A Critical Examination of the View that Nucleate Boiling Heat-Transfer Data Exhibit Power Law Behavior[*]

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This article critically examines the widely accepted view that nucleate boiling heat-transfer data exhibit power law behavior, and that the ΔT exponent is approximately 3. The examination reveals that ● the power law view is based on induction methodology which is NOT rigorous; ● the power law view is NOT supported by data in literature. Rigorous induction methodology reveals that nucleate boiling data generally exhibit LINEAR behavior, i.e., nucleate boiling data generally yield straight lines when drawn on a linear scale; i.e. the ΔT exponent is generally unity.

Key Words: Nucleate Boiling, Boiling Curve, Inductive Methodology, Power Laws, Heat-Transfer

1. Introduction

Figure 1 shows the pool boiling curve in linear coordinates rather than the logarithmic coordinates generally used. Linear coordinates better reveal functionality, since straight lines result only from linear functions, and curved lines result only from nonlinear functions. (Logarithmic coordinates mask functionality, since both straight and curved lines on logarithmic coordinates can result from either linear or nonlinear functions.)

In the free convection region of the pool boiling curve, there is NO BOILING, i.e., there are no bubbles. Heat-transfer occurs by one-phase convection at the wall/liquid interface, and by evaporation at the free surface of the pool.

At the point of boiling initiation, the slope of the boiling curve increases markedly because the pumping action of the bubbles greatly enhances heat-transfer across the boiling interface. The end result is that heat flux increases rapidly and monotonically with ΔT from the point of boiling initiation to essentially the CHF. This region is referred to as the nucleate boiling region.

For more than 50 years, it has been widely agreed that nucleate boiling data exhibit power law behavior of the form

$$q=a\Delta T^{n}, \tag{1}$$

where n is an empirically determined constant whose value is approximately 3.

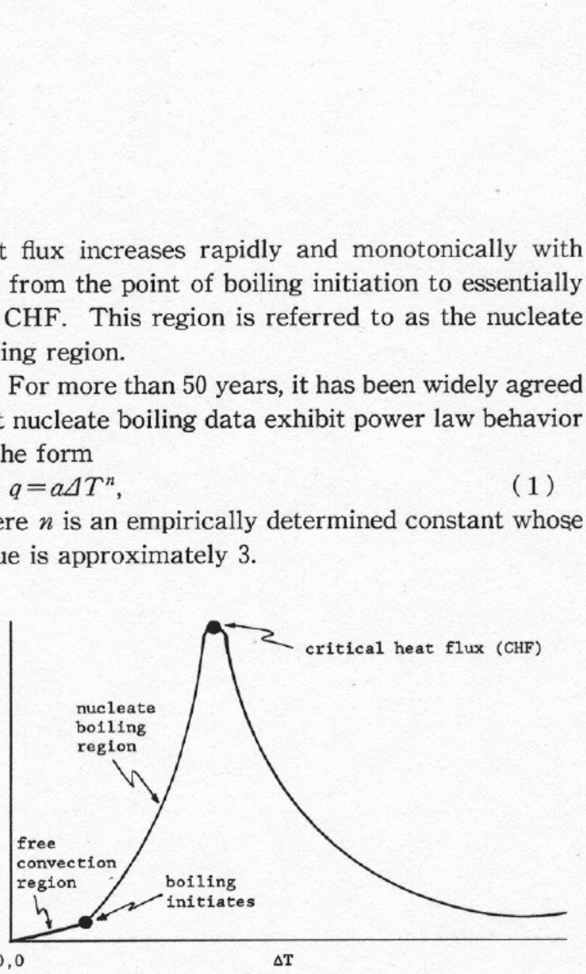

Fig. 1 Conventional pool boiling curve in linear coordinates

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In this article, the power law view of nucleate boiling is critically examined. It is found that this view is based on methodology which is not rigorous, and that nucleate boiling data generally exhibit LINEAR behavior of the form

$$q=b+c\Delta T. \qquad (2)$$

Nomenclature

a : dimensionless constant

b : dimensionless constant

B : dimensionless constant

c : dimensionless constant

h : heat-transfer coefficient defined by $q/\Delta T$, in kW/m^2/K unless otherwise specified

n : dimensionless constant

q : heat flux, in kW/m^2 unless otherwise specified

s : standard deviation

T : temperature, in °K unless otherwise specified

2. Development and Acceptance of the Power Law View

The power law view of nucleate boiling was developed in the 1930's, and has been widely accepted since that time. Cryder and Finalbargo⁽¹⁾ state that

> (In 1933), McAdams⁽²⁾ assembled data from various sources for boiling water at atmospheric pressure and has shown that there is no general agreement on ... the value of the exponent to be assigned to ΔT.

Note that, even before Nukiyama's⁽³⁾ pioneering experiment in 1934, it was generally agreed that nucleate boiling data exhibit power law behavior. The only question to be decided in 1933 was the value of the exponent.

Cryder and Finalbargo⁽¹⁾ concluded that their data, and also data in literature, indicate that the ΔT exponent in Eq. (1) is generally 3.5.

> ... The above value of 3.5 as the exponent for ΔT checks fairly well with results obtained (by Linden and Montillon⁽⁴⁾, Cryder and Gilliland⁽⁵⁾, Williams⁽⁶⁾, Jakob and Fritz⁽⁷⁾, and King⁽⁸⁾). In view of this agreement in results it is felt that some emphasis should be placed on a value of the exponent between 3.4 and 3.5.

Cichelli and Bonilla⁽⁹⁾ describe a comprehensive experiment in which numerous fluids were boiled on a horizontal surface. With regard to the ΔT exponent in Eq. (1), Cichelli and Bonilla state that

> At atmospheric pressure n was found to cover the range from 3.15 for the ethanol-water mixture to 5.31 for pentane, which blankets the average values reported in practically all previous published work.

Rohsenow⁽¹⁰⁾ presented a nucleate boiling power law correlation in the form of Eq. (1) with a ΔT exponent of 3. Rohsenow validated the value of 3 by reducing literature data to dimensionless groups, plotting the group values on a log-log scale, and showing that the group values are correlated by straight lines of slope 3. Log-log figures by Rohsenow are reproduced in Appendix 1. Note that the slope of the straight line in each figure is 3.

Berenson⁽¹¹⁾ presented boiling data on log-log graphs, one of which is reproduced in Appendix 2. Note that straight lines are drawn through the nucleate boiling data, and the slope of the lines ranges from 2 to 6, indicating exponents of 2 to 6 in Eq. (1).

Cooper⁽¹²⁾ described an ongoing effort to generate a data bank of all the nucleate pool boiling data reported in the literature. He states that computer analysis of 6,000 data points resulted in the following conclusion:

> For a given fluid on a surface of given roughness, at constant pressure, $h \propto q^m$. The average value of m, determined from all data sets, is 0.67.

(If this statement were in terms of q and ΔT rather than h and q, the value of the exponent would be 3 rather than 0.67.)

Incropera and Dewitt⁽¹³⁾ state that

> ... the first and most useful correlation for nucleate boiling ... was developed by Rohsenow⁽¹⁰⁾.

The Rohsenow correlation is also recommended by Eckert and Drake⁽¹⁴⁾, Rohsenow and Hartnett⁽¹⁵⁾, Holman⁽¹⁶⁾, Kreith and Bohn⁽¹⁷⁾, and numerous others. Other power laws cited are as follows.

- McAdams et al.⁽¹⁸⁾, exponent = 3.96.
- Jens and Lottes⁽¹⁹⁾, exponent = 4.
- Levy⁽²⁰⁾, exponent = 3.
- Kutateladze⁽²¹⁾ recommends the Aladiev correlation, a power law with exponent = 3.33.

In summary, the power law view of nucleate boiling heat-transfer behavior has been the generally accepted view for more than 50 years.

3. Methodology which Results in the Power Law View

The methodology which results in the power law view is described by Cryder and Finalbargo⁽¹⁾:

(The nucleate boiling) relation may be expressed as follows:

> $h=\phi_1(\Delta T)\phi_2(T)$
>
> To determine $\phi_1(\Delta T)$, the coefficient (h) for water is plotted against ΔT for the different runs at constant boiling temperature. A log-log plot (Fig. 4) results in a series of straight lines with a slope of 2.5 ... The data would therefore indicate that
>
> $\phi_1(\Delta T)=C_1(\Delta T)^{2.5}$

The figure referred to in the above quote is reproduced in Appendix 3.

Cooper(12) describes the digital analog of the above graphical method in reference to his correlation of nucleate boiling data:

> Correlations in the form of (power laws) are produced directly from raw data by a ... least squares program ... Here the fit is among $\log(h)$, $\log(q)$ ...

The graphical induction by Cryder and Finalbargo(1), and its digital analog by Cooper(12), exemplify the methodology generally used to induce Eq. (1). This methodology is based on drawing a straight line through nucleate boiling data plotted in log-log coordinates, or equally, on proportional regression of logarithmic values of nucleate boiling data.

4. Critical Examination of Methodology which Results in the Power Law View

The methodology which results in the power law view is not rigorous because it includes a questionable and unverified assumption. The assumption is revealed by noting that Eq. (1) is the form of ALL straight lines in log-log coordinates, and it is also a particular form of Eq. (3).

$$q=a\Delta T^{n}+B \qquad (3)$$

Therefore, when nucleate boiling behavior is induced by drawing a straight line of positive slope through data plotted in log-log coordinates (or by proportional regression of logarithmic values), it is implicitly ASSUMED that B in Eq. (3) is zero, i.e., that the boiling curve passes through the origin.

There is NO a priori reason to assume that B in Eq. (3) is zero. In fact, there is sound reason to assume B is NOT zero. This is seen by noting that

- as indicated in Fig. 1, boiling requires a finite ΔT, i.e., boiling does NOT occur at small values of ΔT. At small values of ΔT, the heat-transfer mechanism is one-phase free convection, and there is NO boiling.
- because boiling does not occur at small values of ΔT, the boiling curve does NOT pass through the origin, and therefore B in Eq. (3) is FINITE.

If B in Eq. (3) is assumed to be zero when in fact it is finite, the slope of a straight line on a log-log plot will NOT equal the value of n actually exhibited by the data. Therefore, if the resultant value of n is to be reliable, the assumption that B is zero MUST be verified.

Texts and articles which endorse the power law view do NOT verify that B in Eq. (3) is zero. Therefore the values of n they present are suspect, and the supporting data must be reexamined rigorously in order to determine the value of n truly exhibited by the data.

5. Specific Data Cited to Support the Power Law View

The best way to appraise the validity of a widely held view is to examine the specific data cited to support it. In the case of the power law view of nucleate boiling, this view has been widely held for so many decades that it is now regarded as a scientific truth not open to question. Consequently, specific data to support the power law view are not generally cited in the current literature. Therefore it is necessary to search the literature of several decades ago in order to find specific data cited to support the power law view.

5.1 Examining the data cited by Rohsenow(10)

Rohsenow(10) cites specific data to support the nucleate boiling power law correlation he presents. The Rohsenow correlation is in the form of Eq. (1), and the ΔT exponent is 3. It is important to note that the value of the exponent is NOT the result of deduction. It is the result of arbitrary selection intended to bring about agreement between the Rohsenow correlation and nucleate boiling data which had earlier been reported in the literature.

Rohsenow presents five log-log figures intended in part to demonstrate that $q(\Delta T)$ is a power law in which the exponent is 3. One figure is derived from data of Cryder and Finalbargo(1), three from data of Cichelli and Bonilla(9), and one from data of Addoms(22). Several of Rohsenow's figures are reproduced in Appendix 1. Note in each figure that

- the y axis is a dimensionless group which contains q, and the x axis is a dimensionless group which contains ΔT;
- a straight line with slope 3 is drawn in each figure.

The Rohsenow figure based on data of Cryder and Finalbargo(1) must be disregarded because the data were obtained only at very small values of heat flux. (Nukiyama(23) notes that this was generally true of boiling experiments which preceded his pioneering experiment reported in 1934.) Heat flux values can not be determined from this figure because it is in dimensionless form. However, the largest value of heat flux reported by Cryder and Finalbargo was 14,000 B/hr/ft^2 (44,000 W/m^2), which is slightly more than the heat flux required to initiate boiling. (See Appendix 3, and note that the largest heat flux value in the figure is 14,000 B/hr/ft^2.)

The Rohsenow figure based on data of Addoms(22) is for water boiling on a wire of small diameter. The figure does not contain sufficient information to relate it to specific data reported by Addoms. Moreover, although boiling on a fine wire may shed light on the fundamental mechanism of boiling, it must be regarded as a laboratory curiosity because it is of little practical importance relative to the importance of boiling on flat surfaces and tubes.

With regard to Rohsenow's three figures based on data of Cichelli and Bonilla(9), the question to be answered is

> Do the data which underlie these figures exhibit the power law behavior described by the Rohsenow correlation?

This question is definitively answered by plotting the data in linear coordinates, and noting whether curves fitted to the data do in fact exhibit power law behavior with exponent equal to 3, in accordance with the Rohsenow correlation.

This is precisely what Mesler and Banchero(24) did —— they plotted data of Cichelli and Bonilla in linear coordinates —— the SAME data Rohsenow plotted in dimensionless form in logarithmic coordinates. They found that the data were correlated by straight lines in linear coordinates, and they concluded that the Cichelli and Bonilla data did NOT support Rohsenow's power law correlation. Mesler and Banchero state that

> In this study, it was determined that the nucleate-boiling data for organic liquids are well represented by straight lines on a LINEAR plot of heat flux vs. the temperature difference. This observation is verified by data in the literature (reported by Cichelli and Bonilla(9), Perry(25), and Corty(26)).

In summary, the data cited by Rohsenow(10) in fact do NOT support the power law view for the following reasons.

- The data by Cryder and Finalbargo(1) were obtained only at very small values of heat flux. Therefore these data do not describe functionality over a substantial part of the nucleate boiling region.
- The data by Addoms(22) were obtained in an apparatus which little resembles practical boiling heat-transfer equipment.
- The data by Cichelli and Bonilla(9) in fact exhibit highly linear behavior rather than power law behavior, as demonstrated by Mesler and Banchero(24).

5.2 Verification of the assumption that B in Eq. (3) is zero

The power law view implicitly assumes that B in Eq. (3) is generally zero, and this is equivalent to assuming that boiling initiates at $\Delta T=0$. With regard to boiling initiation, Nukiyama(23) states that

> In the early stages of my study (in 1934), I found that the temperature of a metal wire easily reached as high as 105°C without the water boiling. I was in the skies because this was contrary, or so I thought, to the invariable principle that "Water boils at 100°C." ... However, when I happened to read an old textbook, Theory of Heat, written by Clerk Maxwell, Lord Rayleigh and others ... I realized they had already known the phenomenon.

In other words, water does NOT begin to boil at $\Delta T=0$ because boiling requires a finite ΔT. Therefore the assumption that B in Eq. (3) is zero CANNOT be verified in a general way.

The assumption that B in Eq. (3) is zero can be verified in a specific way if it can be demonstrated that an extrapolated line of specific nucleate boiling data passes through (0, 0). This extrapolation cannot be accomplished on logarithmic coordinates, since logarithmic coordinates do not include the coordinate (0, 0). However, the extrapolation is readily accomplished if the data are plotted on linear coordinates.

For example, nucleate boiling data presented by Berenson(11) in log-log coordinates (see Appendix 2) are replotted on linear coordinates in Fig. 2 herein. Inspection of Fig. 2 reveals that the extrapolated line fitted to Berenson's data does NOT pass through (0, 0) for any of the runs shown.

Because the extrapolated line fitted to the nucleate boiling data of Berenson does NOT pass through (0, 0), these data DENY the assumption that B in Eq. (3) is zero, and strongly suggest that this assumption CANNOT be verified in either a general or a specific way.

6. Rigorous Induction Methodology

Induction methodology is rigorous only if it excludes prejudice with regard to the value of parameter y at any and all values of parameter x. The following describes induction methodology which is rigorous.

- Plot the data on LINEAR coordinates.
- Fit a curve through regions which contain data spaced sufficiently close to provide a continuous description of behavior.
- Draw curves of mathematical expressions which resemble the curve faired through the data.
- Select the expression which most closely resembles the curve fitted to the data, i.e., the expression which results in the minimum standard deviation.

6.1 Application of rigorous induction methodology to nucleate boiling data of Berenson(11)

Berenson(11) presents nucleate boiling data on log-log graphs, one of which is reproduced in Appendix 2. Note that straight lines fit the data in the nucleate boiling region quite well, and the slopes of the lines range from 2 to 6.

As noted above, rigorous induction methodology is achieved by: plotting data on linear coordinates and allowing the data to describe the correlation.

Table 1 Nucleate boiling data by Berenson(11)

Run 2		Run 3		Runs 17/22		Run 31		Run 32	
q □	ΔT	q ■	ΔT	q ○	ΔT	q ●	ΔT	q +	ΔT
26000	43	7250	25	10500	9	13500	23	16000	14
40500	52	14500	36	20600	10	26500	27	29000	16
55000	66	24000	44	33500	11	49000	31	52000	19
56500	67	47000	56	62000	13	71000	35	79000	23
70000	76.5	74200	69	88500	14	86000	38	91000	26
79500	80	78500	73	90000	14	90000	42	96000	27
82000	85			96000	16			100000	29

UNITS: q = B/hr ft^2 ΔT = F

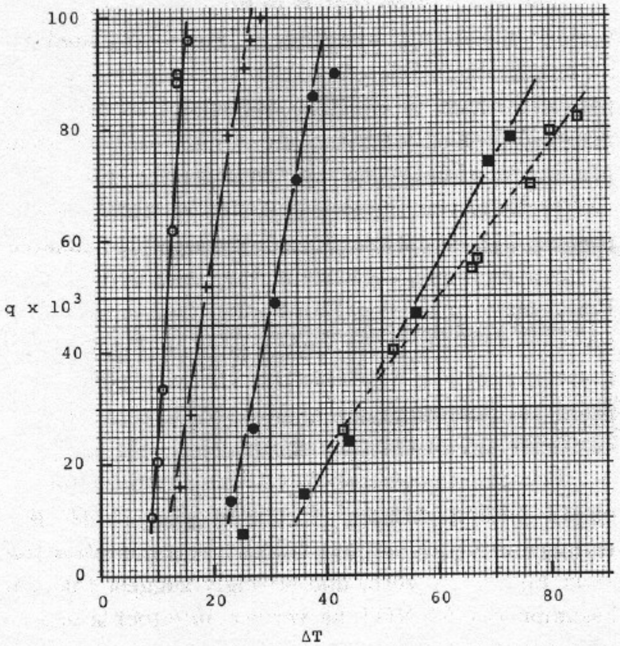

Fig. 2 Linear presentation of Berenson's(11) logarithmic figure in Appendix 2——from Adiutori(28)

Toward this end, the nucleate boiling data in Berenson's logarithmic figure are replotted on linear coordinates in Fig. 2.

Note in Fig. 2 that Berenson's nucleate boiling data exhibit linear behavior, even though these same data yield seemingly straight lines of slope 2 to 6 when plotted on logarithmic coordinates. Also note that the average deviation from the straight lines in Fig. 2 is approximately 1°F, whereas it is not possible to read Berenson's logarithmic figure with 1°F precision because the symbols are as much as 5°F wide.

Figure 2 indicates that Berenson's(11) data bear no resemblance to the widely accepted view of power law behavior of nucleate boiling with exponent approximately equal to 3. Of coure, these data alone are not sufficient to disprove the power law view, but comparison of Fig. 2 with Berenson's logarithmic figure in Appendix 2 demonstrates that highly linear data may describe seemingly straight lines of slope 2 to 6 when plotted in log-log coordinates. Therefore the fact that nucleate boiling data describe seemingly straight lines of slope 2 to 6 when plotted in log-log coordinates does NOT rigorously demonstrate that the data exhibit power law behavior with exponent equal to 2 to 6.

6.2 Alternative view of nucleate boiling behavior

With few exceptions, texts and articles support the power law view of nuleate boiling behavior. Among the exceptions are Nukiyama(3), Mesler and Banchero(24), Carne and Charlesworth(27), Adiutori(28), and Ivaskevich et al.(29)

Nukiyama is widely and appropriately regarded as the pioneer of the boiling curve. He was the first (1934) to report nucleate boiling data at large values of heat flux——the first to investigate the full range of nucleate boiling from initiation to CHF. Nukiyama used rigorous induction methodology. He made no a priori judgement about the value of q at $\Delta T=0$, or at any other value of ΔT. He simply plotted the data on linear coordinates, and allowed the data to describe the functionality.

Several of Nukiyama's figures are reproduced in Appendix 4. Note the change in slope at the initiation of boiling, and the pronounced linearity in the nucleate boiling region. Also note that the slight nonlinearity in the nucleate boiling region indicates that the second derivative of q with respect to ΔT is negative. Therefore Nukiyama's data indicate that the ΔT exponent is somewhat less than one. However, the nonlinearity has no practical significance, since an exponent of one fits the data within approximately 1°K.

As noted above, Mesler and Banchero(24) used rigorous induction methodology to analyze their nucleate boiling data, as well as considerable data from the literature which had earlier been judged to exhibit power law behavior. They demonstrated that nucleate boiling data for organic liquids generally exhibit linear behavior. They state that

> In this study it was determined that the nucleate-boiling data for organic liquids are well represented by straight lines on a LINEAR plot of heat flux vs. the temperature difference.

Carne and Charlesworth(27) used rigorous induction methodology to correlate their data, and data of Stock(30) and of Berenson(11). They state that

> Both Berenson(11) and Stock(30) originally presented their data on a log-log basis, but it is evident from Figures 10 and 11 that plotting (their) data arithmetically leads to an equally satisfactory, and in the opinion of the authors of this paper a better and more meaningful, presentation.

Ivashkevich et al.(29) used rigorous induction methodology to correlate data of Aladiev(31) on forced convection nucleate boiling of water in tubes over a wide range of flows, pressures, and temperatures.

They state that

> As can be seen from Figs. 1 and 2, (the linear equation which we induced from Aladiev's data) is in no worse accord with the experimental data than (the power law with exponent 3.33) proposed by Aladiev.

In summary, a few researchers have presented an alternative view of nucleate boiling behavior, in spite of the long and widespread acceptance of the power law view. These researchers utilized rigorous induction methodology, and invariably concluded that nucleate boiling data exhibit linear behavior.

7. Conclusions

- The power law view of nucleate boiling behavior is based on inducing the nucleate boiling correlation from straight lines drawn through data plotted in log-log coordinates. This methodology implicitly assumes that boiling initiates at $\Delta T=0$, an assumption which is contradicted by the data.
- Rigorous induction methodology is achieved by plotting data in linear coordinates, and fitting a curve through regions which contain closely spaced data.
- Examples of data originally judged to support the power law view, and later shown to be highly linear, are those of Perry(25), Cichelli and Bonilla(9), Corty(26), Stock(30), Aladiev(31), and Berenson(11).
- Data cited by Rohsenow(10) to validate his widely accepted power law correlation in fact exhibit linear behavior.
- Examples of data originally judged to support the linear view are those of Nukiyama(3) and Mesler and Banchero(24).
- Since nucleate boiling heat-transfer data reported in the literature generally exhibit linear behavior, the power law view should be abandoned in favor of the linear view.

APPENDIX 1 Excerpts from Rohsenow[(10)]

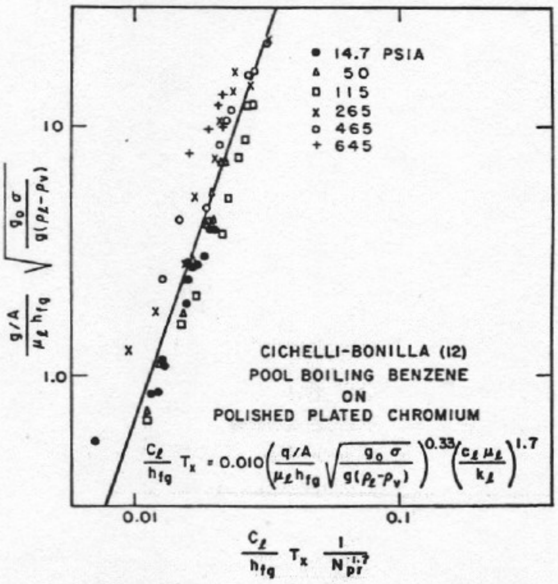

Fig. 6 Correlation of Data of Cichelli-Bonilla, Reference 12, for Chromium-Ethyl Alcohol Interface for Pool Boiling

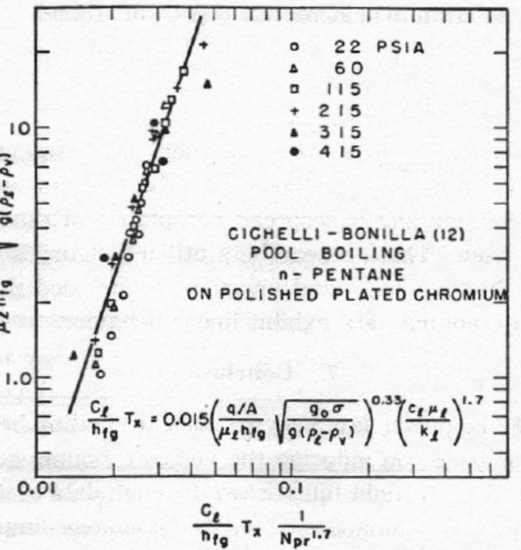

Fig. 7 Correlation of Data of Cichelli-Bonilla, Reference 12, for Chromium-*n*-Pentane Interface for Pool Boiling

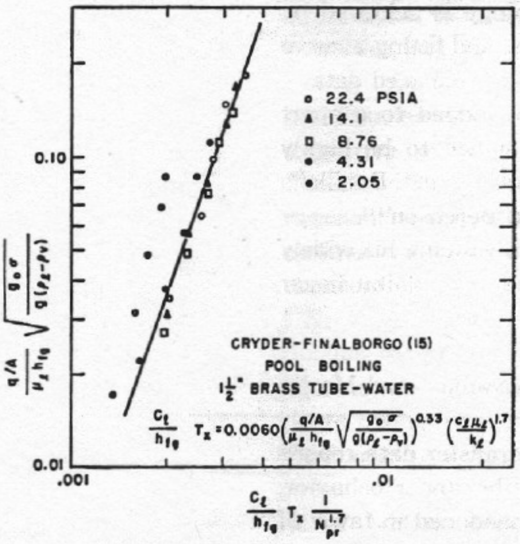

Fig. 8 Correlation of Data of Cryder-Finalborgo, Reference 15, for Brass-Water Interface for Pool Boiling

APPENDIX 2 Excerpt from Berenson[(11)], reprinted from International Journal of Heat and Mass Transfer with permission from Pergamon Press Ltd., Headington Hill Hall, Oxford OX3 OBW, UK.

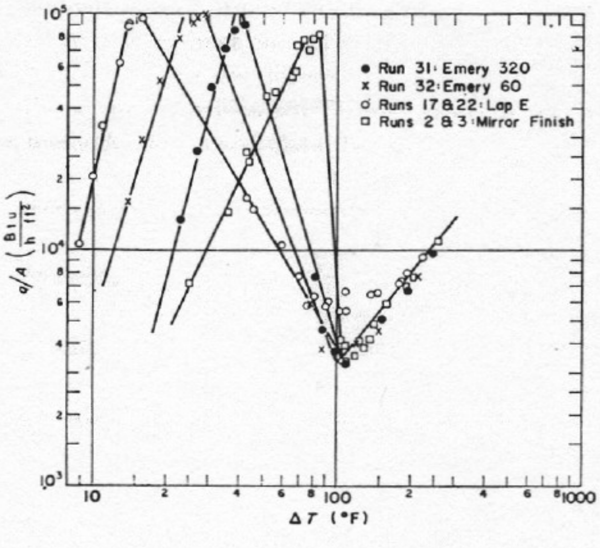

Fig. 2. Copper–pentane test results: effect of roughness.

APPENDIX 3 Excerpt from Cryder and Finalbargo[1], reprinted from Transactions of the American Institute of Chemical Engineers, Vol. 33, 1937.

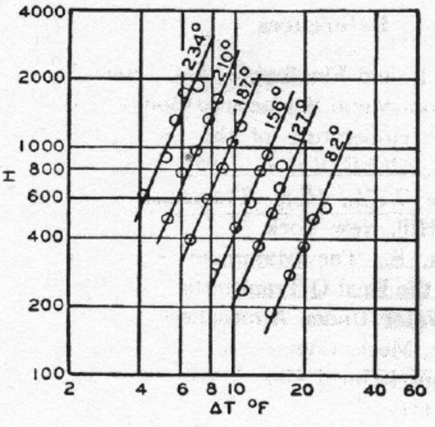

FIG. 4.

APPENDIX 4 Excerpts from Nukiyama[3]

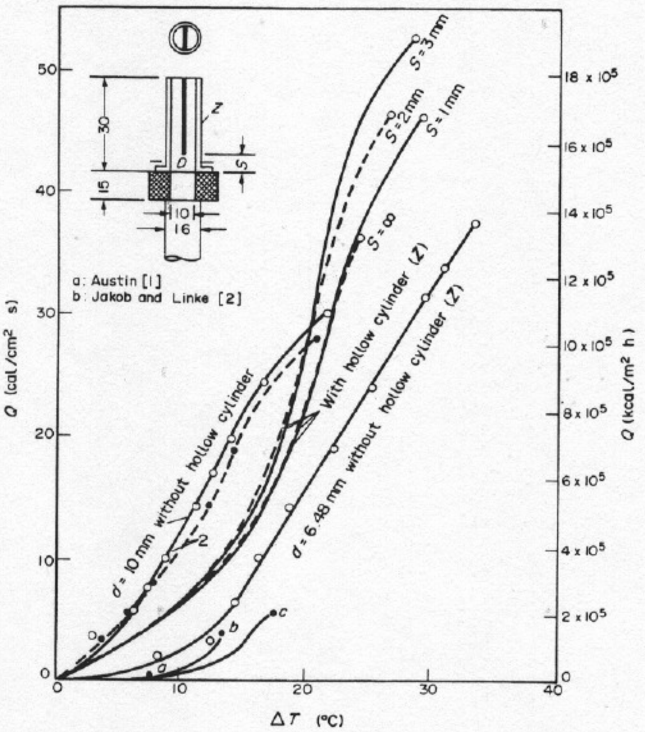

FIG. 1. ΔT vs Q curve; water temperature = 100°C.

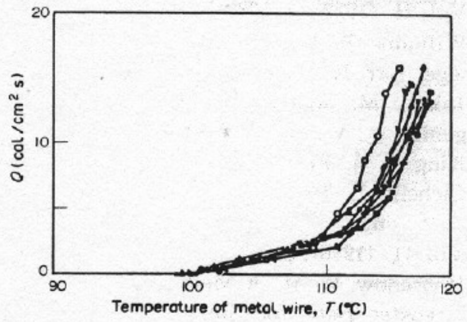

FIG. 4. Platinum wire, d = 0.14 mm; water temperature = 100°C

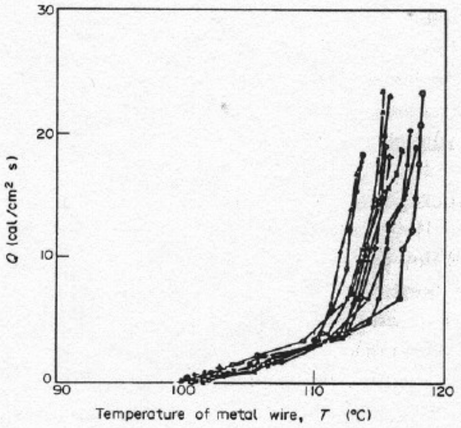

FIG. 5. Nickel wire, d = 0.14 mm; water temperature = 100°C.

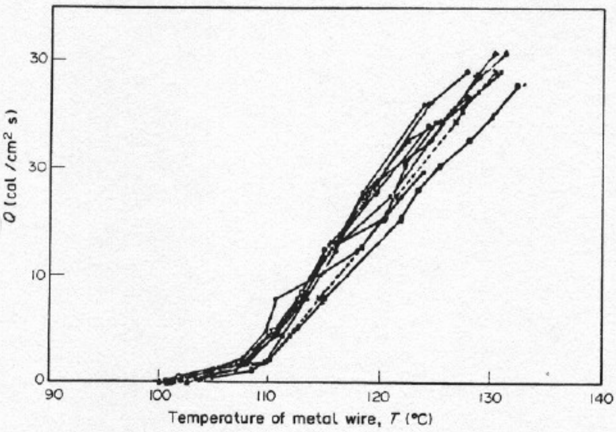

FIG. 6. Nickel wire, d = 0.40 mm (Nos. 1–10); water temperature = 100°C.

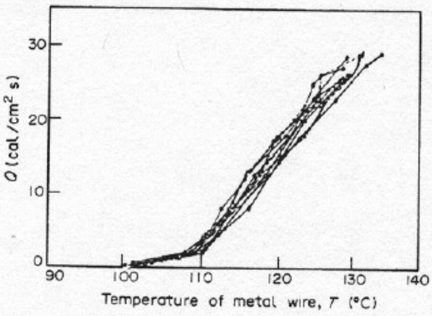

FIG. 7. Nickel wire, d = 0.40 mm (Nos. 11–20); water temperature = 100°C.

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