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# Theoretical thermal study of wire-plate mini heat pipes

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ABSTRACT

In the present study, a theoretical thermal study of a wire-plate mini heat pipe is presented. The wire-plates are considered grooved type heat pipes. Two models are used: a hydrodynamic model (taken from literature) and a thermal model, developed in the present paper. The influence of vapor channel hydraulic diameter and evaporator length are determined by the hydrodynamic model, which takes into account the geometry of the liquid layer in the groove. For the thermal model, for both evaporator and condenser, the liquid film cross section area is divided into three regions, represented by three resistances in parallel. Each one of these resistances is individually modeled and are connected by thermal circuit, which is used to predict the temperature distribution along the heat pipe. A parametric study of the influence of the major design parameters in the heat transfer performance of the device is performed. In addition, the maximum heat transfer capacity of the heat pipe, defined as the heat power level beyond which the overall thermal resistance starts to increase sharply, are determined by the models. An experimental setup was built and several wire-plate heat pipes were constructed and tested. The resulting data compared favorably with the models.

## 1. Introduction

Electronics is probably the technical area of faster development in world in the last century, undoubtedly influencing people lives around the planet. A few decades ago, portable computers were very expensive, had a small processing capacity and weighted around 10.7 kg [1]. Today, due to the industry effort to accomplish the market demands for light, compact, efficient and nice looking computers, portable, high velocity laptops are available at popular prices.

Electronic component development is one of the pillars of such accomplishments, as new technologies made them smaller and more efficient. In contrast, these components dissipate heat and their miniaturization causes the overheating of electronics devices, which, in turn, decreases the equipment performance. New electronics thermal control technologies are needed for the solution of the thermal problems in compact environments, which, in the past, were solved by heat dissipaters associated to fans.

Mini heat pipes are one of the technologies considered for dissipation of concentrated heat, as they are able to control the temperature of electronics. They are reliable and simple devices, but, as its size decreases, the fabrication process complexity increases, and so its cost. Wire plate heat pipes can be considered a good alternative for grooved mini heat pipes due to high quality of the sharp grooves, associated with low cost and simple fabrication process. Usually, grooves provide low liquid pressure drops along heat pipes, while sharp grooves provide high working fluid pumping capacity. In wire plate heat pipes, the working fluid, in the liquid state, is mainly confined to the groves. Due to evaporation and condensation, its layer thickness varies along the heat pipe, being thicker in the condenser and thinner in the evaporator regions. The hydrodynamic and heat transfer phenomena along the heat pipe is directly related to the working fluid layer thickness.

To understand the thermal behavior of wire mini heat pipes, fundamental modeling of heat transfer phenomena must be conducted, including, among other aspects: phase change phenomena, surface tension, contact angle between working fluid and capillary structure, etc. These models, which are also useful for the design of such devices, are not available in the literature.

In the present paper, models for the determination of the maximum heat transfer capacity and of the temperature distribution of wire-plate mini heat pipes, constructed using technologies develop at the Heat Pipe Laboratory in the Federal University of Santa Catarina (Labtucal – UFSC), in Brazil, are presented, providing wire-plate heat pipe design tools. Two models are necessary a hydrodynamic and thermal. The hydrodynamic model was

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**Nomenclature**

| | |
|---|---|
| $A$ | coefficient, Hamaker constant [N m] |
| $A_p$ | cross section area of ¼ of the wire and half the channel wall [m$^2$] |
| $c$ | line segment (Fig. B.1) [m] |
| $D_w$ | wire diameter [m] |
| $f$ | accommodation coefficient |
| $h_{lv}$ | latent heat [kJ/kg] |
| $\dot{m}_e$ | mass flow rate per unit evaporated surface [kg/s m$^2$] |
| $\dot{m}_l$ | liquid mass flow rate [kg/s] |
| $M$ | molar mass [kg/mol] |
| $K_c$ | meniscus curvature [m$^{-1}$] |
| $k_p$ | copper plate thermal conductivity [W/mK] |
| $k$ | thermal conductivity [W/mK] |
| $L_1$ | transition region length [m] |
| $L_2$ | intrinsic thin film length [m] |
| $L_3$, $L_4$, $L_5$ | lengths (Fig. 4a) [m] |
| $p$ | Line segment (Fig. B.1) [m] |
| $P$ | pressure [Pa] |
| $P_d$ | disjoining pressure [Pa] |
| $q$ | line segment (Fig. B.1) |
| $Q$ | heat transfer rate [W] |
| $q$ | heat flux [W/m$^2$] |
| $r$ | line segment (Fig. B.1) |
| $R$ | thermal resistance [K/W] |
| $r_h$ | hydraulic radius [m] |
| $r_c$ | capillary radius [m] |
| $R_{l,i}$ | longitudinal thermal resistance of node i [K/W] |
| $R_{t,i}$ | transverse thermal resistance of node i [K/W] |
| $R_w$ | wire radius [m] |
| $R_g$ | gas constant [J/mol K] |
| $s$ | transversal meniscus coordinate [m] |
| $t_w$ | copper plate thickness [m] |
| $T$ | temperature [°C] |
| $T_i$ | Interface temperature [°C] |
| $T_p$ | wall temperature [°C] |
| $u_l$ | liquid velocity [m/s] |
| $u_v$ | vapor velocity [m/s] |
| $V_l$ | molar volume [m$^3$/mol] |
| $w$ | space between wires [m] |
| $w_{cont}$ | plate/wire contact width [m] |
| $x$ | axial coordinate [m] |
| $x_{exp}$ | experimental data |
| $x_{th}$ | theoretical results |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | contact angle [°] |
| $\beta_1$ | half of angle between the liquid and the wire [°] |
| $\beta_2$ | half of angle of meniscus [°] |
| $\delta$ | thin film thickness [m] |
| $\delta_d$ | thickness [m] |
| $\delta_{fio}$ | thickness [m] |
| $\Delta T$ | temperature difference [K] |
| $\eta$ | normal to the solid liquid interface coordinate [m] |
| $\mu_l$ | liquid viscosity [kg/ms] |
| $\mu_v$ | vapor viscosity [kg/ms] |
| $\rho_l$ | liquid density [kg/m$^3$] |
| $\rho_v$ | vapor density [kg/m$^3$] |
| $\sigma$ | surface tension [N/m] |
| $\theta$ | angle (Fig. B.1) [°] |
| $\omega$ | opening angle [°] |

*Subscripts*

| | |
|---|---|
| $a$ | adiabatic section |
| $c$ | condenser |
| $cap$ | capillary |
| $cond$ | condenser |
| $e$ | evaporator |
| $evap$ | evaporator |
| $ex$ | experimental |
| $h$ | hydraulic |
| $i$ | interface, index for node |
| $l$ | liquid |
| $m$ | meniscus |
| $max$ | maximum |
| $ope$ | operation |
| $sat$ | saturation |
| $v$ | vapor |
| $w$ | wire, wall |

developed by the present authors and previously published in [2]. In the present work, a thermal model for the wire-plate mini heat pipe is developed and the results obtained are compared with data for the mini heat pipes constructed with this technology, which picture is shown in Fig. 1.

## 2. Literature review

Mini heat pipe working principles are very similar to conventional heat pipe ones [2]. Generally speaking, mini heat pipes can be considered as heat pipes of small dimensions [3–6]. Due to its reduced size, the fabrication of mini heat pipes, especially concerning the wick structure, can be quite different from the conventional ones. Two parameters control the performance of a wick: capillarity and permeability. The capillarity is responsible for the pumping of the working fluid from the condenser to the evaporator while the permeability shows the ability of the media to transport the fluid. An ideal wick should present high capillarity and high permeability. Actually, these parameters are conflicting: small porous or grooves result in high pumping capacity and low permeability (high fluid pressure drops). Therefore, a good wick design must provide a good balance between these effects. The most commonly used wick structures in normal heat pipes are screens, grooves and sintering materials [7].

The heat pipes studied in the present paper can be classified as grooved mini heat pipes. They are composed by a sandwich of two flat plates with wires between the plates, as presented in Fig. 1. The working fluid capillary pumping is performed by the sharp grooves formed between the plates and the wires. The vapor moves through the core formed between wires.

Not many models are available for grooved heat pipes in the literature. In 1990 and 1991, analytical, steady state models, aiming to establish the heat transfer limits of mini trapezoidal grooved heat pipes were developed [8,9]. Later, in 1995, a numerical transient tridimensional study [10], highlighted the potential advantages of the use of grooves in micro heat pipes as an integral part of the semiconductor chips. Another one dimensional hydrodynamic heat transfer model was developed for rectangular grooves [11], where the importance of the liquid film, contact angle and interface stress in the determination of the capillary limit of micro heat pipes was emphasized. In 1994, a one-dimensional theoretical study was developed, to determine the maximum heat transfer