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A new flow pattern-based boiling heat transfer model for micro-pin fin evaporators

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ABSTRACT

This study presents the development and results of a new flow pattern-based prediction method for two-phase boiling heat transfer in a micro-pin fin evaporator. The heat transfer mechanisms associated with slug flow and annular flow regimes are inferred by updating the widely used three-zone model of Thome et al. (2004), Dupont et al. (2004) and the algebraic turbulence model of Cioncolini and Thome (2011), respectively. In order to predict the trends in the heat transfer coefficient versus the vapor quality, these two models are linearly combined by utilizing a smoothing function acting on a buffer zone centered in the slug-to-annular flow transition region, which is here obtained by means of a new method based on flow visualization analysis and time-strip technique of the available experimental data.

The model is compared to a wide experimental database (7219 points), which covers three refrigerants, R134a, R236fa and R1234ze(E), three outlet saturation temperatures (25, 30, and 35 °C), mass fluxes varying from 500 to 2000 kg m^{-2} s^{-1} and heat fluxes from 20 to 44 W cm^{-2}. The new flow pattern-based model predicts 72% of the experimental databank within the ±30%, with a Mean Absolute Error of 23.4%.
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1. Introduction

Current trends in the microelectronics industry indicate that integrated circuits (ICs) are becoming ever more densely packed, in order to reduce the interconnects length and increase the total computing performance. The exponential integration of transistors per area described by Moore's law is going to be surpassed [4], as the demand of computational power is increasing dramatically. To achieve this, one of the roads being followed by the semiconductor industry is towards 3D structures of integrated-circuit dies, where single dies are stacked and connected by means of Through-Silicon-Vias (TSVs), yielding proximity and inter-connectivity between units, and a reduction of the signal delay time and power dissipation [5,6]. This novel 3D architecture represents a smart alternative to follow the ongoing miniaturization trend, and a number of researchers provided deep insight into its technological development and advantages [7–12]. However, the thermal management of 3D stacks emerges as one of the major challenges, as the stacking causes an increase in heat dissipation per unit volume [13,14].

Two-phase flow cooling is nowadays recognized as one of the most efficient and promising solution [15–17], due to its substantial advantages compared to other cooling technologies: (i) higher heat transfer rate, thanks to the latent heat absorbed by the vaporization of the coolant, which yields a reduction of sizes and required flow rates and (ii) a more uniform surface temperature, as already outlined by several studies [18–23].

The goal of the present study is to predict the thermal performances of micro-pin fin evaporators, as they represent a potential alternative to the widely studied multi-microchannel geometries [19,24–26]. In fact, micro-pin fins are compatible with the Through Silicon Vias (TSV) connections, and their dimensions are in line with the die thickness needed for embedded microfluidic cooling [27,28]. Besides, they enhance the fluid mixing by disrupting the boundary layer, leading to an increase of the heat transfer, as already outlined by previous comparative experimental and numerical studies [29–37].

In order to estimate the thermal and hydraulic performances of a micro-evaporator, and therefore the efficiency of the whole cooling system, a fundamentally based heat transfer predictive model is required that incorporates the complex flow geometry and flow pattern effects. Despite the extensive research conducted for microchannels, the literature regarding boiling heat transfer in micro-pin fin evaporators is very limited: the few predictive models available to date are empirical correlations based on the fit of specific experimental data sets to only one single fluid, water in the majority of cases. The few existing micro-pin fin prediction

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Nomenclature

Roman letters

A	area
Bo	Boiling number, q/Gh_{lv}
Bo_a	acceleration Bond number, $\rho A_v d_h^2/\sigma$
Ca	Capillary number, $\mu U/\sigma$
d_h	flow passage hydraulic diameter
f_{tp}	Fanning friction factor
G	mass flux
H	height
h	heat transfer coefficient
h_{lv}	vaporization latent heat
k	thermal conductivity
L	heated area length
$\dot{m}$	mass flow rate
Nu	Nusselt number, hd_h/k
P	perimeter
P_{red}	reduced pressure
Pr	Prandtl number, $Pr = \mu c_p/k$
q	heat flux
Re	Reynolds number, Gd_h/μ
S	micro-pin fin pitch
T_{sat}	saturation temperature
U	velocity
W	width
We	Weber number, $\rho U^2 d_h/\sigma$
x	vapor quality
y, z	widthwise and streamwise coordinates
w	width of the hyperbolic smoothing function

Greek letters

δ	liquid film thickness
μ	dynamic viscosity
Ω	bubble frequency
ρ	density
σ	surface tension
Σ	smooth function

Subscripts

AF	annular flow
ch	channel
f	liquid film
fin	micro-pin fin
ftp	footprint
l	liquid
loc	local
$onset$	onset of two-phase flow
sat	saturation
SF	slug flow
$SF-AF$	slug-to-annular flow transition
sp	single phase
tp	two-phase
g	gas

methods, which are basically modifications of macro-channel flow boiling method approaches [38], are listed in Table 1.

As modelling strategies, physics-based mechanistic models are a preferred alternative, as they attempt to capture the two-phase characteristics and transport processes. Flow pattern specific methods assume that a single flow regime occurs along the channels in that range of flow conditions, see for instance the three-zone model developed by Thome et al. [1,2] for the slug flow regime, and the annular flow models of Qu and Mudawar [44] and Cioncolini and Thome [3]. With respect to the former, Magnini and Thome implemented transient and dynamics effects of elongated bubbles [45,46] and updated the three-zone model of Thome et al. [1,2] by introducing a new liquid film thickness prediction method and a new bubble nose velocity calculation based on capillary flow theory [47].

Flow pattern based models consider the development of different flow regimes along the channel to better catch the two-phase hydrodynamics and its related heat transfer fundamental mechanisms. As an example, Costa-Patry and Thome [48] merged the three-zone model [1,2] and the annular flow model [3] to create a two-pattern prediction method, and they implemented a heat flux-dependent transition criterion between slug and annular flow. Harirchian and Garimella [49] developed a flow regime-based model to predict the heat transfer coefficient accounting for the successive development of bubbly, slug and annular flow regimes. Huang and Thome [50] modified the coefficients of the Costa-Patry and Thome correlations for the heat transfer coefficient and the transition criteria to fit their new experimental data for 100 µm size channels, also including a heat transfer prediction for the subcooled region. A number of previous studies [51,48,52,49] focused

Table 1
Existing heat transfer predictive models for flow boiling across a micro-pin fin array. H, W and D indicate respectively the height, width and diameter of a single pin fin. ζ is a correction factor, and Φ^2 is the frictional multiplier [39].

Reference	Test conditions	Geometry	Correlation	Main observations
Kosar and Peles [40]	$q = 19–312\ \mathrm{W/cm^2}$	$H = 243\ \mu\mathrm{m}$	$h_{tp} = \frac{3.42\cdot10^7}{(Gh_{lv})^{1.16}} q^{1.01} + 0.12 h_{sp}^{0.7}$, low G	Nucleate boiling (low G), h_{tp} depends on Bo
	$G = 976–2349\ \mathrm{kg/(m^2\ s)}$	$W = 100\ \mu\mathrm{m}$	$h_{sp} = (0.24 Re_l^{0.75} - 8.88)\frac{k_l}{D_h}$	h_{sp} derived from their experimental data
	Fluid: R-123	Hydrofoil shape	$h_{tp} = 819 Re_l^{0.6}(1-x_e)^{0.22}\left(\frac{1-x_e}{x_e}\right)^{0.01}$, high G	Convective boiling (high G), h_{tp} depends on Re_l
Krishnamurthy and Peles [39]	$q = 20–350\ \mathrm{W/cm^2}$	$H = 250\ \mu\mathrm{m}$	$h_{tp} = Fh_{sp} = \zeta(\Phi^2)^{0.247} Pr^{0.33} h_{sp}$	Two correlations based on Chen-type equation [38]
	$G = 346–794\ \mathrm{kg/(m^2\ s)}$	$D = 100\ \mu\mathrm{m}$	Corr. 1: $\zeta = 1.4$; Φ^2 from Kawahara et al. [41]	Effects of nucleate boiling neglected
	Fluid: water	Circular, staggered	Corr. 2: $\zeta = 1$; Φ^2 based on pin fin data [40]	h_{sp} evaluated from Short et al. [42]
Qu and Siu-Ho [43]	$q = 23.7–248\ \mathrm{W/cm^2}$ $G = 183–420\ \mathrm{kg/(m^2\ s)}$ Fluid: water	$H = 670\ \mu\mathrm{m}$ $W = 200\ \mu\mathrm{m}$ Square, staggered	$h_{tp} = Fh_{tp,eq}$ $F = 1-12.2 x_e^{-(101x+29.4)x}$ $h_{tp,eq} = 50.44\ \mathrm{kW/(m^2\ K)}$	h_{tp} constant at higher x. F accounts for subcooling effects $h_{tp,eq}$ obtained by averaging data at high x

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