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Piranha Pin Fin (*PPF*) – Advanced flow boiling microstructures with low surface tension dielectric fluids

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ABSTRACT

Flow boiling of HFE7000 in a new class of structured microchannel, termed Piranha Pin Fin (*PPF*), is studied. The novel heat sink consists of an array of 150 micron diameter microstructures entrenched in a 2.4 mm wide silicon channel, with overall device dimensions of 12 by 28 mm. Mass fluxes ranging from 1200 to 7000 $kg/s/m^2$ are used to dissipate base heat loads up to 700 W/cm^2, provided over a 6 mm^2 heating element located beneath the *PPF* array. Experimental single phase and flow boiling heat transfer data is presented for two flow configurations within the microdevice – *open flow* and *extraction flow*. The effect of system pressure on phase change heat transfer is experimentally examined at operating pressures of 1.4 atm and 2.8 atm. Single and two phase heat transfer coefficients, Nusselt numbers, exit quality, and pressure drop data is presented to develop a comprehensive system-level analysis of the unique heat sink.

1. Introduction

Interest in micro-scale flow boiling heat sinks has been steadily increasing over the last two decades. Flow boiling at the micro scale offers several distinct benefits over its single-phase counterpart due to a combination of low pumping power, steady saturation temperature, and relatively high heat transfer coefficients [1–4]. Previous efforts have mainly focused on explicating flow boiling heat transfer characteristics at rudimentary micro domains [3–14] and, more recently, on microstructures such as cylinders, ellipsoids, foils, and rectangular prisms [15–26], as well as micro-scale features such as reentrant cavities and engineered nucleation sites [27–31]. Only within the past few years have researchers begun to investigate more progressive cooling approaches, with a fair amount of work focused on reaching high exit qualities [10,16,24,30], such as the experiments performed by Reeser et al. [24] who exceeded exit qualities of 90% in a micro-gap heat sink with copper micro pin–fins.

A compromise between convective heat transfer and pressure drop has been well established in both numerical and experimental work. In flow boiling experiments with refrigerant R113, Mcneil et al. [21] explored fundamental differences in heat transfer between a plane copper plate and one with micro-pin–fins. Studying mass fluxes from 50 to 250 $kg/s/m^2$ and heat fluxes from 5 to 140 kW/m^2, it was found that the heat transfer coefficients were similar for plane and micro-finned surfaces. However the increased heat transfer area reduced surface temperatures for the device with micro-pin–fins. The 25 cm^2 array of 1 mm square micro-pin–fins spaced 1 mm apart produced a sevenfold increase in the pressure drop in contrast to the plane device.

Tullius et al. [26] performed numerical, single-phase optimization studies of micro-pin–fins with water as the working fluid and heat loads up to 150 W/m^2. Their results suggest that the addition of any shape micro-pin–fins increased the Nusselt number over a plane surface, but produced increased pressure drops as well. In general micro-pin–fins with a large fin height and small width cause the largest Nusselt number increase (44% and 88% increase for the tallest, and narrowest pin–fins modeled, respectively) as well as the largest pressure increase – about 16 times that of an un-finned surface at velocities of 1 m/s. The work also concluded that triangular shaped micro-pin–fins produced the highest Nusselt numbers, while ellipsoids produced the lowest pressure drop.

Extensive microfluidic flow boiling work has been performed by Koşar et al. [10,16,28,35]. In two-phase experiments with hydrofoil-shaped fins [16], R-123 was used as a working fluid at mass fluxes ranging from 976 to 2349 $kg/s/m^2$. The array of 100

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Nomenclature

Variables and parameters

A	area [cm^2, m^2]
c_p	specific heat [J/kg/°C]
E	full scale reading [mL/min]
G	mass flux [kg/s/m^2]
H	height [cm, m]
h	heat transfer coefficient [kw/m^2/°C]
h_{fg}	heat of vaporization [J/kg]
I	current [ADC]
K	flowmeter class [–]
k	thermal conductivity [W/cm/°C]
L_c	characteristic length [cm, m]
$\dot{m}$	mass flow rate [kg/s]
n	sample size [–]
Nu	Nusselt number [–]
P	perimeter [cm, m]
p_o	operating pressure [kPa, atm]
p	pressure [kPa]
Δp	pressure drop [kPa]
$\dot{Q}$	volumetric flow rate [mL/min]
q''	heat flux [W/cm^2]
R	resistance [Ω]
T	temperature [°C]
V	voltage [VDC]
x_{ex}	exit quality [–]

Greek letters and letter-like symbols

ϵ_{AS}	surface area enhancement As/Ap [–]
δ	uncertainty [–]
Ø	diameter [mm]
η	efficiency [–]
μ	viscosity [kg/m/s]
Ψ_e	extraction ratio [–]
ρ	density [kg/m^3]

Subscripts

b	bypass flow (*open flow*)
base	applied to the base of the microdevice
C	cross-sectional
c	heat transfer due to convection
d	bubble detachment
e	extracted flow (*open flow*)
ext	extraction (extraction only) flow
eff	effective
f	fluid
h	heater
in	inlet
m	*PPF* mouth
min	minimum
p	planform
S	wetted surface area
sp	single phase
TC	thermocouple reading
tp	two-phase
u	upstream
v	vapor

micron hydraulic diameter NACA 66-021 hydrofoils was fabricated in a 260 micron deep silicon minichannel. A peak in the two phase heat transfer coefficient was attributed to a transition from nucleate boiling to convective boiling. The research also concluded that critical heat flux (CHF) was triggered by device dryout and was proportional to mass velocity, and inversely proportional to mass quality.

Recently, much interest has been focused on hydrofluoroethers due to their inert chemical properties, relatively high thermal conductivity, dielectric properties, and low greenhouse potential [32]. Fu et al. [33] performed experiments with HFE7100 in diverging copper microchannels at aspect ratios of 0.83, 0.99, 1.65, 2.47, 4.23, and 6.06 — all with a hydraulic diameter of 1.12 mm. It was concluded that a thicker liquid film existed in the corners of the device with aspect ratio close to unity, compared to devices with a rectangular cross-section. The work also showed heat transfer coefficients that monotonically decreased with increasing mass quality until a quality of 0.4 was reached, the value was constant between qualities of 0.4 and 0.6, then decreased as the mass quality approached unity and CHF conditions were incipient. The research also confirmed the familiar trend of increasing CHF with increasing mass flux.

In microchannel flow boiling experiments with HFE7000, Kuo and Peles [29] studied plain channel devices, as well as structured microchannels with reentrant cavities. The use of reentrant cavities helped to extend and stabilize the subcooled boiling regime by initiating boiling at a lower wall superheat compared to the plain channel device. At mass fluxes greater than 1600 kg/s/m^2, the reentrant cavity device produced heat transfer coefficients up to 30% greater than the plain device. The enhancement was attributed to a more uniform distribution of bubbles. Consequentially, the effect diminished at higher mass qualities. Kuo [30] observed that with the low surface tension fluid, CHF would occur at much lower boiling numbers and mass qualities with increasing mass flux; a finding that confirmed earlier work by Koşar and Peles [10] using low-surface tension R-123 in silicon microchannels.

From the aforementioned discussion it can be concluded that micro pin–fins enhance the heat transfer process, however excessive pressure drops should be avoided [21,26]. The pin aspect ratio should be relatively large (e.g., tall, slender fins) to increase the Nusselt number [26], and circular or ellipsoid pin–fins produce the lowest friction factor [16,26], while triangular pin–fins improve heat transfer [26]. The maximum heat transfer coefficient is located at the transition from nucleate to convective flow boiling [16], and decreases at higher mass qualities [3,10,16,24,28,30,33]. Therefore, to avoid CHF using low surface tension fluids, finned microdevices should operate at very low qualities to dissipate high heat flux loads, or may operate at high mass qualities with very low heat flux loads. It has been well established that higher mass fluxes extend CHF, and it has been suggested that higher operating pressures may also extend CHF [10].

Here we report on a heat sink engineered to extend the performance of current micro heat sinks. By use of advanced microstructures within the heat sink, the microdevice developed for the present study has been designed to dissipate heat fluxes up to 700 W/cm^2 using the hydrofluoroether HFE7000, with minimal pumping power. The working fluid proposed is of a low surface tension and dielectric, making the heat exchanger favorable in compact or embedded electronics cooling applications. The unique microstructures within the device selectively remove high mass quality flow by directing vapor pockets to local outlets. The addition of localized outlets also reduces pressure drop within the microdevice by mitigating the fluid expansion realized during phase change heat transfer, allowing for high mass fluxes without excessive pressure drops. Large aspect ratio features (e.g., 20:3) are used to increase surface area and enhance the Nusselt number.