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The effect of lateral thermal coupling between parallel microchannels on two-phase flow distribution

Tijs Van Oevelen, Justin A. Weibel, Suresh V. Garimella *

School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907, USA

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A B S T R A C T

Evaporating flows in parallel channels occurring in a variety of industrial heat exchange processes can encounter non-uniform flow distribution between channels as a result of two-phase flow instabilities. Such flow maldistribution can have a negative impact on the performance, robustness and predictability of these systems. Two-phase flow modeling can assist in understanding the mechanistic behavior of this flow maldistribution, as well as determine parametric trends and identify safe operating conditions.

The work described in this paper expands on prior two-phase flow distribution modeling efforts by including and assessing the effect of thermal conduction in the walls surrounding the parallel channels. This thermal conduction has a critical dampening effect on wall temperature gradients. In particular when a channel is significantly starved of flow rate and risks dryout, channel-to-channel thermal coupling can redistribute the heat load from the flow-starved channel to neighboring channels. The model is used to simulate the two-phase flow distribution in a system of two parallel channels driven by a constant flow rate pump. A comparison between thermally isolated and coupled channels indicates that thermally coupled channels are significantly less susceptible to maldistribution. Furthermore, a parametric study reveals that flow maldistribution is only possible in thermally coupled systems beyond a certain critical heat flux threshold. This threshold heat flux increases as the lateral wall conductance is increased, converging to a constant value in the limit of very high lateral conductance.

1. Introduction

Many industrial processes ranging from steam generation to air conditioning and nuclear reactor cooling rely on two-phase heat exchangers. Microscale two-phase heat sinks are also being considered in microelectronics cooling applications such as high-performance computing clusters, power conversion systems, and radar technologies. Some of the advantages of two-phase heat transfer include higher heat transfer coefficients, a smaller fluid temperature rise and lower pumping power than for single-phase heat sinks. However, two-phase cooling technologies are subject to flow instabilities that can adversely impact heat transfer performance, cause reliability issues and hamper broad-scale implementation.

Two-phase flow instabilities have been reviewed in the literature [1–5], and are commonly categorized into static and dynamic instabilities. Static instabilities occur when a disturbance causes a steady-state operating point to jump to a different operating point (*e.g.*, the Ledinegg instability, boiling crisis, and flow pattern transition instabilities). Dynamic instabilities occur when several physical mechanisms interact through feedback, influenced by inertia and delay (*e.g.*, pressure-wave oscillations, density-wave oscillations, and pressure-drop oscillations). Two-phase heat exchangers usually consist of parallel channel arrays to maximize the heat transfer area density. Additional instability mechanisms that may occur in these parallel channels include flow maldistribution instability and parallel-channel instability. Flow maldistribution occurs when the distribution of flow rate across parallel channels becomes non-uniform.

The focus of this work is on two-phase flow maldistribution in parallel-channel systems. The underlying mechanism for this maldistribution depends heavily on the state of the inlet flow. With subcooled liquid inflow, flow maldistribution is a consequence of the non-monotonic characteristic channel load curve. With two-phase inlet mixtures, in contrast, the flow distribution is largely determined by the uniformity of the phase distribution in the inlet header feeding the parallel channels. A comprehensive literature review on flow maldistribution in systems with two-phase inlet mixtures can be found in Ref. [6]. The present work is directed only at systems with subcooled liquid inflow.

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* Corresponding author.
E-mail addresses: tijs.vanoevelen@gmail.com (T. Van Oevelen), jaweibel@purdue.edu (J.A. Weibel), sureshg@purdue.edu (S.V. Garimella).

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Nomenclature

A	cross-section area
$\mathbf{A}$	linearized system matrix
C_{amb}	ambient thermal conductance
C_{lat}	lateral thermal conductance
c_{p}	specific heat capacity
Co	confinement number
D_{h}	hydraulic diameter
F_{p}	pump curve
F_{w}	frictional pressure gradient
f	friction factor
f_i	channel load function
G	mass flux (W/A_{c})
g	gravitational acceleration
H	height
h	specific enthalpy
h	heat transfer coefficient
k	thermal conductivity
L	length
$\widetilde{\mathbf{M}}$	mass matrix
M	molar mass, g/mol
m	channel inertial coefficient ($L_{\mathrm{c}}/A_{\mathrm{c}}$)
N	number of parallel channels
N_z	number of streamwise grid cells
P	perimeter
$P_{[0,1]}$	projection on the interval [0,1]
Pr	Prandtl number ($c_{\mathrm{p,f}}\mu_{\mathrm{f}}/k_f$)
p	pressure
Δp	pressure drop ($p_{\mathrm{in}} - p_{\mathrm{out}}$)
Q'	heat transfer per unit length
Re	Reynolds number
S	slip ratio ($u_{\mathrm{V}}/u_{\mathrm{L}}$)
T	temperature
t	time
u	streamwise velocity
v	specific volume
$\mathbf{v}$	eigenvector
W	mass flow rate
W	width
$\mathbf{W}$	vector of all flow rates
x	vapor quality
$\mathbf{y}$	vector of state variables
z	streamwise coordinate

Greek symbols

α	void fraction
β	aspect ratio
δ	deviation
λ	eigenvalue
μ	dynamic viscosity
ρ	mass density
σ	surface tension

Subscript

amb	ambient
c	channel
conv	convective
cr	critical
e	channel element
eq	thermodynamic equilibrium
f	fluid
fb	flow boiling
i	channel index
in	inlet
int	internal
L	liquid
L,0	all liquid
lat	lateral
nb	nucleate boiling
out	outlet
p	pump
sat	saturation
src	source
th	threshold
tp	two-phase
V	vapor
V,0	all vapor
w	wall
ϕ	phase ϕ (L or V)

A detailed discussion of the physical mechanisms underlying flow maldistribution and related modeling studies has been presented in our previous work, Ref. [7]; a summary of this discussion is provided here. Flow maldistribution in parallel-channel two-phase heat sinks has been observed experimentally in various studies [8–13]. It can have several causes: asymmetrical inlet header designs, differences among the parallel channels in geometry or surface properties, non-uniform heating, or the non-monotonic nature of channel pressure drop as a function of flow rate. Most of these maldistribution mechanisms can simply be attributed to differences in each channel load curve due to external factors. In order to satisfy hydraulic equilibrium in the parallel-channel array, the pressure drop for each flow path must be identical. Naturally if the load curve is different for each channel, then the flow rate distribution must also be non-uniform to lead to the same pressure drop. However, due to the non-monotonicity of the channel load curve for two-phase flows, even identical channel load curves can lead to maldistribution. This point is illustrated in the schematic diagram of pressure drop Δp versus flow rate W in Fig. 1. This diagram depicts a schematic load curve of a channel with fixed heat input, as well as several example pump curves. These curves represent the system-level relationships between pressure drop Δp and flow rate W for the heated channel and pump. Pump curves are typically monotonically decreasing functions of flow rate, while for single-phase flows, channel load curves are monotonically increasing functions of flow rate. However, this is not the case for two-phase flow due to the phase change that occurs at low flow rates (*i.e.*, lower than the flow rate at point E). At sufficiently low flow rates, the fluid evaporates before it reaches the outlet. The evaporation is accompanied by a reduction of the average fluid density. This leads to an increase of the flow velocity and a corresponding increase in pressure drop when the flow rate is reduced. As a result, the pressure drop peaks with a maximum at point C. At this point, the average density of the flow approaches the vapor density and the pressure drop again decreases with further decreases in flow rate.

Steady system operating points must satisfy both the load curve and pump curve and are therefore found at the intersections of the two curves. Due to the non-monotonic behavior of the two-phase channel load curve, this can result in several different possible operating points. In Fig. 1, the general pump curve and the constant pressure-drop pump curve each intersect the channel load curve at three distinct points: respectively (B, D, F) and (A, D, G). Additionally for parallel-channel systems, the pressure drop must