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Frequency analysis of pressure oscillations in large length-to-diameter two-phase micro-channel heat sinks

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ABSTRACT

Two-phase micro-channel heat sinks are prime candidates for incorporation into thermal control systems (TCSs) of future space vehicles and planetary habitats. Unlike small heat sinks employed in the electronics industry, TCS heat sinks are characterized by large length-to-diameter ratio, for which limited information is presently available. This study employs a 609.6-mm long by 203.2-mm wide heat sink containing 100 of $1 \times 1\ mm^2$ micro-channels and uses R134a as working fluid. The large length-to-diameter ratio of 609.6 is especially instrumental to capturing detailed axial variations of flow pattern and corresponding variations in local heat transfer coefficient. High-speed video analysis of the inlet plenum shows appreciable vapor backflow under certain operating conditions, which is also reflected in periodic oscillations in the measured pressure drop. In fact, the backflow frequency captured by video matches closely the frequency obtained from Fourier analysis of the pressure drop signal. While density-wave oscillations are encountered in individual channels, the phenomena observed are more closely related to parallel-channel instability. It is shown the periodic oscillations and vapor backflow are responsible for initiating intermittent dryout and appreciable drop in local heat transfer coefficient in the downstream regions of the channels. A parametric study of oscillation frequency shows a dependence on four dimensionless parameters that account for amount of vapor generation, subcooling, and upstream liquid length, in addition to Weber number. A new correlation for oscillation frequency is constructed that captures the frequency variations relative to these individual parameters.

1. Introduction

1.1. Emergence of Two-phase cooling technologies

During the past four decades, the rate of heat dissipation in a number of technologies, especially electronics and power applications, has increased enormously, exasperated by a quest for smaller and more lightweight system architectures. To cope with these challenges, a variety of two-phase high-heat-flux thermal management techniques, with device heat fluxes in the range of 10^2–$10^3\ W/cm^2$, have been proposed, and some have evolved into practical solutions [1]. The most basic of these techniques are passive cooling schemes such as capillary-driven devices (heat pipes, capillary pumped loops, and loop heat pipes) [2–4] and pool boiling thermosyphons [5–7]. But the more demanding cooling situations are tackled with the aid of a mechanical pump to capitalize upon the heat transfer merits of faster fluid motion. The pumped cooling schemes are the focus of extensive studies that have been performed at the Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL). They include falling film [8], channel flow boiling [9–13], mini/micro-channel flow boiling [14–20], jet-impingement [21–23], and spray [24–28], as well as hybrid cooling schemes combining the merits of mini/micro-channel flow boiling and jet impingement [29].

1.2. Two-phase mini/micro-channel cooling

As discussed in [30], mini/micro-channel flow boiling has received unprecedented attention because of its ability to not only achieve high heat fluxes, but also reduce size and weight of cooling hardware as well as coolant inventory, let alone their design simplicity and low manufacturing cost. It is important to note that single-phase mini/micro-channel heat sinks have also received significant attention, especially in the electronics industry. The primary merit of this single-phase cooling scheme is the inverse dependence of heat transfer coefficient on hydraulic diameter for laminar flow typically encountered in mini/micro-channels, meaning cooling performance may be enhanced simply by decreasing

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Nomenclature

A	cross-sectional area of micro-channel [m^2]
A_{base}	total base area of heat sink [m^2]
Bo	boiling number
C_n	complex Fourier coefficient
c_p	specific heat at constant pressure [J/kg K]
D_h	hydraulic diameter [m]
f	frequency [Hz]
f_k	complex form of Fourier series
f_{margin}	marginal frequency [Hz]
$\hat{f}$	discrete Fourier transform
$\hat{f}^*$	complex conjugate of discrete Fourier transform
G	mass velocity [kg/m^2 s]
h	enthalpy [J/kg]; heat transfer coefficient [W/m^2 K]
H_{ch}	height of micro-channel's cross-section [m]
h_{fg}	latent heat of vaporization [J/kg]
$I_{sp,f}$	dimensionless single-phase liquid length parameter
j	superficial velocity [m/s]
k	thermal conductivity [W/m K]
L	micro-channel length [m]
L_H	heated length of channel [m]
m	fin parameter
$\dot{m}$	total mass flow rate of heat sink [kg/s]
N	number of measurement points
N_{ch}	number of micro-channels in heat sink
N_{pch}	dimensionless phase change parameter
N_{sub}	dimensionless subcooling parameter
p	pressure [Pa]
Pe	Peclet number
P_F	friction perimeter of channel [m]
P_H	heated perimeter of channel [m]
P_r	reduced pressure
Δp	pressure drop [Pa]
q''	heat flux [W/m^2]
q''_B	heat flux based on total base area of heat sink [W/m^2]
q''_H	heat flux based on heated perimeter of micro-channel [W/m^2]
Q	volumetric flow rate [m^3/s]
Q_g	vapor generation rate [m^3/s]
T	temperature [°C]
t	time; oscillation period [s]
T_{sat}	saturation temperature [°C]
T_w	wall temperature [°C]
$\bar{u}$	mean fluid velocity [m/s]
W_{ch}	width of micro-channel's cross-section [m]
We	Weber number
W_w	half-width of copper sidewall separating micro-channels [m]
x_e	thermodynamic equilibrium quality
x_k	sampling point in time, $0 \leq x_k \leq 2\pi$ [rad]
z	coordinate along micro-channel [m]

Greek symbols

α	thermal diffusivity [m^2/s]
δ	film thickness [μm]
η	fin efficiency
ρ	density [kg/m^3]
σ	surface tension [N/m]
τ	period [s]

Subscripts

avg	average
b	bottom of micro-channel
evap	evaporation
exp	experimental
f	liquid
fo	liquid-only
g	vapor
in	micro-channel inlet; inlet
out	micro-channel outlet; outlet
pred	predicted
s	solid material of heat sink
sat	saturation
sp	single-phase
super	superheated
tc	thermocouple
up	upstream plenum
w	wall

Acronyms

CHF	critical heat flux
DNB	departure from nucleate boiling
DWO	density-wave oscillation
EBO	explosive boiling oscillation
LED	Ledinegg instability
ONB	onset of nucleate boiling
PCI	parallel-channel instability
SPDO	severe pressure-drop oscillation

the channel diameter. However, the cooling performance of these single-phase devices is limited by their sole dependence on sensible heat rise of the coolant. On the other hand, two-phase heat sinks can achieve orders of magnitude enhancement in the heat transfer coefficient by utilizing the coolant's both sensible and latent heat. They also result in smaller temperature gradients both between the device and coolant, and axially along the channel.

Despite these merits, two-phase mini/micro-channel heat sinks are not without shortcomings. By decreasing the hydraulic diameter in order to increase the two-phase heat transfer coefficient, pressure drop across the channels can increase appreciably, resulting in significant compressibility (resulting from axial changes of vapor and liquid specific volumes with pressure) and flashing (resulting from axial changes of vapor and liquid enthalpies with pressure), as well as increased likelihood of two-phase choking [30]. These performance drawbacks are, in fact, closely related to the distinction between channel sizes: one to a few millimeters for mini-channels versus ten to several hundred micrometers for micro-channels. For example, Bowers and Mudawar [31] compared the cooling performances of a mini-channel heat sink with D_h = 2.5 mm to that of a micro-channel heat sink with D_h = 0.51 mm, and showed that, while they produce fairly similar heat transfer performances, the latter produced significantly higher pressure drop and incurred appreciable compressibility and flashing.

Recently, the authors of the present study explored the implementation of two-phase mini/micro-channel heat sinks as multi-kilowatt evaporators for future space vehicles that could tackle heat removal from both avionics and crew [32]. They also proposed the concept of using the same evaporators in a 'Hybrid Thermal Control System' (H-TCS) for space vehicles, allowing the cooling loop to be automatically reconfigured into a vapor compression loop, a pumped two-phase cooling loop, or a pumped single-phase loop.