Contents lists available at ScienceDirect



International Journal of Heat and Mass Transfer

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

Flow boiling characteristics in porous heat sink with reentrant microchannels



IEAT and M

Daxiang Deng^{a,b,*}, Yong Tang^a, Dejie Liang^a, Hao He^a, Song Yang^a

^a Key Laboratory of Surface Functional Structure Manufacturing of Guangdong High Education Institutes, School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510640, China

^b Department of Mechanical & Electrical Engineering, Xiamen University, Xiamen 361005, China

ARTICLE INFO

Article history: Received 8 March 2012 Received in revised form 23 October 2013 Accepted 24 October 2013 Available online 5 December 2013

Keywords: Microchannels Reentrant Flow boiling Porous heat sink Flow instabilities

ABSTRACT

A novel porous heat sink with reentrant microchannels has been developed by traditional sintering fabrication method. It features 14 parallel Ω -shaped reentrant microchannels with a hydraulic diameter of 786 µm. Two-phase boiling heat transfer performance of the reentrant porous microchannels (RPM) was evaluated to explore the feasibility of the enhancement and application in heat sink cooling. Using deionized water as coolant, flow boiling tests were conducted at the inlet temperature of 33, 60 and 90 °C, mass flux of 125–300 kg/m² s. Comparisons with solid copper microchannels of the same reentrant configuration were performed, and the test results show that the reentrant porous microchannels presented a significant decrease of the wall superheat for the boiling incipience, delay and mitigation of two-phase flow instabilities, and 2–5 folds enhancement in two-phase heat transfer coefficient at low to moderate heat fluxes. It was also found that during the flow boiling of the reentrant porous microchannels, nucleation boiling governed the heat transfer mechanism at low heat fluxes and vapor quality, while forced convective boiling associated with thin film evaporation dominated at moderate to high heat fluxes. Furthermore, the two-phase flow instabilities characteristics were also accessed for the reentrant porous microchannels.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

With high heat dissipation capacity for electric and aerospace systems, microchannels has been widely utilized in two-phase heat transfer devices such as heat sinks, micro heat exchangers, heat pipes and jet impingement cooling systems [1]. Classic microchannels are of circular (micro tubes) or rectangular shapes, which have been intensively investigated in the last three decades [2,3]. Other kinds of microchannels have been seen in the literatures with triangular [4,5], trapezoidal [6], diverging [7], and fractal tree-like [8] shape. Though there are still many challenges for the studies within the current types of microchannels, researchers in the heat transfer community are ready to develop more sophisticated ones. Microchannels with micro-pin fins [9,10], carbon nanotube coating [11], drilling holes on the bottom surface as artificial nucleation sites [12] has been developed, and enhanced two-phase heat transfer [9,11] or moderation of wo-phase flow instability [12] were reached.

Besides of the aforementioned means, microchannel with reentrant cavities is another good choice. As a matter of fact, reentrant cavities has been widely used in the outside finned tubes of heat exchangers, such as the Gewa-T tubes [13] and Thermoexcle-E tubes [14], since Benjamin and Westwater [15] in 1961 demonstrated their superior performance as a vapor trap during nucleate boiling. It was widely accepted that the reentrant cavities enhanced pool boiling heat transfer with the decrease of wall superheat and the increase of stable nucleation sites, which were demonstrated repeatedly by Ayub and Bergles [13], Chien and Webb [14], Chen et al. [16] and recently, Das et al. [17]. Moreover, reentrant channels exhibit a prominent performance in high capacity Ω -shaped grooved heat pipes [18,19], which combines a high capillary pumping pressure with a low axial pressure drop, and minimize the retardation of liquid flow induced by the countercurrent vapor flow. The superior performance of reentrant cavities can be also extended to microchannel heat sinks. Goyal et al. [20] investigated a silicon reentrant cavity heat sink by etching and bonding process for enhanced liquid cooling of silicon multichip substances. Boiling tests indicated that reentrant cavities suppress the temperature overshoot of transition between free convective to nucleate boiling. Boer et al. [21] fabricated parallel reentrant microchannels in silicon wafers by buried channel technology, which employs complicated MEMS procedures. The reentrant microchannel heat sink can be easily integrated with electronic

^{*} Corresponding author. Tel.: +86 592 2186926; fax: +86 592 2186383. *E-mail address:* dengdaxiang88@gmail.com (D. Deng).

^{0017-9310/\$ -} see front matter 0 2013 Elsevier Ltd. All rights reserved. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.10.057

Nomenclature

A_{ch} A_t total heat transfer area of microchannels, m^2 P_t R_{hs} P_{port} conductive thermal resistance in heat sink, C/W R_{por} A_{ch} $CHFplatform area of copper block, m^2P_{pr}R_{por}specific heat of fluid, k/k/gR_{por}conductive thermal resistance of reentrant porousmicrochannels, C/WC_{P}P_{pr}specific heat of fluid, k/k/gR_{teil}R_{total}total thermal resistance along the heat conductiondirection, C/WM_{ceil}H_{ceil}height of unit cell, mmH_{ceil}T_{tot}total fluid temperature, CH_{reil}H_{slot}height of sincrochannels heat sink, mmH_{slot}T_{tot}H_{tot}T_{tot}H_{tot}H_{rot}H_{slot}height of sincred porous powder, mmR_{tot}T_{satxci}H_{satxci}V_{total lic almeret area, CH_{rot}H_{rot}h_{p}local two-phase heat transfer coefficient, kW/m^2 KKthermal conductivity of fooper block, W/m KK_{cu}thermal conductivity of fluid, W/m KK_{cu}W_{cu}Width of heat sink, mmK_{cu}k_{t}thermal conductivity of solder paste, W/m KLlength of heat sink, mmL_{total}Greek symbols\epsilone porosity\mudistance between the thermocouple coation in thestream-wise direction, mM_{tot}Greek symbols\epsilone porosityR_{total}R_{total}R_{total}R_{total}Greek symbols\epsilone porosityR_{total}R_{total}R_{total}R_{total}R_{total}R_{total}R_{total}R_{total}$
A_t CHFplatform area of copper block, m^2 critical heat flux, kW/m^2 G_p specific heat of fluid, kJ/kg k d powder particle diameter, um R_{por} conductive thermal resistance of reentrant porous microchannels, $^{\circ}C/W$ D_h height of mit cell, mm T_{rci} total thermal resistance along the heat conduction direction, $^{\circ}C/W$ D_h height of microchannels heat sink, mm T_{rci} total thermarure, $^{\circ}C$ H_{heil} height of slot, mm T_{rci} total thermarure, $^{\circ}C$ H_{hst} height of slot, mm T_{out} outlet fluid temperature, $^{\circ}C$ H_{wit} thickness of plastic cover plate, mm H_{wit} thermal conductivity, M/K $T_{sat,tci}$ tocal two-phase heat transfer coefficient, $kW/m^2 K$ K permeability of sintered porous powder, mm2 k thermal conductivity of copper block, $W/m K$ K_r thermal conductivity of fluid, $W/m K$ K_r thermal conductivity of fluid, $W/m K$ K_r thermal conductivity of solder paste, $W/m K$ L length of heat sink, mm L_i distance between the thermocouple location in the stream-wise direction, m1 L_u distance between the thermocouple and the top surface of copper block, m $Greek symbols$ ε porosity μ density of fluid, Kg/m^3 m fin parameter m mfin parameter m m mmin fin parameter m m mSubscripts cell cell unit cell cricular portion of reentrant microchannels corcular portion o
CHFcritical heat flux, kW/m²microchannels, °C/W C_p specific heat of fluid, kJ/kg kmicrochannels, °C/W C_p specific heat of fluid, kJ/kg k K_{total} D_h hydraulic diameter, um T_{total} D_h hydraulic diameter, um T_{tot} D_h hydraulic diameter, um T_{tot} H_{effl} height of nicrochannels heat sink, mm T_{out} H_{slot} height of slot, mm T_{out} H_{slot} height of slot, cover plate, mm $T_{satteri}$ H_{w1} thickness of plastic cover plate, mm $T_{satteri}$ h_{rp} local two-phase heat transfer coefficient, kW/m² Kt K permeability of sintered porous powder, mm² u K_cu thermal conductivity, Wm KW K_{cu} thermal conductivity of copper block, W/m K W_{cell} k_{rem} thermal conductivity of fluid, Wm K W_{inn} k_{por} thermal conductivity of solder paste, W/m K L_{l} distance between the thermocouple location in the stream-wise direction, m $Greek symbols$ ϵ L_{l} distance between heat sink bottom surface and the bottom of circular portion of reentrant microchannels $Greek symbols$ ϵ R_{rot} minometer $Greek symbols$ ϵ R_{rot} greet sprethret $Greek symbols$ ϵ R_{rot} distance between heat sink bottom surface and the bottom of circular portion of reentrant microchannels R_{rot} min fin parameter $Greek symbols$ R
$ \begin{array}{llllllllllllllllllllllllllllllllllll$
dpowder particle diameter, umdirection, °C/W D_h hydraulic diameter, mm T_{rei} thermocouple reading (i = 1~5), °C H_{cell} height of unit cell, mm T_{in} inlet fluid temperature, °C H_{hs} height of slot, mm T_{out} outlet fluid temperature, °C H_{slot} height of vaporization, k//kg T_{sattci} channel bottom wall temperature, °C H_{w1} thickness of plastic cover plate, mm T_{sattci} local sturation temperature, °C h_{fg} latent heat of vaporization, k//kg T_{sattci} local sturation temperature, °C h_{fg} latent heat of vaporization, k//kg T_{sattci} local sturation temperature, °C h_{cp} local two-phase heat transfer coefficient, kW/m² K k_s thickness of solder paste, m k thermal conductivity of sopper block, W/m K W width of heat sink unit cell, mm k_{cu} thermal conductivity of fluid, W/m K W_{cell} k_{f} thermal conductivity of solder paste, W/m K W_{slot} L_i length of heat sink, mm $Creek symbols$ L_i distance between the thermocouple location in the stream-wise direction, m μ k_s distance between the thermocouple and the top surface of copper block, m μ n fin afficiency ρ h_{sh} distance between the thermocouple and the top surface of copper block, m μ h_s distance between the thermocouple and the top surface of copper block, m μ n fin afficiency
$ \begin{array}{llllllllllllllllllllllllllllllllllll$
$\begin{array}{cccccccccccccccccccccccccccccccccccc$
Then hight of microchannels heat sink, mmTout T_{wtci} outlet fluid temperature, °C T_{wtci} H_{slot} height of slot, mm T_{out} outlet fluid temperature, °C H_{slot} height of slot, mm T_{wtci} channel bottom wall temperature, °C H_{w1} thickness of plastic cover plate, mm $T_{sat,tci}$ isluperheat, °C h_{fg} latent heat of vaporization, kJ/kg $T_{sat,tci}$ local saturation temperature, °C h_{fp} local two-phase heat transfer coefficient, kW/m² K $T_{sat,tci}$ local saturation temperature, °C K permeability of sintered porous powder, mm² u flow velocity of fluid, m/s k thermal conductivity of copper block, W/m K W width of heat sink, mm k_{cu} thermal conductivity of rentrant porous W_{fn} width of flom between two reentrant microchannels, mm k_{por} thermal conductivity of solder paste, W/m K W_{fn} width of slot, mm k_s thermal conductivity of solder paste, W/m K W_{slot} width of slot, mm L_i distance from the inlet to thermocouple location in the
$ \begin{array}{llllllllllllllllllllllllllllllllllll$
$\begin{array}{llllllllllllllllllllllllllllllllllll$
hr_{pp} local two-phase field thanker conflicting ky/m k t_s information of the set in the field of the set in the set i
kpermeability of sintered portors powder, minanow velocity of nuid, m/skthermal conductivity, W/m KWwidth of heat sink, mmkcuthermal conductivity of copper block, W/m KWwidth of heat sink unit cell, mmkrthermal conductivity of fluid, W/m KWwidth of slot, mmkporthermal conductivity of reentrant porousWwidth of slot, mmmicrochannels, W/m KKWwidth of slot, mmksthermal conductivity of solder paste, W/m KKKLlength of heat sink, mmGreek symbolsLidistance from the inlet to thermocouple location in the stream-wise direction, mFlcudistance between the thermocouple and the top surface of copper block, m ρ density of fluid, N s/m²lnsdistance between heat sink bottom surface and the bottom of circular portion of reentrant cavity, m η fin efficiencymfin parameterSubscriptscellunit cell circircular portionNnumber of reentrant microchannelsCucopperNnumber of reentrant microchannelsCu <t< td=""></t<>
kInternal conductivity, w/m Kwwidth of meat sink, mm k_{cu} thermal conductivity of copper block, W/m K W_{cell} width of fin between two reentrant microchannels, mm k_{por} thermal conductivity of reentrant porous microchannels, W/m Kwidth of slot, mm k_{por} thermal conductivity of solder paste, W/m K W_{slot} L length of heat sink, mm x L length of heat sink, mm $Greek symbols$ L_i distance from the inlet to thermocouple location in the stream-wise direction, m $Greek symbols$ l_{cu} distance between the thermocouple and the top surface of copper block, m μ d_{lance} between heat sink bottom surface and the bottom of circular portion of reentrant cavity, m η m fin parameter mSubscripts cell m mass flow rate, (kg/s)Subscripts cell N number of reentrant microchannelscell N number of reentrant microchannelscu ONB onset of nucleation boilingCu P_{cir} perimeter of circular portion of reentrant microchannel, m
k_{cu} thermal conductivity of copper block, w/m K W_{cell} width of finear sink min cent, min k_{por} thermal conductivity of fluid, W/m K W_{fin} width of fin between two reentrant microchannels, mm k_{por} thermal conductivity of reentrant porouswidth of fin between two reentrant microchannels, mm k_{s} thermal conductivity of solder paste, W/m Kwidth of fin between two reentrant microchannels, mm L_i length of heat sink, mm K_s L_i distance from the inlet to thermocouple location in the stream-wise direction, m $Greek symbols$ l_{cu} distance between the thermocouple and the top surface of copper block, m $Greek symbols$ l_{cu} distance between heat sink bottom surface and the bottom of circular portion of reentrant cavity, m μ m fin parameter m mass flow rate, (kg/s) $Subscripts$ cell unit cell cir N number of reentrant microchannelscult copper h_s $Cult copper$ hs P_{cir} perimeter of circular portion of reentrant microchannel, m h_s $h_{eat} sink$
k_{f} thermal conductivity of rentrant porous microchannels, W/m K W_{fin} Width of min between two reentrant microchannels, min width of slot, mm x k_{por} thermal conductivity of reentrant porous microchannels, W/m K W_{slot} width of slot, mm x k_s thermal conductivity of solder paste, W/m K L length of heat sink, mm $Greek symbols$ L_i distance from the inlet to thermocouple location in the stream-wise direction, m $Greek symbols$ l_{Cu} distance between the thermocouple and the top surface of copper block, m μ dynamic viscosity of fluid, N s/m² l_{hs} distance between heat sink bottom surface and the bottom of circular portion of reentrant cavity, m ρ density of fluid, kg/m³ m fin parameter mSubscripts cell unit cell cir perimeter of circular portion of reentrant microchannelsCu ONB onset of nucleation boiling P_{cir} Cucopper heat sink P_{cir} perimeter of circular portion of reentrant microchannel, mhs h_{ext} heat sink M function from the inter of circular portion of reentrant microchannel, mfin efficiency h_{ext} copper h_{ext} function from the inter of circular portion of reentrant microchannel, mfin efficiency h_{ext} function from the inter of circular portion of reentrant microchannel, mfin efficiency circular portion h_{ext} function from the inter of circular portion of reentrant microchannel, hsfin efficiency circ
k_{por} thermal conductivity of reentrant porous W_{slot} Width of slot, film $microchannels, W/m K$ x thermodynamic quality k_s thermal conductivity of solder paste, W/m K x L length of heat sink, mm $Greek symbols$ L_i distance from the inlet to thermocouple location in the stream-wise direction, m μ l_{cu} distance between the thermocouple and the top surface of copper block, m μ l_{cu} distance between the thermocouple and the top surface of copper block, m η l_{hs} distance between heat sink bottom surface and the bottom of circular portion of reentrant cavity, m μ $dustrophysicaldensity of fluid, kg/m3mfin parametermass flow rate, (kg/s)Subscriptscellunit cellcirperimeter of circular portion of reentrant microchannelsCuONBonset of nucleation boilingP_{cir}Cucopperheat sinkmfin efficiencyCuCumh_sheat sinkh_sh_sheat sinkh_sheat sink$
$\begin{array}{cccc} & \text{interformatives, w/m k} & x & \text{intermodynamic quarty} \\ k_{s} & \text{thermal conductivity of solder paste, W/m K} \\ L & \text{length of heat sink, mm} & Greek symbols \\ L_{i} & \text{distance from the inlet to thermocouple location in the stream-wise direction, m} & \mu & \text{dynamic viscosity of fluid, N s/m}^2 \\ l_{cu} & \text{distance between the thermocouple and the top surface of copper block, m} & \mu & \text{dynamic viscosity of fluid, N s/m}^2 \\ l_{hs} & \text{distance between heat sink bottom surface and the bottom of circular portion of reentrant cavity, m} \\ m & \text{fin parameter} & Subscripts \\ m & \text{mass flow rate, (kg/s)} & \text{cell unit cell} \\ N & \text{number of reentrant microchannels} & \text{cust copper} & \text{fin early} \\ N & \text{number of reentrant microchannels} & \text{fin early} & \text{fin early} \\ P_{cir} & \text{perimeter of circular portion of reentrant microchannel,} \\ m & \text{m} & \text{fin constant of circular portion of reentrant microchannel,} \\ m & \text{m} & \text{fin constant portion of reentrant microchannel,} \\ N & \text{m} & \text{fin constant portion of reentrant microchannel,} \\ P_{cir} & \text{perimeter of circular portion of reentrant microchannel,} \\ m & \text{m} & \text{fin constant portion of reentrant microchannel,} \\ m & \text{m} & \text{fin constant portion of reentrant microchannel,} \\ m & \text{m} & \text{fin constant portion of reentrant microchannel,} \\ m & \text{m} & \text{fin constant portion of reentrant microchannel,} \\ m & \text{m} & \text{fin constant portion of reentrant microchannel,} \\ m & \text{m} & \text{fin constant portion of reentrant microchannel,} \\ m & \text{m} & \text{fin constant portion of reentrant microchannel,} \\ m & \text{m} & \text{fin constant portion of reentrant microchannel,} \\ m & \text{m} & \text{fin constant portion of reentrant microchannel,} \\ m & \text{m} & \text{fin constant portion of reentrant microchannel,} \\ m & \text{m} & \text{fin constant portion of reentrant microchannel,} \\ m & \text{m} & \text{m} & \text{fin constant portion of reentrant microchannel,} \\ m & \text{m} & \text{m} & \text{m} & \text{fin constant portion of reentrant microchannel,} \\ m & \text{m} & \text{m} & \text{m} & \text{m} & \text{m} & \text{m} & \text$
k_s thermal conductivity of solder paste, W/m K L length of heat sink, mm $Greek symbols$ L_i distance from the inlet to thermocouple location in the stream-wise direction, m ω l_{cu} distance between the thermocouple and the top surface of copper block, m μ l_{cu} distance between the thermocouple and the top surface of copper block, m μ l_{hs} distance between heat sink bottom surface and the bottom of circular portion of reentrant cavity, m η m fin parameter mass flow rate, (kg/s) $Subscripts$ cell cir N number of reentrant microchannels $cirONBonset of nucleation boilingCucopperP_{cir}perimeter of circular portion of reentrant microchannel,mhsheat sinkheat sink$
Llength of near sink, mmGreek symbols L_i distance from the inlet to thermocouple location in the stream-wise direction, m ω ω l_{cu} distance between the thermocouple and the top surface of copper block, m μ dynamic viscosity of fluid, N s/m² l_{hs} distance between heat sink bottom surface and the bottom of circular portion of reentrant cavity, m η fin efficiency m fin parameter ρ density of fluid, kg/m³ m fin parameter $cell$ unit cell N number of reentrant microchannelscircircular portionONBonset of nucleation boilingCucopper P_{cir} perimeter of circular portion of reentrant microchannel, m h_s heat sink
L_i distance from the linet to thermocouple location in the stream-wise direction, m ε porosity l_{cu} distance between the thermocouple and the top surface of copper block, m μ dynamic viscosity of fluid, N s/m² l_{hs} distance between heat sink bottom surface and the bottom of circular portion of reentrant cavity, m η fin efficiency m fin parameter ρ density of fluid, kg/m³ m since between heat sink bottom surface and the bottom of circular portion of reentrant cavity, m ρ m fin parameterSubscripts m mass flow rate, (kg/s)cell N number of reentrant microchannelscir ONB onset of nucleation boiling Cu P_{cir} perimeter of circular portion of reentrant microchannel, m
$\begin{array}{ccc} & \text{stream-wise direction, m} & \mu & \text{dynamic viscosity of fluid, N s/m}^2 \\ l_{\text{Cu}} & \text{distance between the thermocouple and the top surface} & of copper block, m & \eta & \text{fin efficiency} \\ h_{\text{hs}} & \text{distance between heat sink bottom surface and the} & bottom of circular portion of reentrant cavity, m & m & \text{fin parameter} \\ \dot{m} & \text{mass flow rate, (kg/s)} & \text{cell} & \text{unit cell} \\ N & \text{number of reentrant microchannels} & \text{circular portion} \\ ONB & \text{onset of nucleation boiling} & Cu & \text{copper} \\ P_{\text{cir}} & \text{perimeter of circular portion of reentrant microchannel,} \\ m & \text{m} & \text{fin parameter} \\ P_{\text{circular portion of reentrant microchannel,} \\ m & \text{m} & \text{fin parameter} & \text{subscripts} \\ \hline ONB & \text{onset of nucleation boiling} & Cu & \text{copper} \\ P_{\text{circular portion of reentrant microchannel,} \\ m & \text{m} & \text{fin parameter} & \text{fin efficiency} \\ \hline ONB & \text{onset of nucleation boiling} & Cu & \text{copper} \\ \hline ONB & \text{onset of nucleation portion of reentrant microchannel,} \\ \hline M & \text{m} & \text{fin parameter} & \text{fin efficiency} \\ \hline ONB & \text{onset of nucleation boiling} & Cu & \text{copper} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ \hline ONB & \text{onset of nucleation boiling} & Cu & \text{copper} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ \hline ONB & \text{fin efficiency} & \text{fin efficiency} \\ $
$\begin{array}{ccc} l_{Cu} & distance between the thermocouple and the top surface \\ of copper block, m & \eta & fin efficiency \\ l_{hs} & distance between heat sink bottom surface and the bottom of circular portion of reentrant cavity, m \\ m & fin parameter & Subscripts \\ \dot{m} & mass flow rate, (kg/s) & cell & unit cell \\ N & number of reentrant microchannels & cir & circular portion \\ ONB & onset of nucleation boiling & Cu & copper \\ P_{cir} & perimeter of circular portion of reentrant microchannel, \\ m & m & fin parameter & fin parameter & fin parameter & cir & circular portion \\ ONB & onset of nucleation boiling & Cu & copper \\ P_{cir} & perimeter of circular portion of reentrant microchannel, \\ m & m & fin parameter & fin parameter & fin parameter & fin parameter & circular portion & circul$
of copper block, m η fin efficiency l_{hs} distance between heat sink bottom surface and the bottom of circular portion of reentrant cavity, m η fin efficiency density of fluid, kg/m³mfin parameterSubscripts \dot{m} mass flow rate, (kg/s)cellunit cellNnumber of reentrant microchannelscircircular portionONBonset of nucleation boilingCucopper P_{cir} perimeter of circular portion of reentrant microchannel, m h_{s} heat sinkmfin efficiency h_{s} heat sink
l_{hs} distance between heat sink bottom surface and the bottom of circular portion of reentrant cavity, m ρ density of fluid, kg/m³ m fin parameterSubscripts \dot{m} mass flow rate, (kg/s)cellunit cell N number of reentrant microchannelscircircular portionONBonset of nucleation boilingCucopper P_{cir} perimeter of circular portion of reentrant microchannel,hsheat sinkmfunctional sinkfunctional sinkfunctional sink
bottom of circular portion of reentrant cavity, mmfin parameterSubscriptsmmass flow rate, (kg/s)cellunit cellNnumber of reentrant microchannelscircircular portionONBonset of nucleation boilingCucopperP_cirperimeter of circular portion of reentrant microchannel, mfin beat sink
mfin parameterSubscriptsmmass flow rate, (kg/s)cellunit cellNnumber of reentrant microchannelscircircular portionONBonset of nucleation boilingCucopperP_cirperimeter of circular portion of reentrant microchannel, mKheat sink
mmass flow rate, (kg/s)cellunit cellNnumber of reentrant microchannelscircircular portionONBonset of nucleation boilingCucopperP_cirperimeter of circular portion of reentrant microchannel, mhsheat sink
N number of reentrant microchannels cir circular portion ONB onset of nucleation boiling Cu copper P _{cir} perimeter of circular portion of reentrant microchannel, hs heat sink m For the sink For the sink
ONBonset of nucleation boilingCucopperPcirperimeter of circular portion of reentrant microchannel, mCucopperhsheat sinkhsheat sink
P _{cir} perimeter of circular portion of reentrant microchannel, hs heat sink
m Gran Gran
$q_{\rm eff}$ effective heat power, W i thermocouple location
$q_{\rm in}$ total power input, W in inlet
$q_{\rm loss}$ heat loss, W out outlet
$q_{\rm eff}^{\prime\prime}$ effective heat flux, kW/m ² por porous
<i>Ra</i> surface roughness, um
RPM reentrant porous microchannels sat saturation
RCM reentrant copper microchannels slot slot
$R_{\rm Cu}$ conductive thermal resistance in copper block, (°C/W) total total
$R_{\rm s}$ thermal resistance of solder layer, (°C/W) the two-phase
the two huge

circuits for forced cooling. Also utilizing MEMS fabrication methods, Peles et al. [22–24] conducted several consecutive researches on flow boiling in rectangular silicon microchannels with interconnected and nonconnected reentrant cavities on the side wall. Compared to the plain-wall microchannels, the microchannels with nonconnected reentrant cavities [23] exhibited significant reduction in the wall superheat of boiling incipience and more consistent and reproducible bubble formation. The flow instabilities were also suppressed [24]. The critical heat flux was enhanced significantly to 643 W/cm² in the mass velocities of 303 kg/m² with deionized water as coolants.

Similarly as aforementioned reentrant cavities in metal or silicon substrates, sintered porous channels have been also found to be promising for the application in heat sink cooling. For porous heat sink, the enhancement of single-phase convective heat transfer was demonstrated repeatedly, such as Jiang et al. [25], Tzeng and Ma [26], Hetsroni et al. [27]. It also enhanced two-phase boiling heat transfer thanks to the significant increase of the solidfluid contact area, which was early demonstrated by Peterson and Chang [28]. The flow boiling experiments of Ammerman and You [29] shows that, for a small rectangular channel with diamond powder porous coating, boiling initiated at lower wall superheats; both heat transfer coefficients and CHF level increased compared to the uncoated channels. The enhancement of porous coating was attributed to the considerable increase of nucleation sites and bubble departure frequency. Recent works by Sun et al. [30] revealed that by using sintered porous surface in a rectangular minichannel, the heat transfer coefficients can be up to 2.7 times of the smooth surface value in subcooled flow boiling and 3 times in saturated flow boiling.

It is worth to mention that the regular packed and porous channels for heat sink need more pump power, and sometimes introduce worse heat transfer performance at high heat flux, which has been pointed out by Rainey et al. [31]. Since the counterflow of liquid and vapor happens in the same pores of porous matrix, it give rise to higher pressure losses, hinders the download of liquid towards the heated surface and results in earlier transition from nucleate boiling to film boiling. Existence of some open small paths in sintered porous channel is helpful for the separate flow of two phases in porous structures, which is analyzed and experimentally studied in pool boiling conditions by Stubos and Buchlin [32], Liter and Kaviany [33]. These merits of porous channels with open paths

Download English Version:

https://daneshyari.com/en/article/657611

Download Persian Version:

https://daneshyari.com/article/657611

Daneshyari.com