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Research paper

A mass-spring-damper model of a pulsating heat pipe with a non-uniform and asymmetric filling

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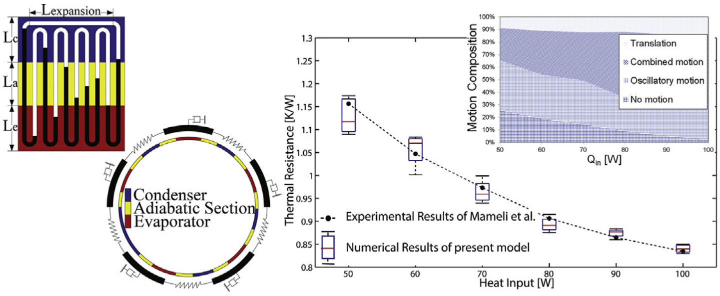
HIGHLIGHTS

- A non-linear mass-spring-damper model for a PHP is developed.
- Good agreement with numerical and experimental results from literature.
- Effective thermal resistance decreases with increasing heat input.
- Four different modes of motion can be distinguished.
- More translational and combined motion observed when heat input increases.

GRAPHICAL ABSTRACT



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ABSTRACT

A pulsating heat pipe (PHP) is a device that transfers heat from a hot spot to a cold side by oscillating liquid slugs and vapor plugs. Its working principle is based on interplay between convective heat transfer, evaporation of the liquid at the hot side and condensation of the vapor at the cold side. Several factors play an important role including pressure differences, frictional forces, inertia forces, capillary forces and gravitational forces. The goal of this paper is to analyze the effects of non-uniform and asymmetric filling of a PHP on its thermal performance. In this paper, a 1D mass-spring-damper model is developed to predict the motion in a PHP. Also, a heat transfer model is developed. These two models are coupled to analyze the motion and performance of a PHP and can also take asymmetry into account. The model is compared with both numerical and experimental results from literature. Simulations show that including asymmetry into the system results in a good agreement with experimental results. Finally, four different modes of motion are observed: Oscillatory motion, translation, combined oscillatory-translation motion and no motion. Motion composition of a PHP as a function of heat input is studied. It is seen that translational and combined motion become dominant with increasing heat input. Also, the thermal performance of the PHP increases when the percentage of the translational and combined motion increases.

1. Introduction

The electronic industry is undergoing continuous and rapid developments. This manifests itself in advancement of performance of processors and miniaturization of components. Another advancement is the use of plastic foils for flexible electronic applications. Flexible electronics are getting increasingly appealing due to their mechanical flexibility, lightweight and low price [1]. However, their lower thermal conductivity compared with metals and silicon hinders their application. Conventional cooling approaches are difficult to integrate with plastic foils. This

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Nomenclature

A	area
Ca	Capillary number
C_p	heat capacity
D	inner diameter
F	force
$\bar{f}$	mean frequency
g	gravitational acceleration
h_{fg}	latent heat of evaporation
h	heat transfer coefficient
L	length
m	mass
N_s	number of slugs
P	pressure
$\dot{Q}$	heat flux
R_{th}	thermal resistance
T	temperature
t	time
t_{mean}	mean time interval
V	velocity
V_{th}	velocity threshold
L	length
X_{th}	amplitude threshold
x	position

Greek symbols

α_{inc}	inclination angle
β	constants in Antoine equation
ϕ	filling ratio
θ_d	dynamic contact angle
θ_s	static contact angle
μ	dynamic viscosity
σ	surface tension
ω	oscillation frequency

Subscripts

l	liquid
v	vapor
s	surface
c	cross-section
$pres$	pressure
adi	adiabatic section
$turn$	property of single turn
$fric$	friction
cap	capillary
$grav$	gravitational
$evap$	evaporator section
$cond$	condenser section
sat	saturation
$init$	initial value

has called for the development of miniature/micro heat pipes characterized by two-phase heat transfer to transport heat from chips to heat sinks. Traditional heat pipes have stretched the limits of cooling power [2]. However, they cannot work below the capillary limit, which poses problems for miniaturization. The pulsating heat pipes (PHPs) invented in 1990s by Akachi [3] are very promising heat transfer devices. In contrast with conventional heat pipes, a PHP does not have an internal wick structure [4]. Also, it does not require mechanical pumps or valves. It can enable miniaturization to be used in the next generation of flexible microelectronic systems.

A pulsating heat pipe is made of a serpentine tube of capillary dimensions with a certain number of turns (Fig. 1a). It is evacuated and then filled partially with a working fluid. A PHP is heated from one end and cooled at the other end. Therefore, an evaporator and a condenser section can be distinguished (Fig. 1a). The tube may be either closed or open loop, where the tube ends are connected to each other or sealed respectively [4]. The closed loop PHP has a better heat transfer performance [5], so most research is done with this type of PHP.

The working principle of a PHP is not yet fully understood. An interplay is assumed between convective heat transfer, evaporation of liquid on the hot side and condensation of the vapor on the cold side. As the evaporator section gets heated, a pressure build-up in the vapor plugs occurs. Due to this pressure difference, a liquid slug is pushed to the condenser section where both vapor and liquid are cooled down. The vapor plug, that reaches the condenser section, condenses and the pressure decreases. This forces the liquid slug to move back towards the evaporator section. In this way, oscillatory motion can occur inside the PHP.

Several modeling approaches can be found in the literature. Shafii et al. [6] described oscillations as a combination of several factors, including pressure difference, frictional force, gravitational force, capillary force and energy and mass balances. Dobson [7,8] investigated the influence of geometry on the motion of one vapor plug and two liquid slug system in an open pulsating heat pipe. He found that surface tension has a vital role on the formation of the liquid slug but friction, gravity and pressure forces are more important for motion. Ma et al. [9] described how oscillations are affected only by the thermal energy due to the temperature difference between the evaporator and condenser. Sakulchangsatjatai et al. [10] developed a mathematical model including coalescence of the liquids to predict the heat flux at normal operating state of a closed end PHP. They also studied the effects of evaporator length, inner diameter and working fluid. They showed that the maximum heat transfer rate of the closed end PHP occurred at the highest evaporator temperature (150 °C for their study). Jiansheng et al. [11] developed a model to study the effects of non-uniform heating patterns. They showed that using non-uniform heating patterns are more efficient than using a rising heat input during the start-up period of the PHP. Lin et al. [12] used a mixture model in FLUENT to predict the heat transfer mechanism of miniature oscillating heat pipes with different inner diameters and lengths. They found that the inner diameter has more effect on the heat transfer performance of miniature oscillating heat pipes than its length.

These models assume a uniform distribution of liquid slugs and vapor plugs which is not observed in experiments. According to Khandekar et al. [13] the vapor plugs and liquid slugs are not symmetrically distributed which cause an uneven capillary pressure difference. Yang et al. [14] performed closed loop PHP experiments to investigate the effects of inner diameter, filling ratio, orientation and heat load on thermal performance and occurrence of performance limitation in the form of evaporator dry-out. They found that a PHP with a 2 mm inner diameter has a lower thermal resistance than a PHP with a 1 mm inner diameter. Tong et al. [15] conducted experiments to investigate the flow characteristics of PHPs and they stated that slugs and plugs are unevenly distributed during initial and operating state. They stated that large amplitude oscillations from evaporator to condenser occur in the PHP during the start-up period. After the start-up period, rotational motion of