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Experimental investigation of flow boiling performance in microchannels with and without triangular cavities – A comparative study

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ABSTRACT

Flow boiling in microchannel is a potential technology for the thermal management of high-heat flux microelectronic devices. A microchannel with triangular cavities (TC) is proposed for flow boiling enhancement in this work. Flow boiling experiments with high speed flow visualization are performed in the TC microchannel and the conventional rectangular (R) microchannel using pure acetone liquid as the working fluid. The bubble characteristics, heat transfer, pressure drop and wall temperature performances for the TC microchannel are investigated and compared with that for the R microchannel at inlet temperature of 29 °C and mass flux ranging from 83 to 442 kg/m^2 s. Moreover, the effects of mass flux and heat flux on the flow boiling performance are also studied. The experiment results show that the TC microchannel presents significant enhancement of heat transfer, obvious reduction of pressure drop, more stable and uniform wall temperature compared to the R microchannel. The triangular cavity configuration causes the enlargement of heat transfer area, the formation of developing liquid film, the increase of nucleation density and bubble departure. The novel micro heat sink obtains a high heat transfer coefficient with the increment as high as 9.88 and 1.55 times accompanied by a low pressure drop with 50.3% and 12.8% reduction compared to the R microchannel at $G = 83$ and 442 kg/m^2 s, respectively, which makes it more promising and efficient for microelectronic cooling.

1. Introduction

In recent years, the thermal management has become a crucial issue for electronic devices. Due to the integration and the miniaturization of the electronic components, the cooling requirement of the microelectronic devices increases rapidly, thus the conventional thermal management techniques are no longer effective. The microchannel heat sink has been considered as one of the promising solutions to meet the cooling demand due to its high surface area-to-volume ratio, large convective heat transfer coefficient and compact structure compared to the macrochannel. Comparing with the single-phase liquid flow, flow boiling in microchannel heat sinks has some attractive advantages, such as higher heat transfer coefficient, lower coolant flow rate and more uniform wall temperature. Therefore, flow boiling in microchannels is promising to meet the heat dissipation requirement in the field of microelectronics, advanced energy and power system, aerospace, etc. [1–5].

During the last few decades, a number of efforts have been dedicated to the conventional smooth/straight microchannels with different cross-sectional shapes including circular, rectangular, triangular and trapezoidal ones [6–9]. The results showed that the bubbles usually expanded to both upstream and downstream directions rapidly when boiling occurred in the smooth/straight microchannels. For a given mass flux, the reasons of the rapid bubble expansion in the smooth/straight microchannel are that (1) the smooth surface (small size of nucleation cavity) leads to a high wall superheat at the onset of nucleate boiling (ONB). The high wall temperature results in a high temperature of local liquid, which causes the extremely rapid bubble growth immediately after phase change; (2) the small hydraulic diameter limits the bubble growth in the radial direction, the vapor can only expand along the axial direction of the microchannel. Thus, the phenomena of inferior heat transfer performance, serious flow boiling instability and non uniform wall temperature usually occur in the conventional smooth/straight microchannels and need to be solved urgently.

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Nomenclature

A_c	total heat transfer area of the microchannel, m^2
A_{fin}	cross-section area of the interval fin, m^2
c_p	specific heat capacity, J/(kg K)
d	distance from film heater to channel bottom surface, m
G	mass flux, kg/m^2 s
h	heat transfer coefficient, W/(m^2 K)
H	height of the microchannel, m
I	current, A
L	length of the microchannel, m
m	fin parameter
$\dot{m}$	mass flow rate, kg/s
N	total number of the microchannels
p	pressure, Pa
Δp	pressure drop, Pa
P_{fin}	cross-section perimeter of interval fin, m
q	total input power, W
q_{eff}	effective heat dissipation, W
q_{loss}	heat loss, W
q''_{eff}	effective heat flux, W/m^2
t	time, s
T	temperature, K
w	width of a single microchannel, m
W	total width of microchannel region, m
Greek symbols	
η	fin efficiency
λ	thermal conductivity, W/(m K)
σ	standard deviation
Subscript	
ave	average
b	bottom
c	contraction
e	expansion
f	fluid
in	inlet
out	outlet
s	solid
sat	saturation temperature
w	wall
x	local
tp	two-phase

In order to understand the nucleation characteristics and enhance the boiling performance, a number of studies had been conducted to propose the nucleation criterion and predict the incipient heat flux for the ONB. Hsu [10] proposed that the cavity would get activated if the liquid temperature at the top of the bubble was at least equal to the saturation temperature of the vapor inside the bubble. The size of active nucleation cavities was associated with the subcooling, system pressure, physical properties and the thickness of the superheated liquid layer. Sato and Matsumara [11] studied the conditions of the incipient subcooled-boiling with forced convection and an analytical relationship between the incipient heat flux and the wall superheat was presented. The analytical results coincided with the experimental data at the atmospheric and high pressure. Kandlikar et al. [12] investigated the temperature at the stagnation point around the bubble numerically. The minimum temperature in the ONB criterion was given considering the effect of the contact angle. Liu et al. [13] studied the ONB in forced convective flow in a microchannel experimentally and an analytical model was developed which could predict the incipient heat flux as well as the bubble size at the onset of flow boiling depending on fluid inlet subcooling, wall boundary conditions and microchannel geometry. Kandlikar [14] focused the nucleation characteristics in microchannels and put forward the relationships between the local bulk subcooling and local wall superheat as a function of nucleation cavity diameter.

Due to the important influence of the boiling surface on the bubble generation process, the microchannel surface modification is a popular method to improve flow boiling performance [15–20]. Kandlikar et al. [15] studied the effect of pressure drop elements and artificial nucleation sites with diameters 5–30 μm on the flow boiling performance in microchannels. The artificial nucleation cavities in the microchannels were helpful to initiate nucleation at lower wall superheat. Kuo et al. [16,17] proposed microchannels with artificial nucleation microcavities on the channel sidewall. The mouth of the reentrant cavities is 7.5 μm and the inside diameter of the reentrant body is 50 μm based on the active nucleation size range proposed by Hsu [10]. The results indicated that the enhanced microchannels provided higher heat transfer rate, better wall temperature uniformity and more stable flow boiling as a result of the increased nucleation density. Deng et al. [18] compared the flow boiling performances in a microchannel with unique Ω-shaped reentrant and the conventional rectangular microchannel. The novel microchannel presented significant heat transfer enhancement associated with the pressure drop reduction due to the uniform liquid film distribution in the circular cavities. In a subsequent study, they fabricated porous microchannel with the same Ω-shaped reentrant configurations [19]. They found that the porous microchannel was able to reduce the wall superheat at the ONB. Bai et al. [20] experimentally investigated the flow boiling characteristics in porous-coated microchannels. The results showed that the microchannels with porous coating achieved significant enhancement of flow boiling performance compared to the bare microchannel. As stated above, the main reason of the boiling heat transfer enhancement for the surface alteration is the increase of nucleate site.

Another effective flow boiling enhancement method is to modify the flow passages of the microchannel [21–32]. The expanding microchannel was one of the enhanced microchannels, which could be divided into the microchannels with increased height [21,22] and the microchannels with increased width [23,24]. The increased cross-sectional area promoted the vapor growth in spanwise and downstream direction instead of the upstream direction, which mitigated the flow boiling instability obviously. The microchannel with single row of micro pin fins, proposed by Krishnamurthy et al. [25], presented significant heat transfer enhancement due to the increased heat transfer area, the disturbed boundary layer and the intensified convective mixing. Deng et al. [26] proposed a novel microchannel with micro pin fins on the bottom surface. The structured microchannel presented obvious heat transfer enhancement and mitigating two-phase flow instability by producing lots of tiny reentrant cavities and introducing significant wicking effect. Some novel micro heat sinks can achieve high heat transfer coefficient by combining two or more mechanisms of flow boiling enhancement. The cross-linked microchannel was able to achieve uniform temperature distribution as well as high heat transfer coefficient [27,28]. The transverse microchannels provided more nucleation sites, established “communication” between neighbouring channels to offer more space for vapor expansion and fluid mixing. Based on the similar mechanism, Zhang et al. [29] conducted a series of experiments to study the flow boiling