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1D and Q2D thermal resistance analysis of micro channel structure and flat plate heat pipe

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A B S T R A C T

Heat pipes and two-phase heat transfer devices are widely used in electronics cooling, and the thermal resistance is a key issue to ensure the system performance and reliability. In this study, the traditional one dimensional (1D) and quasi-two dimensional (Q2D) methods were utilized to analyze the thermal resistance of the previous boiling experiments of evaporator tests with silicon (Si) and copper (Cu) micro channel structures as well as the existing flat-plate heat pipe tests with aluminum micro channels as wick structures. The temperature distributions and variations under different test conditions were collected, and the 1D and Q2D methods were applied to calculate the overall thermal resistance for evaporator tests and heat pipe tests and compared with the experimental data. The results showed that the Q2D method can predict the overall thermal resistance for the evaporator region and the whole heat pipe with a higher accuracy because the spreading resistance was significant and should be considered under small heater area (hot spot) conditions. Detailed distributions of thermal resistance and the calculated errors of each test sample under different heat loads were presented and compared. For present tests, the Q2D method can reach a lower average error (about 10%) and is recommended for calculations. Furthermore, the spreading resistance of Q2D method is further applied to calculate the selected test cases to investigate the wall thickness effects. The spreading resistance of the selected evaporator tests and heat pipe tests may decrease and increase, respectively, as wall thickness increases due to different evaporative heat transfer conditions. The present results demonstrate the applicability of the Q2D methods for both evaporator and heat pipe tests, and the present analyses can be a reference for future thermal management and electronic cooling designs.

1. Introduction

Two-phase heat transfer devices such as heat pipes and vapor chambers are widely used in electronics cooling due to the superior heat transfer performance and low thermal resistance on heat removal, which are the key issues to ensure the reliability of the electronic chips, computers and lighting systems [1–2]. In order to achieve the optimal performance of heat pipes, several design parameters should be considered such as geometry and material of micro wick structures, proprieties and state of working fluids, power and heat flux of the hot spot, temperature and pressure of operation, etc. Previously, Chi [3] and Peterson [4] have developed the models to predict the heat pipe performance and wick structure characteristics, such as limitations of capillary and boiling phenomena as well as wick flow resistances. Further, Peterson and Ha [5], Cao and Gao [6] examined the flow and boiling phenomena on micro triangular grooves, and the burn-out limitations were investigated. Chen et al. tested the capillary and boiling limits with copper (Cu) and silicon (Si) micro channels [7–9], analyzed the thermal performance, heat removal capability and dry-out power [9], and they also developed the empirical correlations of boiling and capillary limitations for micro-channel structures [10]. In order to gain more understanding on thermal performance, specifically for the temperature distribution of each component, the detailed thermal resistance analysis is required. Traditionally, the thermal resistance analysis is used in one-dimensional (1D) systems, which is simple and sufficient for uniform heating with constant-area heat transfer condition. However for non-uniform heating cases such as heat transfer from local hot spots to a larger surface or through a drastic change of

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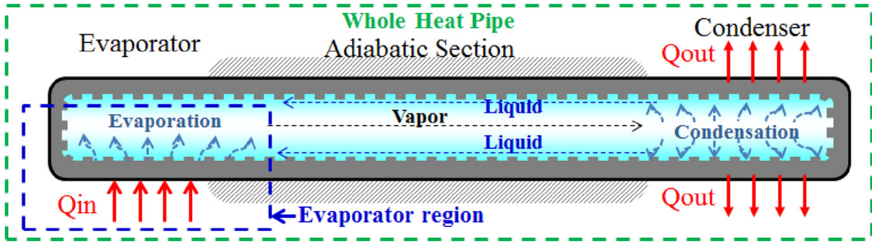

Fig. 1. Schematic of a heat pipe and the evaporator/whole heat pipe regions.

area, the 1D method may not be sufficient to model the system thermal performance. To solve the non-uniform heating issue, several researchers proposed the ideas and models for spreading resistance [11–13]. Yovanovich et al. [11] and Lee et al. [12] presented the spreading resistance for a circular hot spot with the cylindrical coordinate. Muzychka et al. [13] developed the spreading resistance (R_{sp}) models for rectangular coordinate systems, and Ellison [14] proposed models for rectangular sources with non-unity aspect ratios. By considering the spreading resistance, the traditional 1D thermal resistance model can be improved to include the heat spreading effects with R_{sp} and become the quasi-two dimensional (Q2D) method. Based on this strategy, one can evaluate the thermal performance in a simple and efficient way with a higher accuracy. In order to verify and validate these methods, the previous experimental data [7–9] tested with micro channel wick structures as an evaporator can be used for thermal resistance analyses and benchmark for 1D and Q2D methods. Furthermore, the present method can be further applied to the whole heat pipe tests by comparing the thermal performance of flat plate heat pipes (with micro channel wick structure) [15] to examine the applicability of 1D and Q2D thermal resistance analyses in a heat pipe system under different operating conditions.

2. Modeling methodology

In general, a heat pipe is constructed of a low-pressure chamber (normally a tube or flat box) with working fluid and wick structures. Fig. 1 shows the schematic of a heat pipe in operation. While the heat is loaded to the evaporator (at left-hand side), the working fluid inside the chamber can be evaporated and heat can be transferred to the condenser (at right-hand side) via the vapor flow. The vapor is then condensed at the condenser (right-hand side) and driven back to the evaporator (left-hand side) by the capillary force generated by the wick structures on the inner wall. It should be noted that on Fig. 1, two scales can be selected for local and global (system) analyses: (1) the evaporator region (circled by blue dash-line) and (2) the whole heat pipe system (circled by green dash-line), respectively. The evaporator region may contain complicated boiling phenomena and dominate the local boiling/dry-out limitations; whereas the whole heat pipe performance requires the system analysis on thermal and fluid-flow conditions, which are related to the boundary and operating conditions. Based on these considerations and the heat transfer paths of both scales, the thermal resistance analyses can be carried out with respect to the evaporator region (local) and the whole heat pipe (global) system, respectively.

2.1. Modeling of thermal resistance for evaporator region

Since most of the complicated boiling/flow phenomena and operating limitations are related to the evaporator region, a simulated region circled by blue dash-lines of Fig. 1 can be assumed and analyzed. Chen et al. [7–9] tested the performance of micro channel wick structures via a evaporator test setup, as shown in the left portion of Fig. 2. In order to analyze the thermal resistance of the evaporator test setup, a total thermal resistance ($R_{th,tot}$) network was assumed and shown in the right portion of Fig. 2. The $R_{th,tot}$ can be expressed as follows:

$$R_{th,tot} = R_{th,heater} + R_{th,cont.} + R_{th,wall} + R_{th,wick} + R_{th,evap.} \quad (1)$$

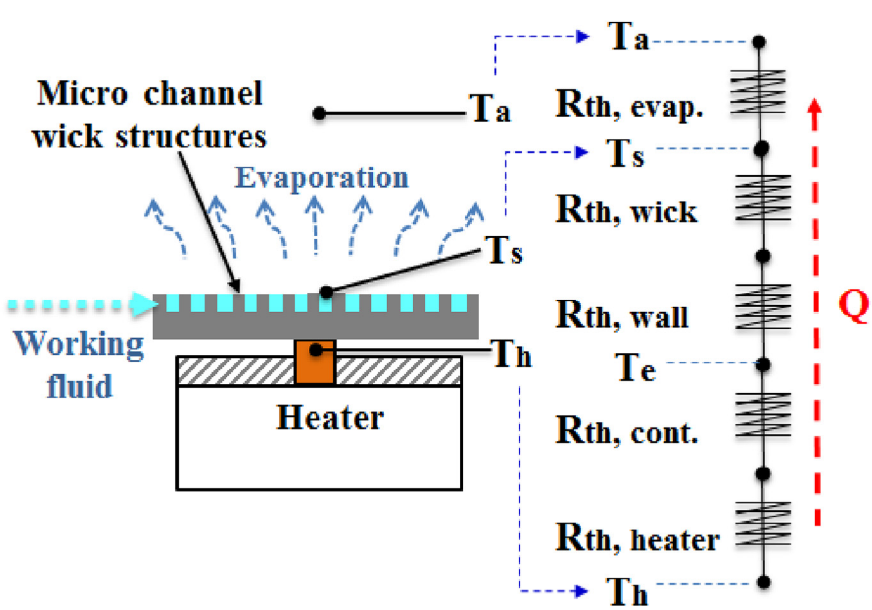

Fig. 2. Schematics of evaporator tests for micro channels and the thermal resistance network [7–9].