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GENERALIZED DISPLACEMENT OF THE NUCLEATE BOILING HEAT-FLUX CURVE, WITH PRESSURE CHANGE

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Abstract—A rational generalized correlation for the displacement of the nucleate boiling heat-flux curve with pressure, as a function of reduced pressure, is formulated. Comparison of the correlation with experimental data shows that it is successful.

A hypothesis that the wall superheat at any pressure is proportional to maximum theoretical superheat at that pressure is advanced. The hypothesis appears valid insofar as it can be checked experimentally.

NOMENCLATURE

A,	property dependent constant in the Yamagata equation;
B,	an undetermined constant;
a, b, c, d,	undetermined constant exponents;
$f(x), g(x)$,	undetermined functions of x;
g,	the specific Gibbs function;
p,	pressure;
q,	nucleate boiling heat flux;
s,	specific entropy;
T,	temperature;
T_w,	temperature of heating element (wall temperature);
ΔT,	wall superheat, $T_w - T_s$;
v,	specific volume;
v_{fg},	increase of specific volume upon vaporization.

Subscripts

c,	denoting a critical property;
f,	denoting a saturated liquid property;
g,	denoting a saturated vapor property;
r,	denoting a reduced (i.e. divided by critical value) property;
s,	denoting a saturated property;
M,	denoting a variable evaluated for the maximum theoretical superheat a liquid can sustain;
$1, 2, 3, 4, \ldots, i, \ldots$,	denoting various undetermined functions.

INTRODUCTION

A PROBLEM of great importance in contemporary applications of nucleate boiling is that of determining how the nucleate boiling heat flux, q, changes with the system pressure, p. Bonilla *et al.* [1, 2] have provided an important insight into this question by showing that the observed wall superheat, ΔT, in saturated nucleate pool boiling can be correlated with the relation:

$$\left.\frac{\partial \ln \Delta T}{\partial \ln p}\right|_q = -\text{ constant.} \quad (1)$$

This expression—insofar as it is accurate—solves the heat-flux displacement problem by showing us how to displace the heat-flux vs. wall superheat curve.

Data for water and a variety of organic liquids implied [1] that the constant in equation (1) should be about $\frac{1}{4}$, while later experiments with mercury [2] implied that it should be about $\frac{1}{3}$. Equation (1) was established in each case at pressures up to only about one one-hundredth of the critical pressure, p_c. At higher pressures the Jens–Lottes [3] empirical correlation of subcooled, forced-convection, nucleate boiling heat-transfer data for water:

$$\Delta T \,\text{degF} = 1{\cdot}9 \left[q \,\frac{\text{Btu}}{\text{ft}^2\text{h}}\right]^{\frac{1}{4}} \exp\left(-\frac{p \,\text{psia}}{900}\right) \quad (2)$$

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implies a considerably different form of equation (1), namely:

$$\left.\frac{\partial \ln \Delta T}{\partial \ln p}\right|_q = -\frac{p \text{ psia}}{900}. \tag{3}$$

Clearly we will have a tool of some importance if we can make a general statement about the form of this logarithmic derivative. Indeed, Forster and Greif [4] have already employed equation (1) in their formulation of nucleate boiling heat-flux correlations, although they did not point out the low pressure limitation implied by its use.

The present study is an attempt to fix the form of this derivative, and to indicate how it can be used in practice.

ANALYSIS

Recent work* in nucleate boiling has shown that the Yamagata equation:

$$q = A\Delta T^a n^b \tag{4}$$

gives good representation of the heat flux. The function, A, represents the entire dependence of q upon the physical properties of the fluid; a and b are constants, roughly equal to $\frac{6}{5}$ and $\frac{1}{3}$, respectively; and the population density of active nucleation sites, n, reflects the influence of the heater surface. Although equation (4) is intended to describe only saturated boiling in the regime of isolated bubbles, it has been employed successfully up to rather high heat fluxes.

The site density, n, could be eliminated from equation (4) if it were possible to say how many sites are generated on a given surface at a given temperature. Despite our inability to do this, the fact that the expression:

$$q \sim \Delta T^c$$

will nicely represent the data for any specific system leads us to assume that:

$$n = B\Delta T^d \tag{5}$$

where c as well as B and/or d depend upon the surface. Substitution of equation (5) into equation (4), and logarithmic differentiation of the result, leads to:

$$\left.\frac{\partial \ln \Delta T}{\partial \ln p}\right|_q = \left[-\frac{1}{c}\frac{\mathrm{d} \ln A}{\mathrm{d} \ln p}\right] \tag{6}$$

where $c = 1{\cdot}2 + d/3$. For most common surfaces d/3 varies between 1·5 and 2·5. Accordingly equation (6) will be only slightly dependent upon surface roughness.

The many proposals that have been advanced as to the form of A include a correlation by Kurihara and Myers [6], a theoretical expression by Tien [7], and a semi-rational expression by Lienhard [8]. These expressions are all simple products of relevant properties raised to different powers. Furthermore these properties are all uniquely defined by the vapor pressure which, for saturated boiling, is the system pressure. Each of these properties has also, at some time, successfully been generalized in accordance with the Law of Corresponding States (see, for example, [9] and [10]). Thus:

$$A = \prod_i \left\{ f_i \begin{bmatrix} p_c, T_c, \text{and other constants} \\ \text{characteristic of the fluid} \end{bmatrix} \right\} \times \{g_i(p_r)\} \tag{7}$$

where f_i and g_i are unknown functions, and p_r is the reduced pressure, p/p_c.

The substitution of equation (7) into equation (6), gives:

$$\left.\frac{\partial \ln \Delta T}{\partial \ln p}\right|_q = \left.\frac{\partial \ln \Delta T_r}{\partial \ln p_r}\right|_q = \frac{f_1(p_r)}{c} \tag{8}$$

or:

$$\left.\frac{\partial \ln \Delta T_r}{\partial p_r}\right|_q \simeq f_2(p_r, \text{only}) \tag{8a}$$

Equation (8a) is the correlation equation that we wish to advance in this study. Equations (1) and (3) are special cases of equation (8a).

AN HYPOTHESIS AS TO THE FORM OF THE FUNCTION, $f_2(p_r)$

The best knowledge of the properties of superheated liquids that we have is contained in van der Waals' approximate equation of state. In reduced coordinates, this equation is:

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* See, for example, a recent commentary by Boehm and Lienhard [5].

$$p_r = \frac{8T_r}{3v_r - 1} - \frac{3}{v_r^2}. \tag{9}$$

Figure 1 displays typical isotherms of van der Waals' equation. For any liquid saturated at pressure, p_s, van der Waals' equation specifies a maximum superheat, $\Delta T_M \equiv T_M - T_s$, that the liquid can sustain. This ΔT_M is a unique, monotonic function of pressure that can be determined from equation (9) in the following way:

The stable equilibrium saturation pressure, p_s, for the isotherm, T_s, is determined by equality of the specific Gibbs function, g, in the liquid and vapor phases. Accordingly:

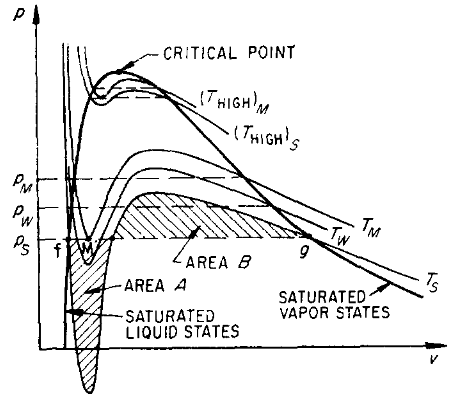

FIG. 1. The behavior of isotherms in a real fluid.

$$\int_f^g \mathrm{d}g|_{T_s} = \int_f^g (v\,\mathrm{d}p - s\,\mathrm{d}T)_{T_s} = \int_f^g v\,\mathrm{d}p = 0 \tag{10}$$

or (with reference to Fig. 1):

$$\text{Area}\,(A) = \text{Area}\,(B). \tag{11}$$

Equation (11) makes it possible for us to write:

$$p_{r_s}(v_{r_g} - v_{r_f}) = \int_{v_{r_f}}^{v_{r_g}} p_r(T_{r_s}, v_r)\,\mathrm{d}v_r \tag{12}$$

and the substitution of equation (9) in equation (12) gives:

$$p_{r_s} = \frac{8T_{r_s}}{3(v_{r_g} - v_{r_f})}\ln\left[\frac{3v_{r_g} - 1}{3v_{r_f} - 1}\right] - \frac{3}{v_{r_f}v_{r_g}}. \tag{13}$$

The van der Waals vapor pressure curve was determined by trial and error solution between equations (13) and (9). First a trial p_{r_s} was chosen; then v_{r_g} and v_{r_f} were evaluated at that pressure using equation (9). Finally these numbers were tried in condition (13). This process was repeated until the condition was satisfied.

The minimum points of instability (point M) of the van der Waals isotherms were found by setting $(\partial p_r/\partial v_r)_{T_r}$ equal to zero, whence:

$$\left.\frac{8T_r}{(3v_r - 1)^2}\right|_M = \left.\frac{2}{v_r^3}\right|_M. \tag{14}$$

Substitution of equation (14) into equation (9) gives:

$$p_{r_M} = \left[3 - \frac{2}{v_{r_M}}\right]\frac{1}{v_{r_M}^2} \tag{15}$$

which was solved by trial and error for v_{r_M} at a given pressure. Substitution of this v_{r_M} in equation (9) gave the desired T_{r_M}. Values of T_{r_M} obtained by these computations are included in Table 1.

Table 1(a). Properties of a saturated van der Waals fluid

T_{rs}	p_{rs}	v_{rg}	v_{rf}	$(v_{fg})_r$	T_{rM}	ΔT_{rM}
1·0	1·0	1·0	1·0	0	1·0	0
1·90	0·64595	2·34	0·602	1·74	0·93431	0·03431
0·8814	0·59179	2·61	0·5825	2·03	0·92580	0·04440
0·80	0·38334	4·17	0·5174	3·65	0·89477	0·09477
0·67591	0·16726	9·23	0·45778	8·77	0·86520	0·18929
0·576506	0·068712	20·63	0·4259	20·20	0·85250	0·27600
0·43766	0·010651	107·7	0·39355	107·3	0·84508	0·40742
0·350	0·0015642	594·0	0·37772	594·0	0·84375	0·49375
0·240	0·00001953	32750·0	0·36116	32750·0	0·84375	0·60375
0	0	∞	$\frac{1}{3}$	∞	0·84375	0·84375

Table 1(b). Properties of a saturated van der Waals fluid

p_r	$-\dfrac{\mathrm{d}\ln \Delta T_{rM}}{\mathrm{d}p_r}$
0	∞
0·00002	1600
0·0001	370
0·0005	118
0·001	71
0·005	21·2
0·01	12·8
0·05	5·48
0·1	3·93
0·20 → 0·38	3·17
0·4	3·25
0·45	3·41
0·5	3·53
0·55	3·98
0·6	4·35
0·65	5·524
1·0	∞

The hypothesis that we wish to advance in this section is:

> *The superheat, ΔT, for any configuration and heat flux is directly proportional to the van der Waals maximum superheat, ΔT_M.*

That is to say:

$$\left.\frac{\partial \ln \Delta T_r}{\partial p_r}\right|_q = \frac{\mathrm{d}\ln \Delta T_{rM}}{\mathrm{d}p_r}. \tag{16}$$

This idea is advanced intuitively and can be justified only by comparison with experiment.

Table 1 accordingly includes values of the derivative $\mathrm{d}\ln \Delta T_{rM}/\mathrm{d}p_r$ determined by graphical differentiation. A further discussion of the use of van der Waals' equation as a description of the real gas isotherms is made in the Appendix.

COMPARISON OF THEORY WITH EXPERIMENTAL DATA

The correlating equation, equation (8a), is used in Figs. 2 and 3 to correlate data from a variety of sources [1–3, 11, 12]. These data are tabulated in Table 2. The data of Bonilla *et al.* [1, 2] and the Jens–Lottes equation are represented by modifications of equations (1) and (3). The data of Cichelli and Bonilla [11] and of Addoms [12] have been plotted and differentiated graphically. Table 2 also indicates the relative accuracy of these graphical differentiations. The Jens and Lottes equation is only included in Fig. 2 as a matter of interest, since it represents (somewhat roughly) a large variety of forced-convection, and subcooled, boiling data.

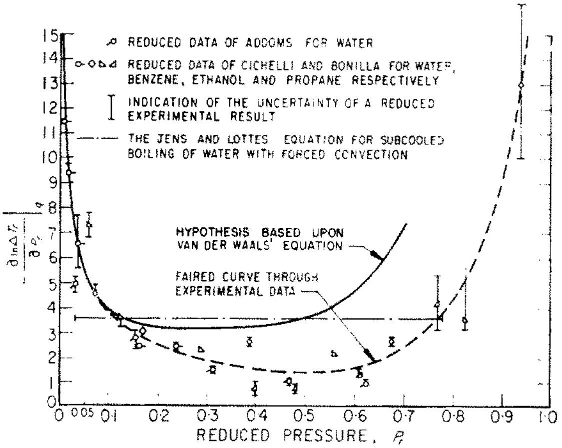

FIG. 2. Correlation of $(\partial \ln \Delta T_r/\partial p_r)_q$ in the high pressure range.

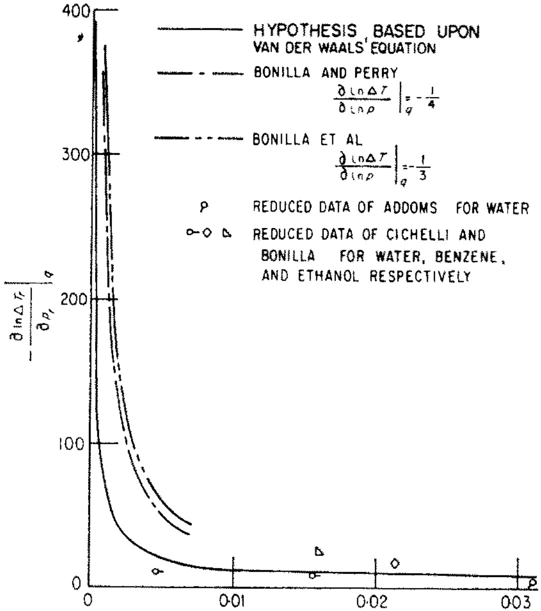

FIG. 3. Correlation of $(\partial \ln \Delta T_r/\partial p_r)_q$ in the low pressure range.

Table 2. Experimental values of $\left.\frac{\partial \ln \Delta T_r}{\partial p_r}\right|_q$

p_r	$(\partial \ln \Delta T/\partial p_r)_q$ High	Low	Best value	Reference	Substance, symbol
0·0312	−4·65	−5·3	−4·95	12	water, ⌕
0·156	−2·37	−3·04	−2·8		
0·312	−1·38	−1·70	−1·6		
0·469	−0·87	−1·2	−1·1		
0·624	−0·99	−1·15	−1·0		
0·00459	−11·4	−11·5	−11·45	11	water, ⟜
0·0156	−9·38	−9·77	−9·4		
0·0359	−5·55	−7·72	−6·6		
0·161	−2·43	−2·50	−2·5		
0·238	−2·37	−2·62	−2·5		
0·0214	−16·3	−20·5	−17·5	11	benzene,
0·0728	−4·55	−4·94	−4·65		
0·1674	−2·97	−3·20	−3·10		
0·386	−2·50	−2·80	−2·65		
0·677	−2·45	−2·80	−2·70		
0·939	−10·0	−16·25	−13·0		
0·016	−24·0	−26·0	−25·0	11	ethanol, ▷
0·0594	−6·8	−7·8	−7·3		
0·123	−3·17	−3·75	−3·7		
0·286	—	—	−2·32		
0·556	—	—	−2·2		
0·825	−3·13	−8·25	−3·57		
0·397	−0·57	−1·1	−0·8	11	propane, ◁
0·479	−0·60	−0·92	−0·8		
0·611	−1·23	−1·64	−1·3		
0·767	−3·15	−5·3	−4·15		
0·0007 to 0·007	—	—	$-\frac{0.25}{p_r}$	1	water, *n*-butanol, and isopropanol —— – —— – ——
0·0007 to 0·012	—	—	$-\frac{0.333}{p_r}$	2	mercury —— – – ——
0·03 to 0·77	—	—	$-\frac{p_c\,\text{psia}}{900}$	3	water —— · —— (subcooled forced convection)

Figure 2 shows that equation (8a) is successful in correlating the data. The scatter of the data probably arises in part from the slight surface roughness introduced through the factor $1/c$ in equations (6) and (8a). The dashed line faired through the data represents our best estimate of the function, $f_2(p_r)$. The van der Waals hypothesis, equation (16), is also tested against these data. It matches the best fit curve in the range $p_r < 0.1$. For this reason, the van der Waals hypothesis is displayed in Fig. 3 (the low pressure range) as the best line through the sparse data in this range.

The information in Figs. 2 and 3 can be put into more convenient form if we integrate equation (8a):

$$\exp\left[-\int_0^{p_r}\frac{\partial \ln \Delta T_r}{\partial p_r}\bigg|_q \mathrm{d}p_r\right] = \exp\left[-\int_0^{p_r} f_2(p_r)\,\mathrm{d}p_r\right] \qquad (17)$$

we get:

$$\frac{\Delta T \text{ at } p_r = 0}{\Delta T} = f_3(p_r). \qquad (18)$$

The function $f_3(p_r)$ is obtained graphically from Figs. 2 and 3, except for the very low p_r range which is obtained strictly from the calculated van der Waals data in Table 1.

Equation (18) is plotted for both the empirical curve and the van der Waals hypothesis in Fig. 4. This is our proposed design relation. If we know the form of the nucleate boiling heat-flux curve at some reference pressure we can displace it at constant q for a higher or lower pressure of interest by correcting ΔT at each point in the following way:

$$\frac{\Delta T_{\text{reference}}}{\Delta T_{\text{interest}}} = \left[\frac{\Delta T \text{ at } p_r = 0}{\Delta T_{\text{interest}}}\right]\left[\frac{\Delta T_{\text{reference}}}{\Delta T \text{ at } p_r = 0}\right] \qquad (19)$$

where the bracketed terms are obtained from Fig. 4.

To illustrate the ability of the working form of the correlation [Fig. 4 together with equation (19)] to reproduce the effect of pressure on the superheat, an arbitrary example is shown in Fig. 5. A single value of Addoms' data, at $p_r = 0{\cdot}120$ and $q = 10^5$ Btu/h ft^2, is used here to predict the pressure effect, and the result is compared with Addoms' data at other pressures. A word of caution is needed in this connection. Since Addoms' data were used in generating the correlation, Fig. 5 does not constitute a true comparison of theory and experiment. Rather it illustrates the fact that after considerable processing of the available data by the proposed correlative method the pressure effect is described with good accuracy.

We can also write from Fig. 4, for design purposes:

$$\frac{\Delta T \text{ at } p_r = 0}{\Delta T} \simeq 1{\cdot}6 + 6{\cdot}5 p_r; \qquad 0{\cdot}01 < p_r < 0{\cdot}65 \qquad (20)$$

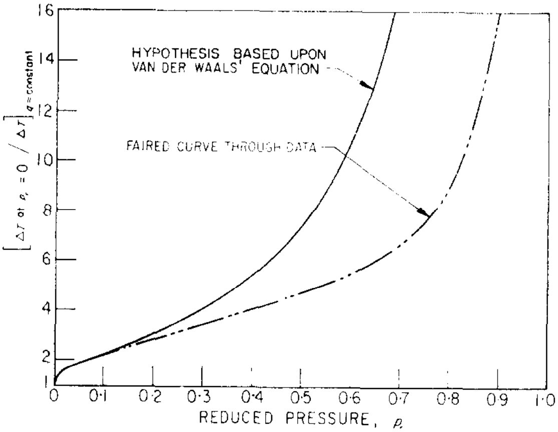

FIG. 4. The pressure dependence of the wall superheat in nucleate boiling.

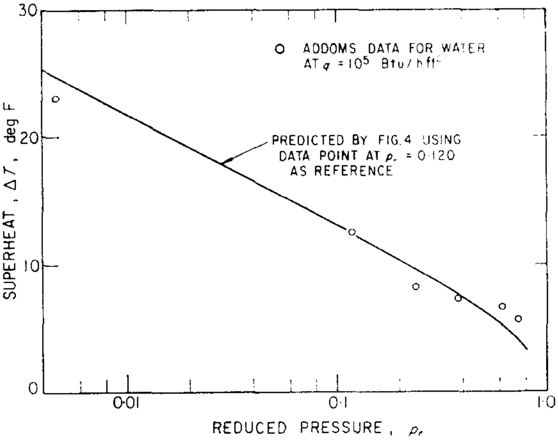

FIG. 5. Use of the correlation to reproduce Addoms' water data at 10^5 Btu/ft^2 h.

or, with the help of equation (19):

$$\frac{\Delta T_{\text{reference}}}{\Delta T_{\text{interest}}} \simeq \frac{1{\cdot}6 + 6{\cdot}5 p_{r_{\text{interest}}}}{1{\cdot}6 + 6{\cdot}5 p_{r_{\text{reference}}}}; \qquad 0{\cdot}01 < p_r < 0{\cdot}65. \qquad (21)$$

The use of a correlation of the kind proposed here is not without precedent. In 1961 Borishansky *et al.* [9] successfully correlated experimental data with the empirical expression:

$$\frac{(q^{0{\cdot}3}/\Delta T)}{(q^{0{\cdot}3}/\Delta T) \text{ at } p_r = 0{\cdot}025} = f_4(p_r). \qquad (22)$$

Equation (22) is very similar to our rational expression, equation (8a), although it imposes the additional restriction that $q \sim \Delta T^{3.33}$ at any specified pressure. This restriction is a reasonable approximation for many typical surface finishes (see, for example, the curves of Berensen [13]). The present correlation assumes $q \sim \Delta T^{c}$ but the magnitude of c is not specified.

CONCLUSIONS

(1) Displacements of nucleate boiling heat-flux curve, with changes in pressure, have been correlated in Figs. 2 and 3 with equation (8a).

(2) The success of the present van der Waals hypothesis suggests very strongly that ΔT stands in direct proportion to the maximum superheat that a liquid can sustain at any pressure.

(3) For design purposes, Fig. 4 together with equation (19) [or the approximation of equation (21)] can be used to predict the pressure dependence of the superheat, ΔT, along a line of constant heat flux from an experimental value at one pressure.

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APPENDIX

The van der Waals vapor pressure curve is plotted along with the experimental curve for water, in Fig. 6. The failure of these curves to coincide is not surprising since the van der

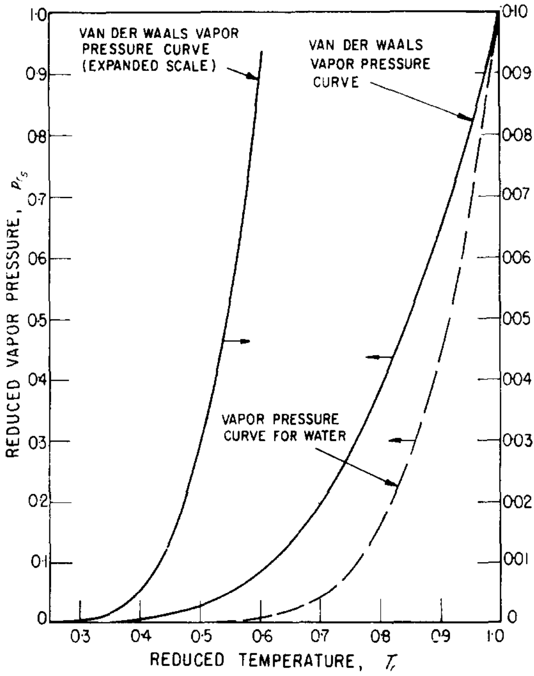

FIG. 6. Comparison of the van der Waals vapor pressure curve with the experimental curve for water.

Waals equation does not obey the Law of Corresponding States, closely. This misalignment raises two questions: (1) How do we match points between the two curves—at equal pressures or equal temperatures? and (2) Does van der Waals' equation give an estimate of ΔT_M that is sufficiently accurate to merit our attention?

The extreme superheat data recorded by Kenrick *et al.* in 1924 [14] will be of some help in answering these questions. Table A1 presents these data in raw and reduced form, along with properties of the liquids, and predicted values ΔT_{r_M} based upon matching both the vapor pressures and saturation temperatures.

The data imply that ΔT_M should be chosen at the p_s—not T_s—of interest for the following reason: the ΔT_M prediction based upon T_s indicates that the experiment attained and even exceeded T_M, while the ΔT_M prediction based upon p_s indicates that the experiments attained only $\frac{1}{3}$ to $\frac{2}{3}$ of ΔT_M. Since the unstable bubble nucleus size attains molecular proportions as ΔT maximizes it is probable that even in the finest experiments, microscopic fluctuations would initiate the formation of a nucleus bubble at temperatures well below T_M. Accordingly the van der Waals prediction of ΔT_M based on p_s appears to give reasonable values.

An earlier attempt to relate the van der Waals equation with the results of Kenrick *et al.* was made in 1947 by Temperley [15]. His approach was considerably simplified, however, in that he computed only the limiting value of T_{r_M} at zero pressure. The result is

$$T_{r_M} = 27/32 = 0{\cdot}84375.$$

Since all of Kenrick's data were made at "low" pressures (1 atm.), Temperley then compared them directly with ΔT_{r_M} based upon the *real* vapor pressure, and the *van der Waals* maximum temperature at $p_r = 0$. The result is an attractive comparison of data with theory based upon a somewhat inconsistent use of the theory.

Table A1. *Some extreme superheats recorded for a variety of liquids by Kenrick* et al.

						Experimental			Prediction based upon saturation	
Liquid	T_c (°R)	p_c (psia)	$T_{B.P.}$ (°F)	T_{r_s}	P_{r_s}	$T_{\max}$ (°F)	$\Delta T_{\max}$ (degF)	$\Delta T_{r_{\max}}$	Press. ΔT_{r_M}	Temp. ΔT_{r_M}
Water	1165	3206	212·0	0·5765	0·00458	518·0	306·0	0·2626	0·4545	0·278
Ethanol	930	927	173·0	0·680	0·01586	394·0	221·0	0·238	0·382	0·188
Methanol	914	1156	148·6	0·665	0·01271	356·0	207·4	0·227	0·397	0·200
Acetone	915	691	133·0	0·649	0·02127	345·5	212·5	0·2325	0·3625	0·214
CS_2	984	925	115·4	0·585	0·01590	334·5	219·1	0·223	0·382	0·279
SO_2	774	1142	14·0	0·613	0·01286	122·0	108·0	0·1397	0·3965	0·245
Benzene	1013	720	176·2	0·629	0·02055	397·4	221·2	0·2184	0·365	0·231
Chlorobenzene	1139	656	269·0	0·640	0·0224	482·0	213·0	0·187	0·3595	0·222
Bromobenzene	1206	656	312·0	0·6405	0·0224	502·0	190·0	0·1576	0·3595	0·221
Aniline	1258	769	361·4	0·654	0·01911	503·6	142·2	0·1131	0·370	0·210

Résumé—Une corrélation rationnelle généralisée pour le déplacement de la courbe du flux de chaleur par ébullition nuclée avec la pression est formulée en fonction de la pression réduite. La comparaison entre la corrélation et les données expérimentales montre qu'elle est couronnée de succès.

On a supposé que la surchauffe pariétale à n'importe quelle pression est proportionnelle à la surchauffe théorique maximale à cette pression. Cette hypothèse semble valable jusqu'à ce qu'elle puisse etre confrontée avec l' expérience.

Zusammenfassung—Eine rationelle, verallgemeinerte Beziehung für die druckabhängige Verschiebung der Wärmestromkurve beim Blasensieden wird als Funktion des reduzierten Druckes angegeben. Der Vergleich der Beziehung mit experimentellen Daten zeigt ihre Gültigkeit. Eine Hypothese wird weitergefürht, die besagt, dass die Überhitzung an der Wand bei jedem Druck proportional der maximalen theoretischen Überhitzung bei diesem Druck ist. Die Hypothese scheint soweiet gültig zu sein als sie experimentell nachgeprüft werden kann.

Аннотация—Сформулировано рациональное аналитическое выражение в относительных переменных для смещения кривой теплового потока при пузырьковом кипении, как функция приведенного давления. Сравнение аналитического выражения с экспериментальными данными показывает хорошее соответствие.

Выдвигается гипотеза о том, что перегрев на стенке при любом давлении пропорционален максимальному теоретическому перегреву при этом давлении. Проведенные до сих пор эксперименты показывают ее справедливость.