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Confined jet array impingement boiling

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ABSTRACT

Confined jet array impingement boiling heat transfer is investigated for water at atmospheric pressure and inlet subcooling of 8 °C for flow rates ranging between 0.33 and 0.67 L/min. Three jet configurations consisting of 2×2, 3×3 and 5×5 arrays of 1.0 mm diameter jets were tested for a jet-to-target spacing of 2 mm. A 15 mm × 15 mm plane copper surface was used as the heat transfer surface which formed a confined channel with the upper jet orifice plate. For a Reynolds number (*Re*) range of $900 \leq Re \leq 11{,}800$, tests were performed by fixing the flow rate and progressively increasing the heat flux until the Critical Heat Flux (*CHF*) was reached. The results show that the single phase heat transfer coefficient increases with increasing *Re* and is reasonably predicted by a recent jet array heat transfer correlation. However, once fully developed boiling conditions are achieved, the heat transfer is generally insensitive to the flow rate and is predicted by the well-established Cooper pool boiling correlation. Consistent with earlier confined boiling studies, this suggests that the dominant heat transfer mechanisms are associated with the local bubble activity opposed to convective influences. Contrastingly, both the Onset of Nucleate Boiling (ONB) and CHF were found to be strongly dependent on the jet velocity. For the latter, it is related to the ability of the flow to clear the confined channel of vapour. CHF predictions are compared with the measurements showing good agreement.

1. Introduction

As technologies in the electronics, aviation and military industries rapidly advance, more aggressive and effective means of cooling are required. It is predicted that heat fluxes in excess of 1000 W/cm^2 are expected to be generated in high-end electronic components in the coming years [1]. Two phase cooling is a promising candidate for high heat flux applications due to its ability to transport large thermal loads with very low effective thermal resistances. For example, Kandlikar [2] reported pool boiling experiments achieving effective heat transfer coefficients as high as 629 kW/m^2 K. To the best of knowledge, this is the highest effective thermal conductance achieved to date. Heat fluxes up to 300 W/cm^2 were reached which, albeit is very high for pool boiling, is not at the level of current high heat flux electronics nor suitable for the projected 1000 W/cm^2 target. Furthermore, pool boiling heat exchangers are not amenable to highly integrated, light weight (low liquid volume) and compact packages and are sensitive to the gravitational field.

Kalani & Kandlikar [3] demonstrated a compact tapered channel flow boiling technique with a micro-grooved surface and achieved a CHF of just over 1000 W/cm^2 and a heat transfer coefficient up to ~300 kW/m^2 K with 10 °C subcooled water as the working fluid at a moderate flow ($Re \sim 1100$). This heat exchanger not only achieved the 1000 W/cm^2 with a very low thermal resistance, it also reiterated the importance of hydraulic considerations such as requiring a moderate flow rate and low pressure drop, since they will ultimately dictate the applicability for electronics cooling applications.

Jenkins et al. [4] recently tested convective boiling for a 3×3 array of 1.0 mm water jets for similar conditions tested by Kandlikar et al. [5]. In this study, straight and radial micro-grooved surfaces were investigated and an effective heat transfer coefficient of up to ~230 kW/m^2 K was achieved with the radial micro-groove surface, transporting a heat flux of 380 W/cm^2 with a flow rate of 0.66 L/min ($Re \sim 5400$). Unfortunately, CHF was not reached for these experiments due to temperature limitations of the test facility and the pressure drop was not measured. Regardless, the results show that impinging jets are also a promising technology for high heat flux applications. This echoes earlier findings by Zhao et al. [6] who investigated single jet impingement heat transfer on a diffusion-bonded mesh microporous enhanced surface. Although

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Nomenclature

A_r	jet area to surface area ratio ($A_{jets}/A_{heated\ surface}$) (dimensionless)
CHF	critical heat flux (W/cm^2)
Co	confinement Number (dimensionless)
$C_{p,l}$	specific heat capacity of the liquid at constant pressure
d	jet diameter (m)
g	acceleration due to gravity (m/s^2)
h	heat transfer coefficient (W/m^2 K)
h_{fg}	enthalpy of vaporization
h_{tot}	combined single-phase & two-phase heat transfer coefficient (W/m^2 K)
H	jet-to-target spacing (m)
k	thermal conductivity (W/m K)
M	molar mass
Nu	Nusselt number based on jet diameter (hd/k) (dimensionless)
ONB	onset of nucleate boiling
P_{crit}	critical pressure (Pa)
P_{out}	outlet pressure (Pa)
P_r	reduced pressure (P_{out}/P_{crit})
Pr_l	Prandtl number of liquid (dimensionless)
Q	flow rate (L/min)
q''	heat flux
q''_{CHF}	critical heat flux (W/cm^2)
q''_{ONB}	heat flux at the onset of nucleate boiling (W/cm^2)
Re	Reynolds number based on jet diameter ($Re = \rho dV/\mu$) (dimensionless)
R_p	roughness parameter (μm)
S	inter-jet spacing (m)
T	temperature (K)
T_{sat}	saturation temperature (K)
T_w	surface wall temperature of the chip (K)
V	jet velocity (m/s)
Z	distance between the thermocouple and the exposed surface (m)
z	asymptotic matching parameter (-)

Greek symbols

ΔP	pressure difference across the manifold (Pa)
ΔT_{lm}	log mean temperature difference (K)
ΔT_{sub}	subcooling temperature difference ($T_{sat} - T_l$) (K)
ΔT_w	wall superheat temperature difference ($T_w - T_{sat}$) (K)
Δx	thermocouple spacing in the neck of the heater block (m)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

Cu	copper
L	liquid
g	vapour
1Ø	single phase
2Ø	two phase

the heater was quite small (6.35 mm diameter), they were able to achieve heat fluxes as high as 700 W/cm^2, though similar to the Jenkins et al. [4] study, CHF was not reached due to facility limitations and the pressure drop was not considered.

These recent jet impingement boiling studies illustrate that very high heat fluxes can be achieved with exceptionally low effective thermal resistance, especially when surface modifications are used to enhance boiling and increase the heat transfer surface area. However, these studies quantify enhancement by comparing to a baseline jet or jet array on non-enhanced surfaces, which may not be globally indicative of performance since jet arrays offer a broad range of parameters that are known to influence both single and two phase heat transfer and pressure drop. These include though are not limited to jet diameter, inter-jet spacing, jet-to-target spacing, jet area to surface area ratio, jet velocity and surface heat flux [7–10]. Within the literature, the preponderance of the jet impingement boiling studies are for single free jets and very few focus on confined submerged jet arrays [11]. Because of this our understanding and predictive capabilities for confined submerged boiling jet arrays is limited at best.

Recently, confined boiling of R134a with arrays of 112 μm jets on a 1.0 mm^2 non-enhanced surface was investigated by Browne et al. [12,13]. The influence of flow rate, jet area to surface area ratio, subcooling and heat flux on the heat transfer were tested. ONB tended to occur at higher heat fluxes for lower inlet subcooling and flow velocities and was not sensitive to the jet to surface area ratio. Both increased subcooling and area ratio improved the heat transfer. Generally, increased jet velocity resulted in higher heat transfer performance overall. Investigating oblique jets of R245fa, Buchanan and Shed [14] revealed similar findings. They found that the single phase heat transfer was dependent on jet geometry and volumetric flow rate. However, under convective boiling conditions, the heat transfer was governed by fluid inlet thermodynamic state and heat flux. Interestingly, they showed that for fully developed boiling, the heat transfer was well predicted by a pool boiling correlation indicating that the heat transfer is dominated by the presence of bubbles. Rau and Garimella [15] used the thin-foil thermography technique to study the local heat transfer to single and two phase impinging jet arrays using HFE-7100 as the working fluid. They tested 3 jet configurations, including a single jet, and kept the jet to surface area ratio constant. Albeit for relatively low heat fluxes, the results showed the coexistence of single and two phase heat transfer mechanisms under the impinging jets and jet arrays outperformed the single jet. Interestingly, the pressure drop was found to be insensitive to applied heat flux over the range tested.

The literature clearly shows that jet impingement boiling is a viable technology for cooling current and future high heat flux electronics. However, few studies exist for confined submerged jet array impingement boiling, particularly ones which carry out controlled parametric studies. Furthermore, little data is available for water nor is pressure drop typically considered. To address these, the current investigation aims to contribute to the understanding of confined water jet array impingement boiling by investigating the effects of jet configuration, flow rate and heat flux on both the heat transfer and pressure drop from single phase flow to CHF.

2. Experimental apparatus and data reduction

2.1. Experimental setup

Fig. 1 depicts the flow loop used in this investigation. Distilled water is circulated by a Grundfos Alpha2 variable speed pump. After exiting the pump, a valve is used to control the flow rate before it is measured with an inline flow meter (Swagelok VAF-M1-A5M-1-0). Prior to entering the test section, the water is pre-heated to the desired temperature, here 92 °C, using a 1 kW Omega AHPF series inline circulation heater connected to a CAL 9900 PID