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Sub-cavity liquid volume beneath spray droplet impacts into static liquid layers, and initial estimates of the heat flux required to dry out this volume

Nicholas L. Hillen [a], John M. Kuhlman [b,*]

[a] West Virginia University, Mechanical & Aerospace Engineering Dept., ERB 120A, P.O. Box 6106, Morgantown, WV 26506, United States
[b] West Virginia University, Mechanical & Aerospace Engineering Dept., ESB 317, P.O. Box 6106, Morgantown, WV 26506, United States

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ABSTRACT

The time variation of the sub-cavity liquid volume beneath individual droplet impact cavities was measured for ranges of drop Weber and Reynolds numbers that match those for a full cone spray nozzle of interest. Cavity lifetime was also measured. These results will be used in a Monte-Carlo model of the spray cooling process that is currently under development. Droplet Weber numbers were varied between 140 and 1000. Corresponding Reynolds numbers ranged between approximately 1200 and 3600. These ranges matched Phase Doppler results that were obtained for the water spray under study. Thickness of the static liquid layer into which the single droplets impacted was varied between 0.2 and 1.0 times the droplet diameter.

The measured sub-cavity liquid volume generally was between 60% and 80% of the original droplet volume over much of the cavity lifetime. Increasing the static liquid layer thickness increased this plateau value of the sub-cavity liquid volume between these lower and upper bounds, for Weber numbers greater than around 400. Sub-cavity liquid volume also increased somewhat as Weber number was increased. The cavity lifetime increased significantly as Weber number increased.

The sub-cavity liquid volume and cavity lifetime results were scaled to values for the corresponding spray droplets at equal (*We*, *Re*). These were then used in an energy balance between the energy transferred through a heated wall to the sub-cavity liquid and the sum of the sensible heating and latent heat required to dry out the spray drop sub-cavity liquid volume within the cavity lifetime. These computed heat fluxes to dry out the drop impact cavities were then used to estimate the overall average heat flux for a heated surface that would dry out these individual spray droplet impact cavities. The resulting average heat flux values were between 400 W/cm^2 and 800 W/cm^2. These predictions are similar to the range of CHF values reported in the literature for water, of 500 W/cm^2 to 1000 W/cm^2.

1. Introduction and background

Spray cooling shows significant promise for applications where a uniform, high heat flux is necessary at low surface superheats [1–4]. However, a complete understanding of the complex spray cooling phenomena is lacking. This complexity also makes it infeasible to fully simulate a spray cooling process using computational fluid dynamics (CFD). A preliminary Monte-Carlo (MC) model of spray cooling has been developed by Kreitzer [5,6] and is being improved in an effort to develop a quantitatively accurate model that can be used for design purposes. Early work to improve the model is described in Kuhlman et al. [7]. This model uses pseudo-random number generation to match the measured spray droplet diameter distribution and average radial spray flux distribution for a spray nozzle of interest. The model also uses dimensional time scales and correlations taken from existing spray data and CFD simulations to model the detailed impacts of all droplets over the entire heater surface, in an attempt to predict the overall average heat transfer rates. This original model showed significant promise; for example it correctly predicted that the onset of critical heat flux would occur at the outer edges of the circular heater. The model also showed that droplet impact cavities formed by the smaller drops (below about 50 μm) would generally fill in due to surface tension and gravity prior to being covered over by subsequent droplet impacts. Conversely, cavities formed by the larger drops were generally covered over by subsequent droplet impacts prior to filling in due to capillary action. However, the

* Corresponding author. Tel.: +1 304 293 3180; fax: +1 304 293 6689.
E-mail address: john.kuhlman@mail.wvu.edu (J.M. Kuhlman).

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Nomenclature

A	area
B	dimensionless constant in remote asymptotic solution for h^*, from [28].
C_p	specific heat at constant pressure
D	droplet diameter
D_{10}	droplet average diameter
D_{32}	Sauder mean diameter
Fr	Froude number = $V^2/(gD)$
h	local cavity liquid film thickness
h_{fg}	latent heat
h_0	initial liquid layer thickness
h_0^*	nondimensional initial liquid layer thickness = h_0/D
q''	heat flux
R	radial location in cavity
Re	Reynolds number = $\rho VD/\mu$
t	time
T	temperature
V	droplet impact velocity
Vol	sub-cavity liquid volume
We	Weber number = $\rho V^2 D/\sigma$
x	horizontal coordinate normal to spray centerline along PDPA optical axis
y	lateral horizontal coordinate normal to spray centerline
z	coordinate along spray centerline, originating at nozzle exit

Greek Symbols

$\Delta\tau$	dimensionless cavity lifetime
η	index of refraction
μ	viscosity
ρ	density
σ	surface tension
τ	dimensionless time = tV/D

Superscripts

*	dimensionless quantity

Subscripts

b	bottom
c	cavity
crown	crown value
dry	dry out
f	film
Fluid	fluid
Glass	glass
i	time index
max	maximum
s	spray
sat	saturation
Total	total value
w	wall
0	initial

MC model was not able to quantitatively predict either the heat transfer rates or the value of the CHF. The present work is a step in our ongoing studies that aim to improve the accuracy of this initial MC model to the point where it may be used as a design tool.

In the present work, Phase Doppler Particle Analyzer (PDPA) system results are presented for the spray characteristics of a Spraying Systems 1/8G full cone spray nozzle using water as the test liquid [8–10]. The droplet axial and radial mean velocities and arithmetic mean and Sauter mean diameters were determined for nozzle operating gage pressures between 1.38 and 4.14 bar. The PDPA data was analyzed to determine a test matrix of relevant Weber numbers and Reynolds numbers for studies of single droplets impacting into static liquid layers of various depths. Larger droplets were used (approximately 3 mm, versus about 60–200 μm for the spray droplets), to make the measurements easier to obtain. The single droplet experiments were conducted using a mixture of 46.2% glycerol in water by mass [8,11,12] to enable matching of the spray droplet Reynolds numbers at the corresponding Weber numbers. Data was obtained at residual liquid layer thicknesses covering the range reported in the literature ($h_0^* = h_0/D$ between 0.2 and 1.0). For each single drop experiment, the time history of the liquid film thickness beneath the drop impact cavity (the "sub-cavity film thickness") was measured both versus the radial coordinate measured from the drop impact centerline, and versus time, using a non-contact confocal chromatic optical thickness sensor [13,14]. The sub-cavity film thickness data was then integrated radially at each time step to compute the time variation of the total liquid volume beneath the cavity (the "sub-cavity liquid volume"). The lifetime of the droplet impact cavity was also determined. The measured sub-cavity liquid volumes and cavity lifetimes have been used to compute the sub-cavity heat flux that would be required to dry out the drop impact cavities within the cavity lifetime. The heat fluxes averaged over the heater surface have been estimated by an approximate method using the computed local sub-cavity heat fluxes for cavity dry out; these average values are found to be on the same order of magnitude as the range of reported critical heat flux (CHF) values reported in the literature [3,4]. The first application of this method for one single droplet impact case at a Weber number of 600 for a very thin liquid layer ($h_0^* = 0.113$) using pure water as the test liquid has recently been reported by Kuhlman et al. [15]. This experiment [15] used Weber numbers representative of those in the spray of interest, but the drop Reynolds numbers were approximately an order of magnitude too large to apply to typical water sprays. As a result, the reported sub-cavity liquid volume was significantly smaller than in the present experiments, being nominally 30% of the droplet liquid volume, versus 60–80% for the current, new results at the appropriate range of Reynolds numbers.

The possibility that the time history of the thin liquid films that form on a heated surface during each individual spray droplet impact during spray cooling may be a significant contributor to the enhanced heat transfer rates achievable in spray cooling was first discussed by Kuhlman et al. [16]. The cooler droplet liquid is brought into close contact with the heated surface, thereby resulting in increased local transient wall heat fluxes during the lifetimes of the droplet impact cavities. However, these regions of enhanced local heat flux would also be more susceptible to localized dryout of the heated surface. They are thus also expected to contribute to the onset of CHF. The three-dimensional single droplet impact CFD simulations by Sarkar and Selvam [17] focused primarily on high local transient heat fluxes they observed in the contact line regions as a vapor bubble moved along the heated surface due to a nearby droplet impact. However, their results also showed a significant enhancement of the local transient heat flux into the droplet impact cavity itself. Work by Soriano et al. [18] and Gerhing et al. [19] on periodic trains of identical droplets, all impacting at the same location, were also consistent with these speculations. They observed the highest wall-normal temperature gradients at the droplet impact centerline, during the initial impact. Also, cold drop liquid was observed to penetrate the existing liquid film