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Development and validation of a semi-empirical model for two-phase heat transfer from arrays of impinging jets

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ABSTRACT

Two-phase jet impingement is a compact cooling technology that provides high-heat-flux dissipation at manageable pressure drop, with applications in cooling power electronics and server modules. The extensive set of geometrical parameters and operating conditions that determine the heat transfer behavior of jet impingement systems provide an attractive level of design flexibility. In the present study, a semi-empirical approach is developed to predict heat transfer from arrays of jets of liquid that undergoes phase change upon impingement. In the modeling approach developed, the jet array is divided into unit cells centered on each orifice that are assumed to behave identically. Based on prior experimental observations, the impingement surface in each unit cell is divided into two distinct regions: a single-phase heat transfer region directly under the jet, and a surrounding boiling heat transfer region along the periphery. Single-phase convection and boiling heat transfer correlations available in the literature are used to estimate the heat transfer coefficient distribution in each region, and the mean surface temperature of the unit cell is estimated via area-averaging. An analysis is performed to show that the model outputs are sensitive to the heat transfer coefficient correlations used as inputs, with the choice depending on the heat flux input and the expected operating regime. Experiments are performed to validate the area-averaged thermal performance predictions. The model results are also compared against experimental data in the literature. The semi-empirical modeling approach developed in this work successfully represents the different heat transfer modes and transitions that occur during two-phase jet impingement. The location of transition to boiling predicted by the model is consistent with prior experimental observations of an inward-creeping boiling front with increasing heat flux. The predicted temperature difference between the surface and the jet inlet across all experimental comparisons has a mean absolute percentage error of 3.88%. The proposed modeling approach is demonstrated to be a practical tool in the development of two-phase jet array impingement devices, allowing for parametric exploration across the expansive design space.

1. Introduction

Two-phase jet impingement is an attractive approach for cooling densely packed electronics systems due to the integration of highly effective heat transport mechanisms into a compact and flexible design. The heat transfer behavior of an impinging jet array is dependent on many design parameters, such as the orifice dimensions, array size and distribution, orifice-to-target spacing, and operating/boundary conditions, as illustrated in Fig. 1. Prediction of the heat transfer performance when the jets undergo phase change is particularly challenging due to the coupled phase-change phenomena and flow dynamics. On the other hand, exhaustive parametric evaluation via experimentation is infeasible.

During two-phase jet impingement, both single-phase convection and boiling occur concurrently at different regions of the heat transfer surface. On a smooth, flat surface, nucleate boiling initiates at the periphery of the wall jet as the heat flux is increased, and creeps inwards toward the stagnation region directly under the jet orifice [1–3]. In a study that used infrared thermography to measure the temperature of a thin-film heater cooled by jet array impingement, Rau and Garimella [1] observed a stable boiling front, beginning furthest away from the jet centers and moving inward with increasing heat flux. At the highest heat fluxes tested for a single jet case, the boiling front reached the jet center

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Nomenclature

A_c	jet unit cell area (s^2)
A_f	ratio of orifice area to cell area ($\pi/(4(s/d)^2)$)
C	constants in heat transfer profile
c_p	liquid specific heat
d	orifice diameter
H	orifice-to-target spacing
h	local convective heat transfer coefficient
$\bar{h}$	area-averaged heat transfer coefficient
h_0	stagnation-point heat transfer coefficient
k	liquid thermal conductivity
l	orifice plate thickness
M	fluid molecular mass
$\dot{m}$	mass flow rate
N	number of jets in the array
Nu	local Nusselt number (hd / k)
$\overline{Nu}$	area-averaged Nusselt number ($\bar{h}d/k$)
Nu_0	stagnation Nusselt number ($h_0 d/k$)
p_c	fluid critical pressure
p_{op}	operating pressure
Pr	liquid Prandtl number ($c_p\mu/k$)
q''	heat flux
r	radial distance from stagnation point
r_{eq}	equivalent radius of jet unit cell ($s/\sqrt{\pi}$)
R_p	peak roughness
Re	Reynolds number ($\rho v_j d/\mu$)
s	jet-to-jet spacing and square unit cell dimension
T	temperature
ΔT_{sub}	degree of subcooling (T_{sat} - T_j)
v	velocity

Greek symbols

μ	liquid dynamic viscosity
ρ	liquid density
σ	heat transfer profile width parameter

Subscript

f	evaluated at film temperature
j	jet inlet condition
nb	nucleate boiling region
ref	reference heat transfer value for single-phase jet impingement
s	surface condition
sat	saturated condition
sp	single-phase heat transfer region

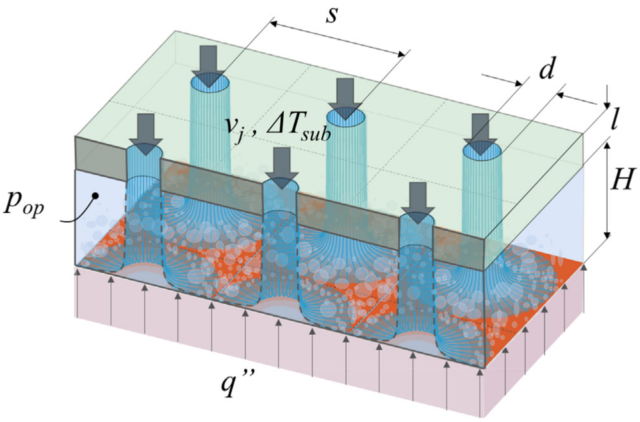

Fig. 1. Geometrical parameters and operating conditions relevant in jet array impingement heat transfer.

($r_{nb}/d = 0$), such that boiling occurred across the entire surface. The behavior of the boiling front was also investigated by Dukle and Hollingsworth [4,5] using liquid crystal thermography in a submerged unconfined liquid jet. They found that the boiling front was marked by the location at which the level of wall superheat was sufficient to cause nucleation. Because the local wall superheat in the single-phase region is controlled by the local convective transport, a correlation between the location of the boiling front and the convection coefficient profile was identified [4,5]. Orifice-to-target spacing, jet-to-jet spacing, orifice plate thickness, jet diameter, and jet velocity determine the shape of this local convection coefficient profile [6–9].

In submerged jet impingement, the local single-phase heat transfer coefficient achieves a maximum value near the stagnation point under the jet orifice and decreases radially outward in a monotonic fashion as the wall jet boundary layer grows in thickness [1,5,6,9,10]. In some cases, a secondary peak in the local convection coefficient has been observed to occur at a short radial distance from the stagnation region [5], and is associated with transition to turbulence in the wall jet; in confined jet impingement, this transition is also associated with reattachment of the recirculating flow pattern created by the confinement gap [11,12]. This secondary peak is more significant at higher jet Reynolds numbers and smaller orifice-to-target spacings [7,11]. In jet arrays with significant jet-to-jet interactions, the secondary peak is less pronounced than for a single jet [6].

Correlations that predict the local and average convection coefficient during single-phase jet impingement heat transfer have been developed [13–17]. Chang et al. [14] correlated both local and average single-phase heat transfer data for a single jet and compared these correlations with average heat transfer data from jet arrays. Using fluids with Prandtl numbers ranging from 0.7 to 25.2, Li and Garimella [9] developed correlations for both area-averaged convection coefficients and stagnation-point convection coefficients that took into account fluid-property dependence. Martin [16] developed such single-phase correlations for single round and slot nozzles, as well as for arrays of nozzles. Campbell et al. [17] performed experiments over a relatively wide range of Reynolds numbers (141–6670), small jet diameters (0.377–1.01 mm), and large numbers of jets (16–324) and developed a correlation for area-averaged convection coefficients. For two-phase jet impingement, Chang et al. [11] proposed a correlation based on superposition of nucleate boiling and single-phase convective heat transfer mechanisms. Buchanan and Shedd [18] also proposed a superposition-based correlation; one mode of heat transfer is suppressed when the other is dominant.

The current work develops and validates a semi-empirical model to predict area-averaged two-phase heat transfer from arrays of impinging jets. The model considers confined and submerged liquid jet arrays impinging on a smooth, flat surface generating a uniform heat flux. The model separately treats the single-phase and boiling regions, and thereby is uniquely able to provide performance predictions across the single-phase, partial boiling, and fully boiling heat transfer regimes that have been observed experimentally. Correlations from the literature are used to predict the single- and two-phase heat transfer coefficients in sub-regions of a unit cell under each jet. An analysis is performed to assess sensitivity of the model outputs to changes in key input parameters.