International Journal of Heat and Mass Transfer 78 (2014) 527–537

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Two-phase flow maldistribution in minichannel heat-sinks under non-uniform heating

Seok Ho Yoon [a], Navid Saneie [b], Yoon Jo Kim [b,*]

[a] Department of Advanced Thermal Systems, Korea Institute of Machinery and Materials, 305-343, South Korea
[b] Department of Mechanical Engineering, Washington State University, Vancouver, WA 98686, United States

ARTICLE INFO

Article history:
Received 31 October 2013
Received in revised form 4 July 2014
Accepted 6 July 2014
Available online 28 July 2014

Keywords:
Two-phase
Microchannel
Nonuniform heating
Maldistribution
Pin–fin
Hot-spot
Thermal management

ABSTRACT

In the present study, two-phase heat transfer characteristics in minichannel heat sinks under non-uniform heating were experimentally investigated. Pin–fin and strip-fin minichannel heat sinks were fabricated on a thin brass plate such that the channel dimensions were 25 mm wide × 26 mm long × 1 mm deep. 2 mm × 5 mm spot-heater was attached on the backside of the minichannel heat-sinks to simulate the non-uniform heating. The surface temperature distribution caused by the non-uniform heating was measured using the thermocouples attached on the 9 uniformly spaced locations of the minichannel heat-sinks. It was observed that the two dimensional expansion of vapor in the pin–fin minichannel heat-sink allowed improved distribution of vapor and thereby lower vapor quality. The temperature rises at the hot-spot locations was also significantly lower in the pin–fin minichannel heat-sink, which means pin–fin structure is more suitable for hot-spot cooling. The effects of mass flow rate and heat flux on heat transfer capability were explored and the total thermal resistances of the heat-sinks were also evaluated and discussed.

1. Introduction

Recent advances in semiconductor technologies have led to an increase in power density for high performance chips, such as microprocessors. According to the International Technology Roadmap for Semiconductors [1], these chips were expected to dissipate an average heat flux as high as 75 W/cm^2, with the maximum junction temperature not exceeding 85 °C, in 2012, while in 2024 the numbers are extremely challenging, 120 W/cm^2 and 70 °C, respectively [1]. Conventional chip packaging solutions, which use air-cooling, face difficulties in dissipating such high heat fluxes in the limited space allocated to thermal management.

Since the pioneering work of Tuckerman and Pease [2], great attentions have been given to investigations of heat transfer characteristics and heat removal capabilities of mini/microchannel heat-sinks. It has been widely acknowledged that mini/microchannel cooling is the most promising and viable thermal management solution for futuristic high power, high heat-flux microprocessors. Two-phase flow (phase-changing) in mini/microchannel heat-sinks can offer further enhancement in heat transfer coefficient, which is mainly attributed to the decreased thermal resistance through the thin liquid layer and the highly efficient interfacial heat transfer due to evaporation. Further, significant reduction of caloric thermal resistance is readily attainable by the constant temperature (latent) heat transfer during phase change. Two-phase heat transfer characteristics in various mini/microchannel configurations such as plain mini/microchannels [3–7], silicon microchannels [8–11], micro-gaps [12,13], pin–fin mini/microchannels [14–16], and fractal-like mini/microchannel networks [17,18] have been explored. According to Ebadian and Lin [19], the largest experimentally measured heat removal with two-phase mini/microchannel was 276 MW/cm^2 by Mudawar and Bowers [20] which evidently demonstrated the superior cooling capability of two-phase flow mini/microchannel heat-sink. Qu and Mudawar [3] reported experimentally measured heat transfer coefficients up to 13 W/cm^2 K, with which more than 500 W/cm^2 of cooling is feasible assuming the temperature difference between the fluid and junction temperature around 50 °C. Moreover, most of the predictive models [5,21–25] yield two-phase heat transfer coefficients of above 100 W/cm^2 K.

Kandlikar et al. [26] indicated, however, two general reasons of maldistribution in parallel mini/microchannels: (i) uneven local pressure distribution in the inlet/exit manifolds apparent at the channel entrance/exit, caused by the specific placement of the inlet/outlet pipes, fluid distribution in the headers, buoyancy

---

* Corresponding author. Address: Washington State University Vancouver, 14204 NE Salmon Creek Avenue, Vancouver, WA 98686-9600, United States. Tel.: +1 360 546 9184; fax: +1 360 546 9438.

E-mail address: yoonjo.kim@wsu.edu (Y.J. Kim).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.07.013
0017-9310/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature

A	Area [m^2]
Bo	Boiling number
G	mass flux [kg/m^2 s]
h	heat transfer coefficient [W/m^2 K]
i	specific enthalpy [J/kg]
k	thermal conductivity [W/m K]
$\dot{m}$	mass flow rate [kg/s]
L_f	fin height [m]
N_f	number of fins
P	power [W]
P_f	fin perimeter
q''	heat flux [W/m^2]
Q	heat transfer rate [W]
R	Thermal resistance [K/W]
t	thickness [m]
T	temperature [K]
U	overall heat transfer coefficient [W/m^2 K]
x	vapor quality

	Greek symbols
η_f	fin efficiency
η_o	overall surface efficiency [kg/s]
λ	latent heat [J/kg]

Subscripts	
avg	average
b	minichannel base
c	cross-section
cond	conduction
contact	contact
f	fin
fluid	fluid
hs	hot-spot
i	inlet
l	liquid
loss	loss
o	outlet
s	saturation
t	total
v	vapor

effects, two-phase separation and resultant flow non-uniformity, and (ii) uneven flow resistances in the parallel channels caused by variations in channel dimensions, different flow lengths, uneven fouling, density and viscosity variations, and presence of two or more phases. Normal hot-spot strengths from state-of-the-art microprocessors are ~100 W/cm^2, which can be in the excess of ~750 W/cm^2 in the near future [27]. Excessive consumption of liquid-phase by strong hot-spots results in significantly biased phase distribution; vapor-phase dominantly occupies the channels passing over hot-spots, while liquid-phase detours the hot-spot area; namely, 'phase separation' indispensably takes place [28]. The phase separation resulted from hot-spot causes the 'uneven flow resistances' in parallel mini/microchannels which will induce two-phase maldistribution.

Two-phase flow maldistribution greatly reduces both thermal and hydraulic performance in parallel mini/microchannels [29]; parallel channel heat exchangers typically, therefore, operate in the single phase regime to avoid such maldistribution instability [30]. While most of research efforts have been given to the inlet header (or manifold) maldistribution issues [29–32], Hetsroni et al. [33] experimentally observed the maldistribution due to non-uniform heating. They found that two-phase flow boiling heat transfer brought significant heat transfer enhancement as well as the irregularities in temperature and flow distributions caused by hydraulic instabilities. However, irregularities were drastically increased under non-uniform heating conditions. Cho et al. [34] tested four different types of two-phase microchannel heat sinks under the various heat flux conditions and reported severe irregularities in temperature and flow distributions under non-uniform heating conditions. Issacs et al. [35] tested two-phase staggered pin–fin microchannel and observed maldistribution induced by hydraulic instabilities but the generated vapor phase was quickly distributed transversely. Revellin et al. [36] also reported phase separation caused by hot-spots. They found that hot-spot strength over ~200 W/cm^2 (with the working fluid, R134a, saturation temperature of 30 °C, the corresponding chip temperature was not indicated but can presumably be ~85 °C) can cause dry-out at the hot-spot locations. Kim et al. [28] adopted Penryn power map (Intel Core 2 Duo processor), which has hot-spot strength up to ~300 W/cm^2, and conducted numerical analyses with single- and two-phase microchannel heat sinks for 3D stacked-IC cooling. They reported strong maldistribution caused by the non-uniform heating with the Penryn power map, which drastically increased pressure drop and thus degraded the cooling performance of the two-phase microchannel heat sink.

In the present study, the significance of hot-spot induced maldistribution is explored. Two-phase heat transfer characteristics and flow behaviors in plain minichannel and pin–fin minichannel are experimentally investigated and compared. Later, the plain minichannel will be referred as "strip-fin minichannel" in contrast to "pin–fin minichannel" to more clearly deliver the geometrical features and difference between the configurations. It is expected that the transverse flow motions allowed in pin–fin minichannel can contribute to mitigating the strong maldistribution and phase separation. Based on the flow visualization, it is discussed how the two-phase maldistribution affects two-phase heat transfer performance in minichannel heat sinks. Average heat transfer coefficients and thermal resistance are also measured using the low pressure refrigerant R245fa.

2. Experiment

2.1. Test section

To explore the effects of non-uniform heating, strip-fin and pin–fin minichannel heat sinks were fabricated and tested in the present study. As shown in Fig. 1, the minichannel heat sinks are composed of inlet manifold, minichannel array and outlet manifold. As described, geometry of manifold has influence on flow distribution inside micro/minichannels [37–40]. Kumaraguruparan et al. [37], in their experimental analysis, reported minor flow maldistributions of ±2% channel wise flow rate variation with water. However, when air was used as a working fluid, the maldistribution was severely signified with the ±40% channel wise normalized flow rate variation, whereas thick working fluid, ethylene glycol, effectively attenuated the maldistribution strength resulting in even more uniform flow distribution than water. Jones et al. [38] conducted both numerical and experimental analysis on maldistribution in microchannel. They showed that maldistribution was