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Research Paper

Experimental studies on a novel thin flat heat pipe heat spreader

Ji Li [a,*], Lucang Lv [b]

[a] Laboratory of Advanced Thermal Management Technologies, College of Physics, University of Chinese Academy of Sciences, 19A Yu-quan-lu Road, Shijingshan District, Beijing 100049, China
[b] College of Physics, University of Chinese Academy of Sciences, 19A Yu-quan-lu Road, Shijingshan District, Beijing 100049, China

HIGHLIGHTS

- A thin flat heat pipe with novel wick structure was fabricated.
- Operation characteristics of the flat heat pipe were identified.
- High heat flux of 100 W/cm^2 was achieved for this 2 mm flat heat pipe.
- Gravity has very small impact on its thermal performance.

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ABSTRACT

The thermal performance of a copper-water flat heat pipe (100 mm × 50 mm × 2 mm) composed of a novel wick structure with an inner thickness for working fluid less than 1 mm has been investigated. The wick structure was made of sintered hybrid copper fine powder with diameters ranging from 50 µm to 100 µm. The effects of heating input, tilt angle, and cooling temperature on flat heat pipe working performance were studied experimentally. Results showed that the proposed flat heat pipe could effectively dissipate 120 W (100 W/cm^2) in the horizontal orientation with a thermal resistance of 0.196 °C/W. Moreover, it has been demonstrated that under air natural convection condition, the performances of the novel flat heat pipe were higher than those of thin copper sheet, showing an effective thermal conductivity more than 4 times of copper.

1. Introduction

The heat per unit area generated by chips continuously increases and thermal control becomes a very attractive research topic in the electronic industry. Local and global high temperatures can both significantly influence the working performance of the electronic components or lead to high thermal stress [1]. Thus, to cool these devices efficiently in narrow spaces, thin, high-performance, and lightweight cooling devices are demanded. Micro/mini flat heat pipe is one of the most promising approaches for the thermal management of electronic components [2], especially for high power mobile electronics, e.g., portable game PC or automobile LED lighting.

The early information concerning the micro/mini-scale heat pipes can be found in [3]. In the past two decades, many investigations on the working performance of thin flat heat pipes have been carried out. One of the most common wick structures is micro/mini grooves [4–7]. Cao et al. [4] tested a 2 mm-thick rectangular-grooved heat pipe which had a maximum heat transfer rate of 24.8 W when cooled at 90 °C. Hopkins et al. [5] experimentally investigated a 2.4 mm-thick flat heat pipe with micro trapezoidal capillary grooves manufactured by a rolling method. When heated at both sides of the evaporation section and positioned in the horizontal orientation, the flat heat pipe had a minimum thermal resistance of 0.3 °C/W with a maximum heat flux of 17.3 W/cm^2. Lin et al. [8] made a 6.35 mm thick flat heat pipe whose wick structure was a folded copper sheet fin. A maximum heat flux of 158 W/cm^2 (122.3 W) was obtained when the evaporator temperature reached 112.6 °C. In 2008, Lim et al. [9] presented a relatively small flat copper heat pipe (56 mm × 8 mm × 1.5 mm) with radial microgrooves fabricated by using a femtosecond laser micromachining technique. This device could only perform functionally at heat loads below 12 W cooled by a refrigeration bath circulator. Recently, Zaghdoudi et al. [6] found that the thermal resistance of flat heat pipe decreased with the increase of the heat sink temperature.

By flattening a metal tube, some flat heat pipes [10–12] have been fabricated. The limitation for the pressed thickness between 2 mm and 2.5 mm was obtained by Moon et al. [10]. With sintered copper powder wick structure, the spreading resistance from the heat source to the evaporator for a 5 mm thick flat heat pipe [13] was measured about 40 times smaller than that of the copper plate at 28 W/cm^2. Rulliere et al. [14] studied the maximum heat transfer capability of a flat heat pipe with a large evaporator area. A small thermal

* Corresponding author. Tel.: +86 13522278866; Fax: +86-010-69671698.
E-mail address: jili@ucas.ac.cn (J. Li).

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resistance of 0.05 °C/W was obtained at 155 W. Tsai et al. [15] tested a copper-water vapor chamber with an inner height of 1.4 mm and its maximum heat transfer rate was 50 W. Some wire mini-heat pipes [16,17] were also investigated experimentally. To sum up, the above-mentioned researches showed that the different types of metal thin flat heat pipes could only work functionally under relatively low heat fluxes when the inner height was less than 1.5 mm and the saturation temperature was within 60 °C.

To further decrease the thickness, some researchers [18–21] studied the behavior of silicon-based flat heat pipes with microscale capillary grooves. Moreover, Ding et al. [22] presented a Ti-based flat heat pipe (30 mm × 30 mm × 0.6 mm) that could dissipate 7.2 W. Oshman et al. [23–25] fabricated three different polymer-based flat heat pipes whose inner heights were 1 mm [23], 1 mm [24], and 0.9 mm [25], respectively. The performance of the heat pipe [23] with a hybrid wick structure consisting of micro pillars and woven mesh was tested; experimental results showed that the heat pipe could work under 11.94 W at adverse-gravity direction. Famouri et al. [26] numerically investigated the transient heat transfer in this flat heat pipe. However, the application of these silicon/polymer-based flat heat pipes will be confined in consideration of their reliability and fabrication.

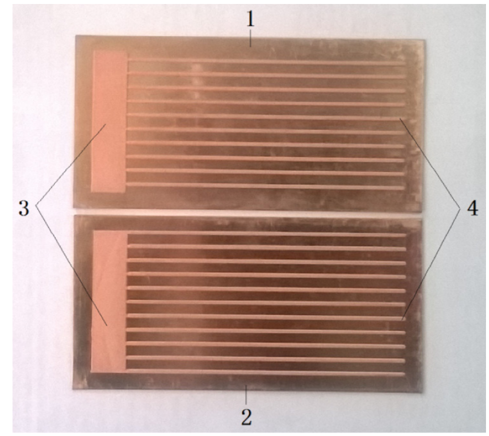
With the assistance of visualization, Wong [27,28], Lefevre and their staffs [29–31] studied the thermal performance and the mechanism inside flat heat pipes with small internal space. As declared in [29], the presence of nucleate boiling could improve the thermal performance of a flat heat pipe; moreover, the heat flux at the beginning of the nucleate boiling was much lower than the dry-out heat flux. With n-pentane as the working fluid, the effect of the vapor space thickness on the thermal performance of a flat heat pipe has been analyzed systematically in [30].

The above-mentioned researches highlight that the limited spaces available for the evaporation process and for the fluid circulation limit the high performance of flat heat pipes. In particular, thickness plays a key role in flat heat pipe performances. Meanwhile, the above-referred works all adopted traditional structure, as being used in a conventional heat pipe or a conventional vapor chamber, in which vapor phase and liquid phase flow reversely inside the envelope, especially at the evaporation zone.

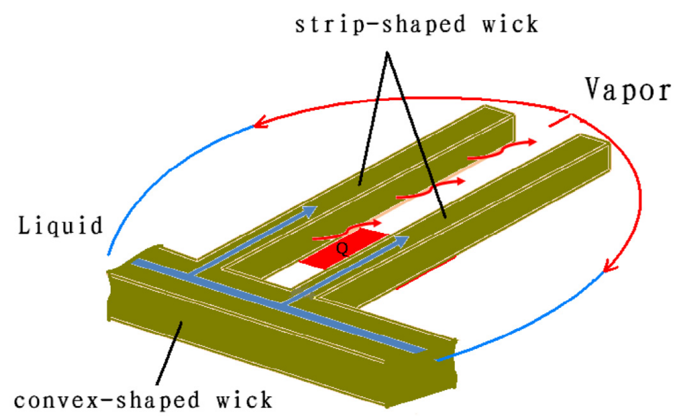
The present work describes a thin high-performance copper-water flat heat pipe in detail, aiming to cool high power portable electronics or optoelectronic equipment. This flat heat pipe has a novel sintered hybrid copper powder wick structure, whose internal space height is less than 1 mm. The working performance of the heat pipe device has been tested and analyzed under different heat loads, tilt angles, and cooling water temperatures. Furthermore, the thermal performance of the flat heat pipe device under natural convection at different heating inputs has been evaluated both experimentally and numerically. In addition, a comparison has been made using a copper plate with the same size of the proposed device. Experimental tests demonstrated that this flat heat pipe could manage high heat flux with a quite low thermal resistance.

2. Heat pipe construction

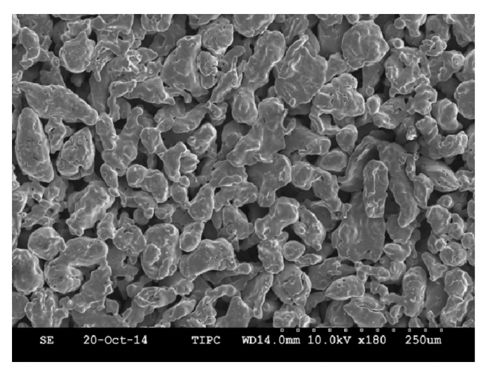
The proposed flat heat pipe is primarily composed of two copper plates with sintered wick structure on the inner surface. Referring to Fig. 1a, 1 and 2 are the copper plates, 3 and 4 are sintered copper powder wick structures; the convex region collects condensate, while liquid flows within the striped region. Both convex and striped regions also serve as the supporting structure to avoid concave deformation during the fabrication and operation process. The channels formed by the strip-shaped wick structures are the paths for the vapor and part of the returned liquid. This type of sintered wick structures is believed to enhance the working efficiency of flat heat pipe by lowering the thermal resistance, because the flow of most part of liquid and vapor is restricted mainly in the same direction. Therefore, the flow resistance is reduced by restraining the counterflow as happening in conventional heat pipes, which is somewhat similar to the working mechanism of loop heat pipe described in [32]. Fig. 1b shows the flow inside the flat heat pipe schematically. The vapor generated in the wicked strips near the convex region flows through the channels formed between the wicked strips and the condensate returns driven by capillary force and accumulates in the convex region. Meanwhile, in order to provide a high capillary force and a low flow resistance in the wick, hybrid copper



(a)



(b)



(c)

Fig. 1. Flat heat pipe schematic: (a) upper and lower plates; (b) working mechanism; (c) sintered hybrid powder wick.