International Journal of Heat and Mass Transfer 126 (2018) 401–413

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Heat transfer correlations for jet impingement boiling over micro-pin-finned surface

Yonghai Zhang [a], Bin Liu [a], Jinjia Wei [a,b,*], Bengt Sundén [c], Zan Wu [c]

[a] School of Chemical Engineering and Technology, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, PR China
[b] Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, PR China
[c] Solid State Physics and NanoLund, Lund University, Box 118, SE-22100 Lund, Sweden

ARTICLE INFO

Article history:
Received 2 January 2018
Received in revised form 12 April 2018
Accepted 29 April 2018

Keywords:
Jet impingement
Heat transfer enhancement
FC-72
Micro-pin-fins
Correlations

ABSTRACT

Heat transfer performance of submerged jet impingement boiling over staggered micro-pin-finned surfaces was investigated using air-dissolved FC-72. The dimension of the silicon chips is $10 \times 10 \times 0.5\ \text{mm}^3$ (length × width × thickness) on staggered micro-pin-fins with four dimensions of $30 \times 30 \times 60\ \mu\text{m}^3$, $50 \times 50 \times 60\ \mu\text{m}^3$, $30 \times 30 \times 120\ \mu\text{m}^3$ and $50 \times 50 \times 120\ \mu\text{m}^3$ (width × thickness × height, named S-PF30-60, S-PF50-60, S-PF30-120, and S-PF50-120) were fabricated by using the dry etching technique. The effects of micro-pin-fins, jet-to-target distance (H = 3, 6, and 9 mm), and jet Reynolds number (Re = 2853, 5707, and 8560) on jet impingement boiling heat transfer performance were explored. For comparison, experiments with jet impinging on a smooth surface were also conducted. The results showed that all micro-pin-finned surfaces show better heat transfer performance than that of a smooth surface. The largest Nusselt number is 1367, corresponding to a heat transfer coefficient of 26387 $\text{W·m}^{-2}\text{·K}^{-1}$ with S-PF30-120 at Re = 8560, H/d = 2, and q = 151 W·cm^{-2}, which is approximately twice the largest Nusselt number of Chip S. In the single-phase heat-transfer-dominant region, the Nusselt number (Nu) is mainly influenced by several dimensionless numbers, including Reynolds number (Re), boiling number (Bo), the ratio of jet-to-target distance to jet diameter (H/d), the ratio of micro-pin-finned surface area to smooth surface area A/A_S, and a dimensionless number corresponding to flow resistance D_h/L_h. Correlations to predict Nu in both single-phase heat-transfer-dominant region and two-phase heat-transfer-dominant region for smooth and micro-pin-finned surfaces were proposed. The results show that most data (96%) in the single-phase heat-transfer-dominant region and most data (96%) in the two-phase heat-transfer-dominant region were predicted within ±13% and ±15%, respectively. In addition, CHF correlations for smooth and micro-pin-finned surfaces were also proposed, and most data (95%) are predicted within ±20% for a smooth surface and all the data within ±5% for the micro-pin-finned surfaces.

1. Introduction

The microelectronics industry has been growing very rapidly in the past few decades. Demands for efficient heat transfer technologies have never become more evident and urgent than today. Technologies such as avionics and electronics cooling are driving the demand for thermal management schemes toward increasing heat flux and decreasing surface temperature. Electronics cooling by using boiling heat transfer has become an increasing significant subject due to its high efficiency in heat transfer. Until now, numerous studies focusing on jet impingement heat transfer have been conducted over the past sixty years involving experiments, analytical works, and numerical simulations, many of which before 1993had been summarized comprehensively by Wolf et al. [1] and Ma et al. [2], and the recent developments of jet impingement boiling in the last two decades are reviewed by Qiu et al. [3].

Compared with air impingement, some fluids with low boiling point such as R134a [4], water [5], FC-72 [6], FC-40 [7], HFE-7100 [8], can achieve much higher critical heat flux (CHF) or heat transfer coefficient (HTC) for electronic components. Effects of jet parameters such as jet velocity, liquid subcooling, impact distance, jet diameter, jet array as well as heater size and target surface parameters such as surface condition and surface aging on boiling heat transfer characteristics are emphasized and discussed. By controlling or changing these parameters can enhance jet impingement boiling heat transfer performance significantly. Ai et al. [9] have conducted experimental study on the heat transfer of jet

* Corresponding author.
E-mail address: jjwei@mail.xjtu.edu.cn (J. Wei).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.167
0017-9310/

Nomenclature

A	heat transfer area of micro-pin-fins, m^2
A_j	area of the jet impingement square, m^2
A_p	projective area of the heat source, m^2
A_r	total area of the jet arrays, m^2
A_S	heat transfer area of smooth surface, m^2
Bo	boiling number, $Bo = \frac{q}{\rho V_j h_{fg}}$
CHF	critical heat flux, $W \cdot cm^{-2}$
$C_{p,l}$	specific heat capacity, $J \cdot kg^{-1} \cdot K^{-1}$
d	jet diameter, m
d_e	equivalent jet diameter calculated by the total area of all jets, $d_e = N^{(1/2)} \cdot d$, m
D	heat-source diameter, m
D_e	equivalent heat-source diameter, $(4A_p/\pi)^{0.5}$, m
D_g	diameter of glass tube, m
D_h	hydraulic diameter, m
G	mass velocity, $kg \cdot m^{-2} \cdot s^{-1}$
h	fin height, μm
h_{fg}	latent heat of evaporation, kJ/kg
h_v	heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
H	distance between nozzle exit and impinging plate, m
k	thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
l	orifice thickness, m
L	length of heat surface, m
L_1	length of test surface corresponding to one jet cell, m
L_{op}	length of orifice plate, m;
L_h	$L_h = 0.25L$
N	number of nozzles
Nu	Nusselt number, $Nu = \frac{h_v d}{k}$
s	fin gap, μm
s_j	distance between adjacent jets, m
Pr	Prandtl number, $Pr = \frac{\mu c_p}{k}$
q	heat flux, $W \cdot cm^{-2}$
Q	heat load, W
Re	Reynolds number, $Re = \frac{\rho V_j d}{\mu}$
R	half length of heat source, m;
t	fin thickness, μm
V_j	jet velocity, $m \cdot s^{-1}$
w	fin width, μm
W	jet width, m
T_b	bulk liquid temperature, °C
T_{sat}	boiling temperature, °C
T_w	wall temperature, °C
ΔT_{sat}	wall superheat, T_w-T_{sat}, K
ΔT_{sub}	liquid subcooling, T_{sat}-T_b, K
μ	dynamic viscosity, $N \cdot s \cdot m^{-2}$
ρ_l	liquid density, $kg \cdot m^{-3}$
ρ_v	vapor density, $kg \cdot m^{-3}$
σ	surface tension, $N \cdot m^{-1}$

impingement with a moving nozzle, and they pointed that the moving nozzle can more effectively enhance the heat transfer at higher heat fluxes. Meanwhile, to enhance jet impingement boiling heat transfer, some researchers conducted a series of jet impingement experiments by using nanofluids, such as Cu-water nanofluids [10,11], water-TiO_2 nanofluids [12], silver nanofluids [13]. Although nanofluids can enhance heat transfer, the stability problems such as deposition and reunion have long puzzled scientists.

However, modified heater surface condition is one of the most valuable and potential methods to enhance heat transfer performance of jet impingement. Until now, some microstructures have been developed for enhancing jet impingement combined boiling heat transfer, such as TiO_2 coating surface [14,15], micro-studs surface [16], hemispherical surface and flat surface with a needle [17], micro-pin-fins [4], nano-characteristic surface [18], structured-porous surface [19], a flat surface coated with a microporous layer, extended square pin fins, and a hybrid surface on which the pin fins are coated with the microporous layer [8], multi-scale porous surface [20,21], micro-grooved surface [22]. These surfaces can actually enhance jet impingement boiling heat transfer including both CHF and HTC. Bhunia et al. [16] pointed out that the microstructures can significantly improve the impingement boiling performance compared to the plain base surface, including the onset of boiling, fully developed nucleate boiling and the critical heat flux (CHF). The performance is dictated by a combined effect of three distinct roles brought in by the micro-structures: (a) additional surface area, (b) significant increase in the number of potential sites for bubble nucleation, and (c) obstruction of the high speed spreading of the thin liquid film on the impingement surface. Our group [23–26] have made noticeable progress in nucleate boiling enhancement by use of micro-pin-fins which were fabricated on silicon surface using the dry etching technique. It is supposed that the regular interconnected channels formed by the micro-pin-fins can provide a route for fresh liquid supply even at high heat fluxes. The liquid can be driven by capillary force caused by the bubbles staying on the top of micro-pin-fins. The results showed that the boiling curves are almost vertical even in the high heat flux region, and the temperature of heated surface decreased and the heat transfer capacity is improved remarkably.

In the current study, combined the advantages of jet impingement and micro-pin-finned surfaces, the jet impingement boiling heat transfer characteristics on staggered micro-pin-finned surfaces using FC-72 were experimentally investigated. The effects of micro-pin-fins, jet-to-target distance (H = 3, 6, and 9 mm), and jet Reynolds number (Re = 2853, 5706, and 8506) on jet impingement boiling heat transfer performance were explored.

2. Experimental apparatus and procedure

2.1. Experimental apparatus

The test facility used for the present study is shown schematically in Fig. 1. It is a closed-loop circuit consisting of a tank, a scroll pump, a test section, a jet, two heat exchangers and two flowmeters. As shown in Fig. 1, the fluid is pumped from the tank to the heat exchanger. After reaching required liquid temperature, one branch goes into tank and the other one impinges on the test chip. Once finishing heat exchange, the fluid goes back to the tank and begins next circulation. The pump frequency is adjusted to control the mass flow rate and the valves are regulated to realize different jet velocities. The jet mass flow rate can be calculated by the difference value between the two flowmeters. When the loop reaches a steady state, a direct current is initiated to heat the test chip. A short-lived delay is imposed before initiating data acquisition to ensure steady-state conditions. The power input to the test chip is increased in small steps up to the high heat flux region of nucleate boiling. The heat flux q is obtained from the voltage drop of the test chip and the electric current. If the wall temperature increases sharply by more than 20 °C in a short time, the data acquisition algorithm assumes the occurrence of CHF condition and the power supply is immediately shut down. The CHF value is computed as the steady-state heat flux value just prior to the shutdown of the power supply.