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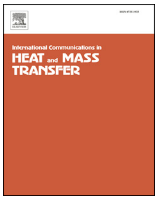

Confined jet array impingement boiling of subcooled aqueous ethylene glycol solution[☆]

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ABSTRACT

A closed-loop experimental setup was built to study the confined jet array impingement boiling of 43% mass concentration aqueous ethylene glycol solution at low jet velocities and large degree of subcoolings. A 20 mm × 40 mm rectangular thin metal film with thickness of 0.03 mm was used as the heating surface. The in-line jet array had an orifice diameter $d = 1$ mm, a dimensionless jet-to-jet spacing $S/d = 5$ or 4, and a dimensionless jet-to-target spacing $H/d = 1$, 1.5 or 3. Experiments were performed at atmospheric pressure with the saturation temperature of 106 °C, jet velocities of 0.2 m/s, 0.31 m/s and 0.5 m/s, and liquid subcoolings of 36 °C, 46 °C and 56 °C. It is found that the heat transfer coefficient in the nucleate boiling regime at first increases with the increase of heat flux and then starts to decrease before the critical heat flux (CHF). Jet velocity and jet-to-target spacing have little effects on heat transfer coefficient in the nucleate boiling dominant regime, while subcooling and jet-to-jet spacing play important roles. Not only the jet velocity but also the liquid subcooling has great influences on the boiling inception and CHF. There exists an optimal jet-to-target spacing to achieve the maximum CHF because of the tradeoff between the breakup and confinement (or expel) of vapor bubbles. For the same flow rate, $S/d = 5$ has a higher heat transfer coefficient and CHF than $S/d = 4$.

1. Introduction

Liquid jet impingement along with microchannel and spray cooling [1,2] are considered to be the most promising cooling technologies for high heat-flux electronic devices. Since nucleate boiling has advantages over single phase cooling with respect to mass flow rate, pressure drop, and uniform temperature, two-phase jet impingement heat transfer has been attracting increasing attention recently. Liquid jet impingement can be implemented in three forms: free jet in which a liquid jet is issued in a gas/vapor ambient, submerged jet in which a liquid jet is issued in a similar or same fluid ambient, and confined jet in which a liquid jet is confined between an orifice plate and a heated wall. For a large heating surface, a jet array is often preferred to achieve more uniform cooling. Because a jet array is usually realized using a jet array (orifice) plate which actually behaves as the top confinement plate, a submerged jet array can also be considered as a confined jet array.

For a single free jet at a given jet velocity, nucleate boiling was typically initiated at a distance away from the impingement zone and then progresses inward with increasing heat flux [3] until critical heat flux (CHF) occurred. Wolf et al. [4] found that in the single phase convection and partial boiling regimes, the downstream position of the stagnant zone did affect heat transfer coefficient, while for the fully developed nucleate boiling regime, it did not affect heat transfer coefficient. Their results also indicated that jet velocity had no influence on heat transfer in the fully developed nucleate boiling regime, although it could delay the onset of nucleate boiling to a higher heat flux and wall superheat. Monde and Katto [5] found that CHF was mainly affected by jet velocity and heater surface area, while CHF had less to do with liquid subcooling.

As to submerged jet impingement boiling, Ma and Bergles [6] found for single circular jet impingement boiling of R113 that the boiling curves for different jet velocities converged asymptotically to the same curve with increasing heat flux, indicating that the fully-developed nucleate boiling was the main heat transfer mechanism when heat flux was high enough. Zhou and Ma [7] further pointed out that the pool boiling heat transfer correlations using stagnant pressure could predict the heat transfer coefficient of jet impingement boiling at high jet velocity in the fully-developed nucleate boiling regime correctly, and that CHF was mainly affected by jet velocity but not by liquid subcooling. Nevertheless, the liquid subcooling could shift the boiling curve (wall superheat versus heat flux) to the left, i.e., enhancing boiling heat transfer coefficient. In another experiment [8], they further found that boiling hysteresis was very obvious for highly wetting fluid (such as refrigerant and electronic cooling liquid), and boiling inception wall

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Nomenclature

A	heating surface area
d	jet orifice diameter
h	heat transfer coefficient
H	jet-to-target spacing
I	electrical current
k	thermal conductivity of the thin film
l	the thickness of the thin film
N	jet orifice number
P	heating power
p	pressure
q''	heat flux
R	electrical resistance of the heater
Re_{jet}	jet Reynolds number
S	jet-to-jet spacing
T_{in}	jet inlet temperature
$T_{w,i}$	local wall temperature
$T_{w,ave}$	average wall temperature
T_{sat}	saturation temperature
ΔT_{sub}	liquid subcooling
ΔT_{sat}	wall excessive temperature (wall superheat)
$\Delta T_{w,ave}$	average temperature difference between wall and jet inlet
U	electrical voltage
V_{jet}	jet velocity

Greek symbols

$\forall$	volumetric flow rate
ρ	density
μ	dynamic viscosity

Subscripts

ave	average value
CHF	critical heat flux
in	jet inlet
w	heating surface temperature
sat	saturated state
sub	subcooled state

superheat was decreased with increasing liquid subcooling, but independent of jet velocity and orifice diameter. Cardenas and Narayanan [9,10] found in their submerged single circular jet impingement boiling experiments of water at sub-atmospheric pressure that jet Reynolds number had a large effect on heat transfer coefficient at the partially developed nucleate boiling regime while plays negligible role when heat flux was high enough, which agreed with Ma's result [6]. Cardenas and Narayanan [11] performed experiments on saturated submerged impingement boiling of FC72, and found that boiling inception wall superheat temperature varied randomly and was relatively independent of jet Reynolds number. They also found that Monde's CHF correlation [5] for a free jet could predict their experimental results very well when Re > 4000, but had a large deviation when Re < 4000 because of the retardment of the jet by ambient liquid.

The literatures on confined jet impingement boiling were only available until recently. Meyer et al. [12] studied the confined jet impingement boiling of FC72 using a one dimensional planar orifice (jet) array with local spent flow retrieve between two jets. The heating surface was simulated by using a heated copper block and surface temperatures were estimated by measuring temperatures within the copper block. They found that the difference of boiling curve for different jet velocities becomes smaller with increasing heat flux, especially for jet velocity below 3 m/s, and the boiling curves converged in the fully-developed nucleate boiling regime. It was also found that CHF was very sensitive to both jet velocity and subcooling, and CHF for a jet array was different from a single jet, indicating that interaction of adjacent jets was significant. Shin et al. [13] carried out an experiment on jet impingement boiling of PF5060 using a single planar jet by measuring the downstream temperature distribution on the thin film heater surface. They focused on the effect of confinement height by conducting experiments under different jet-to-target spacings (H/W = 0.5, 1.0 and 4.0, with W being the width of the planar jet, W = 2 mm). The experiments were conducted under high jet Reynolds numbers of 2000, 3000 and 5000, respectively, with fixed jet inlet subcooling of 25 °C at atmospheric pressure. They found that for small jet-to-target spacing (H/W = 0.5), even in the fully developed nucleate boiling regime, the local wall temperature still increased with increasing distance from the jet impingement centerline. This indicated that the local heat transfer coefficient varied along the wall jet (or spent flow) direction, which was apparently different from the free jet boiling where heat transfer coefficient was very uniform once boiling enters the fully developed regime [4]. Their experimental results also revealed that the worst confinement height was at H/W = 1.0 where the lowest CHF occurred. Sung and Mudawar [14] arranged a one dimensional jet array on top of a microchannel, and found that this kind of "hybrid microchannel and jet impingement" configuration could achieve very high heat transfer coefficient and CHF because of the periodical destruction of large bubbles along the microchannel by cold jets.

From the above literature review, it is found that the coolants used in the previous studies were water, electronic coolants (such as FC72 and PF5052), or refrigerants (such as R113 and R134a). Electronic coolants or refrigerants normally have poor heat transfer performance because of their low thermal conductivity and latent heat of vaporization, and are more likely to result in wall temperature overshooting and boiling hysteresis due to their high wettability. Although water has very good thermal properties, because of its high solidification temperature it cannot be applied in a cold environment, such as in outer space applications where the working environment temperature is normally as low as −20 °C. In this paper, we propose to use 43% mass concentration aqueous ethylene glycol solution (with the solidification temperature of about −25 °C) as a coolant for outer space cooling applications. Although, ethylene glycol aqueous solution has been used as an engine antifreeze because of its good thermophysical properties and its subcooled flow boiling has been investigated previously [15,16], no open references on jet impingement boiling of this fluid can be found. On the other hand, confined jet arrays with small jet-to-target spacings and low flow rates (low jet velocities) are often preferred in many practical applications because of the space limitation and the energy efficiency of cooling method (pumping power consumption). However, most previous research studies were focused on the free or submerged single jet, which had very different heat transfer characteristics from the confined jet. Although some previous studies on confined jets are available, they were mainly for a single planar jet or a one dimensional jet array at high jet velocities, and effects of subcooling and jet-to-jet spacing have not been studied in details. In this study, the impingement boiling characteristics of an in-line confined circular jet array will be investigated experimentally. The effect of jet velocity (at low velocities), liquid subcooling, jet-to-target spacing, and jet-to-jet spacing on heat transfer coefficient and CHF will be discussed in this paper.

2. Experiments

2.1. Experimental setup

The experimental setup is shown in Fig. 1, where the closed loop mainly consisted of a liquid reservoir, a magnetic gear pump, a test section, a plate heat exchanger, a filter, a bank of flow meters, and some