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Research Paper

Development and characterization of a flat laminate vapor chamber

Kei Mizuta [a,*], Rinkoh Fukunaga [b], Kenji Fukuda [c], Susumu Nii [a], Tanemasa Asano [d]

[a] Department of Chemical Engineering, Kagoshima University, 1-21-40 Korimoto, Kagoshima-Shi, Kagoshima 890-0065, Japan
[b] Monatec Co., Ltd., 1607-1 Katsumata, Makinohara-shi, Shizuoka 421-0414, Japan
[c] Shikoku Instrumentation Co., Ltd., 200-1 Minamikamo, Tadotsu-cho, Nakatado-gun, Kagawa 764-8502, Japan
[d] Department of Electronics, Kyushu University, 744, Motooka, Nishi-ku, Fukuoka-shi, Fukuoka 819-0395, Japan

HIGHLIGHTS

- Developed was a type of flat laminate vapor chamber called FGHP (Fine Grid Heat Pipe).
- The FGHP's thermal resistance was a quarter of that for the copper heat spreader.
- The FGHP worked properly even when heat flux exceeds 2.0 MW m^{-2}.
- Thermal resistance of FGHP was compared with various types of vapor chambers.
- The lowest resistance was observed for FGHP when heated area ratio was concerned.

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ABSTRACT

Developed was a type of flat laminate vapor chamber called FGHP (Fine Grid Heat Pipe), and its thermal performance was investigated. Fine etching technique enabled formation of microstructures on laminate parts. The size of FGHP utilized in this study was 50 × 50 mm^2 and 2 mm thick. For reference, tested was a copper heat spreader having the same dimensions. Without regarding the heat input, the FGHP showed more uniform temperature distribution than the copper heat spreader. Even at a high heat flux, more than 2.0 MW m^{-2}, the FGHP had a thermal resistance as low as 0.08 K W^{-1}, which is about a quarter of that of the copper heat spreader. When thermal resistance of the FGHP was compared with various types of flat heat pipes or vapor chambers, it was the lowest among the all vapor chambers by taking the effect of area ratio into account.

1. Introduction

Recently, rapid increase in heat flux emitted from electronic components is becoming more serious than ever because of their shrinking die size and increasing heat generation which, however, must be dissipated effectively. Especially, LED (Light Emitting Diode) and GPUs (Graphic Processing Units) are exposed to massive input power, and the housings including such devices are becoming narrow and thin, resulting in greater power densities, which cannot be cooled by such as simple forced air convection to maintain such electronic devices within operating conditions. Therefore, high performance cooling devices such as flat-plate heat pipes are strongly desired for electronics thermal management. A flat plate heat pipe (or vapor chamber) is more suitable for such applications than conventional heat pipe because of its compact dimension and heat spreading or temperature flattening ability.

Generally a flat plate heat pipe (or vapor chamber) has a rectangular shape with a small aspect ratio, consisting of an evaporator, a condenser and a wick structure. In the operation of the vapor chamber, heat is applied to the evaporator section through a small surface area and evaporates working fluid. The resulting vapor pressure drives the vapor through the vapor chamber to the entire region of the condenser section, where the vapor condenses, releasing its latent heat of vaporization to the provided heat sink, resulting in smaller heat flux at the condenser region with uniform temperature distribution. Then, the capillary force generated in the wick pumps the condensate to the evaporator. Similar to the conventional heat pipe, the heat transfer in flat heat pipes or vapor chambers is also subject to various limitations and constrains, such as viscous, capillary, sonic, entrainment and boiling limitations.

To overcome such limitations, numerous attempts have been already performed to realize better heat spreading ability of the vapor chambers. Thermal characteristics of various types of vapor chambers [1–16] are summarized in Table 1. Key parameters of the vapor chamber are the wick structure, the working fluid, the

* Corresponding author.
E-mail address: kmizuta@cen.kagoshima-u.ac.jp (K. Mizuta).

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Nomenclature

A_{smpl}	surface area of sample [m^2]
A_h	contact area of heat source [m^2]
k	thermal conductivity [W m^{-1} K^{-1}]
L	length [m]
T	temperature [K]
$\langle T \rangle$	area-averaged temperature [K]
x	lateral coordinate [m]
z	axial coordinate [m]
q	heat flux [W m^{-2}]
Q	heat load [W]
R_{total}	total thermal resistance [K W^{-1}]
R_s	spreading thermal resistance of sample [K W^{-1}]
R_{smpl}	thermal resistance of sample [K W^{-1}]
R_{1D}	thickness-wise one-dimensional thermal resistance of sample [K W^{-1}]

Subscripts

air	cooling air
btm	heated bottom surface of sample
c	central region on the top surface
Cu	copper
g	grease
S	heating block surface
in	input
p	peripheral region on the top surface (measured at $x = 23.0$ mm)
top	Top surface of the sample

Greek

β	area ratio (= A_h/A_{smpl}) [–]
δ	thickness [m]

structure of the vapor path, the enhancement of the phase change, and so on.

Koito et al. [1] investigated heat transfer characteristics of a vapor chamber embedded in heat sinks. They have investigated the effects of the size of heat source on thermal resistance. Koito et al. [2] have also conducted numerical analysis along with experiments, and found that the major thermal resistance comes from the evaporation resistance in the vapor chamber. Some other researches have also tested such vapor chambers combined with heat sinks [3–6]. Won et al. [3,4] investigated heat transfer characteristics of heat sink with a new kind of vapor chamber, the inner surface of the evaporator of which was entirely covered with wick structures. The authors concluded that the thermal resistance was lower than that of conventional vapor chambers because of the inner surface structure in the evaporator designed to enhance evaporation.

Boukhanouf et al. [5] investigated the thermal spreading resistance in the evaporator caused by mismatch in the area of heat source and evaluated by utilizing Infrared (IR) imaging technique. The results showed that the thermal spreading resistance was sufficiently low in the optimum conditions, though that of defective heat pipe was nearly the same with that of copper plate of the same size.

Xie et al. [6] proposed a new type of wick structure and introduced the idea of multi-condensers. The results showed that the new type of heat pipe heat sink could realize a higher heat flux at the same operating conditions than the conventional ones. Li et al. [7] investigated the effects of Reynolds number of air flow and the dimensions of heat sink on heat transfer performance, and found that the effects of dimensions of heat sink became weak in higher Reynolds number.

In past studies, several kinds of materials were used to form wick structure. Sintered copper powder was used in Koito et al. [1,2], Chen et al. [10], Wang et al. [11], Yu et al. [12], plate(s) manufactured by etching techniques is(are) in Kang et al. [8], Go [9], Xie et al. [6], Weibel et al. [15,16], and also in this work. Etched silicon material was also used in Cai et al. [13,14]. Mesh was used in Li et al. [7], Wong et al. [3,4]. These results show that the wick structure and the working fluid have great influence on the thermal characteristics. Generally the etching manufactured wicks show higher performance, the mesh follows, and the sintered powder shows the lowest. This suggests that the anisotropic structure of the wick constructed by etched materials is desirable to control coolant circulation to achieve higher thermal performance.

Some different kinds of fluid were used as working fluid. Most of them were water, except some cases. Methanol in Kang et al. [8] and Wong et al. [3], ethanol in Chen et al. [10] and Cai et al. [13], and acetone in Go [9] and Wong et al. [4]. The lowest thermal resistance of respective research is summarized also in Table 1. The thermal resistance of those using water as working fluid is the lowest, methanol the next, and the acetone is the highest, which is the reverse order with the latent heat of the working fluid.

In addition, as pointed out by Koito et al. [2] and Wong et al. [3], thermal resistance depends largely on the sizes of heat source and vapor chambers.

In this study, we present a new type of vapor chamber called FGHP (Fine Grid Heat Pipe) to enhance the thermal performance of vapor chamber by controlling the coolant circulation more desirable than the other types of vapor chambers. This article describes the basic structure of the FGHP and heat spreading experiment utilizing thermocouples and Infrared (IR) technique to estimate its thermal performance, and compared it with that of conventional vapor chambers.

2. Development of Fine Grid Heat Pipe (FGHP)

Fig. 1 shows a structure of the Fine Grid Heat Pipe (FGHP) which is composed of several oxygen-free copper plates (JIS H 3100, C1020) as shown in Fig. 1(a). Each layer is laminated together by vacuum hot press technique without any binder to prevent electric corrosion. Temperature and pressure applied in hot press were 653.15 K and 14.7 MPa, respectively. All inner and outer structures such as wick, vapor path, and dimple are fabricated by a fine wet etching technique so as to be optimum for coolant circulation. In the etching process, Iron (III) chloride was utilized as etchant, and dry film resist (DFR) and casein resist were used for top and bottom plates, and for middle plates, respectively as photo resist. Upper and bottom plates of 0.8 mm thick have almost the same structure except injection holes for coolant. Inner surface of upper and bottom plates have dimple structure, which is designed to enhance boiling at the bottom plate and to avoid film condensation at the top plate, respectively, both to achieve higher heat transfer ability. The size of the surface of the dimple and the depth are approximately 0.3 mm as shown in Fig. 1(c). Each middle plate of 0.1 mm thick has vapor path and wick area, for movement of vapor and return of condensed coolant, respectively. Wick area of a middle plate has fine grid structure and vapor path is a V-shaped opening. Middle plates have two different pattern of wick area to make