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Loop heat pipe for cooling of high-power electronic components

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ABSTRACT

In this paper, we present a new development of loop heat pipe (LHP) technology in its applications to cooling systems for high-power IGBT elements. An advanced method of LHP evaporator wick manufacturing has been proposed. Following this approach, a 16 mm outer diameter and 280 mm-length LHP evaporator was designed and manufactured. Nickel and titanium particles were used as raw material in LHP evaporator wick fabrication. LHP with a nominal capacity as high as 900 W for steady-state condition and more than 900 W for a periodic mode of operation at a temperature level below 100 °C and a heat transfer distance of 1.5 m was designed through the cooling of a high-power electronic module. An experimental program was developed to execute LHP performance tests and monitor its operability over a span of time. An investigation of the effects of LHP performance of parameters such as evaporator and condenser temperatures and LHP orientation in a gravity field was brought about. As regards the results of this initial series of tests, it was found that LHP spatial orientation within the nominal range of heat loads has no drastic effect on overall LHP functioning, whereas condenser temperature does play an important role, especially in the range of heat load close to critical. A 2D nodal model of the evaporator was developed and provides us with confirmation of the suggestion that when high-power dissipation levels are available, low wick conductivity is well adapted for LHP applications.

1. Introduction

Presently there exist two widely used cooling modes for high-power semiconductor components (IGBT, IGHTs and other modules). A low efficiency level, the need to use a liquid pump, and pollution and incrustation of working fluid are the main drawbacks of single-phase cooling systems. Another disadvantage of liquid cooling systems, especially in transport applications such as trains and electrocars, consists in the large mass of working fluid due to the liquid's inertia during the acceleration and braking phases.

As for heat pipe-based heat exchangers, they present greater overall efficiency as well as a low mass of working fluid [1,2]. Another major advantage of a heat pipe is that it furnishes a totally passive mode in transmission of heat from hot electronic components to released area into the atmosphere. The reader may be reminded that a heat pipe is a sealed metallic container containing a capillary wick suffused with a small amount of working fluid. This latter is at the saturation state so that it vaporizes as heat is applied to the heat pipe envelope or condensate as heat is removed. Due to saturation pressure difference, the vapor emanating from the heat pipe evaporator moves to the condenser where it condenses and releases its latent heat energy, which is absorbed by the surroundings. The wick structure in the heat pipe's inner wall provides capillary forces that pump the condensate back to the hot end of the heat pipe and thereby complete the continuous evaporation/condensation cycle.

Two-phase loop with capillary pump (LHP) is a variety of heat pipe in which the evaporator and the condenser are separated, with the working fluid being transported between the two components via tubing or pipes [3–5]. Along with its high cooling capability, this type of flexible design renders LHP a highly promising candidate for advanced cooling systems in modern high-power electronic modules.

Generally speaking, the LHP evaporators present a cylindrical shape with a 12–28 mm diameter and a length/diameter ratio ranging from 5 to 10 [6] on account of the technical difficulties of porous structure realization that impinging upon evaporator performances. In many applications, especially when the length/diameter ratio is greater than 10, it is desirable that the thermal management system assure uniformly high rates of heat removal over a larger area. In this paper, an experimental investigation of LHP with an evaporator length/diameter ratio of close to 18 is to be presented (Fig. 1).

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Nomenclature

G	thermal conductance ($W\ K^{-1}$)	λ	effective conductivity ($W\ m^{-1}\ K^{-1}$)
l_v	latent heat ($J\ kg^{-1}$)	θ	opening angle of the node (rad)
L	node length (m)	μ	liquid dynamic viscosity (Pa s)
M	molecular mass ($kg\ mol^{-1}$)	ρ	density ($kg\ m^{-3}$)
Q	power of heat flux (W)		
R	node internal or external radius (m)	*Subscripts*	
S	node exchange surface (m^2)	if	interface
T	temperature (K)	sat	saturation
		vap	vapor
Greek letters			
α	evaporation coefficient		

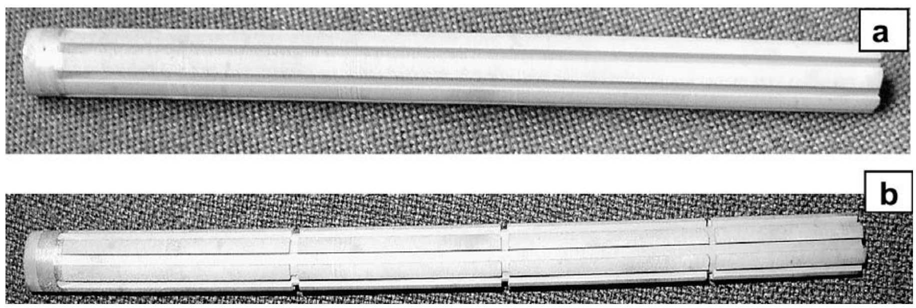

Fig. 1. Photo of LHP evaporator wick. (a) With longitude grooves only; (b) with longitude and transversal grooves.

2. Advanced LHP wick design

Traditional fabrication process of LHP evaporator consists of four main operations: pressing metal powder in a specially designed tool, the sintering process, creation of vapor removal grooves on the wick structure's outer surface, and introduction of the wick structure in a metal envelope.

We wish to propose a new technology for the pressing process in which the pressing metal particles are preliminarily introduced into the soft polymer matrices. Application of the soft (polymer-based) envelope (Fig. 2) along with a radial mode of mechanical pressure (Fig. 3) constitute an advanced method of metal powder treatment ensuring uniform pore distribution and wick density subsequent to pressing throughout the wick.

A good uniformity of the thermophysical properties of porous structure and needed uniform porosity in large porous values range of whole volume of the wick is ensured (Fig. 4).

Since this technology allows for creation of vapor removal grooves simultaneously with metal particle compression, it is less costly than mechanical wick cutting and electro-erosion treatment.

Another major advantage of the proposed metal particle pressing procedures is that they entail no need to apply the vacuum press form, as is customarily done in conventional hydraulic pressing technology.

3. Wick structure hydraulic analysis

It is a well-known fact that in LHP pressure balance, loss of pressure through the wick is a significant factor. Wick permeability K is in direct correlation with wick structure porosity ε, which is defined as the ratio of pore volume to total volume of the wick, and is usually given by:

$$K = \frac{2\varepsilon r_h^2}{f_l Re_l}, \qquad (1)$$

where (f_l) is the friction factor. Given the typically small size of the porous structure's hydraulic radius along with a typically low liquid flow velocity, the liquid flow may be considered laminar. Hence, the values of ($f_l Re_l$) depend only on flow passage shape and can likewise be deemed constant. Such an assumption is basically valid as regards homogeneous porous structures.

Review of the literature shows that most researches have focused on the thermal and hydraulic properties of wick structure in macroscopic point of view. But, in the design of LHP evaporators, vapor removal grooves are found on the outer surface of the wick, which structure of the surface is typically deformed. The degree of deformation hinging upon the mode of groove creation. Due to the convenience of their mechanical and thermal properties, Ni- and Ti-based wick structures are widely used in LHP evaporator fabrication.

In this work, the grooved surface of the wick structure resulting from mechanical treatment, electro-erosion technology and from the powder pressing into the soft polymer matrix and rigid metallic press forms has been submitted to close investigation. Photos of the Ni-sintered wicks for which the vapor removal grooves were created by these different techniques are shown in Fig. 5. The photos were obtained through use of the scanning electron microscope Nanolab-7 (Opton, Germany). Stereological analysis of groove surfaces was performed with the help of the automatic picture analyzer known as "Mini-Magiscan" ("Joyce Loebl", UK) and the "Genias 26" software.

Analysis results attest to the following:

(1) During electro-erosion treatment, some of the metal particles partially melt, and their evaporation stimulates a further procedure of vapor/liquid/crystal formation. As an additional consequence of this application, the range of particle diameters on the wick surface widens, while the range of pore diameters is in no way uniform. Moreover, it is difficult to compare a porous wick surface with a wick surface subsequent to mechanical cutting of the latter. Finally, electro-erosion treat-