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Flow boiling of R245fa in a microgap with staggered circular cylindrical pin fins

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ABSTRACT

In this study, flow boiling of refrigerant R245fa is investigated in a microgap of height 200 μm populated with a staggered pin fin array of diameter 150 μm and spacing 200 μm. For heat fluxes up to 498 W/cm^2, mass flux values up to 7896 kg/m^2 s, and inlet temperatures of 13 °C and 18 °C, average two-phase heat transfer coefficient up to 60 kW/m^2 K are measured. High speed flow visualizations at frame rate of 2229 fps elucidate the flow boiling patterns inside the microgaps, including bubbly and foggy that are generated in the pin finned area. Surface temperatures are measured for heat fluxes up to 498 W/cm^2 which enable determination of heat transfer characteristics.

1. Introduction

Surface heat fluxes in excess of 100 W/cm^2 in microsystems have driven the interest in single phase liquid, and phase change cooling. There have been a number of recent studies on flow boiling in microchannels showing several flow regimes including slug, confined annular, and bubbly, depending on operating conditions [1–9]. Studies have shown that in pre-cooled flow boiling situations, the flow behavior changes less with variation of heat flux compared to higher inlet temperature conditions. In fact, subcooled boiling can enhance convective heat transfer coefficient and make delay on critical heat flux. It also play a significant role in bubbles formation and growth in microchannels. At a given wall temperature, subcooling can result in an increase in the maximum heat flux [10–13]. Microchannel size can directly affect the appearance of these regimes, and may change the heat transfer performance [14].

Microchannels are characterized here as having $D_h < 1$ mm and $W/H \leqslant 10$. Here D_h is the hydraulic diameter given by $2WH/(W+P)$ for a rectangular duct. For $D_h < 1$ mm and $W/H > 10$, we employ the term microgap. Both are often enhanced with microstructures, such as micropillars, or micro-pin arrays. Spanwise flow enabled in the microgap may mitigate two-phase flow instabilities by enabling better temperature uniformity across the heat sink. Additionally the pin fins also provide the ability to route vertical electrical and fluidic interconnections in 3D electronics, where multiple chips may be stacked. Increased flow frontal surface area enabled through microstructures strongly enhances the convective heat transfer performance. Using microfabrication techniques, the pin fins can be fabricated in different cross-sectional shapes such as square, circular, hydrofoil, and piranha, and arranged in-line, or staggered along the microgap [3,15–19]. A recent work has shown that staggered square shape pin-fin arrays cause higher pressure drop than the in-line, with the same base area, at the same mass flux under flow boiling. Based on a set of experiments that was implemented using water as working fluid, in-line and staggered configurations both yielded similar heat transfer coefficient for equivalent mass flux values [17]. Hydrofoil pin-fins provide higher surface area, and therefore higher heat transfer performance compared to the circular pin-finned microgaps [15,18]. Flow boiling in microgaps of a few hundreds of μm have the potential for removing heat fluxes >100 W/cm^2 [19,20].

A wide variety of coolants has been considered as working fluids in microfluidic two-phase cooling systems. De-ionized (DI) water, with superior thermal performance, has been utilized in numerous flow boiling studies [21–24]. However, its saturation temperature at atmospheric pressure is too high for Si devices, which often require sustained operation below 85 °C [22]. Dielectric fluids such as refrigerants are electrically inert, allowing direct contact with active electronics. Refrigerants utilized in prior flow boiling investigations include R245fa, R134a, R113, and R123. R245fa has saturation temperature of 15.3 °C at atmospheric pressure, which makes it a good candidate for electronic cooling [25–27].

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Nomenclature

A_{cf}	pin fin cross-sectional area, m^2
A_p	footprint area of the microgap, m^2
A_s	surface area, m^2
C_p	specific heat, kJ/(kg K)
D_h	hydraulic diameter, m
H	microgap height, m
$\bar{h}_{sp}$	average single-phase heat transfer coefficient, W/(m^2 K)
$\bar{h}_{tp}$	average two-phase heat transfer coefficient, W/(m^2 K)
I	electrical current, A
k_s	silicon thermal conductivity, W/(m K)
k_f	fluid thermal conductivity, W/(m K)
L	microgap length, m
L_{sp}	single-phase region length, m
L_{tp}	two-phase region length, m
m_f	fin parameter
$\dot{m}$	mass flow rate, kg/s
N_f	number of pin fins
P_f	pin fin perimeter, m
q''	heat flux, W/cm^2
q''_{loss}	heat flux loss, W/cm^2
q''_{eff}	effective heat flux, W/cm^2
R_{total}	total chip thermal resistance, (K/W)
t_s	silicon block thickness, m
t_p	SiO_2 passivation layer thickness, m
$\bar{T}$	average surface temperature, °C
$\bar{T}_H$	average heaters temperature, °C
T_{in}	fluid inlet temperature, °C
T_{out}	fluid outlet temperature, °C
T_{sat}	saturation temperature, °C
T_{se}	surface temperature at the end of single-phase region, °C
T_{si}	surface temperature at the inlet, °C
$\bar{T}_{sp}$	average single-phase region temperature, °C
$\bar{T}_{surf}$	average surface temperature, °C
$\bar{T}_{tp}$	average two-phase region temperature, °C
V	applied voltage to the chip, V
W	microgap width, m

Greek symbols

η_f	fin efficiency

Subscripts

tp	two-phase
sp	single-phase

An experimental study is reported here on the flow boiling of R245fa in enhanced microgaps, with circular pin fins of diameter 150 µm and spacing 200 µm. The test chip has one inlet and one outlet and a footprint area of 1 cm × 1 cm. The experiments cover a heat flux range of 15–498 W/cm^2, coolant mass flux range of 781–7896 kg/m^{2}s, and maximum exit vapor quality of about unity is assessed.

2. Experimental setup and procedure

Fig. 1 depicts the schematic of the closed loop assembled using 6.35 mm OD stainless steel tubes and Swagelok fittings. The system is initially evacuated by a vacuum pump (VN-200 N, JB Industries Inc.) to a pressure of 4 kPa to ensure that the air inside the loop is removed. A refrigerant source tank heated up to a temperature up to 15 °C above the ambient (50 °C) is connected to the control valve (charging point) to introduce the working fluid to the system. In order to have the flow always going towards the syringes, the accumulator is heated up to 15 °C above the room temperature. By having one syringe pushing and the other one pulling, continuous flow around the loop is ensured. There are multiple check valves upstream of each syringe pump that guarantee the flow runs only from the pumps to the rest of the loop (no back flow to the syringes). Initially, the refrigerant passes through the pre-cooler to insure liquid phase. It then enters the flow meter (S-114, Mcmillan Co.). Particulate contaminants are removed by running the refrigerant through a 0.5 µm in-line filter (SS-4F-05, Swagelok Co.). A back-wash circuit is incorporated at the test section zone to clean the chip prior to the actual test. It enables running the refrigerant through the test device in both directions. A liquid-to-liquid nickel brazed plate heat exchanger (LL510G14, Lytron Co.) is located right after the test section to bring back the refrigerant into liquid phase, before returning it back to the accumulator. A high-speed video camera (Phantom V211, VISION Research Inc.) is utilized to capture the flow boiling phenomena inside the microgap at 2229 fps.

In order to assure steady state conditions prior to each thermal test, the system is run with the test chip unpowered for a few hours. Temperature and pressure values around the loop are collected and recorded by the data acquisition unit (Agilent 34972A, Keysight Technologies). Once temperature and pressure data are stabilized (0.1 °C for temperature and 0.5 kPa for pressure), the

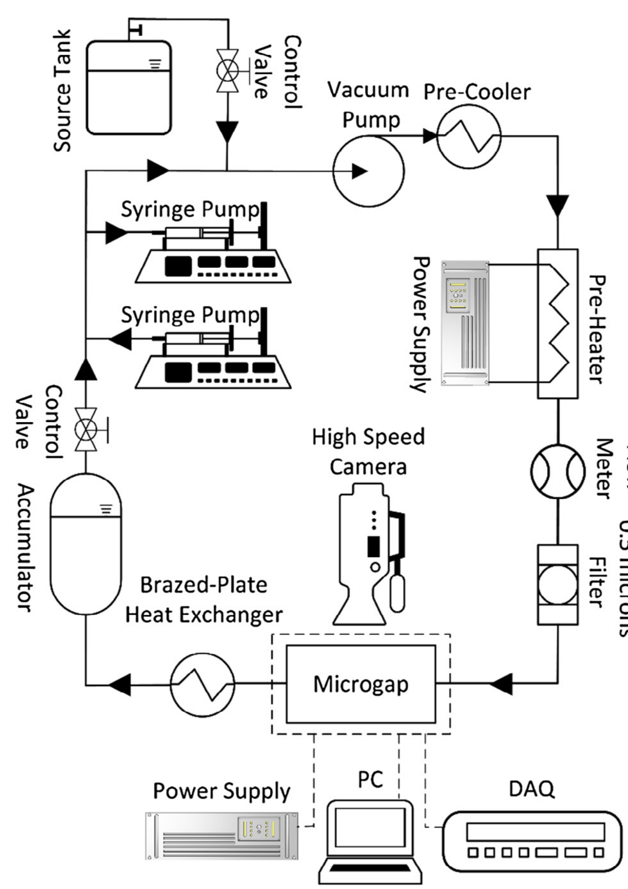

Fig. 1. Flow loop schematic.