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ESTIMATING SURFACE TEMPERATURE IN FORCED CONVECTION
NUCLEATE BOILING - A SIMPLIFIED METHOD

by R. C. Hendricks and S. S. Papell
Lewis Research Center
Cleveland, Ohio 44135
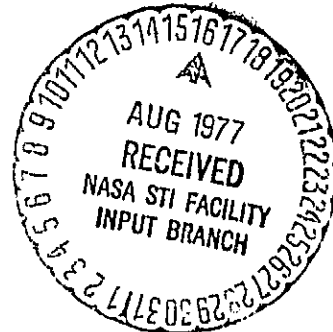
ESTIMATING SURFACE TEMPERATURE IN FORCED CONVECTION NUCLEATE BOILING - A SIMPLIFIED METHOD

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ABSTRACT

A simplified expression to estimate surface temperatures in forced convection boiling was developed using a liquid nitrogen data base. Using the principal of corresponding states and the Kutateladze relation for maximum pool boiling heat flux, the expression was normalized for use with other fluids. The expression was applied also to neon and water. For the neon data base, the agreement was acceptable with the exclusion of one set suspected to be in the transition boiling regime. For the water data base at reduced pressure greater than 0.05 the agreement is generally good. At lower reduced pressures, the water data scatter and the calculated temperature becomes a function of flow rate.

The estimation of wall temperature in forced convection boiling usually involves lengthy calculations. However, a simplified empirical technique was developed using the liquid nitrogen data base of ref. 1, the principle of corresponding states and the Kutateladze expression for maximum nucleate heat flux in pool boiling ref. 2.

The empirical correlation in reduced form is

$$(\Delta T)_r = \frac{(Z_c - \omega/4)}{3} (q_r)^{1/4} \exp\left[\frac{-4P_r}{7(Z_c - \omega/4)}\right] \qquad (1)$$

where

$$(\Delta T)_r = \frac{T_w - T_s}{T_c}$$

$$P_r = P/P_c$$

$$Z_c = \frac{P_c V_c}{R\, T_c}$$

ω = Pitzer's accentric factor

$$q_r = q/q_k^*$$

The critical pool heat flux

$$q_k^* = 0.16\, h_{fg}\, (g\, \sigma\, \rho_g^2\, \rho_{fg})^{1/4} \qquad (2)$$

was deduced from the Kutateladze expression ref. 2, and occurs for most fluids near $P_r = 0.3$. Values of q_k^* for some fluids and a method to estimate q_k^* when data are not available are given in Table I.

The data set for forced convection boiling nitrogen ref. 1 was examined for developed boiling cases. While the wall temperature peaks at incipience and decreases downstream of this point, the difference is not large and the surface temperature 10 to 20 diameters downstream was chosen as the forced convection boiling surface temperature, T_w. Knowing the pressure at this point defines the saturation conditions and q_k^*, and the critical constants follow from Table I. Figure 1 displays the calculated temperature difference $(T_w - T_s)$ as a function of the experimental value for nitrogen. The agreement is generally good.

With an equation established, it is necessary to determine if it can be applied to other nonpolar fluids. Using the forced convection boiling

neon data of ref. 1, and following the previously defined procedure, the calculated and experimental temperature differences are displayed in fig. 2. Again the agreement is reasonably good, with the exception of cne data set at 0.7 MPa. The level appears to be about 1 K higher than calculated. Subsequent examination of the neon data indicates that transition boiling can take place (followed by film boiling - see point on figure 2) and it is suspected that these data may be near the transition boiling regime.

A rather difficult test of the equation would be to apply it to a polar molecule, e.g., water. Sources of forced convection boiling water data such as McDougal, ref. 3; Schaffer, ref. 4; UCLA, ref. 5; Clark and Rohsenow, ref. 6; and Kreith and Summerfield, ref. 7; were considered by Papell, ref. 8. Selecting a few of these points, the calculated and experimental temperature differences are given in figure 3. Here the agreement is not as good as for the nonpolar molecules (especially for $P_r < 0.05$) but for the most part the agreement is reasonable considering the large critical temperature and pressure of water. Reference 5 points out that at low pressure, bubble mechanics have an increased influence on the flow rate which, in turn, makes T_r somewhat dependent on flow rate. For water at pressures less than $0.1\ P_r$ this technique may predict $(T_w - T_s)$ only within 50 percent but in most cases it is conservative.

NOTATION

g	gravitational acceleration (cm/sec^2)
h_{fg}	heat of vaporation (J/g)
P	pressure (MN/m^2)
P_r	reduced pressure (P/P_c)
q	heat flux (w/cm^2)

q_k^* Kutateladze critical pool heat flux (w/cm^2)

R gas constant $\frac{MN}{m^2} \cdot \frac{cc}{g} \cdot \frac{1}{K}$

T temperature, K

ΔT temperature difference, K

V specific volume (cm^3/g)

$Z = \dfrac{PV}{RT}$ compressibility

ρ density (g/cm^3)

σ surface tension

$\dot{\omega}$ Pitzers accentric factor (see ref. 9)

Subscripts

c   critical

fg   liquid to vapor

g   vapor

r   reduced

s   saturated

w   wall

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TABLE I. - q_{max} FROM THE KUTATELADZE POOL BOILING RELATION

Fluid	T_c K	P_c MN/m^2	ρ_c g/cc	Z_c	Kutateladze maximum - heat flux		
					T	P	q
					K	MN/m^2	W/cm^2
Helium	5.2	0.2275	0.0693	0.304	4.06	0.086	0.77
Para-Hydrogen	32.976	1.291	.03143	.302	26.8	.469	12.4
Neon	44.4	2.654	.483	.300	36.3	.796	19.1
Nitrogen	126.3	3.417	.3105	.294	104	1.04	34
Carbon Monoxide	132.91	3.499	.2997	.296	110	1.07	35.4
Fluorine	144.31	5.215	.5738	.288	123	1.89	41
Argon	150.7	4.865	.531	.292	124	1.52	45.3
Oxygen	154.78	5.082	.4325	.292	128	1.55	49.8
Methane	190.77	4.626	.162	.289	157	1.39	58.5
Carbon Dioxide	304.21	7.383	.464	.277	257	2.22	98.3
Water	647.2	22.08	.32	.233	558	6.9	489.3

q_{max} may be approximated as: $q_{max} = \frac{13}{2}(P_c)^{4/3}$ where P_c in MN/m^2 and q_{max} is W/cm^2 to ± 25 percent which is equivalent to ± 6 percent in ΔT_r
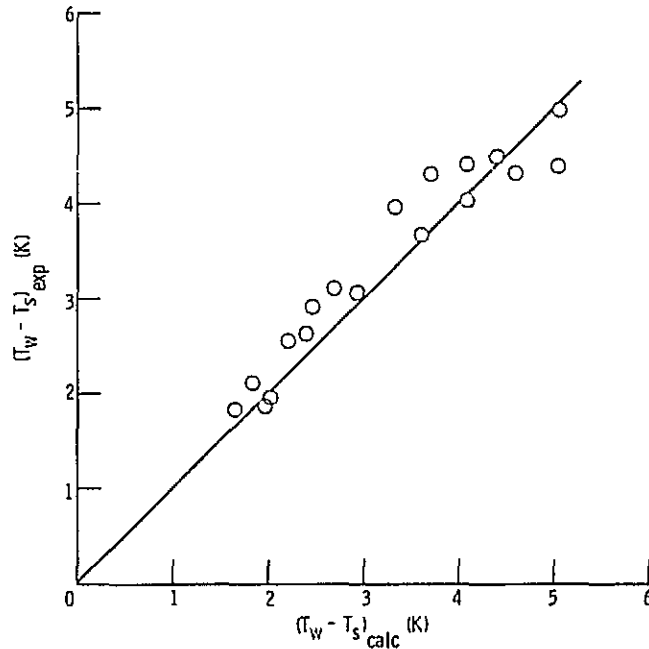
Figure 1. - Accuracy of correlation equation (1) for predicting surface temperature - LIQUID NITROGEN DATA.
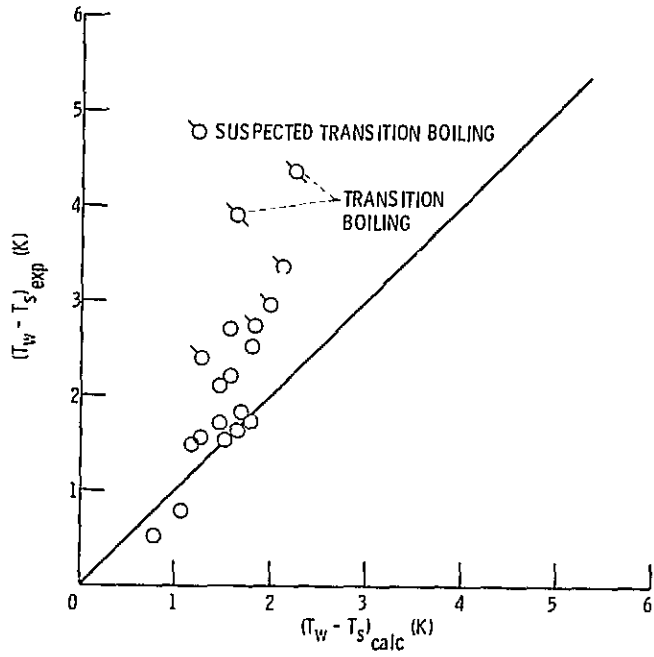
Figure 2. - Accuracy of correlation equation (1) for predicting surface
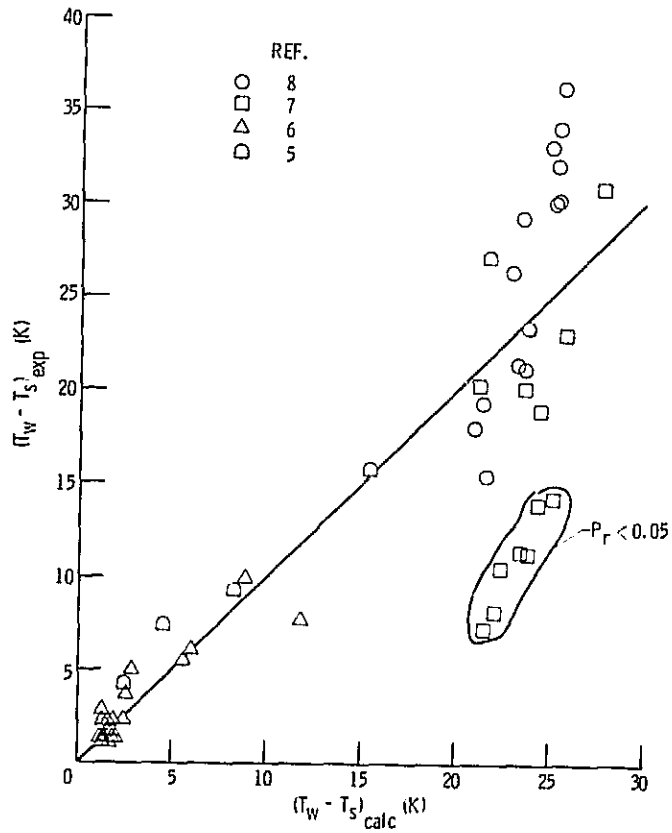temperature - LIQUID NEON DATA.

Figure 3. - Accuracy of correlation equation (1) for predicting surface
temperature - WATER DATA.