

# A survey of experimental heat transfer data for nucleate pool boiling of liquid metals and a new correlation

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The experimental data for heat transfer during nucleate pool boiling of saturated liquid metals on plain surfaces are surveyed and a new correlation is presented. The correlation is  $h = Cq^{0.7}p_r^m$ , where  $C$  and  $m$  are, respectively, 13.7 and 0.22 for  $p_r < 0.001$  and 6.9 and 0.12 for  $p_r > 0.001$  ( $h$  is in  $W/m^2 K$  and  $q$  in  $W/m^2$ ). This correlation has been verified with data for K, Na, Cs, Li, and Hg from 17 sources over the reduced pressure ( $p_r$ ) range of  $4.3 \times 10^{-6}$  to  $1.8 \times 10^{-2}$ . The correlation of Subbotin et al. was found unsatisfactory, but a modified correlation was developed that also gives good agreement with most of the data.

**Keywords:** boiling; nucleate; pool; heat transfer; correlation; liquid metals; natural convection

## Introduction

Liquid metals are uniquely suited for many high-temperature heat transfer applications due to their low pressures at high temperatures and their high heat transfer rates. Considerable theoretical and experimental research has been done on liquid-metal nucleate pool boiling. The research has been reviewed in detail by Dwyer (1976) and briefly by Rohsenow (1985) and Shah (1990). While the research done so far has enhanced our understanding of the mechanism of boiling and has provided test data, as yet there is no well-verified technique, theoretical or empirical, for predicting the heat transfer coefficients during nucleate pool boiling of even a single liquid metal. Since there is clearly a need for reliable methods for calculating heat transfer rates during boiling, the author made efforts that have resulted in the development of a general correlation for nucleate boiling of saturated single-component liquids on plain unbounded surfaces with normal commercial finish.

In the following, previous work by other researchers is briefly reviewed and the proposed correlation is presented. The search for experimental data is described. The proposed correlation is then compared with available experimental data to show the extent of its agreement or disagreement. Various features of the experimental data are discussed as needed to clarify the bases, use, or limitations of the proposed correlation. A comparison is also made with some other well-known predictive techniques.

## Previous work

Studies on bubble nucleation during nucleate boiling of liquid metals have shown that the waiting periods are much longer and the bubble growth periods much shorter than in the boiling of ordinary liquids (Dwyer 1976; Rohsenow 1985). Deane and Rohsenow (1969) estimated that during their tests on sodium, the waiting period was 98 percent of the total ebullition cycle

time, which was on the order of 1 second. For ordinary fluids, total ebullition cycle time usually falls in the range of 0.01 to 0.2 seconds; the waiting period and bubble growth period are usually of the same order of magnitude. Very little data on liquid metals are available for parameters such as bubble departure size and frequency; these limited data do not agree with correlations for ordinary fluids (Dwyer 1976). The differences in these basic phenomena suggest that methods for predicting heat transfer to ordinary fluids may not be applicable to liquid metals.

Many studies to measure heat transfer during boiling of single-component liquid metals on a plain surface have been reported. These include studies on sodium, potassium, cesium, lithium, and mercury. In all cases, heater temperatures were found to fluctuate, the fluctuations being greater at lower pressures and heat fluxes. In some cases, the "bumping" phenomenon was observed, in which the heat transfer mechanism alternates between natural convection and nucleate boiling; see, for example, Marto and Rohsenow (1966). This is attributed to quenching of nucleating cavities due to the inrush of subcooled liquid following bubble departure. These wall temperature fluctuations and tendencies towards boiling instability indicate that more data scatter may be expected with liquid metals than with ordinary fluids.

The studies with mercury showed that nucleate boiling is usually not obtained initially with pure mercury (Bonilla et al. 1957; Wagner and Lykoudis 1981). However, nucleate boiling is achieved after prolonged operation with some materials that include copper, carbon steel, and stainless steel (Dwyer 1976; Farmer 1952; Bonilla et al. 1957; Wagner and Lykoudis 1981). Nucleate boiling is achieved from the beginning by adding traces of wetting agents such as magnesium (Korneev 1955), magnesium and titanium (Lunardini 1963; Bonilla et al. 1957; Wagner and Lykoudis 1981), and sodium (Bonilla et al. 1965).

No general correlation for heat transfer during nucleate boiling of liquid metals has been proposed. The nearest thing to a general correlation is the following formula proposed by Subbotin et al. (1970):

$$h/q^{2/3} = B \left[ \frac{k_L i_{fg} \rho_L}{\sigma T_L^2} \right]^{1/3} (p/p_c)^m \quad (1)$$

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where  $p$  is the system pressure and  $T_L$  is the saturation temperature (in °C) corresponding to it. Furthermore,

$$B = 8 \quad \text{and} \quad m = 0.45 \quad \text{for} \quad \frac{p}{p_c} < 0.001$$

$$B = 1.0 \quad \text{and} \quad m = 0.15 \quad \text{for} \quad \frac{p}{p_c} > 0.001$$

This correlation was based on their own data for Na, K, and Cs boiling on horizontal stainless steel plates over  $p_r = 0.0003$  to 0.012.

Various researchers have correlated their own data in the form

$$h = \text{constant} (q^n p^a) \quad (2)$$

where  $n$  and  $a$  are constants. Most of the studies found  $n$  to be in the range of 0.6 to 0.8, the values of 0.67 and 0.7 being the most common. Subbotin et al. (1968a) have correlated data for sodium from several sources in the form of Equation 2. The deviations from the data are very large. Michiyoshi et al. (1986) have given a similar correlation for potassium based on data from three sources.

Borishanskii and Zhokhov (1965) attempted to develop a corresponding state correlation using a limited amount of data for sodium and mercury, together with water data. They concluded that the data for water and metals fall on the same curve. However, they used 110 bars as the critical pressure of mercury, while the correct value is 1,535 bars. Hence, reevaluation of their conclusion is needed.

Mikic and Rohsenow (1969) assumed that virtually all heat transfer occurs by transient conduction to the liquid layer during the waiting period. Using correlations for bubble frequency and size for ordinary fluids, they developed a correlation for heat transfer in which the slope of the heat transfer curve and other constants can be determined from one set of data at one pressure for a liquid-surface combination; the same slope and constants can then be used at all pressures for the same liquid-surface combination. They verified this correlation with a limited amount of data for water and chemicals. This approach would be very appropriate for liquid metals, since virtually all heat transfer in fact occurs during the waiting period. However, the lack of basic data and correlations for bubble size and frequency (as discussed earlier) does not permit its use for liquid metals at present.

Many correlations for ordinary fluids were developed based on the model that high heat transfer rates during nucleate boiling are due to the stirring action of bubbles. The most common form is

$$\text{Nu}_b = \text{constant} [\text{Re}_b^c \text{Pr}_L^d] \quad (3)$$

$\text{Nu}_b$  and  $\text{Re}_b$  are, respectively, the bubble Nusselt and Reynolds numbers;  $c$  and  $d$  are constants. Some correlations also include some other dimensionless property groups. Dwyer (1976) has listed and discussed many such correlations. He does not recommend any of them for general use. Noyes and Lurie (1966), Subbotin et al. (1968b), and Bonilla et al. (1964), among others, evaluated several such correlations, with generally unsatisfactory results.

Mostinskii (1963) proposed the following simple correlation, which has been found to give good agreement with a wide range of data for many ordinary fluids:

$$h = 0.1 p_c^{0.69} q^{0.7} (1.8 p_r^{0.17} + 4 p_r^{1.2} + 10 p_r^{1.0}) \quad (4)$$

with  $p_c$  in bars. Collier (1981) and Palen et al. (1972) found this correlation equal or superior to all property-based correlations evaluated by them. Cooper (1984) has also given a simple correlation that does not require any fluid properties except critical pressure and molecular weight; it has been verified with a very wide range of data for ordinary fluids.

In summary, no well-verified technique is available for calculating heat transfer during pool boiling of liquid metals. There are considerable differences between the mechanisms of heat transfer of liquid metals and of ordinary fluids. Hence, it is unlikely that predictive techniques for ordinary fluids could be directly applied to liquid metals; the evaluations done so far in fact show many of them to be unsatisfactory for liquid metals. Developing a correlation based on mechanistic analysis is presently not possible, since basic relations for bubble dynamics during liquid metal boiling are not available. The considerable success of the empirical correlations of Mostinskii (1963) and Cooper (1984) suggests that similar approaches (i.e., those not involving fluid properties) may be successful.

## The new correlation

Based on the analysis of experimental data from many sources, the following new correlation is proposed:

$$h = C q^{0.7} p_r^m \quad (5)$$

where

$$p_r < 0.001, C = 13.7 \quad \text{and} \quad m = 0.22$$

$$p_r > 0.001, C = 6.9 \quad \text{and} \quad m = 0.12$$

This correlation has been verified with data for Na, K, Cs, Li, and Hg boiling on plain surfaces for  $p_r$  from  $4.2 \times 10^{-6}$  to  $1.5 \times 10^{-2}$ . Further details of verification are given later. Data selection and analysis are discussed first.

## Notation

(Units listed apply to dimensional formulas)

$h$	Heat transfer coefficient during pool boiling, $\text{W/m}^2 \text{K}$
$i_{fg}$	Latent heat of vaporization, $\text{kJ/kg}$
$k_L$	Thermal conductivity of liquid, $\text{W/m K}$
$M$	Molecular weight of fluid
$\text{Pr}_L$	Prandtl number of liquid
$p$	Pressure
$p_c$	Critical pressure
$p_{LM}$	Saturation pressure corresponding to $T_{LM}$
$p_r$	$= p/p_c$
$p_{HL}$	Pressure at the heater level
$p_{VS}$	Pressure in vapor space above the liquid pool

$T$	Fluid temperature
$T_{HL}$	Saturation temperature at heater-level pressure
$T_L$	Liquid temperature used in defining the heat transfer coefficient
$T_{LM}$	Measured temperature of liquid in the pool
$T_{SAT}$	Saturation temperature
$T_{VS}$	Saturation temperature corresponding to vapor-space pressure

## Greek symbols

$\rho_L$	Density of liquid, $\text{kg/m}^3$
$\sigma$	Surface tension, $\text{N/m}$
$\sigma_a$	Accommodation coefficient

**Table 1** Range of data analyzed for boiling mercury

Data source	Test heater		Wetting agent	$p$ (bar)	$q$ (kW/m <sup>2</sup> )	Basis for	
	Description	Surface finish				$T_L$	$p$
Bonilla et al. (1965)	70-mm dia. plate of low carbon steel	Mirror smooth	0.1% Na	1	31 315	$T_{LM}$	$p_{LM}$
Bonilla et al. (1957)	Same as above	Mirror smooth	None or *	0.068 2.1	38 535	$T_{LM}$	$p_{LM}$
Lyon et al. (1955)	19-mm dia. horiz. tube of type 316 SS	Normal	*	1	79 315	$T_{LM}$	$p_{VS}$
Farmer (1952)	Horiz. copper plate	Normal	None	0.0081	126 441	Not known	$p_{VS}$
Korneev (1955)	22-mm dia. carbon steel vertical tubes	Natural	0.01 to 0.04% Mg	1 10	60 715	$T_{LM}$	$p_{VS}$
Wagner and Lykoudis (1981)	60-mm dia. horiz. SS plate, sandblasted with 0.3 mm sand	Rough	None or *	0.066 1.0	20 300	$T_{LM}$	Not known
Michiyoshi et al. (1975)	Horiz. cylinder	Normal	None	1.0	105 500	Not known	Not known
Lunardini (1963)	Horiz. SS plate	Normal	*	0.68 1.03 0.0081 10.0	107 315 20 715	$T_{LM}$	$p_{LM}$
All							

\* Wetting agent 0.02% Mg plus 0.0001% Ti.

**Table 2** Range of alkali metal data analyzed

Data source	Test heater		Fluid	$p$ (bar)	$q$ (kW/m <sup>2</sup> )	Basis for	
	Description	Surface finish				$T_L$	$p$
Lyon et al. (1955)	19-mm dia. horiz. SS tube	Normal	Na	1.03	126 393	$T_{LM}$	$p_{VS}$
Noyes and Lurie (1966)	9.5-mm dia. horiz. tubes of SS and molybdenum	Fine machined	Na	0.07 0.56	346 2270	$T_{LM}$	$p_{VS}$
Marto and Rohsenow (1966)	63.5-mm horiz. nickel disks	Mirror smooth or machined	Na	0.08	173 760	$T_{VS}$	$p_{VS}$
Pethukov et al. (1966)	29.6-mm dia. SS cylinder	Normal	Na	0.011 0.81	117 1732	$T_{LM}$	$p_{VS}$
Kovalev and Zhukov (1973)	21.5-mm horiz. SS cylinder	Normal	Na	0.01 0.05	504 1386	$T_{LM}$	$p_{VS}^*$
Sakurai et al. (1978)	7.6- and 10.7-mm dia. horiz. Inconel cylinders	Normal	Na	0.018 0.29	1100 2800	$T_{HL}$	$p_{HL}$
Subbotin et al. (1964)	38-mm dia. horiz. disks of Cu, Ni, and SS	Normal	Na	0.14	110 2200	$T_{VS}$	$p_{VS}$
Fujishiro et al. (1971)	40-mm dia. horiz. nickel plate	5 to 10 $\mu$ m roughness	Na	0.02 2.1	232 698	$T_{LM}$	$p_{VS}$
Borishanskii et al. (1965)	20- to 40-mm dia. tubes, horiz. and vertical	Normal	Na	0.12 1.25 K 0.04 1.15	20 145 12 175	$T_{VS}$	Not known
Bonilla et al. (1964)	75-mm dia. horiz. nickel plate	Normal	K	0.003 2.04	38 364	$T_{LM}$	$p_{VS}$
Colver and Balzhizer (1964)	9.5-mm dia. horiz. tube of Haynes 25 alloy	Normal	K	0.63 0.98	315 2200	$T_{LM}$	$p_{VS}$
Michiyoshi et al. (1985, 1986)	40-mm dia. horiz. nickel plate	Normal	K	0.04 1.03	120 1600	$T_{VS}$	$p_{VS}$
Takanaka (1984)	7.8-mm dia. horiz. cylinder, Inconel	Normal	K	0.04 0.13	820	$T_{LM}$	$p_{VS}$
Subbotin et al. (1968b)	38-mm dia. horiz. SS plate	Normal	Cs	0.018 2.96	406 1624	$T_{LM}$	Not known
Wadkins (1984)	9.5-mm dia. SS vertical rod	Normal	Li	0.03	840	$T_{LM}$	$p_{LM}$
All				0.003 2.96	12 2800		

\* Assumed to be the same as in the earlier study (Pethukov et al. 1966), since this reference is not clear.

An alternative correlation has also been developed based on the parameters in the Subbotin et al. (1970) correlation (Equation 1). It is presented in the Appendix.

### Data selection and analysis

The objective of this study was to develop a method for predicting heat transfer during fully developed steady nucleate boiling of saturated single-component liquid metals on unbounded plain surfaces. Data search and selection were made accordingly. As a result, data for mixtures of metals and for surfaces with artificial cavities or other enhancement devices were not considered.

Data from many studies on boiling of mercury, potassium, and sodium were found. Also, one study each on cesium and lithium were located. The range of data analyzed from these studies is listed in Tables 1 and 2. "Surface finish" listed as "normal" means the usual finish of commercial products such as tubes and plates. Where the researchers did not mention surface finish, it was assumed to be normal.

Breitstein and Bonilla (1974) reported their data on pool boiling of selenium and noted that the heat transfer coefficients they measured were very low. Their explanation is that during boiling, selenium behaves as a multicomponent mixture of the different forms of selenium. Boiling of multicomponent mixtures is beyond the scope of this article, and hence these data were not considered.

Some data sets were not considered in developing the correlation due to the following reasons:

- (1) the researchers themselves expressed doubts about the accuracy of their data;
- (2) data for mercury was obtained under inadequate surface wetting conditions; and
- (3) data showed a very low slope of the boiling curve.

The data discarded for the first reason are those of Marto and Rohsenow (1966) for pressures higher than 60 torr, since the authors state that these data are only qualitatively correct due to limitations of measurement accuracy.

Among the mercury data excluded due to incomplete wetting are those of Turner and Colver (1971) for a silver-coated steel surface; Dwyer (1976) has the same view on these data. The data of Takahashi et al. (1982) for a stainless steel cylinder are similar to those of Turner and Colver (1971), and these authors state that heater surface wetting was incomplete. The data of Takahashi et al. (1980) for a stainless steel plate are also similar and do not exhibit fully developed nucleate boiling, as noted by Wagner and Lykoudis (1981). Farmer (1952) has reported data for boiling of mercury on copper and chrome-plated copper surfaces. The heat transfer coefficients for the chrome-plated surface were about half of those for the copper surface. Dwyer (1976) comments that, since mercury does not wet chrome surfaces at all, nucleation probably occurred from rogue sites. Hence, the data for chrome-plated surface were not considered.

As stated earlier, data with very low slope of the  $h-q$  curve were not included in this study, because these do not represent the usual behavior during fully developed nucleate boiling from commercial finish surfaces. Such data include those of Deev et al. (1967) for sodium, which have a slope of 0.27. Subbotin et al. (1968a), who examined data for sodium from many sources, commented that the mechanism of heat transfer for these data appeared to have been mainly natural convection, with bubble nucleation probably occurring only at a few sites.

Only data for stable boiling are considered. Data for intermittent boiling (bumping) conditions have been excluded. Where the slope of the boiling curve varied, only the data at

**Table 3** Critical pressures of liquid metals used in developing this correlation. From Weast (1986)

Fluid	$P_c$ , bar
Cesium	117.3
Lithium	689.0
Mercury	1,510.0
Potassium	163.9
Sodium	256.4

the highest slope were used, since these were considered to represent fully developed nucleate boiling.

Important in data analysis is how  $T_L$  and  $p$  are defined. The definitions used are listed in Tables 1 and 2; these are the same as used by the respective authors of those reports. This topic is discussed in detail later.

Some of the test data for alkali metals were available only in terms of  $h/q^{0.67}$ . To compare them with the present correlation, adjustments were made based on a heat flux of  $1 \text{ MW/m}^2$ . The heat flux in such data sets was in the range of  $0.3$  to  $3.0 \text{ MW/m}^2$ . Hence, the resulting error would have been negligible. Calculations with the Subbotin et al. (1970) correlation have also been done using  $1 \text{ MW/m}^2$  heat flux.

Many of the data sets analyzed were available only in graphical form. The mean curve through the data was generally used for extracting the data points if the data spread around the mean was small. Where the data spread was large, individual data points were generally used to take into account the range of variations. Although using the mean curve through the data in all cases, as was done by Stephan and Abdelsalam (1980) in developing their correlation, would have provided uniform treatment of all data, it would not have conveyed information about the extent of deviations.

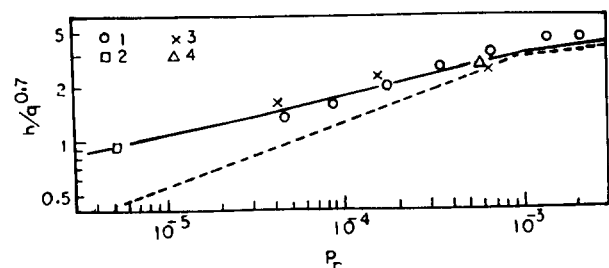
Values of critical pressure used are listed in Table 3. Surface-tension data were taken from Vargaftik (1975). Other property data are from Liley (1987).

### Comparison with experimental data

Experimental data are compared with the new correlation in Figures 1 through 7. The correlation of Subbotin et al. (1970) (Equation 1) is also shown in all figures. The data and results for each fluid are now discussed separately.

#### Mercury

As seen in Figure 1, the data for pure mercury agree well with the new correlation. These data are from four independent



**Figure 1** Comparison of data for pure mercury with Equation 5, the new correlation (continuous line). 1, Bonilla et al. (1957); 2, Farmer (1952); 3, Wagner and Lykoudis (1981); 4, Michiyoshi et al. (1975); dashed line, Subbotin et al. (1970) correlation, Equation 1

studies covering  $p_r$  from  $4.2 \times 10^{-6}$  to  $2.7 \times 10^{-3}$  as well as heaters of several materials.

Figure 2 shows the data for mercury containing wetting agents. Data from three sources agree well with the present correlation. Data from four sources are very high; the wetting agent was 0.01 percent Mg plus 0.0001 percent Ti in all these cases. However, the data of Wagner and Lykoudis (1981) with the same wetting agent are in good agreement with the present correlation. Further, Clark and Parkman (1964) had to use ten times as much additive (i.e., 0.1 percent Mg plus 0.001 percent Ti) to achieve nucleate boiling with Haynes-25 and Sircomo 9M heaters. It therefore appears that the same wetting agents may have different effects depending on surface microstructure and other conditions. It may be noted that the presence of trace amounts of contaminants has been known to greatly increase heat transfer with ordinary fluids. For example, Chaschin et al. (1975) report such effects with traces of organics in water.

Korneev (1955) achieved nucleate boiling with 0.01 percent Mg. Heat transfer coefficients were unchanged with further increase in magnesium concentration up to 0.04 percent, even though critical heat flux increased.

While the cause for the variation in results with wetting agents is not known, the present correlation predicts correctly or conservatively when additives are used to achieve wetting of the heater surface.

### Sodium

The data for sodium are shown in Figures 3 and 4. The data in Figure 3, from five sources, show good agreement with the

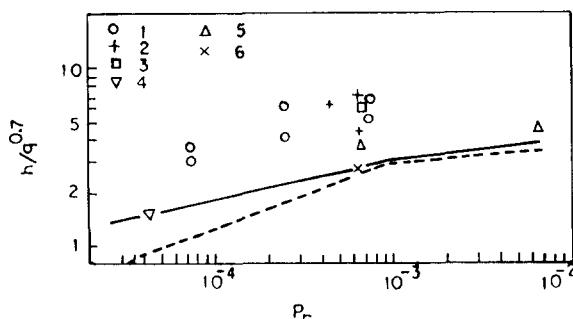


Figure 2 Comparison of data for mercury with wetting agents with Equation 5, the new correlation (continuous line). 1, Bonilla et al. (1957); 2, Lunardini (1963); 3, Michiyoshi (1986); 4, Wagner and Lykoudis (1981) (1-4 all with 0.02 percent Mg + 0.0001 percent Ti); 5, Korneev (1955), with 0.03 percent Mg; 6, Bonilla et al. (1965), with 0.1 percent Na; dashed line, Subbotin et al. (1970), correlation, Equation 1

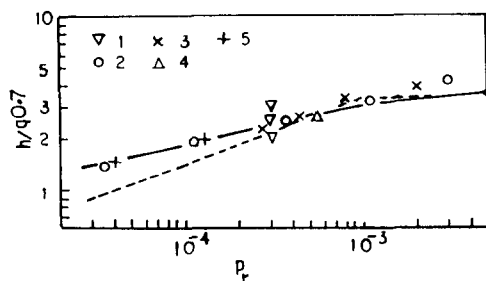


Figure 3 Comparison of some of the data for sodium with Equation 5, the new correlation (continuous line). 1, Marto and Rohsenow (1966), mirror #2; 2, Pethukov et al. (1966); 3, Noyes and Lurie (1966), molybdenum tube; 4, Subbotin et al. (1964), stainless steel plate; 5, Kovalev et al. (1973); dashed line, Subbotin et al. (1970) correlation, Equation 1

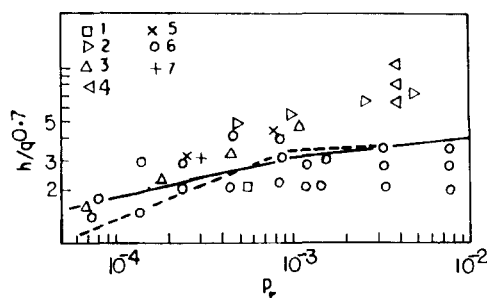


Figure 4 Comparison of some of the data for sodium with Equation 5, the new correlation (continuous line). 1, Subbotin et al. (1964), copper plate; 2, Borishanskii et al. (1965); 3, Sakurai et al. (1978); 4, Lyon et al. (1955); 5, Noyes and Lurie (1966), stainless steel tube; 6, Fujishiro et al. (1971); 7, Marto and Rohsenow (1966), machined nickel plate; dashed line, Subbotin et al. (1970) correlation, Equation 1

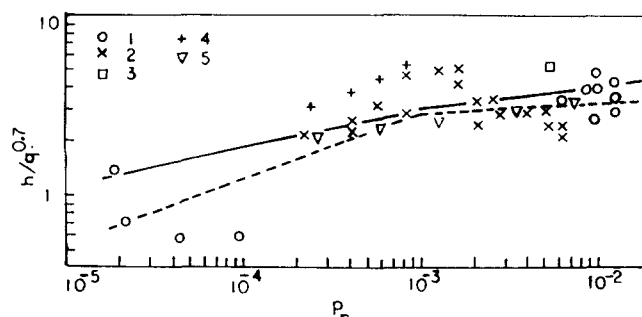


Figure 5 Comparison of data for potassium with Equation 5, the new correlation (continuous line). 1, Bonilla et al. (1964); 2, Michiyoshi et al. (1985, 1986); 3, Colver and Balzhiser (1964); 4, Takenaka (1984); 5, Borishanskii et al. (1965); dashed line, Subbotin et al. (1970) correlation, Equation 1

present correlation. The data in Figure 4 have large scatter, but the present correlation generally represents the mean through the data.

The Subbotin et al. (1970) correlation (Equation 1) predicts low at lower pressures. Note that the lines representing this correlation in Figures 3 and 4 are based on  $p_c = 256$  bars, the currently accepted value. If  $p_c = 368$  bars is used (the value used by Subbotin et al. (1970)), the predictions of Equation 1 will be 14 percent lower at  $p_r < 0.001$ .

### Potassium

The potassium data are shown in Figure 5. The data of Michiyoshi et al. (1985, 1986) show a peak near  $p_r = 0.0015$  and then drop almost suddenly at  $p_r \approx 0.002$ . No other data set shows such a sharp change, although the data of Fujishiro et al. (1971) for sodium shown in Figure 4 also indicate a decrease in heat transfer around  $p_r$  of 0.001. No explanation for this behavior was given by these authors.

The data of Colver and Balzhiser (1964) had such large scatter that these authors state that their data cannot be used to evaluate the accuracy of any correlation. The single data point shown in Figure 5 is based on the mean curves drawn by them, and it shows reasonable agreement with the present correlation.

At  $p_r$  lower than  $2 \times 10^{-4}$ , only a few data from Bonilla et al. (1964) are available. These show large scatter and are generally very low. These low-pressure data are from measurements done without cover gas. As seen in the other figures,

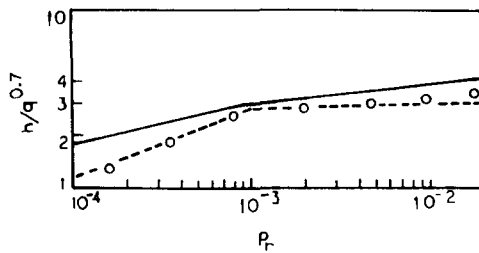


Figure 6 Comparison of the data of Subbotin et al. (1968b) for cesium with Equation 5, the new correlation (continuous line). Dashed line, the Subbotin et al. (1970) correlation, Equation 1

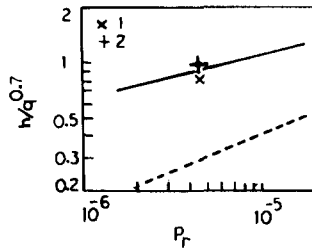


Figure 7 Comparison of the data of Wadkins (1984) for lithium with Equation 5, the new correlation (continuous line). 1, Measured data; 2, data corrected for interfacial resistance; dashed line, the Subbotin et al. (1970) correlation, Equation 1

data for the fluids in this pressure range are generally close to the present correlation.

### Cesium

Cesium data were available only from the study by Subbotin et al. (1968b). As seen in Figure 6, these data are somewhat lower than the present correlation. These show good agreement with the Subbotin et al. (1970) correlation: this is to be expected, since this correlation is based on these data. The agreement with the present correlation is adequate for a general correlation. Only when data from other sources become available can the need for any improvement in the correlation be evaluated.

### Lithium

Wadkins (1984) has provided only one analyzable data point. It is shown in Figure 7 with and without correction for interfacial mass transfer resistance (which is discussed later). The good agreement with the present correlation is encouraging, but additional data are needed to gain full confidence. Some reassurance is found by noting that the low-pressure data for mercury in Figure 1 also show good agreement.

## Discussion on miscellaneous topics

### Choice of liquid temperature

The heat transfer coefficient  $h$  is defined as

$$h = q / (T_w - T_L) \quad (6)$$

where  $T_L$  is the liquid temperature. Various definitions of  $T_L$  that have been used are

- (1) saturation temperature corresponding to vapor-space pressure;

- (2) saturation temperature corresponding to the total pressure at the heater level, i.e., vapor-space pressure plus pressure of the liquid column above the heater surface; and
- (3) measured temperature of the liquid pool.

In their study on pool boiling of mercury on a horizontal plate, Bonilla et al. (1965) measured the temperatures along the liquid depth. They found that except for temperatures very close to the heater surface, the liquid temperature was essentially constant and was within  $2^\circ\text{C}$  of the saturation temperature at the vapor pressure, despite liquid pool depth variation from 20 to 100 mm. They based  $h$  on  $T_L$  and found that liquid depth had a negligible effect on  $h$ . Had they based  $h$  on  $T_{\text{SAT}}$  corresponding to the total pressure at heater level, they would have found  $h$  to increase considerably with increasing liquid depth.

Most of the studies have shown results similar to those of Bonilla et al. (1965) noted above. Examples are studies of Subbotin et al. (1968b) on cesium, Takahashi et al. (1980) on mercury, Wagner and Lykoudis (1981) on mercury, and Takenaka (1984) and Takenaka et al. (1985) on potassium. Thus, generally pool temperature is the same as the vapor-space saturation temperature. However, there are some exceptions as discussed below.

Pethukov et al. (1966) found liquid sodium temperature to be considerably higher than the vapor-space saturation temperature in vapor space. However, their liquid temperature measurements were done below the heater level. Hence their observations do not necessarily contradict the observations of others noted above, which were made in the liquid above the heater surface.

Colver and Balzhizer (1964) found large variations in pool temperature. The liquid below the heater was subcooled, while that above the heater was superheated with respect to the vapor-space saturation temperature. According to Dwyer (1976), these unusual results were probably due to the relatively small cross section of the test vessel compared with the size of the heater and the manner in which the condensate was returned to the boiling pool.

In their study on boiling of sodium, Marto and Rohsenow (1966) did not measure liquid pool temperature and have presented their data mostly in terms of  $T_{\text{SAT}}$  based on the vapor-space pressure. They have, however, discussed the possibility of using  $T_{\text{SAT}}$  based on heater-level pressure. Use of this approach increases the divergence between their data for different liquid depths (see their Figure 13) and reduces the slope of the  $h$ - $q$  curves to values inconsistent with nucleate boiling. Hence, the Marto and Rohsenow (1966) data shows that the use of  $T_{\text{SAT}}$  based on vapor-space pressure is more appropriate.

Sakurai et al. (1978) report that their data for sodium boiling are better correlated if  $T_{\text{SAT}}$  corresponding to the heater level pressure is used. Basic data at only one pressure are presented in their paper. Hence, a full comparison of the effect of using  $T_{\text{VS}}$  instead of  $T_{\text{HL}}$  cannot be made.

In the single data point of Wadkins (1984) for lithium, measured liquid temperature was 1063 K, corresponding to a saturation pressure of 300 Pa. The vapor-space pressure was only 4 Pa, which corresponds to  $T_{\text{SAT}}$  of 850 K. Had  $p_r$  and  $T_L$  been based on vapor-space pressure, this data point would not have agreed with the present correlation. Hence, it appears that for vapor-space pressures close to absolute zero, the liquid temperature is related to the liquid depth.

All the above discussions have been for liquid pool depths of 20 mm or greater. In their test with mercury, Takahashi et al. (1980) found that with 6-mm liquid depth, liquid temperature was significantly higher than the vapor-space saturation

temperature. At depths of 20 mm or more, they also found liquid temperature to be close to the vapor-space saturation temperature. On the other hand, Michiyoshi et al. (1985) correlated their data for all liquid levels, from 5 to 50 mm, with vapor-space saturation temperature as  $T_L$ .

Most of the evidence discussed in the foregoing suggests that for pressures exceeding about 700 Pa,  $T_L$  and  $p_r$  should be based on vapor-space pressure. There is very little data at lower pressures, but these data indicate that at system pressures approaching absolute zero,  $T_L$  should take into account the hydrostatic head of liquid above the boiling surface.

### Effect of liquid depth

In the foregoing discussions on the choice of liquid temperature in defining  $h$ , it was noted that most researchers have found that liquid depth has no effect on heat transfer. The study of Michiyoshi et al. (1985) on potassium included liquid depths from 5 to 50 mm. In all other studies listed in Tables 1 and 2, the liquid depth was greater than 20 mm.

Takahashi et al. (1980) report that during pool boiling of mercury on a horizontal plate, heat transfer with 3- and 7-mm liquid depths was better than with 15- and 35-mm liquid depths. No conclusion can be drawn from these data, since the heating surface was not well wetted by mercury. However, as noted by Takahashi et al. (1980), high heat transfer in thin liquid films has also been reported with ordinary liquid. Hence, further investigations on small liquid depths is needed. Nevertheless, it is clear that the new correlation can be confidently used for liquid depths greater than 20 mm. For potassium, it has been verified down to a 5-mm liquid depth.

### Effect of surface roughness

There have been many studies on the effect of surface roughness during boiling of ordinary liquids. Some of these have been reviewed by Rohsenow (1985). These show that heat transfer and the slope of the heat transfer curve increases with increasing roughness. Smoothing the surface has the opposite effect. The tests on sodium pool boiling by Marto and Rohsenow (1966) showed similar results.

The objective of the present research was to develop a correlation that might be applicable to commercially manufactured surfaces such as tubes and plates. Hence, it would have been desirable to completely discard all data where the surfaces had been smoothed or roughened. However, this would have severely depleted the data base. Hence, data from such surfaces were accepted where there was evidence that the surface still performed like a commercial surface.

The data of Bonilla et al. (1957, 1965) for mercury were obtained on plates polished to a mirror finish. Bonilla et al. (1965) tested such a plate with water. The present author compared these data with the well-verified correlations of Mostinskii (1963) (Equation 4) and Stephan and Abdelsalam (1980). The measured heat transfer coefficients were generally higher than the predictions of these correlations. It is therefore concluded that the heat transfer coefficients measured by Bonilla et al. (1965) for boiling of liquid metals on polished surfaces should be comparable to those with normal commercial finish surfaces.

Marto and Rohsenow (1966) have reported data for boiling of sodium on nickel plates polished to a mirror finish. The  $h$ - $q$  curves show slopes of 0.5 or lower. This is lower than what is usually obtained with commercially finished surfaces. Hence, these data are probably not representative of surfaces normally used in heat exchangers. Only their data with slope near 0.5

have been included here. Their data on a machined nickel plate show a slope near 0.7 and are also included here.

Wagner and Lykoudis (1981) sand-blasted the heater surface with 0.3 mm sand to roughen it. Their data for pool boiling of water on that surface agree well with the Stephan and Abdelsalam (1980) correlation, and the slope of their  $h$ - $q$  curve with mercury is close to 0.7. Hence, their mercury data appear to be applicable to normal commercial surfaces.

The author concludes that the heat transfer performance of moderately roughened or smoothed surfaces is usually comparable to that of surfaces with normal commercial finish.

### Effect of pressure

According to the present correlation, heat transfer rises with increasing pressure, but the rate of rise decreases beyond a reduced pressure of 0.001. This change in the effect of pressure is similar to the correlation of Subbotin et al. (1970) (Equation 1), which was based on their own data for K, Na, and Cs. Dwyer (1976) and Rohsenow (1985) expressed puzzlement about this change but offered no explanation. Similar change in the effect of pressure has been reported by others: Bonilla et al. (1965) with mercury, Fujishiro et al. (1971) with sodium, and Michiyoshi et al. (1986) with potassium. On the other hand, no experimental study can be cited that clearly shows the absence of this change in the effect of pressure.

Neither the correlations based on the bubble agitation model nor the transient conduction model of Mikic and Rohsenow (1969) predict this change. Since the solubility of inert gases in liquid metals increases with increasing temperature (Dwyer 1976) and hence pressure, it could be that at higher pressures inert gases are completely dissolved out of the cavities, thus reducing the number of active nucleation sites. However, there is no evidence supporting this hypothesis. Also, as seen in Figure 4, some data for sodium at higher pressures lie on the extension of correlation for the lower pressures. Hence, further study of the effect of pressure is needed.

### Effect of surface geometry and orientation

Takenaka et al. (1984, 1985) boiled potassium on a horizontal cylinder as well as on a horizontal plate. They found  $h$  on the cylinder to be about 30 percent higher than on the plate. However, when all data from many sources in Figures 1 to 7 are studied together, no consistent trend of difference between horizontal plates and cylinders is seen.

Borishansky et al. (1965) boiled sodium and potassium on horizontal and vertical tubes and report no difference between the two; it should, however, be noted that wall temperatures on horizontal tubes were measured only on the top and sides. The present correlation agrees with the single data point for lithium on a vertical tube. However, Korneev (1955) reports that during his tests with boiling of mercury, the local  $h$  at the bottom of a horizontal tube was lower than at the top and sides. The  $h$ 's at the top and sides of horizontal tubes were found comparable to the  $h$  on vertical tubes. Thus Korneev (1955) found that the circumferentially averaged heat transfer coefficient for horizontal tubes was lower than that for vertical tubes.

Takenaka (1984) boiled potassium on a horizontal cylinder. He reports that the heat transfer coefficients at the bottom of the cylinder were higher than at the sides and top. This is the reverse of Korneev's (1955) results with mercury discussed in the previous paragraph. Kovalev et al. (1973) and Pethukov et al. (1966) measured wall temperatures all around the tube circumference and used their mean in calculating heat transfer

coefficients; they have not made any statement about the variations of temperatures around the circumference.

Taking into consideration all the data analyzed, the author's conclusion is that geometry and orientation generally do not significantly affect the heat transfer coefficients averaged over the surface area.

### Heater material

Subbotin et al. (1964) boiled sodium on stainless steel, nickel, and copper plates. They found  $h$  with stainless steel to be about 20 percent higher than with copper;  $h$  with nickel was in between those with copper and stainless steel. This 20-percent spread in  $h$  with these materials is small compared to the usual scatter in data. As seen in Figures 1 to 6, the data analyzed here do not show any clear connection with heater material. Thus the data for pure mercury on copper, carbon steel, and stainless steel in Figure 1 all show good agreement with the present correlation.

It is concluded that the present correlation can be used with heating surfaces of common metals and their alloys.

### Aging

Wagner and Lykoudis (1981) report that during boiling of pure mercury on stainless steel, heat transfer coefficients gradually diminished for a period of two months and then became constant, the final values being about 20 percent lower than the initial values. Lunardini (1963) has reported similar behavior in boiling of mercury with wetting agents. Some of the scatter in the test data may be due to aging effects. Thus for most of the data of Wagner and Lykoudis (1981) analyzed here, the extent of aging of the heater is not known.

Marto and Rohsenow (1966) report a decrease in heat transfer for the first 20 hours during boiling of sodium. They attribute it to driving out the noncondensibles whose presence improves the boiling process.

### Interfacial phase change resistance

To transfer the mass across the liquid-vapor interface, a temperature drop should occur. This is usually expressed as an interfacial heat transfer coefficient,  $h_1$ . Its value can be calculated by the following dimensionless formula based on the kinetic theory of gases (Hewitt 1978):

$$h_1 = \frac{2\sigma_a}{2 - \sigma_a} \left\{ \frac{M}{2\pi RT} \right\}^{0.5} \left\{ \frac{i_{fg}^2 p M}{RT^2} \right\} \quad (7)$$

where  $\sigma_a$  is the accommodation coefficient, assumed to be equal for evaporation and condensation at the interface. While some theories predict very low values of  $\sigma_a$ , the general consensus is that it is equal to 1.

With  $h_1$  known, the corrected boiling heat transfer coefficient  $h_c$  can be calculated as

$$\frac{1}{h_c} = \frac{1}{h_m} - \frac{1}{h_1} \quad (8)$$

where  $h_m$  is the measured pool boiling heat transfer coefficient.

Calculations using Equations 7 and 8 showed that the interfacial resistance becomes significant only at  $p_c$  less than  $10^{-5}$ . There are only a few data points for mercury and lithium at these low pressures. As seen in Figure 7, correction for interfacial resistance increased the  $h$  for lithium by about 20 percent. The one data point for mercury from Farmer's (1952) study in Figure 1 has been corrected for interfacial resistance; the correction was about 10 percent.

More data at low pressure are needed to reach a reliable conclusion about interfacial resistance. The results obtained using Equations 7 and 8 with  $\sigma_a = 1$  are encouraging, and hence this method is recommended for the present.

### Comparison with Mostinskii (1963) correlation

Since the Mostinskii (1963) correlation is one of the most successful correlations for ordinary liquids, its comparison with liquid-metal data is of interest.

Comparison of the Mostinskii (1963) correlation (Equation 4) with the present correlation (Equation 5) showed that the two agree rather closely for sodium. Since the Mostinskii (1963) correlation contains the multiplier  $p_c^{0.69}$  while the present correlation does not contain  $p_c$ , the predictions for other fluids vary according to their critical pressures. Thus the Mostinskii (1963) correlation's predictions for mercury and lithium are much higher than the present correlation.

### Reliability of the new correlation

The large scatter of some of the data and the extreme simplicity of the correlation may raise doubts about the reliability of the correlation.

First, it should be noted that this much data scatter is found even in the data for pool boiling of ordinary fluids. One of the most verified correlations for pool boiling of ordinary fluids is that of Stephan and Abdelsalam (1980). These authors state in this paper that they started their development effort with 5,000 data points from numerous sources but had to disregard about one third of them, since those points did not agree with the rest of the data. Data varying by a factor of two from this and other successful correlations (for example, that of Cooper 1984) are common. Greater scatter is to be expected with liquid-metal data due to the inherent unsteadiness during liquid-metal boiling.

Second, the properties of mercury, lithium, potassium, sodium, and cesium differ widely. The extent of agreement found with data for such diverse fluids could hardly be a coincidence.

In view of the foregoing, the author believes that the correlation is reasonably reliable. Further improvements and refinements are of course desirable.

### Summary and conclusion

1. The experimental data for nucleate pool boiling of single-component liquid metals boiling on plain surfaces are surveyed. The experimental studies that provide analyzable data are listed in Tables 1 and 2 together with the range of parameters covered by those data.

2. A simple new correlation is presented that does not require any fluid property data except the critical pressure. It shows reasonable agreement with the available data for nucleate pool boiling of saturated liquid metals on plates and on external surfaces of tubes. These data include mercury, potassium, sodium, lithium, and cesium. The range of all data analyzed is listed in Table 4.

3. While the extent of agreement with the data is reasonably good, further verification and development is desirable. Since most of the published data have been analyzed here, further verification may require additional experimentation.

4. The only previously available general correlation, that of Subbotin et al. (1970), underpredicts the data at lower pressures. An alternative correlation using the same parameters is



**Table 4** Complete range of data analyzed

Fluids	Sodium, potassium, lithium, cesium, mercury
Heater geometry	Horizontal plates, horizontal and vertical tubes (boiling on external surfaces)
Heater material	Copper, nickel, carbon steel, stainless steel, Hastelloy, Inconel, molybdenum, Haynes 25
$p$ , bar	0.003–10.0
$p_r$	$4.4 \times 10^{-6}$ – $2.4 \times 10^{-2}$
$q$ , kW/m <sup>2</sup>	12–2,800

presented in the Appendix. It agrees well with all data except the lithium data.

5. Areas for further research suggested by this study include:

- investigation of the transition in the effect of pressure around  $p_r = 0.001$ ;
- heat transfer with mercury containing surface wetting agents, since the results of various researchers show considerable disagreement; and
- boiling at pressures close to absolute vacuum. Very few such data are available at the present.

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## Appendix: An alternative new correlation

During this study, the boiling heat transfer data were also compared with the correlation of Subbotin et al. (1970) (Equation 1). The results are shown in Figures 1 to 7. It is

noted that at  $p_r > 0.001$ , Equation 1 agrees well with the new correlation, Equation 5. However, at  $p_r < 0.001$ , its predictions become lower than Equation 5, and the divergence increases with decreasing pressure. It therefore appeared that a satisfactory correlation may be obtained by modifying the constants and exponents in Equation 1. Further analysis yielded the following correlation:

$$h = Bq^{0.7} \left[ \frac{k_L i_g \rho_L}{\sigma T_L^2} \right]^{1/3} p_r^m \quad (A1)$$

where

$$B = 2.1 \quad \text{and} \quad m = 0.31 \quad \text{for} \quad p_r < 0.001$$

$$B = 0.67 \quad \text{and} \quad m = 0.15 \quad \text{for} \quad p_r > 0.001$$

The units are the same as in Equation 1. This correlation agrees within  $\pm 10$  percent with Equation 5 for all fluids except lithium, for which its predictions are about 25 percent lower than Equation 5.

The use of Equation A1 instead of Equation 5 gives slightly better agreement with cesium data but significantly inferior agreement with lithium data. For other fluids, the predictions of the two correlations are so close that which of the two is more accurate is not clear. Since cesium and lithium data are from only one source each, a reliable conclusion cannot be reached on the basis of these data either.

Considering all the data analyzed here, the agreement of Equation 5 is somewhat better. Also, it is much easier to use, since fluid property data are not needed. Hence, for the present, Equation 5 appears preferable to Equation A1. It is nevertheless a good alternative and should be further evaluated when more data become available.