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Optimal spray characteristics in water spray cooling

Ruey-Hung Chen *, Louis C. Chow, Jose E. Navedo

Department of Mechanical, Materials and Aerospace Engineering, University of Central Florida, 4000 Central Florida Boulevard, Orlando, FL 32816-2450, USA

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Abstract

The dependence of the efficiency of liquid usage (η) at CHF on spray parameters was experimentally investigated for subcooled water spray cooling. A spray can be characterized by three independent parameters (droplet Sauter-mean diameter, d_{32}, droplet velocity, V, and droplet flux, N). In this study, each of these parameters was varied with the other two kept constant by using a combination of spray nozzles, operating pressures, and distance between the nozzle exit and the heater surface. It was found that η varies with $N^{-2/3}$, $d_{32}^{-14/5}$ and $V^{1/4}$, respectively, when two of the three spray parameters are kept nearly constant. It was also found that CHF varies with $N^{1/6}$ and $V^{1/4}$ and is relatively independent of d_{32}. It is concluded that to achieve the maximum possible CHF while using the minimum quantity of water, it is desirable to select nozzles that produce as small a droplet diameter with as high a velocity as possible.

Keywords: Boiling; Critical heat flux; Droplet; Efficiency; Scaling; Spray

1. Introduction

In spray cooling, the heat-removing capability relies largely on phase change, or nucleate boiling, in addition to convective heat transfer associated with the fluid motion [1]. The description of heat transfer process in spray cooling can be found in [1–3].

It is of importance to ask how efficiently the fluid landing on the heater surface removes heat from the heated surface, as it affects the delivery pressure required and the system size of the practical spray cooling system. The efficiency of liquid usage at CHF serves as a convenient indicator. Spray cooling reaches a critical heat flux (CHF, or q''_c) beyond which nucleate boiling ceases to exist [3]. Increasing the liquid flow rate would help to increase CHF for a given spray nozzle. However, the benefit of the increase in CHF is not proportional to the increase in the liquid mass flux (G) [1,3,4]. In this study, the efficiency of liquid usage at CHF (η) is defined as the ratio of the critical heat flux over the latent heat of the liquid flux delivered by the spray nozzle:

$$\eta = q''_c / G h_{fg} \tag{1}$$

It is noted that q''_c is the actual heat flux, including heat transfer due to phase change and convection. Inferring from the data in Ref. [4], the contribution of subcooling to CHF is less than 25%. Since not all the liquid landing on the heater would be heated to the boiling temperature before falling off of the heater, the contribution of subcooling is expected to be less than 25%. The uncertainties in q''_c and G are approximately 5.5% and 10%,

* Corresponding author. Tel.: +1 407 823 3402; fax: +1 407 823 0208.
E-mail address: chenrh@mail.ucf.edu (R.-H. Chen).

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Nomenclature

CHF (or q''_c)	critical heat flux, W/m^2
d_{32}	Sauter-mean diameter, m
G	liquid flux on heater surface, kg/m^2 s
h_{fg}	latent heat of evaporation, J/kg
N	mean droplet flux (=nV), 1/m^2 s
n	mean droplet number density, 1/m^3
q''	heat flux, W/m^2
q''_c	critical heat flux, W/m^2
V	mean droplet speed, m/s

Greek symbols

α	exponent in $N^{-\alpha}$
β	exponent in $d_{32}^{-\beta}$
γ	exponent in $V^{-\gamma}$
η	efficiency of liquid use at CHF

Table 1
Experimental results demonstrating the dominant effects of d_{32} on η over a wide range of V but a still narrow range of N

	Condition		
	(a)	(b)	(c)
Nozzle type	Bete#1	B200	Bete#2
Location, X (cm)	5.0	7.5	9.5
Pressure, P (psi)	80.0	80.0	120.0
V (m/s)	13.6	7.1	13.7
G (kg/cm^2 s)	0.0034	0.0032	0.0014
N (10^6/cm^2 s)	11.21	12.11	14.43
d_{32} (μm)	83.7	79.6	57.4
T_{CHF} (°C)	132.7	132.1	129.2
CHF (W/cm^2)	708.1	640.6	695.8
η (%)	9.0	9.0	22.3

respectively [4]. Therefore, the uncertainty in η is approximately 11%.

In Ref. [4], three independent spray parameters were identified that affect CHF in water spray cooling. They are the mean droplet velocity (V), the mean spray droplet flux (N), and the Sauter-mean droplet diameter (d_{32}). These parameters are also expected to affect the value of η. Attempts were previously made to correlate η with spray parameters and only some success was demonstrated [1,3], mainly because the spray parameters were not independently varied as was done in Ref. [4].

This paper addresses the efficiency of liquid usage under CHF conditions. The data of spray parameters and CHF are taken from a previous paper (Tables 1–7 of Ref. [4]), along with an additional data set (Table 1 in this article), and analyzed and the results are presented. Correlations are sought in the form of $\eta \propto N^{\alpha}$, d_{32}^{β}, and V^{γ}.

2. Experiment

The heater (1×1 cm^2) was made of a pure copper block, heated by four 500-W cartridge heaters. The reader is referred to Ref. [4] for all details regarding the design considerations, fabrication of the heater and uncertainties in the surface temperature (approximately 3 °C) and heat flux (approximately 5% at 1000 W/cm^2) measurements. In Ref. [4], the measurement and verification of G (in Eq. (1)) were also described in detail.

3. Results and discussion

It is noted that the straight lines in all figures presented below represent the slopes or the approximate values of α, β and γ in the $\eta \propto N^{\alpha}$, d_{32}^{β}, and V^{γ} correlations. They are not meant to fit through the data.

3.1. Effect of the mean droplet flux (N)

Two sets of data using different, but narrow, ranges of d_{32} and V are taken from Tables 1 and 2 in Ref. [4]. For one set of the data, N was varied from 7.30×10^6/cm^2 s to 29.00×10^6/cm^2 s (by a factor of 4.2), while d_{32} and V were kept in narrow ranges 56 μm ± 3% and 7.5 m/s ± 10%, respectively. This set of data is represented by the squares in Fig. 1. For the second set of data, where N was increased from 5.52×10^6/cm^2 s to 17.40×10^6/cm^2 s and then to 18.83×10^6/cm^2 s (by a factor of more than 3), while d_{32} and V were kept in narrow ranges, 76 μm ± 5% and 10.5 m/s ± 5%, respectively. The circles in Fig. 1 represent this second set of data. An attempt to correlate data with $\eta \propto N^{\alpha}$ led to $\alpha \approx -2/3$. The wide ranges of values of N are noteworthy, suggesting the scaling can properly correlate the experimental data of η and N. Similar attempts were also made for CHF for the same sets of data. It can be seen from Fig. 2 that CHF correlates well with $N^{1/6}$.

With the ranges of d_{32} and V relaxed (±15% and ±20%, respectively) and N increased from 5.52×10^6/cm^2 s to 29.0×10^6/cm^2 s (data from Table 3 in Ref. [4]), no definite trend of η with N could be found. On the other hand, the CHF data appear to follow a general increasing trend with $N^{1/6}$, as shown in Fig. 3. As will be shown below, the dependence of η on d_{32} is much stron-

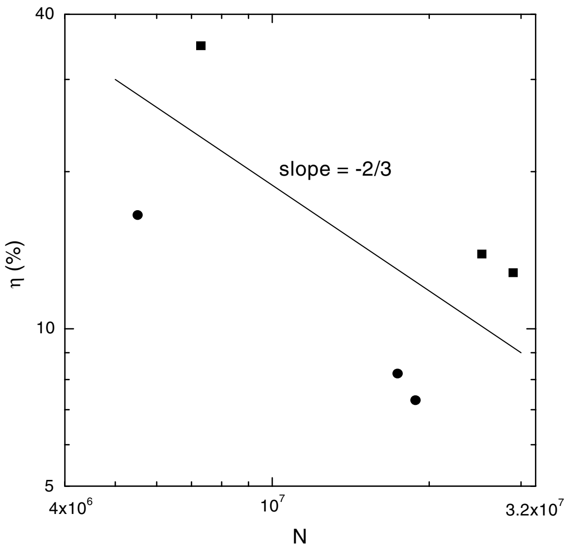

Fig. 1. Results of η by varying N while keeping d_{32} within 56 μm ± 3% and V within 7 m/s ± 10% (squares) and keeping d_{32} within 76 μm ± 5% and V within 10.5 m/s ± 5% (circles). The straight line demonstrates that $\eta \propto N^{1/6}$.

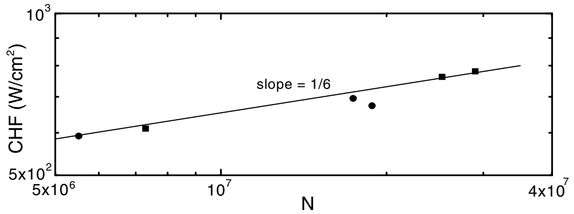

Fig. 2. Results of CHF by varying N while keeping d_{32} within 56 μm ± 3% and V within 7 m/s ± 10% (squares) and keeping d_{32} within 76 μm ± 5% and V within 10.5 m/s ± 5% (circles). The straight line demonstrates that CHF $\propto N^{-2/3}$.

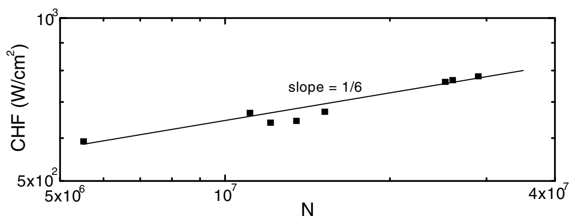

Fig. 3. Results of CHF by varying N while keeping d_{32} within 68 μm ± 15% and V within 7.5 m/s ± 20%. The straight line demonstrates that CHF $\propto N^{1/6}$. Note that for these more relaxed parameter ranges, no consistent trend of η vs. N can be found (see discussion in text).

ger than on N and a slightly more relaxed range of d_{32} would lead to competing effects of N and d_{32}.

3.2. Effects of droplet Sauter mean diameter (d_{32})

Two sets of data were obtained to reveal the effects of d_{32} on η. For the first set of data (Table 4 in Ref. [4]), d_{32} was varied by a factor of approximately 3 from 62.2 to 191.4 μm, while fixing V at approximately 6.0 m/s ± 5% and N at approximately 5.40×10^6/cm^2 s ± 5%. As d_{32} is increased, there is a consistent trend of decrease in η. The reduction in η is significant, from 33.3% to only 1.2%, a factor of approximately 28, over the range of d_{32}.

The second set of data reveal that over the narrow ranges of N and V (Table 5 in Ref. [4]), η decreases by approximately 9 times from 34.8% to 3.9% as d_{32} is increased by a factor of approximately 2, from 57.3 to 115.7 μm. This occurs while the improvement of CHF is a negligible 7% as d_{32} is increased over the range [4]. Attempts to correlate these two sets of data in the form of $\eta \propto d_{32}^{\beta}$ led to $\beta \approx -14/5$, as shown in Fig. 4. This value of β is larger than that of α, suggesting a much stronger dependence of η on d_{32} than on N.

To further confirm the strong dependence of η on d_{32}, values of N and V were then relaxed to be within 30% of 5.80×10^6/cm^2 s and 25% of 6.5 m/s, respectively, while d_{32} was increased by a factor of more than 3 (from 57.3 to 191.4 μm). This relaxed set of data is represented by the triangles in Fig. 4. It can be seen that $\beta \approx -14/5$ is a good approximation.

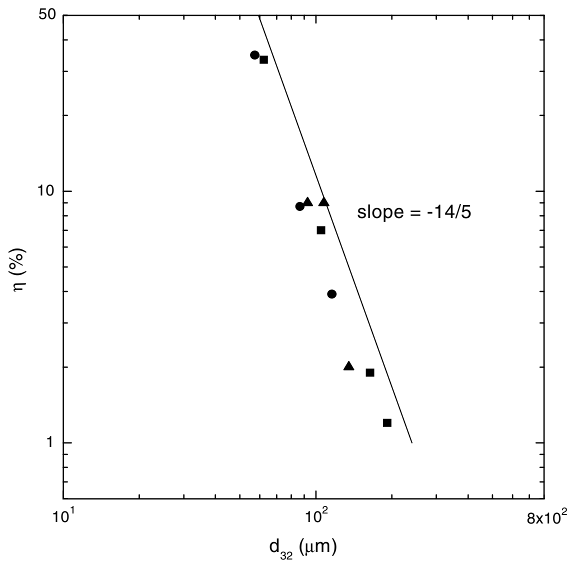

Fig. 4. Results of η by varying d_{32} while keeping N within 5.40×10^6/cm^2 s ± 5% and V within 6.0 m/s ± 5% (squares), keeping N within 8.00×10^6/cm^2 s ± 10% and V within 7.2 m/s ± 7% (circles), and keeping N within 5.80×10^6/cm^2 s ± 30% and V within 6.5 m/s ± 25% (triangles; more "relaxed" ranges of N and V). The straight line demonstrates that $\eta \propto (d_{32})^{-14/5}$.

3.3. Effect of mean droplet velocity (V)

Data from Table 7 of Ref. [4], where N and d_{32} were kept in narrow ranges ($N = 15.0 \times 10^6$/cm^2 s ± 10% and d_{32} = 68.5 μm ± 2%). It is also noted that for nearly constant N and d_{32}, $G = N\pi\rho_l d_{32}^3/6$ is also nearly constant, as shown in that table. By increasing V by a factor of more than 5 (from 4.64 to 24.10 m/s), while keeping N and d_{32} in narrow ranges, η is increased from 10.0% to 15.1%, by a factor of approximately 0.5. It is also found that for the same increase in V, CHF increases also by a similar factor, from 636.7 to 945.7 W/cm^2. It appears that the increase in η is closely related to the increase in CHF for a given mass flux G. If a relationship is sought for CHF (and η) $\propto V^\gamma$, then γ is found to be approximately 1/4, as can be seen in Fig. 5.

An attempt based on all the other data presented in Ref. [4] to correlate the values of η with V revealed a negligible effect of V on η. Also consider conditions (b) and (c) in Table 1 of the present paper, which were not previously presented. The values of N are similar (12.11×10^6/cm^2 s and 14.43×10^6 /cm^2 s, respectively). Increasing V from 7.1 m/s (condition (b)) to 13.7 m/s (condition (c)) leads to an increase η by a factor of 2.47 from 9.0% to 22.3%. However, this increase in η might very well be due to the relatively small decrease in d_{32} from 79.6 to 57.4 μm. This is because varying V by a similar factor of 2 (conditions (b) and (c)) did not lead to a change in η. Taking $\beta = -14/5$, then $(57.4/79.6)^\beta = 2.50$, which is close to the factor by which η was increased.

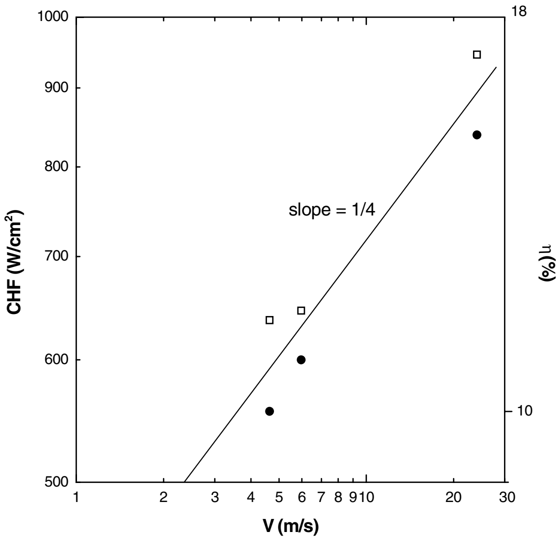

Fig. 5. Results of CHF (open squares) and η (circles) by varying V while keeping N within 15.0×10^6/cm^2 s ± 10%, d_{32} within 68.0 μm ± 2%, and G nearly constant. Both η and CHF have similar increasing trends with V, approximately with $V^{1/4}$. Note the log–log scale.

For similar values of V equal to 13.6 and 13.7 m/s, the smaller value of d_{32} (57.4 μm of condition (c) vs. 83.7 μm of condition (a) in Table 1) results in a larger value of η (22.3% vs. 9.0%, a factor of 2.44). It is apparent that β = [log(22.3/9.0)/log(83.7/57.4)] = 2.70, which is consistent with an above-mentioned value of 14/5. This result also further demonstrates the dominant effect of d_{32}.

4. Concluding remarks

The dependence of η on N suggests an implicit dependence on V and/or n because $N = nV$. As discussed earlier, using a wide range of atomizers one can independently vary N and V. Therefore, $\eta \propto N^\alpha$ for a given V can be rewritten as $\eta \propto n^\alpha$. With $\alpha = -2/3$, this result implies that for a given value of V, increasing n, which is accompanied by a proportional increase in N, leads to a decrease in η. Therefore, dense sprays are not beneficial for enhancing liquid usage efficiency, while dilute sprays are desirable as they increase the efficiency of liquid use. In other words, increasing n for a given V results in excess flow of liquid, which would flow over the heater without being vaporized or significantly heated. There exist evidences that a portion of the droplets may be prevented by the uprising vapor flow from reaching the heater surface [5].

It can readily be noted that to maintain a given N, a combination of small/large n and large/small V can be used. The above discussion leads to the conclusion that a dilute (small n) with large velocity (V) yields a higher efficiency. Increasing the droplet velocity should help droplets overcome the uprising vapor flow to reach and wet the surface, thereby increasing CHF and η.

The above discussion suggests that an optimal combination of small values of d_{32} and N and large values of V would result in large CHF while conserving the liquid usage. Under such conditions, small values of $N(=nV)$ can be achieved by having very dilute sprays (i.e., very small values of n) to offset the large value of V in order to maintain small values of N. For a given value of $G(= nV\pi\rho_l d_{32}^3/6)$, the most efficient combination would be a large V (for large CHF) and a small d_{32} and n (for large η).

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