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Modeling in situ vapor extraction during convective boiling in fractal-like branching microchannel networks

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ABSTRACT

The pressure drop penalty of convective boiling flow in microchannels may be exceedingly large. A proposed method of reducing this penalty is to extract vapor locally along the channel. A potential consequence of this extraction is that the local void fraction reduction positively influences the local heat transfer coefficient. In this study, a one dimensional model was developed to simulate convective boiling flow through a fractal-like branching microchannel network with vapor extraction through a channel wall formed using a hydrophobic porous membrane. The goal of the model is to provide a design tool that can assess the effects of vapor extraction on flow boiling heat transfer performance. Heat was applied through all walls of the channel. Vapor extraction was obtained by applying a pressure difference across the membrane. Membrane transport models of the extraction process based on local channel pressure and local saturation pressure are discussed. Predicted local conditions and global results are presented for two ranges of conditions: (i) relatively low inlet flow rate with low heat flux and (ii) relatively high inlet flow rate with high heat flux. Results shows that as the vapor extraction rate increases, there is a significant reduction in pressure drop through the channel, a reduction of the bulk fluid temperature, and a reduction in exit vapor quality.

1. Introduction

An effective heat sink should achieve a high heat removal rate, maintain a low and relatively uniform and stable temperature and minimize the overall pressure loss and/or flow power requirements. The advantages of using microchannels are higher surface area per unit volume, larger heat transfer coefficients, low flow rate requirements and minimal coolant volume. Flow boiling heat sinks can operate at much higher heat flux and more uniform temperature than single-phase heat sinks, see reviews [1–3]. However, these advantages come with consequences such as large pressure drops and flow instabilities associated with two-phase microscale flow [4,5]. A large pressure drop can also contribute to non-uniform operating temperature when flow is in the two-phase regime.

To help reduce pressure drop, Pence [6] studied the use of a fractal-like branching network which mimics flow distribution patterns found in nature. As fluid flows downstream, the flow cross-sectional area bifurcates and results in an increase in total cross-sectional area. For fixed convective areas (wall area), exit channel dimensions and identical flow rates, the pressure drop and temperature gradient along the branching network are smaller than those of parallel microchannels in both single-phase and two-phase flows; several studies [6–11] have confirmed this both numerically and experimentally. Also, the optimization of the design of the fractal-like branching network was studied by Heymann et al. [12,13].

Studies suggest that the pressure drop across microscale heat sinks can also be improved by locally extracting vapor from two-phase flow through a hydrophobic, porous membrane forming one wall of the channel [14–16]. Apreotesi et al. [14,15] provided experimental results of diabatic boiling water flowing through a fractal-like microchannel heat sink with local vapor extraction that show a decrease in overall channel pressure drop as the extraction pressure difference increases. A study by David et al. [16] with flow boiling in a microchannel heat sink used one wall fabricated from a hydrophobic porous membrane to allow venting of the vapor. Their experimental results with vapor venting show a significantly reduced pressure drop when compared to the non-venting results. Also, David et al. [17] discuss various flow regions with both adiabatic and diabatic flow with venting.

To model pressure drop, separated flow models have been used for two-phase flow in minichannels and microchannels. Most separated flow models are based on the Lockhart and Martinelli [18] relationship, such as the models presented by Mishima and Hibiki [19], Lee and Lee [20], Qu and Mudawar [21], Lee and Mudawar [22], and Hwang and Kim [23]. All of these predictive models do show good agreement with specific experimental data.

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Nomenclature

Bo	boiling number
c_p	specific heat
C_{LM}	phase interaction parameter
D_h	hydraulic diameter
$f_{loc,l}$	local liquid phase friction factor
G	mass flux
h	heat transfer coefficient
H	channel depth
i	enthalpy
i_{lv}	heat of vaporization
k	channel branching level
L	channel branching length
L_{tot}	total flow length
n	number of branches
M	number of branching levels
$MAE_{\Delta P_{chan}}$	mean absolute error between model and experimental results of ΔP_{chan}
$MAE_{\dot{m}_{extr}}$	mean absolute error between model and experimental results of $\dot{m}_{extr}$
$\dot{m}_{in}$	inlet mass flow rate
$\dot{m}_{extr}$	extracted vapor mass flow rate
N_0	number of inlet branches
N_k	number of kth level channels
P_{extr}	extraction absolute pressure
ΔP^0_{vap}	vapor pressure gradient
$\dot{Q}$	heat rate
R_{extr}	extraction flow resistant
Re	Reynolds number
T	temperature
v	specific volume
w	channel width
w_t	terminal branch width
We	Weber number
x	thermodynamic equivalent quality
x^*_{out}	ideal exit quality without vapor extraction
X^2	Lockhart–Martinelli parameter

Greeks

α	void fraction
β_{D_h}	hydraulic diameter ratio
β_w	width ratio
γ	length ratio
ΔP_{chan}	channel pressure drop
$\Delta P_{driv,loc}$	local extraction driving pressure
ΔP_{extr}	extraction pressure differential ($\Delta P_{extr} = P_{chan,out} - P_{extr}$)
δ	thickness
κ	specific permeability
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
ϕ_l^2	two-phase multiplier

Subscripts

acc	acceleration
$back$	porous backing
$fric$	frictional
in	inlet
l	liquid phase
lo	all-liquid
mem	porous membrane
out	outlet
sat	saturation
v	vapor phase
s	surface

The present study has the added complexity of vapor extraction along the channel across a porous membrane. The process can be related to vacuum membrane distillation, which has been described in a number of studies [24–27]. Basically, distillation uses thermally induced transport of vapor through a porous hydrophobic membrane. A heated, aqueous feed solution is brought into contact with the feed side of the membrane. Vapor flow through the membrane has been successfully modeled based on Darcy's law, using the local vapor pressure difference across a membrane of a given permeability.

In order to predict the pressure differential across the membrane, it may be necessary to predict the local wall temperature, using a local heat transfer coefficient. As discussed later, this is to determine a film temperature based vapor pressure. For two-phase boiling flow, flow boiling heat transfer can be divided into nucleate boiling and convective boiling components. The boiling heat transfer coefficient of the nucleate boiling is a function of wall heat flux only whereas convective boiling is a function of quality and mass velocity. Some studies [28,29]suggest that the nucleate boiling mechanism is dominant. Others [30–36] show that the boiling heat transfer coefficient is affected by quality and mass velocity as well as wall heat flux. Bertsch et al. [2] and Ribatski et al. [3] analyzed the experimental results for microscale two-phase flow from various investigators and conclude that the existing flow boiling heat transfer correlations poorly predicts the experimental database. For this study, the model from Lee and Mudawar [36] is used.

In this paper, a predictive one-dimensional model for flow boiling in a microscale fractal-like branching network with local vapor extraction for a range of heat flux and mass flow rate are presented and discussed. Several options of the local extraction driving pressure which drives flow across the membrane are presented. Pressure drop, temperature distribution and extracted vapor mass flow rate are presented. The results are compared with the experimental data of Apreotesi et al. [14,15] for relatively low flow rates and low heat flux conditions; experimental high flow rates and high heat flux data are not available in the literature.

2. Flow geometry

In this study, a generalized model for vapor extraction is developed and applied to a fractal-like branching microchannel heat sink. A cross-section schematic of the flow channel is shown in Fig. 1, whereas representative planform views are provided in

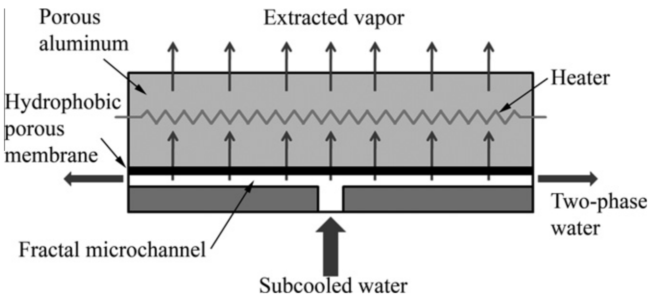

Fig. 1. Schematic cross-sectional of assembled heat sink (adapted from [14]).