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Droplet impact cavity film thickness measurements versus time after drop impact and cavity radius for thin static residual liquid layer thicknesses

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ABSTRACT

Comprehensive measurements are presented of the sub-cavity liquid film thickness for single droplet impacts into a static residual liquid layer, measured both versus the radius away from the cavity impact centerline and the local time since initial contact of the drop with the static residual liquid layer. Droplet Weber and Reynolds numbers are representative of the highest-energy droplets for a water spray of interest, with Weber numbers ranging between 140 and 1000. These high-impact-energy droplets create drop impact cavities with the longest cavity lifetimes, thinnest sub-cavity liquid films, and smallest sub-cavity liquid volumes, all of which are expected to contribute to the droplet impact cavities being both a significant source of enhanced transient local heat flux into the sub-cavity liquid volumes, as well as locations of early local surface dry out.

Sub-cavity liquid film thickness is essentially constant over the inner radial portion of the cavity, but is significantly thinner at large cavity radius, somewhat inboard of the inner crown wall. The inner, constant thickness region ranges between 62% and 85% of the maximum cavity radius in extent, with an average size of 72% of maximum cavity radius. The thickness of this inner, constant thickness region ranges between 100 μm and 162 μm, with an average value of 126.5 μm, or around 4% of the nominal droplet diameter of 3 mm. This thickness varies by only around 3% of its average value for single values of the Weber number and static residual liquid layer thickness. At the end of cavity formation, the thinner regions farther outboard in the cavity are about 23% thinner than the sub-cavity film thickness in the inner region; but later, during the collapse of the crown, the thinner outboard region averages 34% less than the thickness in the inner, constant thickness region.

Two major data accuracy limitations are discussed, and approximate error magnitudes are estimated. Drop-to-drop uncertainty in impact location and the uncertainty in the level of three-dimensionality of the cavity retraction process are both inherent limitations in the present liquid film thickness point-measurement method; these limitations could be avoided if a global thickness measurement over the entire cavity surface could be obtained; e.g., via stereo high-speed imaging.

1. Introduction

Spray cooling has a demonstrated capability to achieve relatively uniform and also very high heat fluxes, at relatively low surface superheats [1–4]. However, application of this technology has been limited due to problems in developing practical closed-loop spray cooling systems, such as difficulties in phase separation, especially in microgravity environments [2,5], and challenges in scale-up of laboratory results to large surface areas [2,6,7]. Another important limitation is the incomplete state of understanding of the complex, interrelated processes influencing the spray cooling performance.

Dimensional-physical reasoning by Kuhlman et al. [8] led to the expectation that the impacts of the larger, higher impact energy spray droplets should lead to enhanced transient heat transfer to the very thin liquid film below the drop impact cavity; that is, the heat flux to the "sub-cavity liquid volume" was expected to be higher than the average heat flux to the surrounding, much thicker residual liquid layer. An experimental investigation has been undertaken [9] to explore this reasoning, and the present data, taken from this thesis by Hillen, is a vital step in this process.

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Nomenclature

D	droplet diameter
Fr	Froude number = $V^2/(gD)$
h	local cavity liquid film thickness
h_0	static residual liquid layer thickness
h_0^*	nondimensional initial liquid layer thickness = h_0/D
h_0'	nondimensional initial layer thickness, normalized by h_0; = h/h_0
R_c	radial location in cavity, measured from cavity centerline
R_{max}	maximum cavity radius
Re	Reynolds number = $\rho VD/\mu$
t	time since drop initial contact with static residual liquid layer
V	droplet impact velocity
We	Weber number = $\rho V^2 D/\sigma$

Greek symbols

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

Superscripts

$*$	dimensionless quantity
$'$	dimensionless quantity, normalized by h_0

Subscripts

c	cavity
max	maximum
0	initial

This full data set has not been fully presented to date. Instead, the raw data were integrated radially to the base of the inner crown wall to compute the sub-cavity liquid volume, and these data were presented in [9]. These computed sub-cavity liquid volume results [9] have then been used to estimate representative average heat fluxes that would be required to dry out the sub-cavity liquid volume by the end of the cavity lifetime [10,11]. In all cases, for 140 < We < 1000, and for 0.2 < h_o^* < 1.0, the estimated average heat fluxes to dry out the sub-cavity liquid volume (between 400 and 800 W/cm^2) from [11] are close to, but somewhat below, the range of critical heat flux values reported for water as the coolant [3,4] of between 500 and 1000 W/cm^2. The goal of the present paper is to fully document the basic sub-cavity liquid film thickness data from [9] that are the basis for this significant observation.

2. Experimental apparatus and procedure

A gravity-driven droplet generator consisting of an adjustable-height reservoir fitted with a solenoid valve and hypodermic needle of appropriate diameter has been used to generate the single drops for the present work. Drop diameters for the present data were nominally 3–3.6 mm in diameter; see Table 1. Drop impact velocity was set by adjusting the droplet height of fall to achieve the desired Weber number values to cover the range of interest for a water spray from a Spraying Systems 1/8G full cone spray nozzle; see Table 1 for the velocity and Weber number values. The drops were impacted into a shallow, static liquid pool in a 15 cm square by 5 cm deep clear acrylic tank that was fitted with a centrally located 2.5 cm diameter, 152 μm thick glass optical port. A schematic of the experimental apparatus is shown in Fig. 1. A Precitec CHR-SE confocal chromatic thickness sensor [12] was mounted beneath the acrylic tank, aligned so that it could be used to measure the thickness of the liquid film at the centerline of the tank through the glass optical access port. By traversing the acrylic tank and CHR optical thickness sensor together horizontally with respect to the fixed location of the droplet generator perpendicular to the view of the apparatus in Fig. 1 using a 2.5 cm linear translation stage fitted with a manual micrometer barrel, the time histories of the liquid layer thickness were measured, both on the drop impact cavity centerline and at several radial locations away from the cavity centerline. This CHR sensor had a nominal measurement range of 3 mm, with a resolution of 0.1 μm and a measurement rate of 4000 thickness measurements per second. Use of a CHR sensor to measure the liquid layer and drop impact cavity thicknesses was first demonstrated by van Hinsberg et al. [13]. The liquid used for the present experiments was a mixture of 46.2% glycerin by mass in distilled water. Fluid properties (density, viscosity, and surface tension) have been computed at the measured laboratory temperature using the methods in references [14,15]. See references [9–11,16] for further details of the apparatus used.

A Photron Fastcam SA-5 high-speed video camera fitted with a Nikon 200 mm macro lens has been used for several purposes in this work. First, by viewing the drop impacts from the side, the maximum diameter of the drop impact cavity was measured for each combination of drop diameter and impact velocity and thickness of the static liquid layer, in order to determine the radial locations at which to measure the sub-cavity liquid film thickness [9]. Generally, a nonuniform spacing of these measurement locations was used, with smaller radial increments at larger cavity radii, near the inner crown wall location. For the fifteen different combinations of droplet impact Weber number and static liquid layer thickness that have been studied, a total of between 8 and 19 different radial measurement locations have been used. Thirteen of these cases used between 8 and 11 different radial locations, while two of the We = 140 cases used 14 (at h_o^* = 0.5) and 19 locations (at h_o^* = 0.2). After the radial measurement locations had been determined, then the camera was synchronized with the CHR sensor, and the video camera was used to determine the time of initial contact of the drop with the static liquid layer [9,16] for each individual droplet impact. This same video clip was also used to

Table 1
Dimensional and dimensionless parameters for single droplet experiments.

Case	h_o (μm)	D (mm)	V (m/s)	h_o^*	We	Re	Fr
5	3160	3.52	4.20	0.9	993	3570	510
	1750	3.54	4.16	0.5	984	3560	499
	707	3.52	4.18	0.2	984	3560	507
4	3120	3.49	3.69	0.9	762	3080	398
	1730	3.47	3.72	0.5	771	3090	407
	695	3.46	3.75	0.2	780	3100	413
3	3010	3.09	3.55	1.0	622	2670	415
	1550	3.08	3.55	0.5	621	2640	415
	606	3.11	3.66	0.19	667	2740	439
2	3500	3.47	2.72	1.01	410	2250	217
	1760	3.47	2.73	0.51	413	2270	215
	714	3.48	2.72	0.21	414	2290	217
1	3020	3.03	1.73	1.0	145	1190	100
	1530	3.06	1.73	0.5	146	1290	98
	724	3.03	1.67	0.24	135	1180	94