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Thermal performance modeling of loop heat pipes with flat evaporator for electronics cooling

I. Gabsi, S. Maalej, M.C. Zaghdoudi*

University of Carthage, Institut National des Sciences Appliquées et de Technologie (INSAT), Laboratoire Matériaux, Mesures et Applications (MMA), Centre Urbain Nord-BP N°676, 1080 Tunis, Tunisia

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ABSTRACT

This work deals with modeling of the thermal performance of a copper-water loop heat pipe (LHP) with a flat evaporator operating in steady state operation. The model is based on steady-state energy and momentum balance equations for each LHP component. Modeling the heat transfer in the evaporator was particularly considered, and the evaporation heat transfer coefficient is determined from a dimensionless correlation which is developed on the basis of experimental data from literature. The validation of this model consists in comparing the experimental results and those obtained by the model for different cooling temperatures. Finally, a parametric study is presented to show the effects of different key parameters such as the radii and the lengths of the liquid and vapor lines, the length of the condenser, the heat sink temperature and heat transfer coefficient as well as the ambient temperature and the heat losses to the ambient.

1. Introduction

The thermal management of high dissipative power electronics becomes a major challenge in various electronic and electrical devices. Hence, more competitive and efficient solutions for electronic cooling applications were developed in order to transfer passively large amount of heat to allow the electronic component operating in safe operation.

Two-phase cooling technologies such as Loop Heat Pipes (LHPs) are considered as high heat transfer capacity devices which can operate at adverse tilts in gravity field, and they are able to transfer heat for important distances, even in harsh operating conditions under ground or space environmental conditions. Their high pumping capability, their ability to operate in gravitational and acceleration fields, as well as the diversity of their geometrical characteristics make the LHP an efficient thermo-capillary driven heat transport for high power electronic components [1].

The thermal behavior of the LHPs is very sensitive to the operating conditions. The steady state modeling of such systems has been the objective of many researches in order to predict their operation and optimize their design. Most of them are 1D models and they are based on the steady-state energy balance equations at each component of the system and the thermodynamics relationships. The main studied parameters can be classified into three groups. The first one concerns the geometrical characteristics of the LHP components such as the length and the diameter of the vapor and liquid lines as well as the length of the condenser. The second group of the parameters concerns the operating conditions such as the heat input power, the sink and ambient temperatures, the heat exchange with the ambient, the LHP elevation, the presence of non condensable gas, and the fill charge. The third group of parameters concerns the thermo-hydraulic properties of the capillary structure such as the effective thermal conductivity, the porosity, the permeability, and the material.

Although the previous studies on LHP modeling contributed significantly in the understanding of the physical phenomena involved in the operation of such systems, the literature survey evidences a lack in the modeling of the evaporation phenomena within the capillary wick. Indeed, many of the published models did not present details about how the evaporation thermal conductance is determined or modeled [2–12]. In addition, according to the literature review, no models for the prediction of the evaporation heat transfer coefficient in the capillary structures have yet been established. Moreover, the evaporation heat transfer coefficient depends on several parameters such as the thermal contact between the evaporator wall and the capillary wick, the wettability of the liquid, the working fluid, the heat input power, the nature of the capillary wick and its hydrodynamic characteristics such as porosity and permeability, and the temperature of the compensation chamber which depends greatly on the operating conditions of the heat sink in the condenser. As such characteristics are not detailed in the published experimental studies; the evaporation thermal resistance was adjusted in the models in order to obtain a good agreement between

* Corresponding author.
E-mail address: chaker.zaghdoudi@insat.rnu.tn (M.C. Zaghdoudi).

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experimental and model results [13,14]. Besides, some published works also considered fixed values of the evaporation thermal resistance (or thermal conductance). They are either based on the experimental results [15,16] or fixed arbitrarily by considering an order of magnitude of the evaporation heat transfer coefficient [17–19]. Moreover, in some works, the evaporation heat transfer coefficient is determined by expressions which are not necessarily valid for the evaporation phenomenon in porous media [20–24].

The aim of the present study is to propose a complete analytical steady state model of a LHP based on momentum, energy conservation equations and thermodynamics relationships. The model takes into account the axial heat flux rates transferred along the porous wick and through the evaporator wall, and the heat dissipated by evaporation at the wick-groove interface. The originality of this study is to improve the analytical model developed by Launay et al. [13]. Indeed, in Launay's model, the evaporator thermal resistance is fixed so that a maximum evaporator temperature of 90 °C cannot be exceeded. Hence, the evaporator thermal resistance value doesn't depend on the heat input power. In the present model, a heat transfer correlation for the calculation of the evaporator thermal resistance is proposed on the basis of experimental data. The complete coupled hydraulic-thermal model is validated on the basis of published experimental results on LHP. Finally, a parametric study is performed in order to simulate the influence of different key parameters on the LHP thermal performances.

2. Description of the modeled LHP

The LHP is composed of an evaporator containing a capillary structure, a compensation chamber filled with a working fluid, vapor and liquid lines, and a condenser. It uses the evaporation and condensation processes in order to remove heat from the heat source and rejects it in the heat sink. The capillary pressure, which is created in the core of the evaporator, allows the circulation of the fluid in the LHP. When the heat is applied to the evaporator wall, the working fluid is vaporized (Fig. 1). The vapor formed at the evaporator, is directed through the grooves to the vapor collector. Due to the difference temperature and pressure created in the evaporator, the vapor flows through the vapor line to the condenser. The condensate flows back to the evaporator through the liquid line by means the capillary forces created in the porous wick. The heat transfer process continues as long as heat is applied.

To operate properly, the capillary pressure created in the core of the evaporator must exceed the summation of all pressure drops occurring in each component of the LHP according to

$$\Delta P_c = \frac{2\,\sigma\,\cos(\beta)}{R_p} \geq \Delta P_g + \Delta P_{vl} + \Delta P_{ll} + \Delta P_w + \Delta P_{vg} \tag{1}$$

ΔP_c is the capillary driving pressure and β is the contact angle. R_p is the pore radius of the wick. ΔP_g is the hydrostatic pressure drop. ΔP_{vl} and ΔP_{ll} represent the viscous pressure drops in the vapor and liquid lines, respectively. ΔP_w represents the liquid pressure drop in the wick, and ΔP_{vg} is the vapor pressure drop in the grooves. When the capillary pressure is equal or greater than the summation of these pressure losses, the capillary structure can ensure the return of the liquid from the condenser to the evaporator. On the other hand, when the capillary pressure cannot overcome all the pressure losses, the porous structure becomes dry.

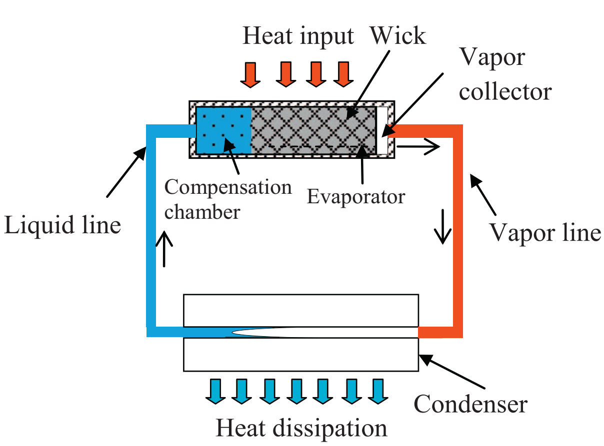

Fig. 1. Principle operation of the Loop Heat Pipe (LHP).

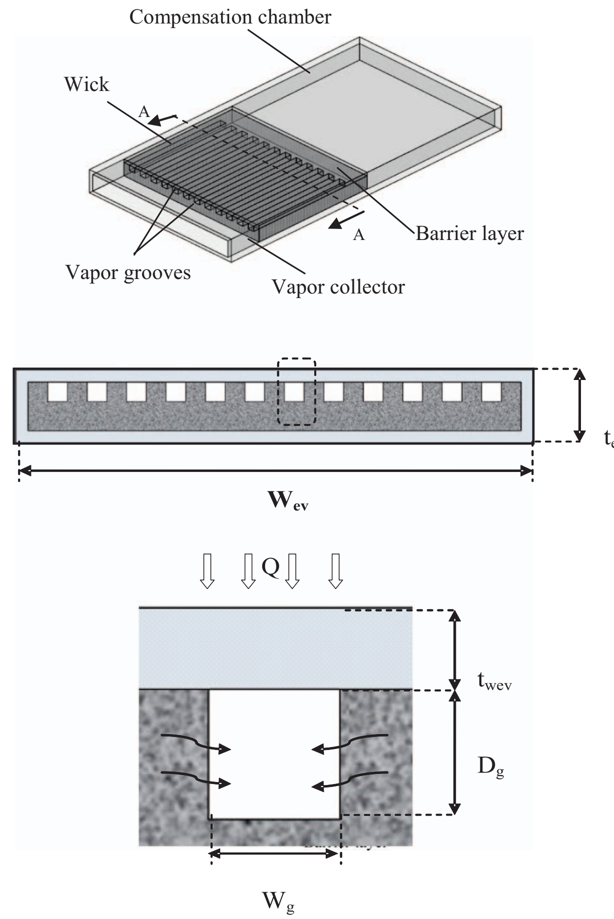

Fig. 2. Configuration of the flat evaporator and its geometrical characteristics.

The present analytical model will be validated using the experimental results presented by Chernysheva et al. [25] who tested a copper-water LHP. The LHP is composed of a flat evaporator with a compensation chamber placed aside and connected to the heat source (Fig. 2), a condenser to dissipate the heat load, and vapor and liquid lines to transport the working fluid between both components. The wick is made of sintered copper powder and rectangular grooves (Fig. 2). The geometrical characteristics of the LHP are given in Table 1. The evaporator is oval and flat and its dimensions are 80 mm × 42 mm × 7 mm. The power input delivered to the evaporator is concentrated in an active zone which measures 32 × 42 mm^2. The lengths of the vapor and the water-cooled condenser with an inner diameter of 4 mm, are 305 mm and 160 mm, respectively. The liquid line has a length of 810 mm and an inner diameter equal to 3 mm. The wick is made of sintered copper powder with a pore radius of 27 μm, and its porosity is equal to 46%. To ensure the cooling of the condenser, a cooling plastic jacket was used through which the water was pumped.

3. Model formulation

The objective of this section is to develop a steady state model to

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