Experimental Thermal and Fluid Science 79 (2016) 134–142

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Transient heat transfer characteristics of segmented finned microchannels

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ARTICLE INFO

Article history:
Received 3 February 2016
Received in revised form 3 July 2016
Accepted 3 July 2016
Available online 5 July 2016

Keywords:
Segmented microchannels
Transient heat transfer
Response time
Deionized water
Flow boiling

ABSTRACT

An experimental investigation has been carried out to study transient heat transfer characteristics of segmented finned microchannels during single-phase flow and flow boiling of coolant. Further heat transfer characteristics of segmented finned channels have been compared with those of uniform cross-section microchannels. Deionized water has been used as coolant. An array of microchannels consisting of 12 numbers of channels has been fabricated in each type of channel configuration. In each configuration, copper blocks of size $25.7 \times 12.02 \times 10\ \text{mm}^3$ have been used to fabricate microchannels of width 400 μm and depth of 750 μm with hydraulic diameter of 522 μm. Experiments have been performed for single-phase flow and flow boiling regimes with coolant mass flux (G) range of 100–350 $\text{kg/m}^2\,\text{s}$ and applied heat flux (q''_{eff}) range of 20–300 kW/m^2. Based on time required to reach steady state temperature, response time of each microchannel configuration has been estimated for different values of coolant mass flux and heat flux. A comparison of bubble growth behaviour in both types of channels has been presented. Coolant mass flux significantly affects the response time. During single-phase flow of coolant, response time decreases with increase in coolant mass flux, whereas response time increases with increase in coolant mass flux in flow boiling of coolant. Response time is less in flow boiling condition compared to single-phase flow of coolant. Segmented channels show less response time and enhanced heat transfer compared to uniform channels. Unhindered bubble growth phenomenon helps in reduction of response time in segmented channels.

1. Introduction

Compared to conventional or macrochannels, microchannels exhibit higher heat transfer rate because of their inherent properties of large surface to volume ratio. From the pioneering work of Tuckerman and Pease [1], microchannels have been widely explored as heat sinks for thermal management of electronic devices. Owing to integration of large number of components and enhanced functionality, heat generation in electronic devices has been increased exponentially during recent years leading to high temperature in devices. As per ITRS (International Technology Roadmap for Semiconductors) guidelines, junction temperature of semiconductors devices must be kept below 85 °C for safe working condition. Thus, proper cooling system is required for effective thermal management of electronic devices for both transient and steady state operation. Electronic devices have to perform various types of tasks and their power consumption and heat generation rate depend on the tasks and operation time. Moreover, environment conditions also affect the heat generation in electronic components. Majority of electronic devices like high-speed servers, processors and transistors operate for long time duration. Cooling systems for such devices mostly dissipate heat in steady state condition. On the other hand, several devices such as switching circuits, and devices used in space applications operate for short duration of time or their environment conditions change frequently. In addition, transient heat generation evolves during turning on or off and changing loads in electronic devices. During all these unsteady operations, heat generation in electronic devices as well as temperature of cooling system rapidly changes. It is obvious that when power is turned on, rate of increase in coolant temperature may not be significant and as time elapses, coolant temperature becomes constant as the system approaches steady state. Thus analysis of transient heat transfer behaviour is important for devices which operate for short duration of time or their environmental conditions changes frequently.

Extensive investigations [2–13] of flow and heat transfer characteristics in mini and microchannels are reported in literature.

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http://dx.doi.org/10.1016/j.expthermflusci.2016.07.004
0894-1777/

Nomenclature

A	area (mm^2)
c_p	specific heat (kJ/kg K)
D_h	hydraulic diameter of channel (mm)
G	coolant mass flux (kg/m^2 s)
H	depth of microchannels (mm)
h	heat transfer coefficient (W/m^2 K)
I	current (A)
L	length of copper block (m)
m	mass flow rate (kg/s)
N	number of microchannels
p	pressure (Pa)
Q	power input (W)
q''	heat flux (kW/m^2)
T	temperature (°C)
t	characteristic time (s)
t_r	response time (s)
W	total width of copper block (m)
w	width of microchannels (mm)
V	voltage (V)

Greek symbols

Δ	gradient (–)
θ	angle (°)
τ	time constant

Subscripts

c	channel
eff	effective
f	fluid
in	input
out	output
w	wall
max	maximum

These studies have analyzed flow patterns and heat transfer characteristics in microchannels both for single-phase flow and flow boiling of coolants. Several investigations have been made to estimate heat dissipation rate of microchannel heat sinks for various types of channel geometry, coolants and for wide range of applied heat flux, coolant flow rate, coolant subcooling, etc. [4–8]. These investigations have also discussed the formation of bubbles, their growth and clogging behaviour during flow boiling in microchannels [9,10]. Analysis of heat transfer and pressure drop characteristics in different flow regimes have also been reported [11]. In addition to experimental investigations, numerical models [12,13] have also been developed for investigating flow and heat transfer characteristics in microchannels. In all the above-mentioned investigations, heat transfer performance in microchannels has been essentially studied for steady state operation conditions. Kandlikar [14] has meticulously reviewed the complete historical background of flow boiling in microchannels considering all aspects of the problem. State of the art research, present status as well as future direction of research were highlighted in the coveted review paper. It was also briefly stated about the necessity of modeling transient nature in flow boiling, heat transfer and conjugating effect.

From literature review, it has been observed that compared to extensive investigations on steady state heat transfer characteristics little attention has been paid on transient heat transfer characteristics. In recent years, only few investigations have reported transient heat transfer characteristics in microchannels. Conti et al. [15] performed numerical investigation on transient heat transfer characteristics in rectangular microchannels for time dependent heat flux. They observed that response time i.e. time needed to reach steady state is smaller for sudden rise in heat flux compared to cooling i.e. switching off heater. Zhu et al. [16] numerically investigated the performance of thermoelectric cooler (TEC) for transient operation. They observed very low response time (in order of millisecond) for very small size of TEC. It was concluded that miniaturizing TECs could effectively enhance the cooling performance and shorten the response time. Kandasamy et al. [17] performed experimental and numerical investigation to examine the feasibility of phase change material (PCM) for thermal management of transient electronic devices. With inclusion of PCM, they observed the increase in response time. Rujano and Rahman [18] numerically investigated the effect of geometrical parameters on transient heat transfer in microchannels. Recently Rao et al. [19] have made experimental and numerical work on transient heat transfer in a single channel to present temperature fluctuation for different flow regimes. Zhang et al. [20] performed numerical and experimental investigation to study transient behaviour of microchip cooling system. They found that thermal capacity and thermal resistance were two critical parameters influencing response time and transient heat transfer. In all the above mentioned studies transient heat transfer characteristics have been investigated for uniform cross-section channels. Recently our group [6] and Law et al. [21] have observed better heat transfer performance of novel segmented finned microchannels compared to uniform and diverging cross-section channels for steady state flow boiling conditions. Law et al. [22] have also studied the different geometrical configurations of segmented channel and reported the pressure drop and heat transfer performance by varying oblique angles. They have observed that larger oblique angle favours the heat transfer enhancement whereas oblique angles have negligible effect on pressure fluctuation pattern.

The objective of present work is to investigate transient heat transfer characteristics in segmented finned microchannels and compare their performance with uniform cross-section microchannels.

2. Experimental set-up

An experimental setup is developed to perform flow boiling experiments in uniform and segmented microchannels. Complete flow loop consists of coolant reservoir, mini gear pump, flow meter, test section, collecting tank and data acquisition system as shown in Fig. 1.

Experiments have been performed in an open loop using deionized water as coolant. A mini gear pump (Make: Cole-Parmer, Model: WW-07012-02) collects coolant from liquid reservoir and circulates in the test loop. In order to reduce flow rate to test section, a bypass valve is used at the delivery of gear pump. A flow meter (make: Eureka, Model: SSRS MGS 5) is used to measure coolant flow rate in the loop. The range of flow meter is 2.4–120 ml/min. Flow meter has been calibrated by measuring volume flow rate through it and measuring in electronic weight balance. Accuracy level of flow meter is found as ±3%. After passing through flow meter, coolant enters to test channels module where it absorbs heat. Heated coolant after leaving test module is