Applied Thermal Engineering 58 (2013) 585–593

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Transient thermal performance analysis of micro heat pipes

Xiangdong Liu, Yongping Chen*

Key Laboratory of Energy Thermal Conversion and Control of Ministry of Education, School of Energy and Environment, Southeast University, Nanjing, Jiangsu 210096, PR China

HIGHLIGHTS

- Transient thermal response of micro heat pipe is simulated by an improved model.
- Control theory is introduced to quantify the thermal response of micro heat pipe.
- Evaluation criteria are proposed to represent thermal response of micro heat pipe.
- Effects of groove dimensions and working fluids on start-up of micro heat pipe are evaluated.

ARTICLE INFO

Article history:
Received 18 February 2013
Accepted 22 April 2013
Available online 30 April 2013

Keywords:
Micro heat pipe
Transient thermal performance
System identification theory

ABSTRACT

A theoretical analysis of transient fluid flow and heat transfer in a triangular micro heat pipes (MHP) has been conducted to study the thermal response characteristics. By introducing the system identification theory, the quantitative evaluation of the MHP's transient thermal performance is realized. The results indicate that the evaporation and condensation processes are both extended into the adiabatic section. During the start-up process, the capillary radius along axial direction of MHP decreases drastically while the liquid velocity increases quickly at the early transient stage and an approximately linear decrease in wall temperature arises along the axial direction. The MHP behaves as a first-order LTI control system with the constant input power as the 'step input' and the evaporator wall temperature as the 'output'. Two corresponding evaluation criteria derived from the control theory, time constant and temperature constant, are able to quantitatively evaluate the thermal response speed and temperature level of MHP under start-up, which show that a larger triangular groove's hydraulic diameter within 0.18–0.42 mm is able to accelerate the start-up and decrease the start-up temperature level of MHP. Additionally, the MHP starts up fastest using the fluid of ethanol and most slowly using the working fluid of methanol, and the start-up temperature reaches maximum level for acetone and minimum level for the methanol.

1. Introduction

Efficient cooling of microelectronics is of significant importance for their safe operation and high performance [1,2]. Recently, due to the powerful heat transfer capability, small size and stable operation, the micro heat pipe (MHP) is introduced as a highly efficient thermal device to fulfill such electronic cooling.

The concept of MHP is originally proposed by Cotter [3] as an efficient heat-transfer element in which the mean curvature of the vapor–liquid interface is of the same magnitude as the reciprocal of the hydraulic radius of the total flow groove. The typical MHP has a hydraulic diameter within the range of 10–500 μm and a length up to several centimeters, which is charged with the appropriate amount of working fluid [4]. Compared with the wick structures such as meshes or grooves in the conventional heat pipes [5–8], the sharp-angled corners of the micro-grooves in the MHPs provide the major capillary pumping pressure for driving the working fluid to circulate from the condenser back to the evaporator.

Considerable experimental investigations have already been conducted to study the design, fabrication and actual performances of the MHPs [9–13]. Experimental studies of the MHPs with polygonal cross-section are also performed to investigate the heat transfer characteristics and heat transfer limit [9]. To increase the heat transfer capacity, MHPs are usually implemented in arrays of several tens. Berre et al. [11] experimentally demonstrated the feasibility of integrating high sensitivity thermistors in all-silicon MHP arrays which consist of 27 parallel triangular shaped grooves. The performances of this novel MHP arrays were experimentally tested with various methanol filling ratios and under various experimental conditions. Wu et al. [12] performed an

* Corresponding author. Tel.: +86 25 8379 2483.
E-mail address: ypchen@seu.edu.cn (Y. Chen).

1359-4311/$ – see front matter
http://dx.doi.org/10.1016/j.applthermaleng.2013.04.025

experimental study on the transient thermal performance under start-up process and the rapid changes in the thermal load, and presented the unsteady temperature distribution throughout the longitudinal position as well as the temperature difference between axial locations on the heat pipe. Moreover, the experimental data were compared with the results of a developed analytical model to validate the reasonability of the model. In addition, a silicon MHP array with arteries was fabricated by Launay et al. [13] for increasing the liquid flow cross-sectional area so as to reduce the liquid pressure drop. Compared with a plain silicon wafer, the MHP with such configure realized a great improvement of effective thermal conductivity, which was experimentally verified.

Besides the experimental investigations, a lot of numerical and analytical models have been developed to study the steady-state and transient thermal performance as well as the optimal geometric designs of MHPs [13–21]. Babin et al. [9] developed a steady-state, one-dimensional model for a single trapezoidal MHP to examine the effects of the extremely small characteristic dimensions on the conventional steady-state heat pipe modeling techniques. And then a steady-state experiment on copper and silver heat pipes was conducted to validate the theoretical model. Suman and Hoda [14] proposed a detailed simulation of a V-shaped MHP. The model studied the effects of operating parameters on the performance of the MHP, and predicted the dry-out length for different heat inputs. Furthermore, Suman [15] presented a model for fluid and heat transfer in an electrohydrodynamically (EHD) augmented MHP, in which the coulomb and dielectrophoretic forces were considered. It is found that the critical heat input increases and the dry-out length decreases with an increase in the electric field. And the numerical solutions were successfully compared with the experimental results. Khrustalev and Faghri [16] also developed a detailed mathematical model of a MHP with a triangular shaped groove. The model demonstrated that the liquid filling ratio, minimum wetting contact angle, and the shear stresses at the liquid–vapor interface play important roles in predicting the maximum heat transfer capacity and thermal resistance. Based on a one-dimensional steady-state model, Qu et al. [17] analyzed the effect of a functional surface with the axial ladder contact angle distribution on the thermal performance of a triangular MHP. The simulation results showed that compared with the traditional MHP with the surface possessing a uniform contact angle distribution, a MHP with a functional surface has a better effective thermal conductivity under the same condition. Sobhan et al. [18] presented a numerical model of the vapor and liquid flow in a micro heat pipe with triangular grooves. The distributions of velocity, pressure, and temperature of the vapor and liquid at transient and steady states were obtained. Suman et al. [19] developed a one-dimensional transient model for fluid flow and heat transfer of heat pipes with axially triangular microgrooves which predicted the steady-state wall temperature distribution. And an improved model considering the shear stress at liquid–vapor interface, disjoining pressure and sensible heat of the solid substrate was also presented [20]. To study the effects of geometric design on the thermal performance of a star-groove MHP, a mathematical one-dimensional, steady-state model was developed by Hung et al. [22]. This model can be used to evaluate the heat transport capacity and the corresponding optimal charge level of the working fluid for different geometric designs and operating conditions. The results showed that, with increasing number of corners, the performance of MHP deteriorates. And it is also observed that the increase in the total length of the MHP results in a decrease in its heat transport capacity.

Despite there have been a great deal of investigations on MHPs, the transient thermal and hydrodynamic performance of MHPs have not been studied enough. The available theoretical modeling of the transient pressure and temperature distributions in MHPs [18,19] only consider the coupled heat and mass transfer processes between gas and liquid [18] or solid and liquid [19] rather than the whole coupled processes of heat and mass transfer among all the gas, liquid and solid in MHPs. Additionally, the expression in the available models [18,19] for evaluating the mass flux during the evaporation and condensation is not sufficiently valid [23], especially under the condition of low mass transfer rate. In particular, it is still lack of efficient tools to quantitatively evaluate the transient performance of MHPs.

Therefore, the current work develops a transient model and numerically analyzes the transient thermal and hydrodynamic performance of a micro heat pipe with triangular shaped grooves, taking consideration of the whole heat and mass transfer processes among gas, liquid and solid as well as the axial heat transfer in the wall of heat pipe. The calculation method for evaluating the mass flux during the evaporation and condensation is also improved in the model. The transient wall temperature profiles along the MHP, and the unsteady distribution of the capillary radius and liquid velocity in the MHP are presented and discussed. Especially, inspired by the introductions of control theory to realize the quantitative evaluations of transient characteristics (e.g. transient response speed, stability, etc.) of thermodynamic problems such as pool boiling [24], thermal-fluid flow in vascular networks [25] and so on, the system identification theory (an important part of control theory) is introduced here to quantitatively evaluate the transient performance of MHPs.

2. Mathematical model

Here, an improved model is developed to numerically simulate the transient performance of MHPs. The model couples heat and mass transfer processes among all the gas, liquid and solid as well as the axial heat transfer in the heat pipe wall. The Kucherov–Rikenglaz equation [23] is used to evaluate the mass flux at the vapor–liquid interface.

The schematic of the MHP including evaporator section, adiabatic section and condenser section is shown in Fig. 1. A constant heat flux is applied, $q_{in} = Q_{in}/A_e$ (Q_{in} is the input power, A_e is the outer surface area of evaporator section) and the condenser is subjected to convective cooling with a constant temperature, T_{cool}. The working fluid is evaporated on the evaporator side and condensed on the condenser side, and then returns to the

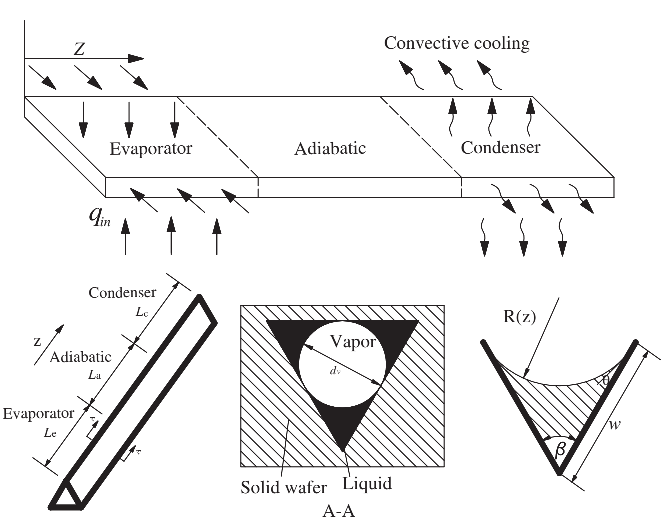

Fig. 1. Schematic of micro heat pipe with triangular shaped grooves.