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NUCLEATE BOILING--THE RELATIONSHIP BETWEEN HEAT FLUX AND THERMAL DRIVING FORCE

by

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ABSTRACT:

It has frequently been stated that, during nucleate boiling, the experimental evidence indicates that the heat flux is proportional to the third or fourth power of the thermal driving force. This article reviews the evidence leading to this conclusion and, in turn, concludes that there is strong reason to doubt the validity of the subject conclusion. It offers (without proof) that, during nucleate boiling, theheat flux is linearly related to the thermal driving force.

INTRODUCTION:

A discussion of boiling appropriately begins with a definition of boiling. This author is partial to the definition suggested by Rohsenow (1):

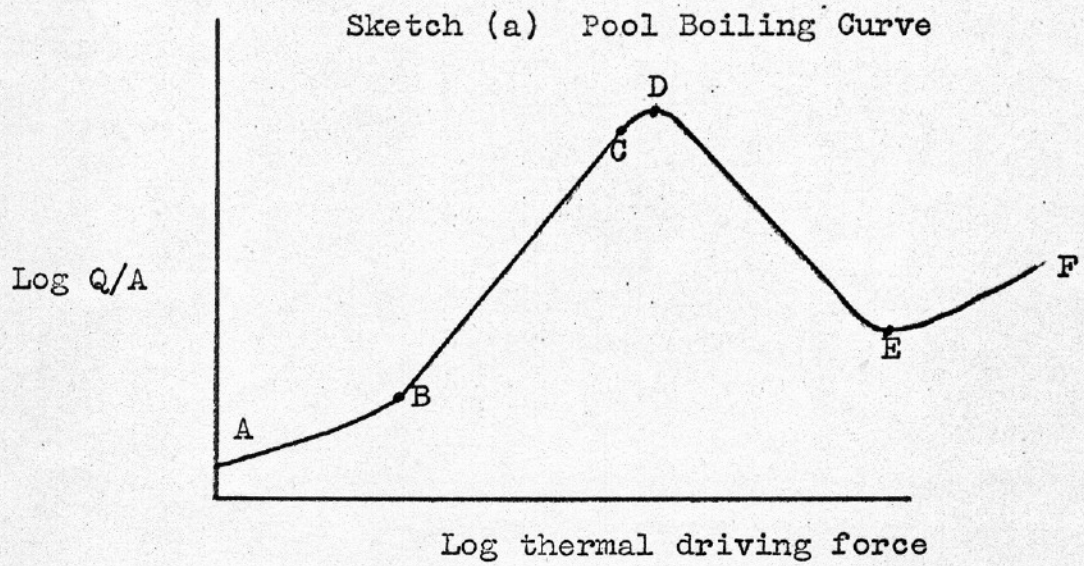
> The process of evaporation . . . results in the conversion of a liquid into a vapor. When this conversion occurs within a liquid, forming vapor bubbles, it is called boiling.

Thus, the key phenomenon which is indicative of boiling is the formation of bubbles within a liquid. If no bubbles are being formed, then no boiling is taking place. (This may seem to be an obvious point, but we shall have use of it later.)

Now that we have defined boiling, we should in turn define what

we mean by nucleate boiling. This is somewhat more difficult, since there are no clear cut phenomena which may be utilized to delineate what we call nucleate boiling. For lack of a better way, it is often defined in a more or less graphical sense to be the boiling which takes place <u>after</u> the inception of boiling but <u>before</u> the departure from nucleate boiling. Using the classical form of the "pool boiling curve", this would be region BC of sketch (a):

Sketch (a) Pool Boiling Curve



The key to sketch (a) is as follows:

AB	the region of natural convection
B	the inception of boiling point
C	the departure from nucleate boiling point
CDEF	do not concern us here

At this point, we must raise an objection due to the fact that there is an anomaly between our definition of boiling and the classical form of the pool boiling curve in sketch (a). Region AB is a region of natural convection and has many times been observed to be totally devoid of bubbles. Since boiling does

not occur in the absence of bubbles, Region AB is not boiling and therefore must not appear on the pool boiling curve. Therefore, we should mentally erase Region AB from sketch (a). This is not to say that Region AB does not exist, but rather to say that it does not boil. With this revised version of the pool boiling curve, we can simplify our definition of nucleate boiling to the following:

> Nucleate boiling is that boiling which occurs at thermal driving forces below that corresponding to the departure from nucleate boiling point.

As shown by the straight line representation of Region BC, it has long been felt that, during nucleate boiling,

$$Q/A \propto \Delta T^n$$

and that n is generally some value from three to four. It is the purpose of this article to review the evidence on which this feeling is based and, in so doing, to determine whether the above should be retained.

BACKGROUND:

A survey of the literature will reveal that most authors agree that a wide range of exponents has been measured, ranging perhaps from a value of 1 to a value of 75. There seems to be further agreement that the most commonly measured values are approximately three or four. Three seems to have gained the widest acceptance, perhaps due to the fact that values very close to three have been derived on a rational basis by several analysts in several different ways.

A close review of the literature indicates that the unanimity with respect to the value three is rather surprising in view of the fact that a preponderance of the data suggest values

far removed from both three and four. To cite a single example, Corty and Foust (2) performed a very extensive experimental program on a number of different facets of boiling and all their measured values fell in the range 12 to 24!

As a result of the above seeming anomalies, the author felt that a detailed study of the data and the reasoning behind the selection of equation (1) and the value three were indicated. This article is the result of that study.

REASONING WHICH LEADS TO AN EXPONENT OF THREE:

One of the techniques which makes statistics such a powerful tool is indicated in the following axiom:

> If you cannot prove what you want to prove, prove something else and pretend it is the same thing.

Of all the techniques in statistics, the above is probably the most powerful--and it is certainly the most widely used. It is a technique which is known and used and loved daily by the advertising genius and one which sometimes creeps into science and engineering. It is a technique which one may innocently fall into and it therefore requires constant and conscious vigilance to avoid. Whenever we are appraising a proof of any kind, it is advisable to keep this technique in mind in order that we may approach the proof with the proper amount of skepticism.

When an experiment is performed, the result is a lot of raw data which is then reduced to a more useable form. In the case of pool boiling experiments, this converted form consists of a family of heat fluxes and their corresponding thermal driving forces. After converting the data, it is usually convenient and desirable to summarize the data with the aid of

an empirical correlation, but how to select such a correlation? Now, there are a myriad of such ways possible, but it is unfortunately true that the worst of these is often selected. Frequently, the experimenter will hypothesize that the data correlates with the form

$$y = mx^n \qquad (2)$$

which in turn suggests that the data be plotted on log log paper. Furthermore, the above hypothesis is checked by inspecting the plotted data to determine whether the data is so warped that a straight line cannot be drawn through it. If a straight line cannot be drawn, this method (in theory) suggests that some other hypothesis be made and that log log paper not be used.

The point of bringing up the above method is that it is the one usually used to demonstrate the rationale of equation (1) for nucleate boiling, with n approximately equal to three. However, in regard to this method, the following are also true:

1. It is a rare set of data on any subject which will not seem to allow a straight line to be drawn through a log log representation of the data (particularly when the axes are of the size commonly used).
2. It is strange but true that, in those rare cases which demand that a curve be drawn through the data, the custom has been to ignore one or the other end of the data and draw a straight line anyway.

Thus, it would seem that no attempt has been made to determine the proper relationship <u>from the data</u>. Rather, the effort has all been the other way--to show that the data can be <u>made to</u> conform to equation (1), whether it wants to or not!

It is strange but true that, when one sets out to prove a thing is true, one is seldom disappointed if only he rely heavily on statistics. The above is a case in point!

REASONING WHICH LEADS TO DOUBTING EXPONENT OF THREE:

As indicated above, our "thinking" and deducing about the relationship between heat flux and thermal driving force has been largely restricted to log log paper. With regard to this type of graph paper, we should bear the following in mind:

1. A straight line of positive slope always goes through the point 0,0, whether or not this is indicated by the data.
2. A straight line with negative slope always goes through the point ∞,0, whether or not this is indicated by the data.

The point of the above observations is to illustrate the fact that, whenever we draw a straight line through data on log log paper, we are assuming a great deal about the data, particularly with respect to its behavior at the origin. Moreover, we make these assumptions without checking their accuracy, since zero coordinates can never be found on log log paper. In a very real sense, whenever we simply draw a straight line on log log paper through a set of data, we are in large part assuming the answer and disregarding the data!

The above is the main reason which creates a doubt as to the validity of equation (1) and an exponent of three or five or any other exponent obtained from drawing lines on log log paper. There is a time and a place for log log paper, but the above example is not one of them.

A BETTER WAY:

At this point, it is appropriate to ask whether the above method, with its inherent drawbacks, is not indeed the best method available? The answer is no--there are a myriad of better ways to accomplish this same end.

To begin with, it seems reasonable to always accept a linear relationship between two variables unless it can be shown that the relationship is non-linear. It is remarkably true that, to date, the non-linearity between heat flux and thermal driving force during nucleate boiling has never been demonstrated. It is the author's contention (offered without proof) that the non-linearity has never been demonstrated because it cannot be demonstrated. That, in point of fact, this relationship is highly linear and is given by

$$Q/A = B + C\Delta T \qquad (3)$$

In answer to the question as to why no proof is offered, it is because no proof would suffice. If the author were to show several examples of such linearity taken from the literature, this would show only that linearity is possible, and this has never been denied. The only proof lies in the data, and the data on this subject has become of such a magnitude as to defy ever again being effectively summarized in a single article. The proof of the applicability of equation (3) must, as always, lie with the reader. To aid the reader in finding data of high precision, the author recommends the extensive and precise data of Berenson (3) in addition to that of reference (2). If the reader will select several of the many runs reported in these two excellent manuscripts and plot the data on linear graph paper, he will almost certainly concur with the conten-

tion of linearity.

It is perhaps worth while to consider why data which conforms to equation (3) was erroneously concluded to conform to equation (1). Certainly part of the reason is due to the understandable desire on the part of the experimenter to moderate the experimental scatter, a feat for which log log paper has long been famous. Unfortunately, the improvement is only a mirage, the seeming improvement being obtained only at the high price of effectively distorting the experimental results. The larger part is probably due to our own charity in not insisting that we prove precisely what we set out to prove.

To be painfully accurate, the old method described above actually proved only that the data did not deny a straight line relationship on log log paper. Thus, it was only a negative form of proof, proving only that we could not disprove what we had assumed in the first place. This, of course, is a far cry from proving anything in a positive sense. It is also true that, in those cases where we cannot disprove something, we have no right to conclude that the inability to disprove demonstrates the truth of what we are trying vainly to disprove. It may be true and it may not be true--this is all we should conclude. We should further realize that the inability to disprove indicates that the tools we are using to disprove may lack the required acuteness--that we should search for sharper tools. This latter conclusion would seem to follow from the realization that what we hold true today--will likely be disproved tomorrow! If the history of science is fraught with any single lesson, it is that progress brings change, whether it be welcome or not.

CONCLUSION AND SUMMARY:

This article:

1. Examines the pool boiling curve and concludes that it is usually drawn incorrectly in that the portion known as the free convection region does not satisfy a reasonable definition of boiling and should therefore not be considered part of the pool boiling curve.
2. Examines the evidence in support of the widely accepted conclusion that, during nucleate boiling, the heat flux is non-linearly related to the thermal driving force to the third or fourth power. Based on this examination, it is concluded that the subject conclusion is without foundation.
3. Offers (without proof) that, during nucleate boiling, the heat flux is linearly related to the thermal driving force as described by equation (3).

It isfelt that correcting the subject relationship should be instrumental in leading to an improved analytical derivation of this relationship which will in turn lead to an improved understanding of the microscopic nature of boiling.

REFERENCES:

1. Modern Developments in Heat Transfer by Warren Ibele, 1963, page 85 by Warren M. Rohsenow
2. Claude Corty and Alan S. Foust, Surface Variables in Nucleate Boiling, Chemical Engineering Progress Symposium Series, Number 17, Volume 51, 1955
3. Paul Berenson, Transition Boiling Heat Transfer from a Horizontal Surface, Sc. D. Thesis, MIT (1960)

SYMBOLS:

Q/A heat flux, Btu/hr ft^2

T temperature, F.

y, x variables with no particular reference

B, C, n constants