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Heat transfer characteristics of double, triple and hexagonally-arranged droplet train impingement arrays

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ABSTRACT

In this study, hydrodynamics and heat transfer of multiple droplet trains impinging a pre-wetted solid surface have been investigated experimentally. A piezo-electric droplet generator has been designed and constructed, which is capable of producing double, triple and hexagonally-arranged droplet trains. A translucent sapphire substrate coated with a thin layer of indium tin oxide (ITO) was used as flat heating element. The effects of droplet Weber number, impact spacing and impingement pattern on liquid film hydrodynamics and heat transfer have been evaluated using high speed optical imaging and IR thermal imaging techniques. High speed images show that a hump was formed between two impact craters for double droplet train impingement. Surface jet flows were observed among impact craters for triple and hexagonally-arranged droplet train impingement arrays. Heat transfer results reveal that horizontal impact spacing and impingement pattern play significant roles in cooling performance. For double droplet train impingement, it was found that higher impact spacing leads to better cooling performance both locally (i.e. within the impingement zone) and globally (i.e. outside the droplet impingement zone). For triple droplet train impingement, there is an optimum impact spacing for heat transfer. For hexagonally-arranged droplet train impingement arrays, lower impact spacing leads to better cooling performance locally. However, higher impact spacing leads to better cooling performance globally. Comparisons have been made between droplet train impingement and circular jet impingement for various impingement patterns. Heat transfer measurements show that droplet train impingement leads to better cooling performance for various impingement patterns. In summary, results reveal that the combined effects of the droplet Weber number and impingement pattern are significant factors in the study of droplet-induced surface heat transfer phenomena.

1. Introduction

Future electronic systems will require the use of high heat flux removal technologies due to the amazing growth in thermal loads, which could lead to decreased reliability and reduced life time. Innovative thermal management technologies are needed to improve the safety and reliability of electronic equipment. Over the past few decades, liquid cooling technologies such as jet impingement cooling, channel flow cooling and spray cooling have shown the ability to dissipate high thermal loads [1]. However, spray cooling does provide the best balance among high heat flux removal capability, isothermality and fluid inventory [2].

During the past few decades, numerous studies [3–10] have been conducted to investigate the effects of spray parameters on spray cooling performance. For instance, Tilton [3] studied spray cooling experimentally by using pressure-atomized water sprays. The average droplet diameter and mean droplet velocity were about 80 μm and 10 m/s, respectively [3]. Tilton [3] claimed that lower droplet diameter leads to higher heat transfer coefficient. Tilton [3] also claimed that mass flow rate of water may not be a factor in controlling Critical Heat Flux (CHF).

Sehmbey et al. [4] studied the heat transfer characteristics of liquid nitrogen spray cooling using different nozzles and various flow rates. Sehmbey et al. [4] found that heat transfer coefficient increases with mass flow rate of the cooling liquid. It was also found that both CHF and heat transfer coefficient increase as the orifice size of the nozzle decreases [4]. Rini et al. [5] studied the effects of droplet-bubble interactions on spray cooling perfor-

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Nomenclature

d	diameter
d_d	droplet diameter
d_j	jet diameter
d_{orf}	orifice diameter
f	droplet impingement frequency
h	heat transfer coefficient
k	thermal conductivity
q''	heat flux
Q	volumetric flow rate
S	impact spacing
T	temperature
V	velocity
V_d	droplet impingement velocity
V_j	jet impingement velocity
ν	kinematic viscosity
σ	surface tension
Pr	Prandtl number
Re	Reynolds number $\left(\frac{V \cdot d}{\nu}\right)$
We	droplet Weber number $\left(\frac{\rho \cdot V_d^2 \cdot d_d}{\sigma}\right)$
Nu	Nusselt number $\left(\frac{h \cdot d}{k}\right)$

mance. Rini et al. [5] claimed that higher droplet flux leads to an increase in secondary nucleation sites, which is favorable for heat transfer. Rini et al. [5] also claimed that higher droplet flux leads to a shorter nucleation bubble growth time (i.e. the early removal of nucleation bubble).

Even though various studies [3–10] have been conducted to understand the effects of spray parameters on spray cooling performance, the physical mechanisms associated with spray cooling are still not well understood [2]. In order to better understand the physical mechanisms of spray cooling, researchers [11–37] have tried to isolate spray parameters and focused their efforts on studying droplet impingement dynamics [11–18] and droplet impingement cooling [19–37]. For instance, Zhang et al. [14] studied the crown propagation dynamics induced by a single droplet train impingement both numerically and experimentally. Zhang et al. [14] revised the crown propagation model proposed by Yarin and Weiss [11] by taking into account the film thickness and velocity distribution within the propagating droplet. Zhang et al. [14] also clarified the definitions of droplet-induced crater and crown.

Trujillo et al. [22] investigated the heat and momentum transfer characteristics of single droplet train impingement numerically. Trujillo et al. [22] claimed that crown propagations induced by multiple droplet train impingement help convect hotter bottom liquid upwardly and outwardly, leading to an effective thermal mixing mechanism. It was also found that the compression of the liquid film to 15 μm inside the impact crater allowed for a significant rise in heat transfer through the liquid film, helping dissipate a large portion of heat [22].

Soriano [24] and Soriano et al. [25] studied the effects of single and collinearly arranged triple droplet train impingement on liquid film heat transfer. Soriano [24] and Soriano et al. [25] claimed that high frequency droplet train impingement cooling leads to a more uniform Nusselt number distribution compared with circular jet impingement cooling. Soriano [24] and Soriano et al. [25] also claimed that single phase forced convection was the main heat transfer mechanism within the impact craters even at high heat flux conditions.

Tsai [26] and Zhang et al. [27] studied single and double droplet train impingement cooling experimentally. It was found that a 0° droplet impingement angle (i.e. droplets impacting heater surface normally) results in optimum heat transfer performance for a single droplet train impingement cooling [26,27]. For double droplet train impingement cooling, heat transfer is highly dependent on horizontal impact spacing [26,27].

Zhang et al. [29] studied the effects of droplet-induced spreading-splashing transition on surface cooling for a single droplet train impingement. Zhang et al. [29] found that the region near the crown's base experiences a shift in wall temperature during the droplet propagation process. Zhang et al. [29] also found that at a fixed flow rate condition, strong splashing is unfavorable for heat transfer at high heat flux conditions.

The effects of droplet impingement arrays on surface heat transfer have only been investigated to a limited extend. Zhang et al. [34] studied the effects of triangulated droplet train impingement array on surface jet flows and heat transfer. Zhang et al. [34] also claimed that a transition from laminar to chaotic surface jet flows was observed by adjusting droplet Weber number and horizontal impact spacing. Zhang et al. [34] claimed that heat transfer performance is highly dependent on the observed surface jet flow regimes.

Even though recent studies of droplet train impingement cooling have received considerable attention, very few studies have considered the effects of droplet train impingement arrays on surface heat transfer. With the goal of gaining a better understanding of droplet train impingement cooling, well-controlled experiments have been performed with the following specific study objectives in mind:

- To study the heat transfer characteristics of various droplet train impingement patterns, such as double, triple and hexagonally-arranged droplet train impingement arrays.
- To investigate the effects of impact spacing and droplet Weber on heat transfer performance for droplet train impingement cooling.
- To develop heat transfer correlations for various droplet impingement patterns.
- To compare the heat transfer performance of droplet train impingement and circular jet impingement.

From this study, experimental results reveal that droplet Weber number, impact spacing and impingement pattern play significant roles in terms of heat transfer performance. Heat transfer correlations have been developed and analyzed for various droplet impingement patterns. Results also show that droplet train impingement leads to better heat transfer performance than circular jet impingement at fixed flow rate and impact spacing conditions.

2. Experimental setup

An experimental setup, as the one shown in Fig. 1, was developed and used to conduct droplet impingement experiments. Detailed information of the experimental setup can be found in references [24–27].

3M^{TM} Novec^{TM} engineering fluid (HFE-7100) was chosen as cooling liquid because of its low saturation point of 61 °C and dielectric properties, which make it suitable for electronic cooling applications. A syringe pump (Cole Parmer dual syringe pump)