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Research Paper

An ultra-thin miniature loop heat pipe cooler for mobile electronics

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HIGHLIGHTS

- A 1.2 mm thick miniature loop heat pipe was developed.
- The mLHP can manage a wide range of heat loads at natural convection.
- A minimum mLHP thermal resistance of 0.111 °C/W was achieved at 11 W.
- The proposed mLHP is a promising solution for cooling mobile electronics.

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ABSTRACT

In this paper, we present a miniature loop heat pipe (mLHP) employing a 1.2 mm thick flat evaporator and a vapor line, liquid line and condenser with a 1.0 mm thickness. The mLHP employs an internal wick structure fabricated of sintered fine copper mesh, comprised of a primary wick structure in the evaporator to provide the driving force for circulating the working fluid, and a secondary wick inside the liquid line to promote the flow of condensed working fluid back to the evaporator. All tests were conducted under air natural convection at an ambient temperature of 24 ± 1 °C. The proposed mLHP demonstrated stable start-up behavior at a low heat load of 2 W in the horizontal orientation with an evaporator temperature of 43.9 °C and efficiently dissipates a maximum heat load of 12 W without dry-out occurring. A minimum mLHP thermal resistance of 0.111 °C/W was achieved at a heat load of 11 W in a gravity favorable operation mode, at which the evaporator temperature was about 97.2 °C. In addition, an analytical analysis was conducted, and the devised equation could be used to evaluate the performance of the mLHP.

1. Introduction

With the recent development of techniques in the manufacturing industry and packaging field, compact electronic devices, such as portable LED projectors, tablet computers and smartphones, have become increasingly miniaturized, resulting in the generation of increasing heat flux density. For mobile electronics, the power consumptions of various dominating high-performance CPU processors are listed in Table 1, where, for example, Qualcomm® Snapdragon™ 820, which is the latest and most successful CPU processor employed in smartphones, has a full-load power consumption of 4.7 W [1]. In the absence of efficient thermal control methods, the high heat generation in the limited space available in the miniaturized electronic devices would lead to an excessively high temperature, deteriorating the usability and working reliability of the electronic components [2]. In addition, the limited space also greatly limits the size of thermal control components. Therefore, developing high performance thermal management solutions applicable to high-power, compact electronic devices is a major challenge for improving their working reliability, stability and life-time [3,4].

Loop heat pipes (LHPs), as highly effective heat-transfer devices, utilize the phase-change latent heat of the working fluid to transport heat from a heat source to a heat sink, and depend on the capillary force developed in the wick structure to complete the circulation of the working fluid in the loop [5]. Compared with conventional heat pipes, LHPs offer many advantages such as long-distance heat transfer, higher heat transport capacity, lower thermal resistance, reliable operation against gravity, and wide flexibility in the packaging of the evaporator and condenser [6–8]. At present, a wide variety of LHP evaporator configurations

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Nomenclature

H	height, m
k	thermal conductivity, W/(m K)
L	length, m
P	pressure, Pa
Q	heat load, W
R	thermal resistance, °C/W
S	surface area, m^2
T	temperature, °C
V	volume, m^3
α	heat transfer coefficient, W/(m^2 K)
β	charging ratio
δ	thickness, m
ε	emissivity
σ	Stefan-Boltzmann constant, W/(m^2 K^4)

Subscripts

a	ambient
c	condenser
ci	condenser inlet
co	condenser outlet
e	evaporator
ei	evaporator inlet
eo	evaporator outlet
l	working liquid
ll	liquid line
v	vapor
vc	vapor removal channel
vl	vapor line

have been designed to improve the thermal performance of LHP applications. The LHP evaporators are typically flat or cylindrical, depending on the shape and dimensions of the heat source as well as the purpose to which it is applied. In contrast to cylindrical evaporators, flat LHP evaporators can directly contact with the flat electronic chips and require no extra thermal interface structures equipped in cylindrical evaporators to ensure a good thermal contact with heat resources, which decreases the thermal resistance between the heat source and the evaporator as well as the total mass of the device, improving the efficiency of heat transfer [9,10]. Therefore, LHPs employing flat evaporator are promising devices for compact electronics cooling.

So as to make LHPs compatible with applications in mobile electronics, e.g., laptop computers, tablet computers, and smartphones, some researchers have studied the miniaturization of LHPs by decreasing the thickness of the evaporator. Refs. [11–15] present the results of the investigation of LHPs applying for the mobile electronics cooling. Maydanik et al. [11] investigated a copper miniature loop heat pipe with a flat 7 mm thick evaporator with acetone as a working fluid. The mLHP was tested in the range heat loads from 5 W to 60 W at different operation orientations in the gravity filed and heat sink temperature from −40 °C to +50 °C. At a heat sink temperature of +50 °C, the heat source temperature did not exceed 68 °C at 50 W. Singh et al. [12] developed an mLHP with a rectangular shaped evaporator, 47 × 37 mm^2 plan area and 5 mm thick, for the thermal control of for laptop computers. The minimum total system thermal resistance R_t of 1.5 °C/W was achieved at the maximum heat load of 50 W with the source temperature of 98.5 °C under forced air convection. Lin et al. [13] experimentally evaluated an mLHP with rectangular 3 mm thick evaporator for laptop computer. The mLHP could efficiently dissipate the high heat load of 45 W with the average temperature of the heater of 63.1 °C by means of forced air cooling, which met the cooling requirements of the laptop computers. Most recently, Hong et al. [14] investigated the heat transfer performance of two ultra-thin LHP (ULHP) with different evaporator structures, parallelogram and trapezoid evaporator configuration (160 mm × 115 mm × 1.5 mm), under multiple orientations, the placing angle ranged from 0° to 90°. The ULHP with parallelogram channel configuration started up steadily at the heat load of 40 W at the angle of 15° while the trapezoid one could not start up until the angle increased to 30°. In addition, the ULHP with parallelogram channel configuration showed superior capability in resisting the gravity field at heat loads from 20 W to 120 W. Shioga and Mizuno [15] introduced a micro LHP employing a flat 0.6 mm thick evaporator fabricated by a chemical-etching and diffusion-bonding process for smartphone applications. The micro LHP startup behavior was initiated at a heat load of 2.5 W, and a minimum LHP thermal resistance of 0.32 °C/W was achieved at a heat load of 15 W with the use of an auxiliary copper plate to extend the cooling area of the micro LHP under natural convection. The detail comparison of the heat transfer capability of mentioned LHPs above is listed in Table 2.

Table 1
Power consumptions of different CPU processors for mobile electronics.

Estimated System Active Power – CPU Load (mW)				
SoC	1 Core	2 Cores	3 Cores	4 Cores
Snapdragon 820 @2.15 GHz/1.59 GHz	2055 –	3330 (2.15 GHz)	4147 (1.59 GHz)	4735 (1.59 GHz)
Kirin 950 @2.3 GHz	1387	2255	3051	3734
Exynos 7420 @2.1 GHz	1619	2969	4186	5486

Till now, through the literature review, it seems that very few works have been done for successful extreme miniaturization of LHPs for mobile electronics, especially under natural air convection. The special requirements for the thermal management of chips employed in mobile electronics are: (1) under natural convection without any active cooling implemented; (2) stable startup at a low heat load; (3) with a case temperature below 85 °C at its full load in operation; (4) insensitive to the gravity. The present work presents a novel miniature copper-water LHP with a flat wicked evaporator for cooling tablet computers and smartphones. Moreover, the present mLHP employs a secondary sintered copper mesh inside the liquid line to promote liquid circulation in small space. The overall dimensions of the proposed mLHP are sufficiently small to allow the direct integration with compact tablet computers and smartphones owing to the use of a flat evaporator with an external thickness of 1.2 mm (inner height of 0.8 mm). In the study, systematic experimental and theoretical investigations of the heat transfer capability of the proposed mLHP under natural heat convection situation, different input heat loads and operation orientations were carried out. The experimental results demonstrated that the present mLHP is a powerful cooling solution to the mobile electronics. In addition, an analytical analysis was carried out and the derived equation could be used to evaluate the performance of the proposed mLHP.

2. Fabrication of the mLHP

The configuration of the proposed mLHP after welding is shown in Fig. 1. It is comprised mainly of five components: a flat evaporator, a vapor line, a condenser, a liquid line and a line for