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Study of the effects of single and multiple periodic droplet impingements on liquid film heat transfer

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ABSTRACT

A study of heat transfer and film dynamics caused by single and multiple streams of impinging droplets using HFE-7100 as the cooling liquid under constant heat flux conditions is presented. Single and multiple streams of mono-dispersed droplets were produced using a piezoelectric droplet generator with the ability to adjust parameters such as droplet impingement frequency, droplet diameter, droplet velocity, and spacing between adjacent impinging droplet streams. In this study, a heater consisting of a thin layer of Indium Tin Oxide (ITO) as heating element, combined with a Zinc Selenide (ZnSe) substrate was used for characterizing the heat transfer behavior and hydrodynamic phenomena of impinged liquid films near or at the onset of critical heat flux (CHF). Film thickness inside the impact crater was measured using the Total Internal Reflection (TIR) technique. Hydrodynamic phenomena of the droplet impact craters were analyzed using a high speed imaging technique. Impact regimes of the impinging droplets were identified and classified, and their effects on heat transfer performance are discussed.

The study supports the notion that forced convection is the main heat transfer mechanism inside the impact crater due mainly to the high frequency and periodic nature of droplet impingement. Furthermore, droplet impingement regimes such as spreading and splashing have been observed to play an important role in the overall heat transfer behavior. Spacing between adjacent impinging droplet streams is also an important factor in surface cooling when multiple droplet streams are used.

1. Introduction

Thermal management of electronic equipment remains one of the most enduring technical challenges of the world today [1]. Modern electronic packages are complex systems, which involve multifunctionality and miniaturization, which result in high thermal loads. Moreover, the intricate configuration of current electronic packages leads to highly concentrated and non-uniform thermal loads from sources such as microprocessors and memory devices.

Proper selection of thermal management technologies is the key to the proper functioning of electronic devices. Passive cooling systems such as heat spreaders, relies on natural or forced convection of air, making them inadequate for high thermal load management applications. Active systems involving a phase change process are clear alternatives for managing high thermal loads. Among the options available to dissipate high thermal loads, which are currently being studied, we include: spray cooling, jet cooling, vapor compression refrigeration, and thermosyphons. Among the phase change thermal management techniques mentioned above, spray cooling is thought to be the most appropriate for future high thermal load management applications due to its high heat removal capability and uniformity.

Despite of the attractive features of spray cooling, the physical mechanisms of spray cooling are still not well understood due to the vast number of physical variables and complexity of sprays. As a result, it is desirable to isolate and control the number of variables found in sprays by using single and multiple streams of mono-dispersed droplets. However, it is important to keep in mind that droplet impingement shares limited resemblance with spray cooling, because spray cooling is characterized by greater droplet density, incoherent droplet impact and random trajectories that arise from droplet collisions. Nevertheless, the purpose of the study was to uncover the thermal and hydraulic mechanisms

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Nomenclature

d_d	droplet diameter
d_j	jet diameter
d_{orf}	orifice diameter
f	droplet impingement frequency
h	heat transfer coefficient
h_{fg}	latent heat of vaporization
k	thermal conductivity
L	distance between adjacent droplets in the same droplet stream
$\dot{m}''$	mass flux rate
n	refractive index
Nu_d	Nusselt number using diameter as characteristic length $\left(\frac{hd}{k_l}\right)$
Pr	Prandtl number
q''	heat flux
q''_c	critical heat flux
q''^{*}_c	normalized critical heat flux $\left(\frac{q''_c}{\dot{m}'' h_{fg}}\right)$
Q	volumetric flow rate
r	radial position
Re_d	Reynolds number using diameter as characteristic length $\left(\frac{\rho v d}{\mu}\right)$
s	spacing between adjacent impinging droplet streams
St	Strouhal number using droplet diameter as characteristic length $\left(\frac{f d_d}{v}\right)$
t	liquid film thickness
T	temperature
V	voltage
v	velocity
We	Weber number using droplet diameter as characteristic length $\left(\frac{\rho v^2 d_d}{\sigma}\right)$
σ	surface tension
μ	dynamic viscosity
ρ	density
δ	viscous boundary layer thickness

Subscripts

c	impact crater
dr	droplet
j	jet
l	liquid
lv	liquid–vapor interface
orf	orifice of droplet generator

produced by successive droplet impacts since they play a dominant role at the liquid-surface interface.

There is a need to understand the interaction between impinging droplets and surface cooling by conducting experiments with high spatial and temporal resolutions to understand how physical parameters such as flow rate, impact spacing and non-dimensional numbers such as Weber number affect the overall heat transfer behavior. With the goal of gaining a better understanding of the physics of droplet impingement cooling, well controlled experiments were performed using a dielectric fluid suitable for electronic cooling applications with the following specific objectives:

- To study the effects of coherent droplet impingement on surface cooling by characterizing the morphology of impact craters formed by successive droplet impingements.
- To measure CHF over a range of experimental conditions.
- To measure the liquid film thickness inside the droplet impact crater.
- To quantify the effects of droplet parameters such as droplet diameter and velocity, and Weber and Strouhal numbers on CHF.
- To quantify the effects of horizontal spacing between adjacent impinging droplet streams on heat transfer behavior.
- To identify the main heat transfer mechanisms inside the droplet impact crater.

2. Literature review

A significant number of spray cooling studies have been reported in the last two decades that have considered the effects of droplet properties. For instance, Yang et al. [2,3] used an air-atomizing nozzle for water spray cooling with flow rates in the range of 1–3 L/h. A major contribution of their research work was the measurement of impinged liquid film thickness and how it relates to heat transfer. Film thickness and liquid film topography were obtained using laser-based and holographic techniques, respectively. It was found that the film thickness was between 75 and 300 μm [2,3]. Yang et al. [2,3] suggested that the main mechanism of heat transfer was thin-film nucleate boiling with secondary nucleation caused by the impinging droplets.

Griffin et al. [4] and Rini et al. [5–7] studied bubble behavior caused by spray cooling when using FC-72 as cooling liquid. Griffin et al. [4] used a transparent heater to observe bubble formation due to entrapped air [4] when droplets impacted the heated surface. They concluded that impinged droplets could provide secondary nucleation sites for the formation of bubbles which was considered to be the main mechanism of heat transfer enhancement in spray cooling applications [4]. Horacek et al. [8] performed a series of experiments using a single nozzle with FC-72 as cooling liquid. Measurements of the Contact Line Length (CLL) were performed on semitransparent heaters using the Total Internal Reflectance (TIR) technique. A strong correlation between CLL and wall heat flux was observed and postulated.

In the parametric study conducted by Navedo [9] and Chen et al. [10], the effects of droplet velocity, droplet flux and droplet diameter on surface cooling were studied. In their study, a dilute spray with large droplet velocity was found to be more effective than a denser spray with low droplet velocity in terms of CHF, when droplet flux was fixed [9,10]. It was found that droplet velocity had the most dominant effect on CHF, followed by droplet flux and droplet diameter [9,10]. These findings and conclusions are in disagreement with the results obtained by Mudawar et al. [11], who argued that volumetric flux and not the mean droplet velocity is the proper scaling factor for heat transfer correlations near CHF. Kim [12] reached similar conclusions, which are presented at length in his review paper [12].

Other physical parameters important in spray cooling such as liquid film thickness have only been studied to a limited extent. Yang [3] measured the maximum film thickness of the entire impinged film. Pautsch et al. [13] used a methodology developed by Shedd et al.[14], which requires complete knowledge of the refractive index of the liquid and vapor phases above the heater. The presence of entrapped air or vapor bubbles, which routinely appear in sprays even without heat transfer [15], would make the accurate measurement of the liquid film thickness difficult because they tend to change the light path across the fluid medium.