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An Alternate to the Dengler and Addoms Convection Concept of Forced Convection Boiling Heat Transfer

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Current literature describes forced convection, boiling heat transfer as primarily convective heat transfer. The original evidence for this concept, reported by Dengler and Addoms, was reexamined and found misinterpreted. Nucleate boiling data, instead, correlate with their data. Subsequent use of the concept in correlations and models now requires close scrutiny.

SCOPE

The current literature on two-phase, forced convection, boiling heat transfer in tubes describes the phenomenon as primarily convection. Although nucleate boiling may occur near the inlet or at low flow, it is suppressed by the effects of vapor induced forced convection. This concept was first enunciated by Dengler and Addoms (1956) in analyzing the results of experiments with a long vertical tube evaporating water at near atmospheric pressure. Recently, inconsistencies have been noted which have given cause to reexamine the experiments and the basis for the widely held concept.

CONCLUSIONS AND SIGNIFICANCE

Dengler and Addoms tested their hypothesis that convection was dominant by preparing a plot of the log of h/h_L against the log of the reciprocal of the Lockhart-Martinelli, two-phase turbulent flow parameter. They cited a positive slope of a line which gave a reasonable fit as support for the hypothesis. A reexamination shows that the positive slope results from plotting quantities against one another containing the same variables rather than from any effect of convection. The hypothesis must therefore be rejected. Subsequent investigations which have used the same method of correlation must now be reexamined to determine whether the Dengler and Addoms concept is still valid in those individual instances, even though it lacks the support its originators claimed.

A model postulating nucleate boiling does correlate the data of Dengler and Addoms at least as well as nucleate boiling data can be correlated with themselves.

In 1956, Dengler and Addoms published a paper which has had a profound impact on the study of vertical tube evaporators and forced convection boiling heat transfer. No previous investigators had attempted to measure the variation of the heat transfer rate with elevation along the tube. As a result of their investigation, they claimed the mechanism of heat transfer during vaporization in tubes is primarily convective. Nucleate boiling is dominant only under conditions of low liquid velocity and is gradually suppressed by the effects of vapor induced forced convection. The paper continues to be cited frequently. Thirteen papers were found between 1970 and 1975 that referenced the paper.

Recently, the paper has come under scrutiny because of the recognition of superior performance of nucleate boiling in thin liquid films (Mesler, 1976). In a vertical tube evaporator, much evaporation occurs in annular flow where the tube is wet with a liquid film. According to Dengler and

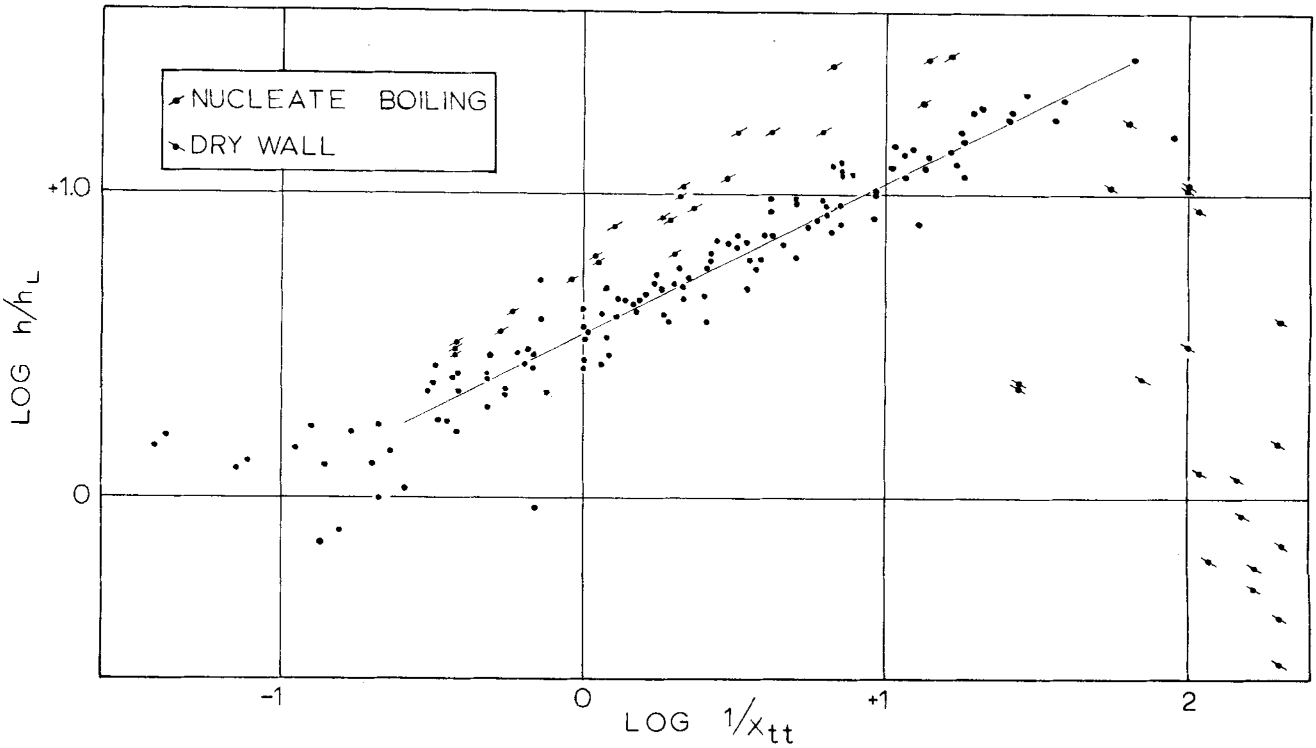

Fig. 1. Log h/h_L vs. log $1/X_{tt}$ from Dengler and Addoms.

Addoms, one should not expect nucleate boiling under such conditions. It is difficult to understand why this would be so, since elsewhere nucleate boiling from thin liquid films has proven so effective.

Water entered the bottom of the vertical tube evaporator that Dengler and Addoms studied. Heat addition along the tube generated vapor so that the proportion of vapor continually increased. Although velocities at the bottom were small, the production of vapor caused a drastic increase in velocity because the ratio of the specific volumes of vapor to liquid is 1 600.

As the proportion of vapor to liquid changes, so does the two-phase flow regime. The regime progresses from bubbly through slug and annular to a drop or mist flow and, finally, to a dry wall with addition of sufficient heat. Given the variety of flow regimes encountered together with the variation in velocity, it is only natural to expect the mode of heat transfer to change.

Dengler and Addoms used a vertical 20 ft, 1 in. ID copper tube with five closely spaced steam jackets to supply heat. Tube wall temperatures were measured at twenty-one positions along the tube. Condensation rates in each jacket were measured individually. Pressure taps were located at the ends of the tube and between the steam jackets.

Upon examining their data, they observed that the heat flux increased sharply along most of the tube, particularly along the latter portion, and that the weight fraction of vapor increased, but the film-temperature difference remained relatively constant. they stated:

"This strongly suggests that nucleate boiling is not the primary heat transfer mechanism in the upper part of the tube as ΔT does not vary with q/A. Rather, vapor-induced two-phase forced convection is believed to be the primary mechanism in this region, as q/A increases with the weight fraction vapor."

There are two serious difficulties with these statements. First, due recognition is not made of the steepness of the relation of heat flux to ΔT during nucleate boiling. During nucleate boiling, a large increase in the heat flux is often accompanied by only a small increase in ΔT. Second, the observation that weight fraction vapor increased with heat flux is a consequence of the first law of thermodynamics and can hardly be expected to be a very meaningful test of any hypothesis concerning the mechanism of heat transfer.

To analyze their premise, Dengler and Addoms calculated the ratio of their measured heat transfer coefficient to the heat transfer coefficient calculated assuming the entire flow was liquid. They plotted the log of this ratio against the log of the reciprocal of the Lockhart and Martinelli two-phase, turbulent flow parameter X_{tt}. The plot is reproduced in Figure 1. The two-phase turbulent flow parameter has been found quite useful in analyzing pressure drop in two-phase flow and would therefore help in sorting out the variation in heat transfer in two-phase turbulent flow. The parameter was defined as follows:

$$\frac{1}{X_{tt}} = \left(\frac{x}{1-x}\right)^{0.9} \left(\frac{V_G}{V_L}\right)^{0.5} \left(\frac{\mu_G}{\mu_L}\right)^{0.1} \qquad (1)$$

Variation of this parameter in the experiments of Dengler and Addoms was due almost entirely to variation in quality x.

The liquid phase heat transfer coefficient was calculated with the equation

$$h_L = 0.023 \frac{k}{D} \left(\frac{4w}{\pi D \mu_L}\right)^{0.8} \left(\frac{C_p \mu_L}{k}\right)^{0.4} \qquad (2)$$

The only factor that varied substantially here was w.

Dengler and Addoms distinguished three categories among their data: dry wall, nucleate boiling, and pure convection. At high values of $1/X_{tt}$, some low values of h/h_L were attributed to the drying of the tube wall. Some high values of h/h_L, those on the upper fringe of the data in Figure 1, were attributed to nucleate boiling. These values all occurred near the inlet where quality was the lowest. The remaining points were classified as purely convective. Of course, at very low values of $1/X_{tt}$ they expected that h/h_L would become unity.

Dengler and Addoms found that over a limited range, a straight line fit their convective data as plotted in Figure 1:

$$\frac{h}{h_L} = 3.5\left(\frac{1}{X_{tt}}\right)^{0.5} \quad 0.25 < \frac{1}{X_{tt}} < 70 \tag{3}$$

Eighty-five percent of the purely convective data are correlated by this expression within ±20%.

Pitfalls in the correlation of engineering data have been described by Rowe (1963). Rowe identified the log-log graph, the exclusion of rogue points, and the inclusion of the same variable in the two quantities plotted against each other as all being particularly troublesome. All of these occur in the situation just described.

The use of the two-phase turbulent flow parameter as a correlation factor presents a problem with respect to the last of Rowe's points, which is not immediately obvious. The reciprocal of this parameter depends almost linearly on the quality. The quality, in turn, is dependent upon the heat flux. An energy balance along the tube shows this more clearly. If we assume saturated liquid at the inlet, the energy balance may be written as

$$xw\lambda = \int_0^z \frac{q}{A}\pi D dz$$

$$x = \frac{\pi D}{w\lambda}\int_0^z \frac{q}{A} dz \tag{4}$$

Also

$$\frac{h}{h_L} = \frac{\dfrac{q}{A}\cdot\dfrac{1}{\Delta T}}{0.023\dfrac{k}{D}\left(\dfrac{4w}{\pi D\mu_L}\right)^{0.8}\left(\dfrac{C_p\mu_L}{k}\right)^{0.4}} \tag{5}$$

The only variables that Dengler and Addoms used in their plot of h/h_L *vs.* $1/X_{tt}$ and which were varied in a significant way were q/A, x, w, and ΔT. These variables were contained in h/h_L as

$$\frac{1}{w^{0.8}}\frac{q}{A}\frac{1}{\Delta T}$$

and in $1/X_{tt}$ as

$$\left(\frac{x}{1-x}\right)^{0.9}$$

Therefore, the quantities chosen for plotting vary very nearly as

$$\frac{1}{w}\frac{q}{A}\frac{1}{\Delta T} \quad vs. \quad \frac{1}{w}\int_0^z \frac{q}{A} dz$$

since $\left(\frac{x}{1-x}\right)^{0.9}$ is approximately x for the values of x encountered, and $w^{0.8}$ is approximately w.

It is instructive to examine the effect of including q/A and w in the two quantities plotted against each other. A convenient means of assessing this is to plot log $(\Delta T \cdot h/h_L)$ against log $1/X_{tt}$. This should vary very nearly as log $(1/w \cdot q/A)$ *vs.*

$$\log\left(\frac{1}{w}\int_0^z \frac{q}{A} dz\right)$$

The plot is shown in Figure 2.

The convective data in Figure 2 show that $\Delta T \cdot h/h_L$ increases nearly proportionally with $1/X_{tt}$. This is hardly a surprise, since q/A and w were varied substantially in the experiments, and it is essentially log $(1/w \cdot q/A)$ being plotted against

$$\log\left(\frac{1}{w}\int_0^z \frac{q}{A} dz\right)$$

Dengler and Addoms selected $1/X_{tt}$ as a measure of the convection they expected would occur. They observed that their values of h/h_L increased with $1/X_{tt}$ and concluded that convection was dominant. However, the convection argument must also predict a tendency for ΔT to be smaller when convection is stronger, as would be true for larger values of $1/X_{tt}$. This, in turn, predicts that when h/h_L, which tends to increase with $1/X_{tt}$, is multiplied by ΔT, which tends to decrease with $1/X_{tt}$, the quantity obtained should vary less with $1/X_{tt}$ than did h/h_L. The actual data as seen in Figure 2 contradict this prediction.

This presents an interesting question. If it is not the lower values of ΔT that are responsible for causing h/h_L to increase with $1/X_{tt}$, then what is the cause? The answer is that it is the steeper slope of the data as plotted in Figure 2. As we have already seen, the steep slope stems from including the same variables in both quantities plotted and not at all from any consideration of convection. Therefore, we must reject the hypothesis that convection is dominant.

If convection is not the dominant mode for the heat transfer, is nucleate boiling? A convenient means of examining this is to plot q/A *vs.* ΔT and compare it with what others have reported for nucleate boiling.

In their paper, Dengler and Addoms state: "When total heat flux was plotted against total temperature difference, there was no correlation." They cite Dengler's dissertation in support. No such plot appears either in the paper or in the dissertation to support the authors' contention. It is possible for the readers to check by preparing their own plots. Although the data to prepare such a plot are not contained in the paper, they do appear in the dissertation.

Data in Dengler's dissertation were examined in order to prepare a plot that could be compared directly with other nucleate boiling data. It was found that ΔT's calculated by Dengler were not directly usable. Dengler used the fluid temperature instead of the saturation temperature to calculate his ΔT.

Dengler found the average temperature differences by plotting the temperatures against location. He used a planimeter to evaluate the area and from this calculated an average temperature difference. This required subjectivity. To be more objective for present purposes, the wall temperatures and the saturation temperatures were first averaged separately; then the difference was taken to calculate ΔT. The saturation temperature at each end of a section was calculated from the pressure with steam tables.

An examination of the tabulated wall temperatures showed some thermocouples behaved erratically, sometimes giving unreasonable temperatures compared to their neighbors. Thermocouple 10 (110 in up from the bottom of the tube) often gave low readings. Thermocouple 19 (211 in up) gave both high and low temperatures and often went unreported. No readings were recorded for thermocouple 4 (43 in up). When irregularities occurred, an average temperature for the wall temperature in that section was not calculated. Many average wall temperatures in the bottom, middle, and top sections were thus lost, but none were lost in the other two sections.

In some instances, the stream temperature was un-

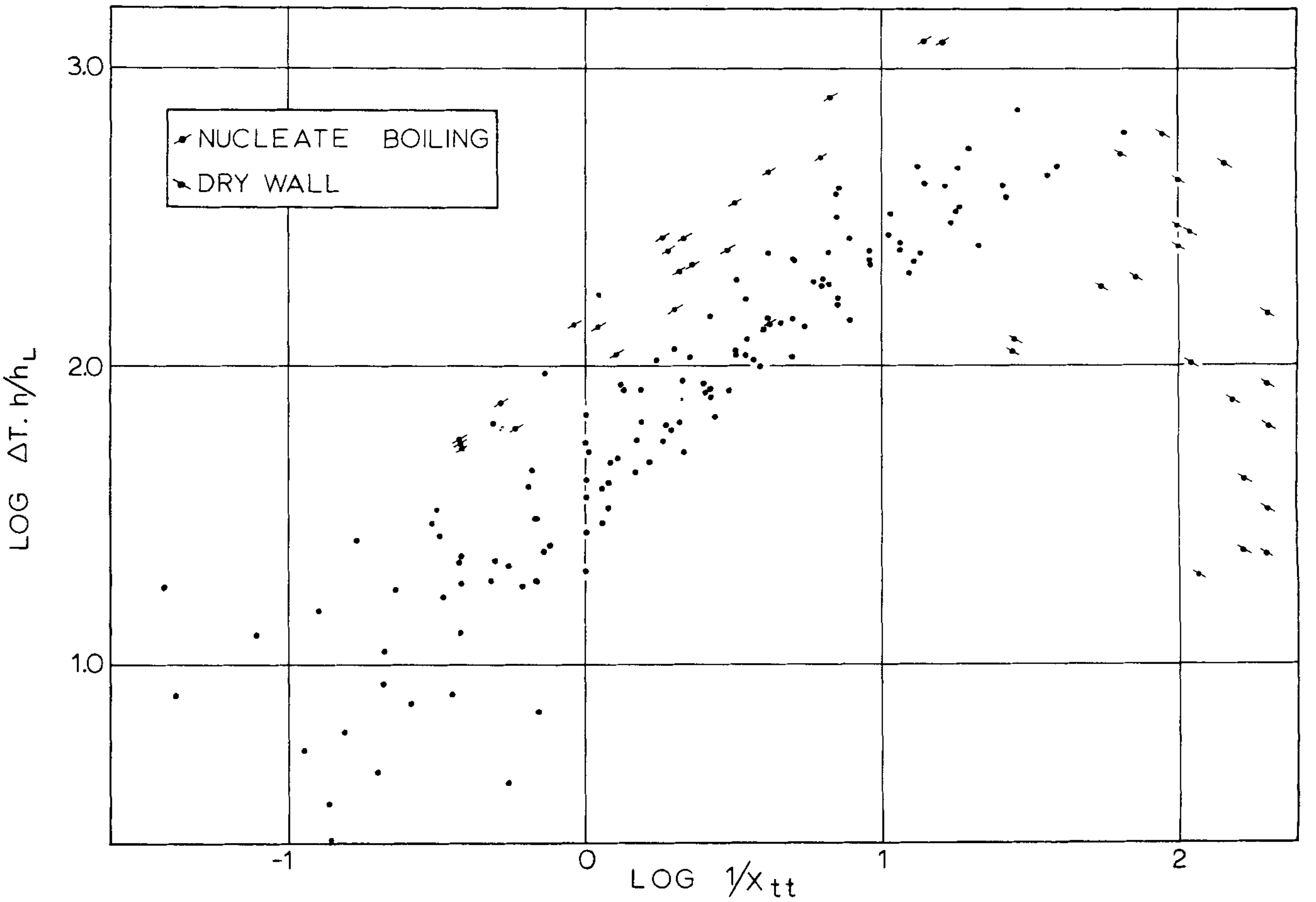

Fig. 2. Log $\Delta T \cdot h/h_L$ vs. log $1/X_{tt}$ from Dengler and Addoms.

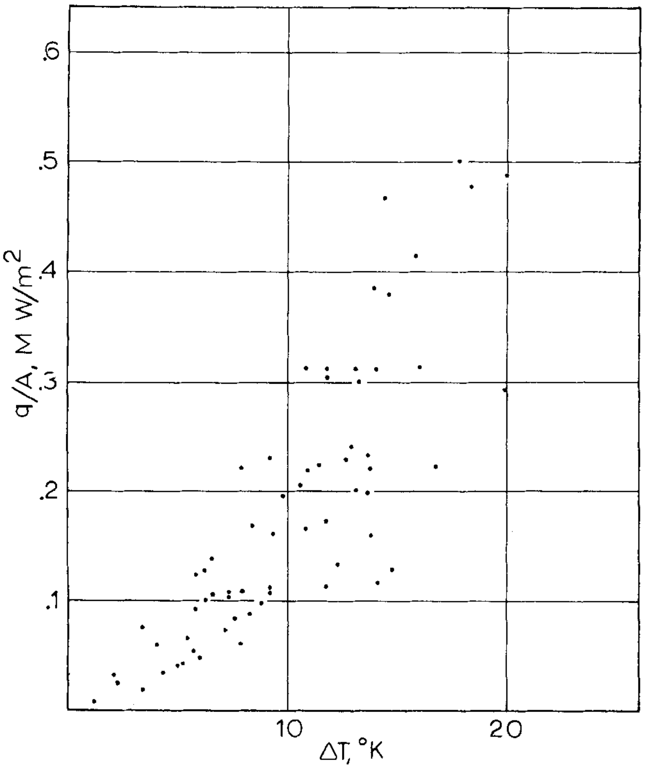

Fig. 3. Heat flux vs ΔT prepared from selected data of Dengler and Addoms.

saturated for the first or second sections, and average wall temperatures were then discarded.

Often in the top section the wall temperature varied so drastically that an average value would not properly characterize the temperature. When the wall temperatures within a section differed by over 5°C, no average was calculated. Of the original 185 data points, 68 remain. The results are plotted in Figure 3.

Let us now examine some nucleate boiling data for comparison. Akin and McAdams (1939) published the results of their investigation of nucleate boiling of distilled water at atmospheric pressure on the outside of a nickel plated copper tube. Figure 4 shows their data at the heat fluxes of interest here.

Gaertner (1965) boiled distilled water at atmospheric pressure on a flat copper surface 5 cm in diameter. The surface was polished with 4/0 emery paper. His results are shown in Figure 5. Also shown are data from a similar study by Kurihara (1960) which Gaertner compared with his own data. In this investigation, Kurihara boiled water at atmospheric pressure on a horizontal copper surface 75 mm in diameter. The surface was also polished with 4/0 emery paper.

Turmeau (1971) studied nucleate boiling using a copper surface 25 mm in diameter. Figure 6 shows the results of one series of tests in which he allowed transition and film boiling to occur during test runs. Even though he boiled distilled water, the surface accumulated a whitish golden deposit as the tests proceeded. The temperature

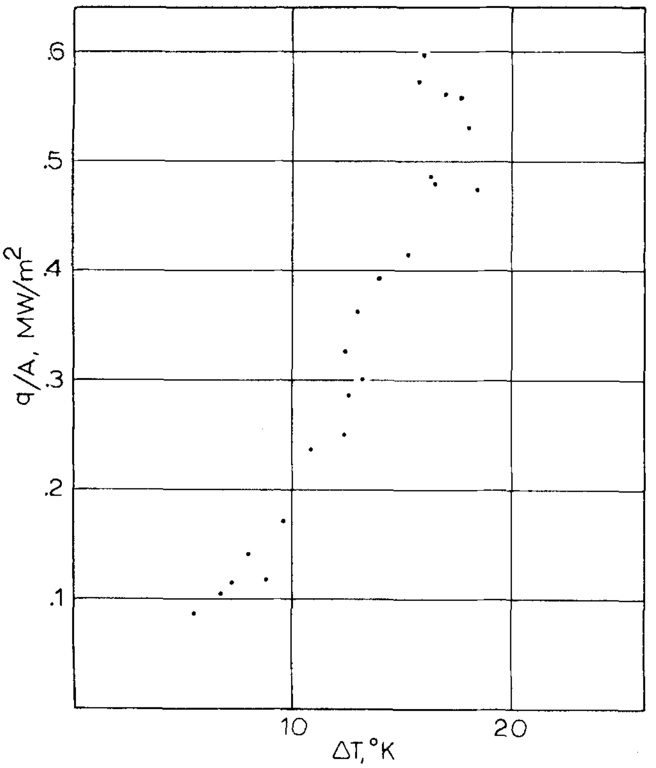

Fig. 4. Nucleate boiling data of Akin and McAdams.

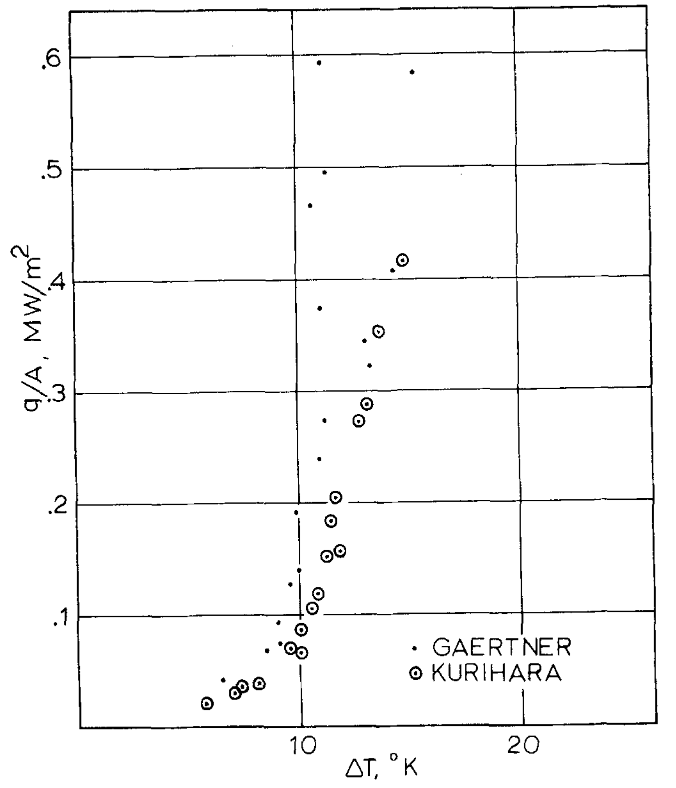

Fig. 5. Nucleate boiling data of Gaertner and Kurihara.

difference in general decreased during the test, and subsequent runs gave stable results at the lower temperature differences.

Figure 7 shows nucleate boiling data reported by Addoms (1948) for boiling water at atmospheric presure on an 0.6 mm diameter platinum wire (0.024 in.).

Piret and Isbin (1954) have reported the results of an experiment with a natural circulation evaporator using a 25 mm diameter vertical copper tube 1.5 m tall. The results of twenty-one runs in which distilled water was evaporated at atmospheric pressure are shown in Figure 8.

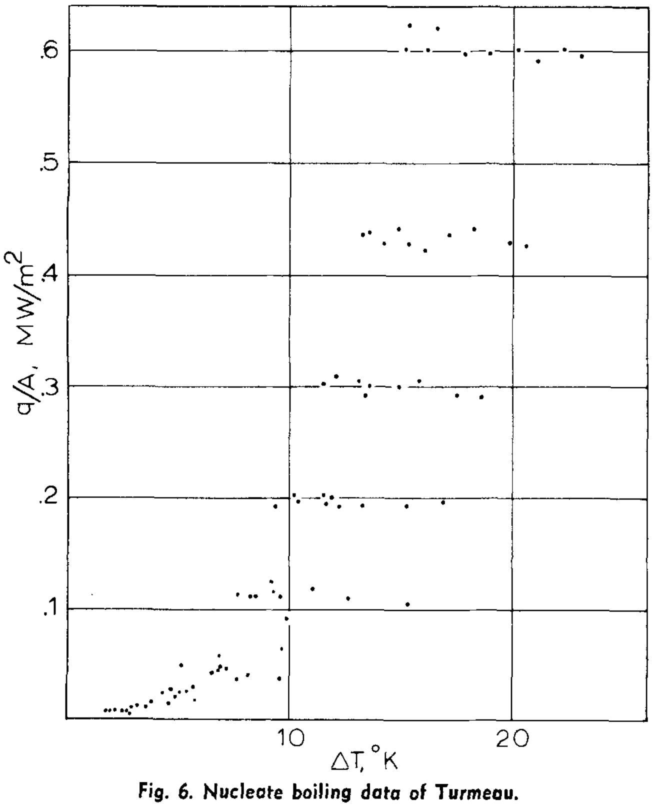

Fig. 6. Nucleate boiling data of Turmeau.

Compare now Figures 3 to 8. The data of Akin and McAdams fall right through the middle of data of Dengler and Addoms. Figures 5 and 6 agree with each other but show noticeably higher ΔT's at heat fluxes below 0.1 MW/m^2. Convection could easily account for this difference. The variation of ΔT in Figure 6 is as large as that seen in the results of Dengler and Addoms. Addom's results in Figure 6 compare very well with those of Figure 5. The data of Piret and Isbin in Figure 8 compare favorably with Figures 5, 6, and 7. They are limited to low heat fluxes and fall on the bottom edge of the results of Dengler and Addoms.

Although there are differences among the data in Figures 3 to 8, the similarities are much more evident. There can be no doubt but that nucleate boiling does account for most of the effect Dengler and Addoms claimed was pure convection.

There are more recent correlations for the convective region in forced convection boiling which utilize X_{tt} in equations similar to the one formulated by Dengler and Addoms. Collier (1972) reviews ones by Guerrieri and Talty (1956), Bennet et al. (1961), Schrock and Grossman (1962), Wright (1961), Collier et al. (1964), and Chen (1966). The difficultites with the analysis of Dengler and Addoms do not necessarily negate the validity of these other correlations. They must all be examined on their individual merits. But until that is done, there can be less confidence in them or in the model derived from them and used in many theoretical studies.

The commonly used model is one of annular flow. A film of liquid on the wall evaporates only at the free interface between it and the vapor which is traveling at a high velocity up the center of the tube. Shear from the high velocity vapor drives convection through the liquid film. Nucleate boiling is assumed not to occur.

Reinterpretation of the results of Dengler and Addoms offers a great simplification of this model for application to their results, especially at their higher heat transfer

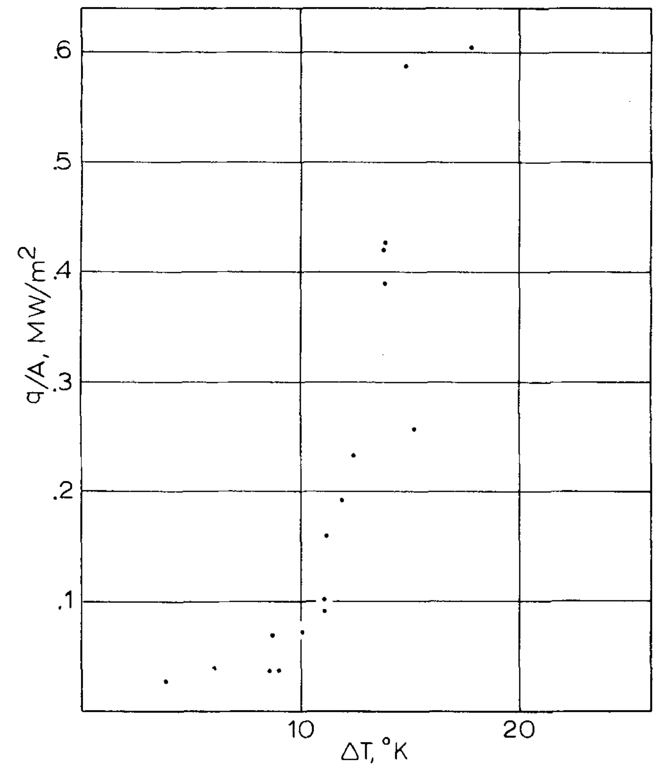

Fig. 7. Nucleate boiling data of Addoms.

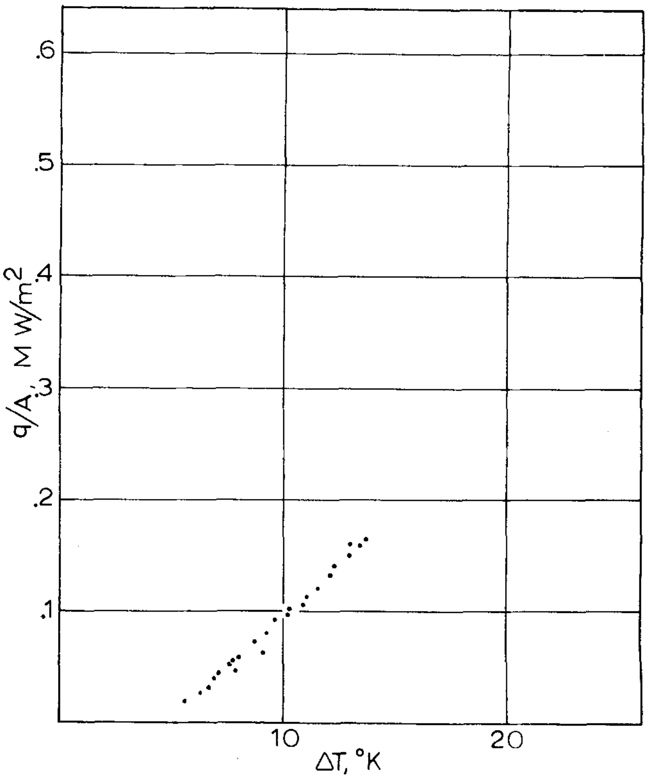

Fig. 8. Nucleate boiling data of Piret and Isbin.

rates. Assume that nucleate boiling occurs in the liquid film. The use of nucleate boiling data such as those of Akin and McAdams estimates very well the observed relation between heat flux and ΔT, at least as well as it does other nucleate boiling data.

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NOTATION

C_p = heat capacity
D = diameter
h = heat transfer coefficient
h_L = heat transfer coefficient assuming entire flow is liquid
k = thermal conductivity
q/A = heat flux
V = specific volume
w = mass rate of flow
x = mass fraction vapor
X_{tt} = two-phase turbulent flow parameter of Lockhart and Martinelli
z = height
ΔT = wall temperature minus saturation temperature
λ = heat of vaporization per unit mass
μ = viscosity

Subscripts

G = gas or vapor
L = liquid

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