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TECHNICAL NOTE

A critical heat flux correlation for droplet impact cooling at low Weber numbers and various ambient pressures

W. M. HEALY, P. J. HALVORSON†, J. G. HARTLEY‡ and S. I. ABDEL-KHALIK
George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0405, U.S.A.

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INTRODUCTION

Spray cooling has received interest as a technique to dissipate extremely high heat fluxes. Potential applications include the cooling of electronics, lasers, and leading edges of aircraft. Sprays are currently employed in automobile fuel injection systems and quenching of metals in foundries. As a first step in studying spray cooling, single streams of droplets impacting a heated surface have been investigated by a number of authors [1–5]. Although many studies have examined droplet cooling beyond the Leidenfrost temperature, there are numerous practical applications which occur below that point. Recently, Sawyer *et al.* [6] developed a correlation for the critical heat flux (CHF) for a monodispersed stream of droplets; this correlation and its range of applicability are given as follows:

$$\frac{\mathrm{CHF}^*}{\rho_l h_{fg} V} = 0.1660\, We^{-0.4138} St^{0.8906}$$

$$207 < We < 866, \quad 0.007 < St < 0.03. \qquad (1)$$

Equation (1) had a 95% confidence level of $\pm 22\%$ and $R^2 = 0.964$ for the data upon which it was derived. Table 1 gives a listing of the experimental parameter ranges used. The asterisk on CHF signifies that it is an average heat flux over the initially wetted surface area rather than the entire heated surface area. As noted in [6], such normalization is necessary in order to make the data universally applicable. The droplet was assumed to form a cylindrical film upon impact, and the Kurabayashi–Yang equation [7], equation (2), was used to calculate the diameter of the film.

$$\frac{We}{2} = \frac{3}{2}\beta^2 \left\{ 1 + 3\frac{We}{Re}\left[\frac{\mu_l}{\mu_{\mathrm{wall}}}\right]^{0.14} \left[\beta^2 \ln(\beta) - \frac{\beta^2 - 1}{2}\right] \right\} - 6. \qquad (2)$$

Healy *et al.* [8] confirmed that this equation provides accurate predictions of the diameter of the film formed by droplet impact. The correlation of Sawyer *et al.* was checked with an additional data set from Messana [9], who examined the CHF associated with a monodispersed stream of droplets at atmospheric pressure with We ranging from 245 to 455 and St ranging from 0.0089 to 0.015. The results showed that the correlation worked well for the new data set with an average absolute error of 9.6%.

Table 1. Experimental parameters from Sawyer *et al.* [6] and Halvorson [15]

	Sawyer *et al.* [6]	Halvorson [15]
We	207–866	55–109
St	0.007–0.03	0.0019–0.037
V (m s^{-1})	2.4–4.6	1.3
D (mm)	1.5–2.7	2.3–4.0
f (s^{-1})	12–42	1–15
P (atm)	1	0.2–2.0
ΔT_{sub} (°C)	75	40–101

As can be seen by the ranges of experimental parameters, equation (1) applies to high values of We. At these values, droplet impact is expected to result in droplet fragmentation. For droplets impacting a surface heated beyond the Leidenfrost point, it has been found that the droplets break up beyond $We \approx 70$ [1, 10]. However, a splashing threshold has not been determined for droplets impacting surfaces at low superheats owing to the complex interactions between the spreading droplet and the surface [11]. From pictures of impacting droplets, however, it appears that droplets fragment when $We > 100$ while lower values of We generally result in droplets which remain intact [12–14]. Video images from the data of Sawyer *et al.* show that droplet fragmentation occurred for the high We used in their study.

Recently, a large data base for droplet impact CHF was presented by Halvorson *et al.* [5, 15]. These authors determined CHF by observing the peak in the heat flux vs surface superheat curve as the surface temperature was increased above the saturation point of the fluid. The experimental procedures are described in detail in ref. [5]. Table 1 gives the experimental parameter ranges for these experiments. The data set, which is tabulated in ref. [15], covers a lower range of We than Sawyer's experiments, and video images of the impact process show no evidence of droplet fragmentation. In addition, ambient pressures for the experiments ranged from 0.2 to 2.0 atmospheres. The results of these experiments were compared to predictions of Sawyer's correlation; Fig. 1 shows a plot of the predicted CHF* vs the experimental CHF* for all data points taken at 1 atmosphere. The correlation clearly does not apply in the lower range of We used in Halvorson's experiments. Furthermore, equation (1) is not able to predict the effects of varying ambient pressure. Distinct trends in the data were observed for different ambient pressures, but the correlation does not include terms to account for the influence of pressure.

The purpose of the present study is to develop a correlation

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† Present address: Siemens Nuclear Power Division, Richland, Washington, U.S.A.

‡ Author to whom correspondence should be addressed.

NOMENCLATURE

c	specific heat [kJ (kg K)$^{-1}$]
CHF*	critical heat flux based on area of spread film [W cm^{-2}]
d	diameter of fully spread film [mm]
D	diameter of impacting droplet [mm]
f	frequency [s^{-1}]
h_{fg}	heat of vaporization [kJ kg^{-1}]
P	pressure [atm]
Re	Reynolds number $= \rho VD/\mu$
St	Strouhal number $= fD/V$
ΔT_{sub}	subcooling = saturation temperature minus initial droplet temperature [°C]
V	impact velocity [m s^{-1}]
We	Weber number $= \rho V^2 D/\sigma$.

Greek symbols

β	spreading ratio $= d/D$
μ	viscosity
ρ	density
σ	surface tension.

Subscripts

atm	atmospheric
f	saturated liquid
g	saturated vapor
l	liquid at room temperature
wall	at wall temperature.

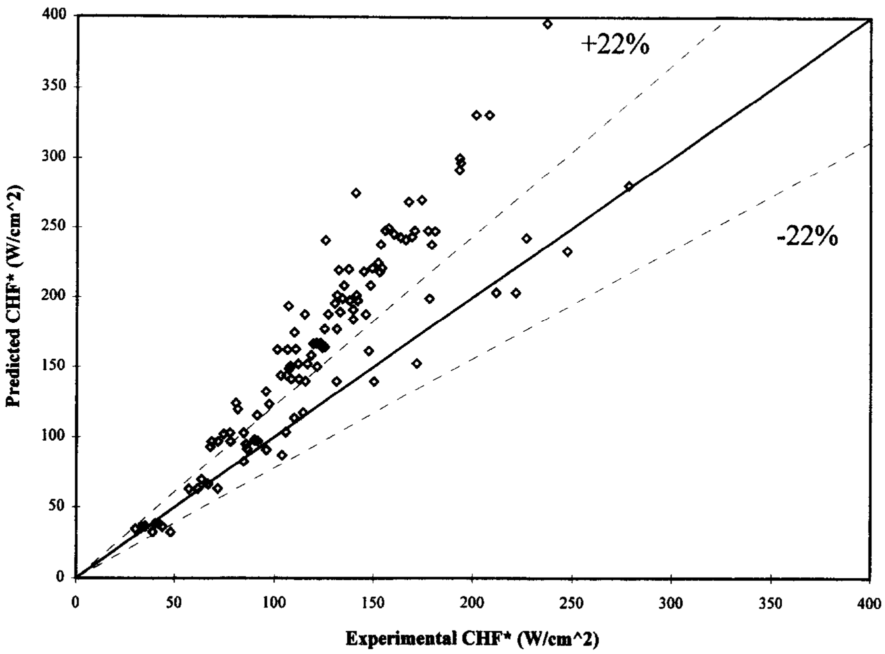

Fig. 1. Comparison between predictions of Sawyer *et al.*'s correlation [6] and experimental data from Halvorson [15] for low Weber numbers at one atmosphere. (Dashed lines represent 95% confidence interval for Sawyer *et al.*'s correlation.)

for CHF* applicable at low *We* and different ambient pressures (i.e. subcoolings) to serve as a companion to the one developed in ref. [6] for high *We*.

CORRELATION DEVELOPMENT

As a first step in accounting for the influence of pressure, all properties were calculated at the saturation temperature of the liquid. In addition to introducing subcooling as part of an independent parameter in the regression analysis, the newly defined *We* and *Re* also changed the spreading ratios predicted by equation (2). The effect of subcooling was further accounted for using the approach of Ivey and Morris [16]. This approach involved adding a subcooling correction to the heat of vaporization in the non-dimensional CHF. Even with this correction included, data from experiments at different pressures were not well correlated. Thus, a pressure ratio (P/P_{atm}) was included as an independent parameter in the regression analysis. The resulting correlation is given as equation (3):

$$\frac{\mathrm{CHF}^*}{\rho_f\left[h_{fg}+0.1\left(\frac{\rho_f}{\rho_g}\right)^{3/4}c\Delta T\right]V} = 0.146\,We^{-0.9816}St^{0.6883}\left(\frac{P}{P_{atm}}\right)^{0.6081}. \quad (3)$$

The least-squares fit has an R^2 value of 0.972, and the 95% confidence level is $\pm 20\%$.

Figure 2 shows a plot of the predictions of the new cor-

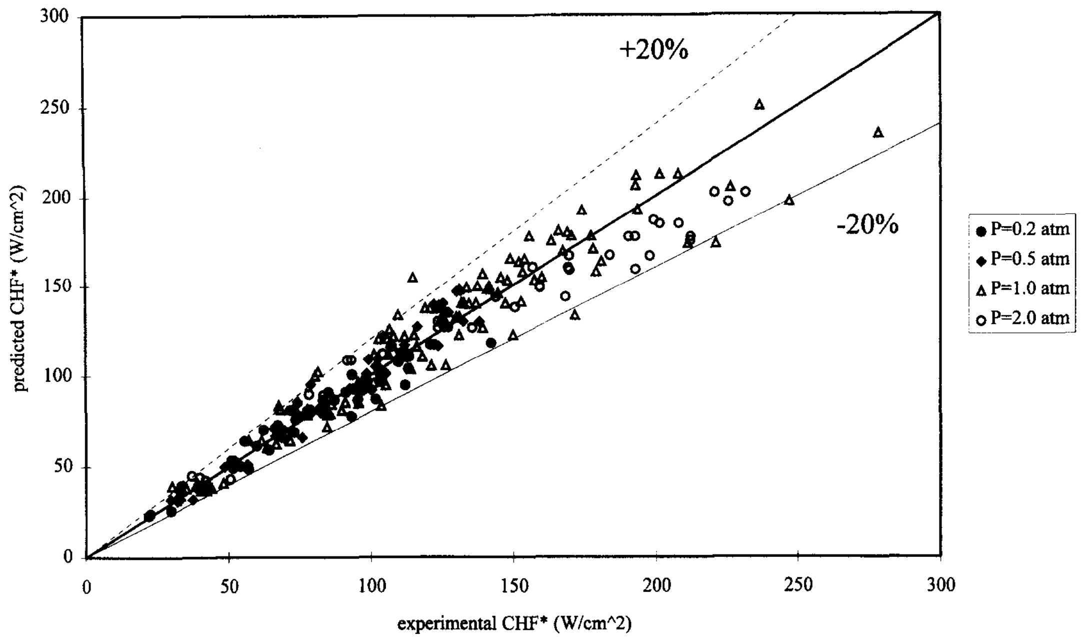

Fig. 2. Comparison between predictions of new correlation and experimental data from Halvorson [15]. (Dashed lines represent 95% confidence interval for new correlation.)

relation versus the experimental value of CHF* for each data point in Halvorson's data set along with lines that delineate 20% deviations from the experimental values. This new correlation effectively predicts the values of Halvorson's CHF* for the entire range of *We* and *St* and for ambient pressures of 0.2–2 atmospheres. Figure 2 also shows that the correlation accounts for the pressure trends in the data. This correlation can be used to estimate the maximum heat transfer rate for a spray consisting of nearly monodispersed drops by multiplying the value of CHF* by the wetted area of the surface.

CONCLUSION

A CHF correlation has been developed for droplet cooling for a range of Weber numbers between 55 and 109 and Strouhal numbers between 0.0019 and 0.037. In this range, it was observed that droplets do not fragment upon impact. The correlation of Sawyer *et al.* [6], developed for higher Weber numbers, did not predict the CHF for this data range well because droplet fragmentation was observed in their experiments and, hence, the heat transfer mechanisms in the two situations are different. For this reason, a separate correlation was developed from that of Sawyer *et al.* [6]. In addition, corrections were made to account for influences of ambient pressure on the CHF resulting in a correlation which is applicable for a variable ambient pressure between 0.2 and 2 atmospheres.

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