copper heat sink.
- A monolithic copper heat sink is used to prevent contact thermal resistance.
- EGC-1720 fluorosilane polymer is employed as the waterproof agent.
- Durability of the EGC-1720 coated surface is investigated.
- The relative heat transfer enhancement of the heat sink is compared.

## ARTICLE INFO

*Article history:*
Received 19 June 2014
Accepted 8 October 2014
Available online 17 October 2014

*Keywords:*
Copper surface modification
Superhydrophobic
Condensation heat transfer

## ABSTRACT

In this study, the condensation heat transfer performance on a pure copper surface, as well as a superhydrophobic-modified copper surface were compared. Differing from other condensation heat transfer experimental designs, a monolithic copper heat sink was utilized in this study to prevent contact thermal resistance and/or thermal conduction limitation of the thermal paste applied between the modified condensation surface and heat sink plate. This approach has not yet been documented in the literature. The superhydrophobic copper heat sink surface was prepared using a hydrogen peroxide immersion and fluorosilane polymer (EGC-1720) spin-coating. Experimental results show that the condensation heat transfer performance on the superhydrophobic copper surface is superior to that of a pure copper surface. Additionally, durability tests of the pure and superhydrophobic coating copper surfaces in a harsh vapor environment are discussed in this study.



## 1. Introduction

The wettability of solid surfaces is a very important aspect of materials science and surface chemistry. In recent years, surface modification to change the wettability of a material's surface has become a promising technique and attracted much attention. Generally, surface modification techniques play an important role in many practical and industrial applications, such as self-cleaning [1,2], anti-icing and -frosting [3–5], oil-water separation [6–8], drag-reduction [9], corrosion resistance [10], and condensation heat transfer (CHT), among others.

CHT refers to the heat transfer process when a phase change occurs on a subcooled surface under a vapor environment. Vapor condensates on the subcooled surface and transfers a large amount of latent heat energy onto the surface of the material. Depending on the surface wettability of the material, condensation can be divided into two modes: “dropwise condensation” (DWC) and “filmwise condensation” (FWC). DWC forms sphere-like droplets on hydrophobic surfaces, while FWC appears as a film-like liquid layer on hydrophilic surfaces. DWC and FWC surface nucleation modes have considerable influence on CHT performance. Typically, the CHT performance of DWC outperforms that of FWC because DWC accelerates the processes of condensation, nucleation, droplet-growth, coalescence and droplet-falling per unit time.

To ensure optimal performance of CHT, material selection is important. In this regard, copper [11–13], with its excellent thermal conductivity [14,15], has become one of the most important materials in CHT devices. Many copper surface modification

* Corresponding author. Department of Materials Science & Engineering, National Cheng Kung University, Tainan 70101, Taiwan, ROC.
*E-mail addresses:* q28991059@mail.ncku.edu.tw (D.-J. Huang), tsleu@mail.ncku.edu.tw (T.-S. Leu).

http://dx.doi.org/10.1016/j.applthermaleng.2014.10.019
1359-4311/

techniques have been reported and applied in CHT experiments [15–25]. Edwards & Doolittle [16] developed a copper tube coated with Tetrafluoroethylene (Teflon) and found that it enabled better CHT efficiency than without the coating. Also, comparisons among different coating films were made, which demonstrated that differences between heat transfer coefficients and coating film lifetimes among certain surface coatings influenced CHT performance. A similar issue was investigated by Marto et al. [26], who adapted various surface coating layers to coat different metal tubes and studied the heat transfer performance and endurance at low pressure. Their results indicated that copper and copper–nickel alloys achieved higher heat transfer coefficients when coated with silver; however, durability of the silver coating under a vapor environment was limited compared to other organic coatings like Parylene-D, No-stick or fluoroacrylic. They found that although the copper coated by No-Stick was more durable, its heat transfer performance was inferior to that of the silver coated copper surface. Clearly, heat transfer performance and coating longevity must be studied and tradeoffs optimized. Holden et al. [27] extended the above results by visually verifying the condensate droplets for surface coating endurance and longevity, the results of which can be used as a basic reference for optimization.

In addition to the organic and hydrophobic coating agents mentioned above, some research teams have also used organic self-assembled monolayers (SAMs) as a coating agent for surface modification. Das et al. [22] employed hexadecylthiol to coat the surfaces of copper and other alloys, and found that a SAM on copper or copper alloys was able to achieve superior heat transfer performance to that on gold-coated aluminum or oxidized aluminum. They also investigated these materials by controlling the chamber pressures, and documented high CHT performance of SAMs-coated copper and copper alloys. It still remained true that DWC enhanced heat transfer more at various levels than FWC. In a related study, Vemuri et al. [23] investigated not only SAM coatings, but also bonding strengths with respect to CHT. They examined DWC by using an n-octadecyl mercaptain SAM-coated copper tube and a stearic acid SAM-coated one. Because the n-octadecyl mercaptain SAM layer reduced the cupric oxide layer on the copper surface to form a uniform organic film of closely packed chains of thiols, durable covalent bonding was achieved. According to their findings, the durability of the covalent bonding was superior to the hydrogen bonding formed by the stearic acid SAM layer. The CHT enhancement of the n-octadecyl mercaptain-coated SAM tube was twice as large as that of the heat transfer coefficient of their hydrophilic copper tube, even when the experimental time exceeded 2000 h. Subsequently, Chen et al. [28] used a similar modification method as Vemuri et al. [23,24] for investigating the DWC performance of a copper block condenser. The heat transfer performance was also good due to the bonding strength between the SAM layer and copper surface, thereby extending the lifetime. The average convection heat transfer coefficients of the DWC vertical surfaces were 1.7–2.1 times greater than those of FWC.

Surface roughness is also a factor that influences DWC performance because it is required in fabricating a hydrophobic surface. For example, Izumi et al. [25] investigated the heat transfer characteristics of DWC on a surface with round shaped grooves coated with hydrophobic oleic-acid. The heat transfer performance was clearly enhanced by optimizing groove widths, which indicates that performance improvements may be achieved by tuning surface roughness. It has been suggested that further enhancements could be expected if two-tiered nanostructures [29,30] were fabricated on the grooves to form a superhydrophobic surface.

In the aforementioned study [25], a heat sink-like plate was utilized as the experimental sample, and its feature seemed like a monolithic heat sink bulk. It is well-know that a monolithic substrate is able to prevent thermal resistance between the condensation side and the cooling side; as such, it is preferred in experiments or practical applications, and is commonly adopted in CHT studies. For example, Ma et al. [21] investigated CHT enhancement in the presence of non-condensable gas (NCG), and found that the lower the amount of NCG, the higher the heat transfer coefficient. In addition, their condensing block was similar to a monolithic copper heat sink, so it was a better reference for the choice of experimental substrate. Lan et al. [19] also utilized a similar monolithic condensing block to investigate the CHT performance of a surface with two fabrication processes, but the both featuring the same SAM coating. Through the fabrication processes, they obtained a superhydrophobic surface and a hydrophobic one. Surprisingly, the CHT performance of the superhydrophobic surface was lower than that of the hydrophobic surface. They stated this was because of the adhesion effect of the hierarchical micro- and nano-structures, which induced an adhesion effect that increased the droplet growth cycle time. Their article suggested that the coating and surface processing should be optimized if more heat transfer is desired. Further, Leu et al. [31] also discussed the importance of the plate material and processing features. In their study, a silicon surface was modified as a composite wettability gradient surface, and then attached onto a copper heat sink. Compared with pure silicon, the heat flux of the modified silicon was increased by 10%; however, no details regarding the bonding between their modified silicon and copper heat sink were given. One could expect that a thermal contact resistance surely existed if there was no suitable connection media between the both materials. Moreover, it is possible that the heat transfer performance was limited. In addition, not only did the connection affect the heat transfer enhancement, but also the material of the silicon chip. Silicon has a lower thermal conductivity than copper, which is a shortcoming in thermal properties.

Therefore, from the aforementioned studies, CHT performance appears to be determined by correlations among many factors, such as surface structures, coating agents, gas concentration, etc. Comparatively, combining the use of rough surface structures and chemical coating layers is the general approach for manipulation, and constitutes the simplest way to investigate heat transfer enhancement by controlling the least amount of parameters. In the above, superhydrophobic surfaces were shown to achieve DWC and enhance CHT performance. However, enhancements must be analyzed to determine whether they are truly superior because different material processing conditions and experimental system setups can introduce variability.

In this study, a surface modification technique was developed and applied to the surface of a monolithic copper heat sink for application in CHT, the details of which are addressed for practical utilization. An EGC-1720 coating was utilized to modify the surface, and the heat transfer performance of the modified surface was investigated. For this application, the coating formed by the copper surface modification technique must be able to withstand high temperature vapor environments. Therefore, one of the research goals was to investigate whether the modified copper surface can be sustained under such a harsh environment.

## 2. Experimental process

### 2.1. Types of copper heat sinks

A commercial heat sink of approximately $90 \times 60 \times 27$ ($mm^3$) (Item No. TPCU008, Tai-Pao Int. Corp.) was utilized in our experiment, as shown in Fig. 1. The fabrication of the heat sink mainly included relief cut, planning with shaping, and formation of a monolithic part. Therefore, the contact thermal resistance between