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THE EFFECT OF WATER SUBCOOLING ON FILM BOILING HEAT TRANSFER FROM VERTICAL CYLINDERS *

by

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ABSTRACT

The effect of subcooling on the film boiling heat transfer of water from vertical copper cylinders has been investigated experimentally using a transient quench technique. A lumped parameter model was utilized since the Biot numbers were always less than 0.05. The amount of subcooling varied from 0 K to 70 K and the initial cylinder wall temperatures were of the order of 1100 K. Heat transfer coefficients were measured at the midpoint of the cylinders and were obtained over quench times in which they were verified to be constant.

Subcooling had a significant effect on both the film boiling heat transfer coefficient and the minimum film boiling temperature. As the subcooling varied from 0 K to 70 K, the heat transfer coefficient increased by a factor of five. As the subcooling varied from 0 K to 60 K, the minimum film boiling temperature increased from approximately 600 K to 1000 K.

An attempt to correlate the heat transfer coefficient data with a method recently proposed by Sakurai et al. was only successful at subcooled temperature differences less than 10 K. A modified correlation is presented using the Sakurai et al. parameters which better represents the data over the complete subcooling range.

1. INTRODUCTION

Data for subcooled film boiling from submerged surfaces is of considerable interest in the fundamental understanding of a variety of practical applications. Examples are the transient quenching of superheated metals during continuous casting, safety studies on overheated nuclear fuel rods during the reflood phase of a loss-of-coolant transient, as well as the behavior of solid surfaces in cryogenic systems.

Various processes of film boiling have been investigated over the past four decades. Beginning with Bromley (1950) who presented a model for film boiling on a horizontal cylinder, other studies followed which considered various geometries, orientations, and thermo-fluid mechanical models. Those which are related to the present study include the effect of subcooling on film boiling by Sparrow and Cess (1962) using boundary layer theory, and a treatment by Nishikawa and Ito (1965) who considered a two phase boundary layer on a vertical plate with a subcooled stagnant free stream. This study was later extended by Nishikawa et al. (1976) to consider the effect of variable thermophysical properties on film boiling heat transfer.

In a recent series of papers, Sakurai and his co-workers (1990a, 1990b) studied the effect of subcooling on film boiling on horizontal cylinders and later extended their results to vertical surfaces. Their most recent results will be utilized in the present study to compare with our experimental data.

Apparently, because it is simpler to obtain experimental film boiling data from horizontal electrically-heated wires, data from vertical surfaces are more scarce. Accordingly, the purpose of the present study was to experimentally investigate the effects of pool subcooling on the film boiling heat transfer and minimum film boiling temperatures for vertical cylinders.

During the course of this study, the authors became aware of a recent subcooled film boiling experimental study by Tajima et al. (1990). They also used a transient quench technique utilizing a vertical gold cylinder 0.4 cm in diameter and 4.0 cm long. Their wall temperatures before quench were approximately 975 K and their subcooling range was from 0 K to 80 K. Their results will be compared to the present study in a later section.

2. EXPERIMENTAL APPARATUS

The experimental apparatus consisted of a temperature-controlled water pool with dimensions of 29 cm square by 42 cm deep which was equipped with a calibrated thermocouple to measure the pool temperature. The test cylinder was heated to the required temperature in an adjacent electric furnace and then quickly plunged into the pool in a vertical orientation.

Three copper cylinders were used in the experiments. The thermocouples were inserted into the cylinders through the surface in a radial direction at the locations and to the depths indicated in Figure 1 and specified in Table 1. Thermocouple T_c was not installed in the cylinder for the Series 300 tests because of the small cylinder diameter.

The pool water was steam distilled and the thermocouples were calibrated against a platinum resistance thermometer whose own calibration was traceable to a NIST standard. The thermocouple calibrations were checked against the steam and ice points and are believed accurate to ± 0.5 K over the temperature range 273 K $\leq$ T $\leq$ 1170 K.

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Table 1 - Cylinder Dimensions and Thermocouple Locations and Depths					
Test Series	L, length	D, diameter	a	b	c
Series 200	27.94	3.81	7.62	7.62	0.96
Series 300	27.94	1.27	7.62	7.62	-
Series 400	27.94	2.54	7.62	7.62	0.64
(All dimensions in centimeters)					

3. DATA ACQUISITION

Using the three cylinders, film boiling quench data were obtained for $0 \leq \Delta T_{sub} \leq 70$ K at $T_w \cong 1100$ K. Figure 2 shows the variation of T_w vs. time for a case when the pool was at the saturation temperature (Run No. 206). Referring to Figure 2, the cylinder is suddenly plunged into the water shortly after t=0. The cylinder remained in film boiling until the precipitous temperature drop following time B (minimum film boiling point) when transition from film boiling occurred. The heat transfer coefficient was found to be constant over the time interval from t_A to t_B, which is discussed in more detail in the section to follow. Although it is difficult to see in Figure 2, the temperature difference between T_d and T_c varies between 4-6 K between points A and B. Conversely, the temperature difference between T_c and T_p varies from 764 K (at point A) to 311 K (at point B) over the same time period. The temperature differences indicate small temperature Biot numbers (i.e., $(T_d - T_c)/(T_c - T_p)$) of the order of 0.010 to 0.013 at points A and B, respectively, which are in the lumped parameter range.

4. CALCULATION OF HEAT TRANSFER COEFFICIENT

Bui and Dhir (1985) showed in their experiments that the heat transfer coefficient in film boiling along a vertical surface in a saturated pool was constant along the surface. In the present quench technique, however, it was necessary to determine that the heat transfer coefficient was constant during the time interval that the quench equations were applied.

The quench energy balance for the vertical cylinder is,

$$hA(T_w - T_p) = -\rho c V \frac{dT_w}{dt} \quad (1)$$

or rearranging and integrating,

$$\int_{(T_w-T_p)_{\Delta t=0}}^{(T_w-T_p)_{\Delta t=\Delta t}} \frac{d(T_w-T_p)}{T_w-T_p} = -\int_0^{\Delta t} \frac{\rho c V}{hA}\, dt \quad (2)$$

If it is assumed that $\rho cV/hA$ is a constant or, more specifically, that h = constant, then the integration yields,

$$\ln\left[\frac{(T_w-T_p)_{\Delta t=0}}{(T_w-T_p)_{\Delta t=\Delta t}}\right] = \frac{\rho c V}{hA}\Delta t \quad (3)$$

T_w in the above equations was taken as T_c for the Series 200 and 400 experiments, and was taken as T_d for the Series 300 experiments (see Figure 1 and Table 1). These thermocouples were submerged 20-30 diameters into the test cylinders. If the left hand side of Equation (3) is plotted against Δt and the relation is linear, then h=constant (assuming $\rho cV/A$=constant).

Figure 3 shows a plot of Equation (3) for two typical runs. For all of the runs, graphs such as Figure 3 were plotted and the test periods determined in the manner illustrated in the figure. Heat transfer coefficients were then calculated using the average cylinder wall temperature during the time interval Δt to evaluate ρ and c. Thermophysical property data to evaluate ρ and c for the copper cylinders were obtained from References 8 and 14 respectively, (μ, ρ, c_p) and k for water were

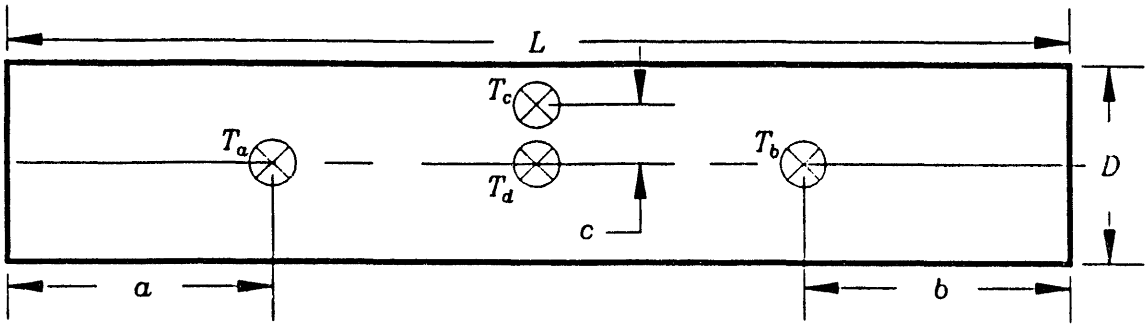

Figure 1. Thermocouple Locations in Test Cylinders (see Table 1)

obtained from References 1 and 4 respectively, and ρ, k, μ and c_p for steam were obtained from References 7, 14, 15 and 16 respectively. The steam and water properties were evaluated at the average of the saturation temperature and either the cylinder wall or water pool temperature, respectively. Water-steam surface tension was evaluated at the saturation temperature.

5. EXPERIMENTAL RESULTS

Using the procedures described in the previous section, a total of 35 runs were selected for analysis. A summary of pertinent measured and calculated quantities is given in Table 2.

Figure 4 shows the results of the heat transfer coefficients vs. pool temperature. As seen in the figure, the data when the pool temperature was near saturation are more reproducible than those with large subcooling temperature differences. At large subcoolings, the boiling process is very rapid and thus short-lived.

Included in Figure 4 and listed in Table 3 are data points from other investigators for comparison. The Bui and Dhir (1985) data were obtained only with the pool at saturation temperature. They used a vertical flat plate 6.3 cm wide and 10.3 cm high. The data were taken at 0.8, 2.6, 5.2 and 7.7 cm from the leading edge and it was found that the heat transfer coefficient was essentially independent of the distance from the leading edge.

The Tajima et al. (1990) data, which were taken from a graph in their paper, were obtained both at the saturation temperature and subcooling temperature differences up to 80 K. However, at subcooling temperature differences greater than 50 K, the quench period was so short that no meaningful data were obtained.

At pool saturation, the Bui and Dhir data fall somewhat below the present data while the Tajima et al. data are in reasonable agreement. In the pool subcooled region, the Tajima et al. data are higher than the present results although the general trend is similar.

It was clear from the experiments that the minimum film boiling temperature was also a strong function of the degree of subcooling. Although it was difficult to measure some of these temperatures (T_{MFB}) from the experimental graphs, a best estimate was determined and these data are listed in Table 2. Although the method used to determine some of these temperatures was quite subjective, a linear regression of the data yields the relationship between the minimum film boiling temperature and the water subcooling given below.

$$T_{MFB} = 593 + 5.9\ \Delta T_{sub} \qquad (4)$$

6. DISCUSSION OF RESULTS

An attempt was made to correlate all of the film boiling heat transfer coefficient data by a radiation corrected method first developed by Sakurai et al. (1990a) for the case of horizontal cylinders. The methodology has its basis in a theoretical pool film boiling analysis based on buoyancy-induced natural convection in the vapor film around a horizontal cylinder including the effects of subcooling, convection, and thermal radiation. The model results in an expression for the film

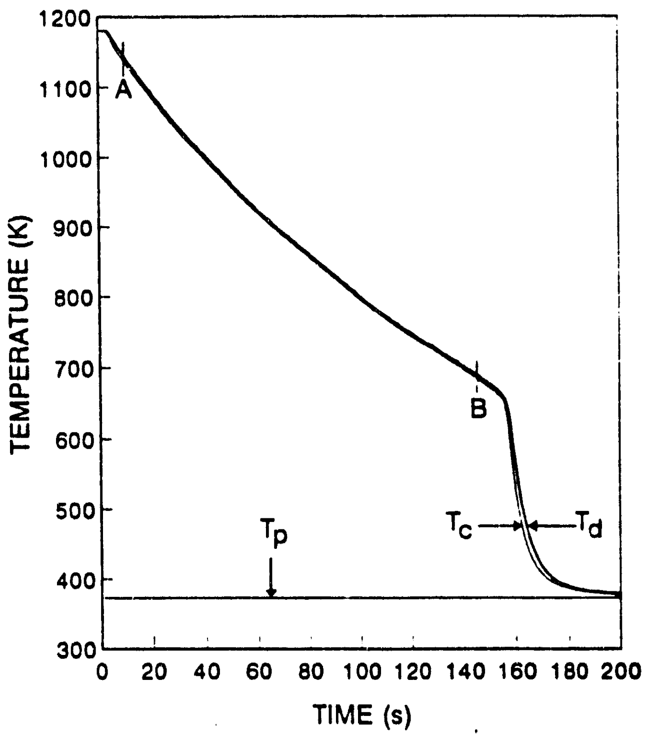

Figure 2. Transient Temperatures of Test Cylinder vs. Time for Run 206: Δt_{A-B} = Quench Time (t_A = 10 s, t_B = 145 s)

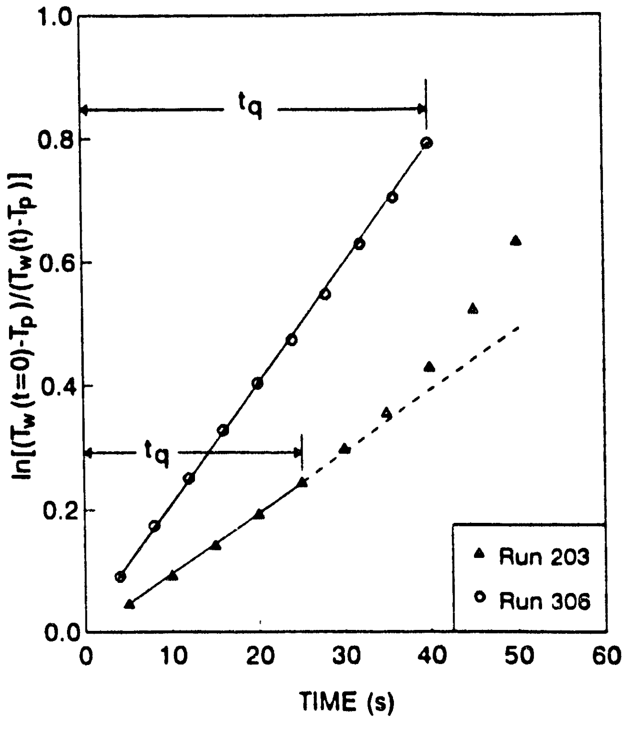

Figure 3. Method of Choosing Quench Times

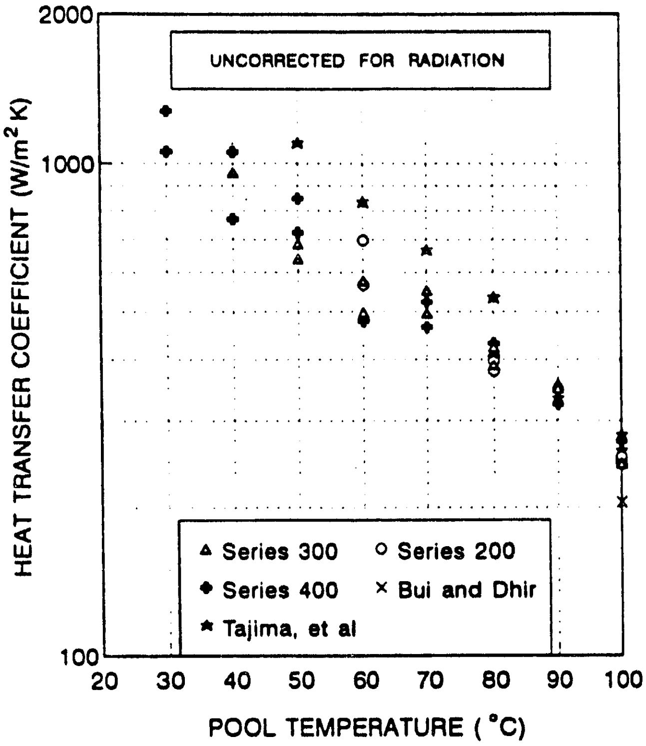

Figure 4. Measured Film Boiling Heat Transfer Coefficients vs. Pool Temperature

boiling Nusselt number as a function of many dimensionless parameters as shown below (see Nomenclature). The reader is directed to [9] for a complete definition of these variables.

$$Nu = f(M) = f(Gr_v,\ Pr_\ell,\ Pr_v,\ Sp,\ Sc,\ (\rho_v\mu_v/\rho_\ell\mu_\ell)) \quad (5)$$

The same authors later extended this analysis to the case of subcooled boiling from vertical surfaces, Sakurai et al. (1990b). However, in their comparison of their analysis to data in the literature only saturated film boiling data were available for vertical cylinders at that time. Figure 5 shows a comparison of the present experimental data with the Sakurai et al. correlation methodology. The dimensionless heat transfer correlation uses the radiation-corrected heat transfer coefficient, h_c, which has the radiative component, h_r, subtracted from the experimentally measured boiling heat transfer coefficient, h, as described in the nomenclature. The data at the lowest range of the parameter M (six data points where $\Delta T_{sub} = 0$) are in good agreement with the Sakurai et. al correlation, which is indicated in Figure 5 by the dashed line. Thus, the Sakurai et al. model agrees with the present data for a saturated water pool. As the subcooling increases (with increasing M) beyond 10 K, the present data depart more and more from the Sakurai et al. model, which is given by Equation 6.

$$Nu = 0.82\ M^{0.25} \quad (6)$$

A better correlation of the present data is given by Equation (7),

$$Nu = 0.056\ M^{0.40} \quad (7)$$

which is shown in Figure 5 as the bold line.

Table 2 - Summary of Experimental Results

Run Number	ΔT_{sub} (K)	h (W/m^2K)	Bi	T_{MFB} (K)
201	40	566	.030	994
203	20	397	.021	690
204	20	379	.020	690
206	0	247	.013	673
208	40	697	.038	1011
209	0	253	.013	----
303	20	423	.007	720
304	20	390	.007	700
305	0	246	.004	----
306	0	245	.004	600
307	40	577	.010	900
308	40	498	.009	820
309	60	959	.017	1000
311	50	639	.011	873
312	50	686	.012	873
313	30	496	.009	773
314	30	552	.010	873
315	10	349	.006	623
316	10	357	.006	633
401	40	480	.017	873
402	40	478	.017	873
403	30	465	.016	823
404	30	523	.019	773
405	20	431	.015	673
406	20	406	.014	673
407	10	324	.011	633
408	10	345	.012	643
409	0	245	.008	573
410	0	272	.009	573
411	50	847	.030	843
412	50	722	.026	833
413	60	770	.028	923
414	60	1056	.037	923
415	70	1277	.045	---
416	70	1058	.038	---

7. CONCLUSIONS

1. Transient quench techniques using lumped thermal capacity heat transfer assumptions were applicable in the present investigation only when the Biot number was 0.05 or less. Otherwise large errors were apparent in the measured heat transfer coefficients.
2. The measured data in the present study indicate an enhancement to the film boiling heat transfer coefficient by as much as a factor of five over the saturated value by a subcooling of 70 K.
3. The experimental data are self-consistent over the range of subcooling investigated and are in reasonable agreement with data in the literature [3, 12].
4. There is no apparent effect of the cylinder diameter in the present data. The present data for three vertical cylinders and reported data for vertical cylinders [12] and a vertical flat plate [3] are in good agreement in both trend and magnitude.
5. The present data are in good agreement in trend with the predictions of the model of Sakurai et al. [9, 10]. A better correlation for vertical circular cylinders is presented (Eq. 7).
6. The minimum film boiling temperature was found to be a strong function of the degree of subcooling (Eq. 4).
7. Traditional techniques [2] were used to correct for the contribution of thermal radiation to the overall film boiling heat transfer coefficient. The radiative contribution to the measured overall heat transfer coefficient varied from 6-22% with the largest contribution occurring for the saturated cases and the least contribution for the cases with the greatest subcooling.

Table 3 - Experimental Data in Literature

h (W/m^2K)	ΔT_{sub} (K)
205 [3]	0
280 [12]	0
260 [12]	0
333 [12]	10
533 [12]	20
666 [12]	30
833 [12]	40
1100 [12]	50

[3] Bui and Dhir, [12] Tajima, et al.

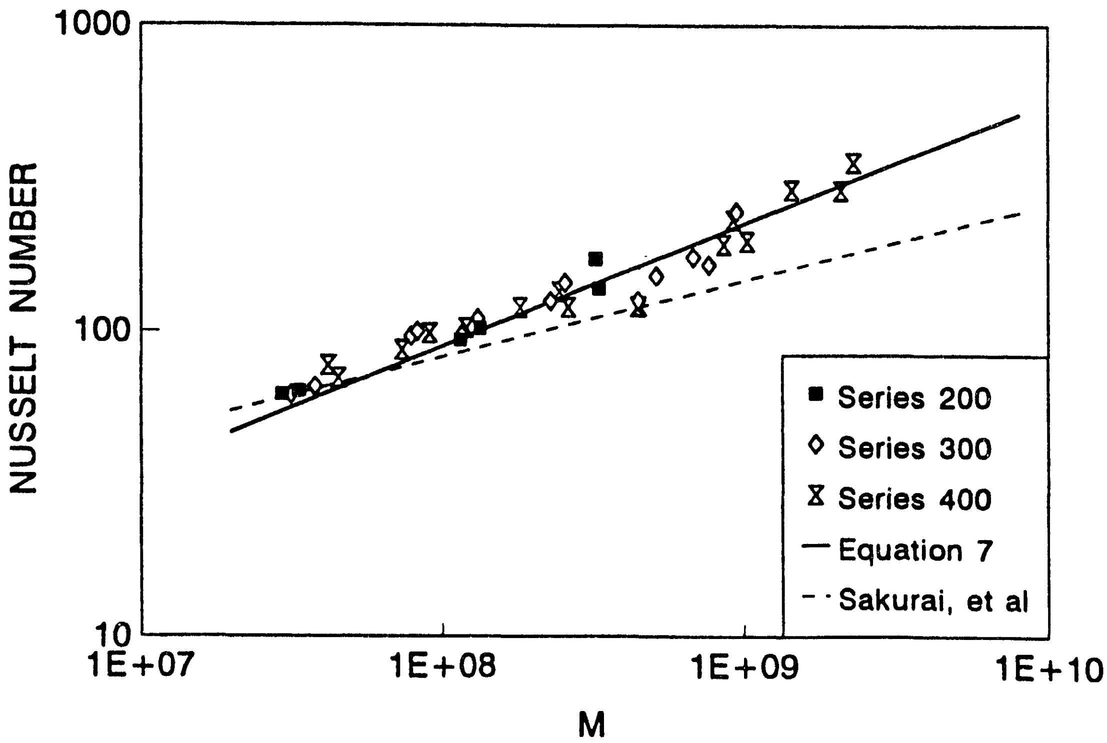

Figure 5. Dimensionless Subcooled Film Boiling Heat Transfer Correlation

NOMENCLATURE

A	Area (m^2)
Bi	Biot number = hR/k
c, c_p	Specific heat (J/kg K)
F_{1-2}	Gray body radiation exchange coefficient for parallel surfaces = $1/(\epsilon_w^{-1} + \epsilon_{p,sat}^{-1} - 1)$
Gr	Grashof number, Eq. (5)
h	Measured heat transfer coefficient (W/m^2K)
h_c	Radiation-corrected heat transfer coefficient = h - 0.75 h_r
h_r	Radiative component of overall heat transfer coefficient = $F_{1-2}\, \sigma(T_w^4 - T_{sat}^4)/(T_w - T_{sat})$
k	Thermal conductivity (W/mK)
M	Correlation parameter, Eq. (5)
Nu	Nusselt number = $h_c\lambda/k_v$
Pr	Prandtl number
R	Cylinder radius (m)
Sc	Correlation parameter, Eq. (5)
Sp	Correlation parameter, Eq. (5)
t	Time (s)
T	Temperature (K)
V	Volume (m^3)
ΔT_{sub}	$T_{sat} - T_p$

Greek Letters

ϵ	Gray body emissivity
ρ	Density (kg/m^3)
μ	Dynamic viscosity (Ns/m^2)
λ	$2\pi\, (\sigma/g(\rho_\ell-\rho_v))^{0.5}$
σ	Surface tension (N/m)

Subscripts

ℓ	liquid
MFB	minimum film boiling
p	pool
q	quench time
sat	saturation
v	vapor
w	wall

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