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Experimental investigation and flow visualization to determine the optimum dimension range of microgap heat sinks

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ABSTRACT

The rapid increase of heat flux in high performance electronic devices has necessitated the development of high capacity thermal management techniques that can support extremely high heat transfer rates. Flow boiling in microgap is very promising for this purpose due to its high heat transfer rate and ease of fabrication. However, the effects of microgap dimension on heat transfer and pressure drop characteristics along with flow visualization have not been investigated extensively. This paper focuses on flow boiling experiments of deionized water in silicon microgap heat sink for ten different microgap dimensions from a range of 80 μm–1000 μm to determine the most effective and efficient range of microgap dimensions based on heat transfer and pressure drop performance. High speed flow visualization is conducted simultaneously along with experiments to illustrate the bubble characteristics in the boiling flow in microgap. The results of this study show that confinement in flow boiling occurs for microgap sizes 500 μm and below and confined slug/annular flow is the main dominant regime whereas physical confinement does not occur for microgap sizes 700 μm and above and bubbly flow is the dominant flow regime. The microgap is ineffective below 100 μm as partial dryout strikes very early and the wall temperature is much higher for a fixed heat flux as microgap size increases above 500 μm. In addition, results show that pressure drop and pressure fluctuation decrease with the increases of gap size whereas wall temperature and wall temperature fluctuation increase with the increases of gap size. A strong dependence of heat transfer coefficient on microgap sizes is observed for microgap sizes 500 μm and below. However, the heat transfer coefficient is independent of microgap size for microgap sizes 700 μm and above.

1. Introduction

Recently, flow boiling in microscale is of great interest due to its high capacity of thermal management in electronic devices. Electronic devices such as those used for the defense application High Energy Laser (HEL) require high capacity cooling due to large power requirements and high heat fluxes (500 W/cm^2). The laser and cooling system must be compact, lightweight and reliable for practical deployment on tactical platforms. The use of flow boiling in microgap is a very attractive approach to satisfy these requirements. Flow boiling in microgaps offers several advantages, such as extremely high heat transfer rate in compact spaces with a smaller rate of coolant flow, easy fabrication process as they require no external attachment to cut channel and micromachining; fluid can flow on the back surface of an active electronic component which in turn reduces interface thermal resistance [1]. Other advantages of this process are the greater temperature uniformity across the heat sink, lower flow boiling instabilities and ability to mitigate hotspots on the heat sink [2,3]. Although progress has been made to characterize the heat transfer and pressure drop during flow boiling in microgaps, a fundamental understanding of boiling mechanisms along with the flow visualization for such microgaps are unavailable. This work also attempts to optimize the gap size of a microgap heat sink for its best possible performance, based on the experimental investigation and observed boiling mechanisms.

In recent years, a number of studies have attempted to better understand the flow boiling mechanism in microgap [1–8]. Kim et al. [1,4] experimentally investigated the two-phase thermo-fluid characteristics of a dielectric liquid, FC-72, flowing in an asymmetrically heated chip scale microgap with channel heights varying from 110μm to 500μm. This exploratory study revealed that the intermittent and annular flow regimes dominate the 110μm to 500μm channel behavior for the two-phase flow of FC-72, with a liquid volumetric flow rates from 0.17ml/s to 0.83ml/s. Bar-Cohen and Rahim [5] performed a detailed analysis of microchannel/microgap heat transfer data for two-phase flow of refrigerants and dielectric liquids, gathered from the open literature and sorted

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Nomenclature

A	wetted area, cm^2
A_{gap}	microgap cross-sectional area, cm^2
A_{man}	manifold cross-sectional area, cm^2
Bl	boiling number
Bo	bond number
c_p	specific heat, J/kg °C
D	microgap depth, μm
g	gravitational acceleration
G	mass flux, kg/m^2s
h	heat transfer coefficient, W/m^2K
h_{fg}	heat of vaporization, J/kg
k_s	thermal conductivity, W/cm°C
K_c	loss coefficient
L	length of the substrate, cm
$\dot{m}$	mass flow rate, kg/s
P	pressure, bar
ΔP	pressure drop, bar
q	total heat dissipation, W
q_{eff}	effective heat dissipation, W
q''_{eff}	effective heat flux, W/cm^2
q_{loss}	heat loss, W
Re	Reynolds number
t	substrate thickness, cm
T	temperature, °C
V_d	voltage drop across diode, V
W	width of the substrate, cm
x	vapor quality
z	*z*-coordinate (axial distance), cm
Greek symbols	
ρ	density, kg/m^3
μ	dynamic viscosity, Ns/m^2
σ	surface tension, N/m
Subscripts	
c	contraction
d	diode
e	expansion
f	liquid
g	vapor
gap	microgap
i	manifold inlet
man	manifold
s	substrate
sat	saturated
w	wall
z	local

by the Taitel and Dukler flow regime mapping methodology. They showed that the annular flow regime is the dominant regime for this thermal transport configuration and its prevalence is seen to grow with decreasing channel diameter and to become dominant for refrigerant flow in channels below 0.1 mm diameter. Sheehan and Bar-Cohen [6] investigated a 210 micron microgap channel, operated with mass flux 195.2 kg/m^2s and heat flux varying from 10.3 to 26 W/cm^2 using infrared thermography to observe wall temperature fluctuation and locate nascent dryout regions. They concluded from their results that wall temperature fluctuations vary independently with both thermodynamic quality of the flow and the wall heat flux and these fluctuations reflect a complex interplay of channel and local instabilities with periodic local dryout and re-wetting. Kabov et al. [7] studied a detailed map of the flow sub-regimes in a shear-driven liquid film flow of water and FC-72 obtained for a 2 mm channel operating at room temperature. They showed that shear-driven films are more suitable for cooling applications than falling liquid films. Utaka et al. [8] experimentally investigated flow boiling of water in narrow gaps of 0.5, 0.3 and 0.15 mm and measured the thickness of the micro-layer by application of the laser extinction method. They showed that the initial micro-layer thickness decreases with the decreasing gap size and the heat transfer was enhanced due to the micro-layer evaporation.

Some preliminary experimental studies were performed in silicon based microgap heat sink having microgap of depth 190 μm, 285 μm and 381 μm, using deionized water at different mass fluxes by Alam et al. [2]. It was observed that confined slug and annular boiling dominate the heat transfer mechanism in these microgaps and the lower the gap size, higher the heat transfer coefficient.

This review of the literature shows the absence of systematic studies on the effect of microgap dimensions on heat transfer and pressure drop characteristics along with flow visualization till date. So, more careful and systematic studies are needed to advance the fundamental understanding of local flow boiling heat transfer and pressure drop mechanisms in microgap. In the present work, flow boiling experiments with simultaneous flow visualizations of deionized water in silicon microgap heat sinks are performed. Ten different microgap dimensions from a range of 80 μm–1000 μm are used to determine most effective and efficient range of microgap dimensions based on heat transfer and pressure drop performance and also to illustrate the bubble characteristics in the boiling flow in microgaps using flow pattern images.

2. Experiments

2.1. Test loop

The test loop consists of a deionized water reservoir, a gear pump to drive water from reservoir to test section through the close loop. A Mcmillan Liquid flow sensor (Model 106-5-D-T4-C6-HT) with a measurement range of 50–500 ml/min is used to monitor the flow rate through the loop. A preheater is installed upstream of the microgap test section to heat the deionized water to the desired inlet subcooling temperature. T-type thermocouples are used to measure the water temperature at inlet and outlet of the preheater and test section. Pressure at the inlet of microgap test section and pressure drop across the microgap are measured using a pressure transmitter having a range of 0–0.6 bar and a differential pressure transmitter having a range of 0–100 mbar, respectively. A liquid-to-air heat exchanger is installed downstream of the test section to cool the exiting hot water from the test section before it enters the reservoir. A high-speed camera (FASTCAM SA5 1000K-M3) is mounted over the microgap test piece to capture visual data. The data from all different sensors are collected using a computer-based Data acquisition and measurement control system Agilent 34980A Multifunction Switch/Measure Unit and typical plug-in modules. A schematic diagram of flow loop with high speed camera and photograph of high speed camera set up are shown in Fig. 1.

2.2. Test section

The microgap test section shown in Figs. 2(a) and (b) consists of a printed circuit board (PCB) having 1.27 × 1.27 cm silicon test