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Research Paper

Experimental investigation on thermal performance of aluminum vapor chamber using micro-grooved wick with reentrant cavity array

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HIGHLIGHTS

- MGRA vapor chamber holds fast temperature response with low start-up heat load.
- Stable thermal resistance during the test range and heat transfer limit > 150 W.
- Good anti-gravity performance with reduced thermal resistance yielded at 30°.
- Hardly affected by the cooling flow rate higher than 10 L/h.
- Competitive thermal performance compared with other ones in literatures.

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ABSTRACT

In order to provide efficient thermal management for high-power electronics while keeping the light weight and compact physical size of the devices, a thin aluminum vapor chamber using micro-grooved wick with reentrant cavity array (MGRA) was developed. The MGRA was featured with high-aspect ratio micro-grooves for capillary capacity enhancement and reentrant cavities for phase change facilitation. The start-up performance, thermal resistance, temperature distribution of the vapor chamber, as well as the effects of heat load, operational orientation and cooling flow rate on its performance were investigated. The MGRA vapor chamber yielded a fast temperature response and low start-up heat load. Besides, the thermal resistance remained stable from 0.055 to 0.074 K/W. It also showed a good anti-gravity performance, with the minimum thermal resistance reached at the inclination of 30°. In addition, the cooling flow rate had little effect on the thermal performance of the chamber, despite the decrease of wall temperature with increase of flow rate. In order to justify the advantage of employing MGRA as enhanced wick, the MGRA vapor chamber was compared with others reported in literatures. The results indicated that this vapor chamber was well suited for thermal management of compact high-power electronics under various operational conditions.

1. Introduction

Thermal management of electronic equipments is a huge challenge, considering the increasingly miniaturized e-devices with unprecedented operational efficiency and heat power. For example, efficient thermal management must be provided for Li-ion EV battery due to the large temperature rise that occurs during operation [1,2]. It is estimated that the battery duration will be reduced by more than 60% should it operate at above 50 °C [3,4]. Besides, the non-uniform temperature distribution of the package also significantly undermines its operational stability [5,6]. Similar conundrum is also encountered for the LEDs and PCBs [7,8] with multiple high-power chips on the board, i.e., multiple heat sources, where both the low operation temperature and uniform temperature field across the board have to be achieved for the overall performance maxima and long-term operation stability [9,10]. Flat heat pipe, or vapor chamber heat spreader, meets the requirements mentioned above. It is a novel kind of two-phase heat transfer device with high thermal conductivity ($\geq$10,000 $W{\cdot}m^{-1}{\cdot}K^{-1}$), ensuring the effective heat dissipation from a local hot spot. More importantly, different from the conventional circular heat pipe, vapor chamber is a 2-dimensional device, making a uniform temperature distribution over a large surface possible. Vapor chamber has been successfully applied for the thermal management of EV [11,12], LEDs [13,14], hard-disk drivers [15] and other e-devices [16–18], and has also been extended to the field of solar thermal

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Nomenclature

d	diameter of the heater, m^2
d_v	thickness of the internal chamber, m
D_{pe}	P/E cutting depth, m
D_g	depth of the major groove, m
D_{sg}	depth of the secondary groove, m
l_t	distance between T_u and T_l, m
MGRA	micro-grooved wick with reentrant cavity array
P_{pe}	P/E pitch, m
P_g	pitch of major groove, m
P_{sg}	pitch of secondary groove, m
P/E	ploughing and extrusion method
Q	heat load, W
q	heat flux, W/m^2
R	thermal resistance, K/W
T_i	temperature, with i = 1 to 4 on vapor chamber, i = u and l on heater, °C
VC	vapor chamber
λ	thermal conductivity, W/m·K

collector [19,20] as well as thermoelectric generation for energy harvesting [21].

In the past decade, various types of vapor chamber with miscellaneous capillary wick structures have been developed, including porous [22–24], grooved [25,26] and composite [27] ones. Tang et al. [22] developed a multi-artery vapor chamber with sintered copper powder porous layer as wick, along with porous rings as supporting columns to facilitate the liquid reflow, which had a low thermal resistance of less than 0.08 K/W and a high limit of above 300 W/cm^2. A similar design was also employed by Tsai et al. [23], which yielded a thermal resistance similar to that in [22]. In addition, the experimental result indicated that the porous wick enhanced the anti-gravity performance of the vapor chamber justified by the low and stable thermal resistances at different orientations. A vapor chamber with porous copper foam as capillary wick was developed by Ji et al. [24], which was able to sustain the heat flux of higher than 216 W/cm^2 with the minimum thermal resistance of 0.09 K/W. The authors attributed the favorable performance of the vapor chamber to the distinct nature of the metallic foam, i.e., the larger pores for vapor release and the smaller pores for liquid replenishment, as well as the shortcut of liquid flow path due to the porous supporting column. Besides the porous wick, micro-grooves, due to the high permeability, have also been widely used for vapor chamber. Peng et al. [25] designed a novel grooved-wick with leaf-vein micro-channel system using chemical etching method. Thanks to the enlarged condensable area and the prevention of liquid blocking, the novel vapor chamber yielded good temperature uniformity and small thermal resistance. Ranjan et al. [26] compared the grooved wick with the conventional sintered porous wicks, revealing that the employment of the micro-pillared structures led to a 10-fold heat transfer enhancement of the vapor chamber. In order to combine both the favorable capillary pressure of the porous media and the high permeability of the micro-grooves, micro-grooves with mesh layer covering on the top was developed by Lefevre et al. [27]. However, such a combination failed to obtain the excellent heat transfer performance that one would expect, possibly due to the rapid bubble expansion between the screen mesh and the grooves, which led to the premature nucleate boiling limit.

In general, most of the previous studies focused on copper-based vapor chamber. Although it has been commercialized for civil use [14–16], its large scale application is still restricted by the high cost of copper. More importantly, the high density of copper fails to meet the requirement of light weight and compact physical size in high-end fields, e.g., the aerospace industry. In this regard, aluminum vapor chambers (AVC), instead of copper-based ones, which takes both the advantages of light density, high thermal conductivity and low-cost, are superior candidates. Nevertheless, the traditional porous structures are not applicable for the AVC because of the technical difficulty. For example, it is infeasible to fabricate Al powder-sintered porous wicks due to the inert mass propagation of the aluminum oxide film on the power surface. Al porous layer can be fabricated by growing CNTs [28] and anodization [29], which, however, are expensive and thus, inefficient for large-scale production. Worse still, the thin porous layer tends to peel off after several cycles [30] or transform in morphology [31] due to the chemical reaction between the coating and working liquid. Therefore, micro-grooved wick may be a better choice for AVC. However, with the aim to produce ultra-thin AVC to meet the physical size requirement, thin substrate must be used. As a result, the micro-grooves are relatively shallow, were the traditional metal-removing method employed. For example, the groove depth was only 0.11 mm for an AVC with the thickness of 2.17 mm [32]. Since the capillary pressure will be significantly reduced with decrease of groove depth, the AVC tends to reach its operational limit at relatively low heat flux.

In order to solve the dilemma for ultra-thin AVC as mentioned above, a micro-grooved wick with reentrant cavity array (MGRA), featured with high aspect-ratio grooves at relatively small cutting depth (i.e., suitable for thin substrate), was fabricated in our previous work [33] using the orthogonal ploughing/extrusion (P/E) method. It was found that the MGRA yielded both high capillary pressure and permeability, making it favorable for the AVC. More importantly, the MGRA possesses the reentrant cavity array on the side-wall, which could facilitate the nucleation [34–36], and as a result, enhance the start-up performance and delay the boiling limit. Therefore, in the present work, aluminum vapor chamber with MGRA as the enhanced wick is fabricated. The MGRA chamber is vacuumed to 7 Pa and filled with acetone as the working fluid. The thermal response characteristics of the MGRA, including the start-up performance, thermal resistance and temperature uniformity are fully investigated. In addition, the effects of operational orientation as well as cooling flow rate are also studied.

2. Vapor chamber design

2.1. Characterization of capillary wick

In this work, the micro-grooved wick with reentrant cavity array, featured with high aspect-ratio micro-grooves and reentrant micro-pores on the side-wall, is fabricated on a thin aluminum substrate (T6061, 1.5 mm thick) as enhanced wick for the AVC using the orthogonal ploughing/extrusion method. One may refer to our previous paper for more details of the MGRA manufacturing process [33]. The structure of the MGRA is characterized in Fig. 1 and the key structural parameters are listed in Table 1. The dimension of the substrate is 90 × 90 × 1.5 mm while that for the MGRA is 70 × 70, with a ring of 10 mm in width around the wick for the purpose of welding. It should be noted that there is a liquid filler hole on the top of the upper plate and 9 support posts uniformly distributed on the wick to avoid the chamber deforming, and more importantly, to facilitate the liquid reflow from the condenser to evaporator. There are two steps involved in the orthogonal P/E pro-