# Peak Heat Fluxes in Boiling as Determined by Steady State and Transient Experiments

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Peak heat fluxes in boiling have been reported as results of two different types of experiments: steady state and transient. The calculated peak heat fluxes in the transient experiments have been significantly lower. Values as much as 50% lower are reported in transient boiling water experiments at atmospheric pressure.

The paper advances the argument that the difference in the peak heat flux calculated by the two experiments may arise because insufficient measurements have been made during the transient experiments. Consequently, it is not possible to determine if the experiment conforms with the analytical model used to calculate the heat flux.

In steady state experiments, steam has been used to supply heat inside tubes which caused boiling to occur on the outside. The temperature of the condensing steam determines whether film, transition, or nucleate boiling occurs. Supply of heat in this manner offers an advantage over electrical heating, since control of temperature is possible. Without control over temperature, it is impossible to investigate transition boiling in a steady state experiment because of a stability problem associated with transition boiling.

In transient experiments, one or more temperatures in a body are measured while the body is quenched from a high temperature (Bergles and Thompson, 1970; Fischer, 1970; Veres and Florschuetz, 1971; Ded and Lienhard 1972; Dhir, 1978). Initially, the temperature is high enough to cause film boiling. As the body cools, the cooling rate falls until boiling changes from film boiling to transition boiling. The cooling rate then rises, passing through a peak as boiling changes from transition boiling to nucleate boiling.

Examples of results from both types of experiments in which water was studied are shown in Figure 1. The transient results reported by Fischer are shown as dots. Fischer measured the center temperature of a 23.8 mm copper sphere quenched in distilled water. The steady state results of Akin and McAdams (1939) appear as circles. Akin and McAdams boiled distilled water on the outside of a horizontal, steam heated ¾ in. nickel plated copper tube. Much higher heat fluxes are evident near the peak heat flux in the steady state results.

Calculation of the heat flux in the transient experiments requires the use of a mathematical model to describe the temperatures in the body being cooled. A simple shape like a sphere or torus is usually chosen for study. The model is always taken as one dimensional, and surface temperature is always assumed uniform. Assumption of uniform surface temperature tremendously simplifies the model. Without this simplification, the problem is practically unmanageable.

Is the assumption of uniform surface temperature justified? How uniform must it be? How would nonuniformity be reflected in results calculated assuming uniformity? These questions have been largely ignored. Bergles and Thompson state they did measure three temperatures simultaneously near the surface of their torus. The thermocouples were installed at 120 deg intervals, and they stated the temperatures indicated were not identical. The temperatures were not reported.

Bergles and Thompson state they saw that the onset of transition and nucleate boiling would occur at some random point and spread rapidly across the rest of the surface. This observation would indicate surface temperature nonuniformity. It also suggests that the peak heat flux does not occur simultaneously across the surface. This nonuniformity would cause the average heat flux over the surface at any time to be less than the peak local heat flux.

Investigators have attempted to minimize temperature variations within the body they quenched by using metal of high thermal conductivity, such as copper. Their object was to simplify further their model by considering temperature uniform throughout the body. The investigators present calculations using the one-dimensional model with uniform surface temperature to support this practice. However, if surface temperature is not uniform, the high thermal conductivity would allow a high heat flux at one location to effect quickly the temperature throughout the body. Variations in heat flux around the surface would thus produce an average cooling rate characteristic of an average heat flux over the surface.

If surface temperature uniformity does not prevail as specified in the model, then use of the model to calculate the heat flux will cause an error. Furthermore, the error will be to calculate a peak heat flux which will be low compared to the local peak heat flux that occurs.

Any surface nonhomogeneity may lead to surface temperature nonuniformity. Thermocouple wires leading from the body are one source of difficulty. Such contact with the body possibly leads to a different behavior of the surface temperature near by for a variety of reasons.

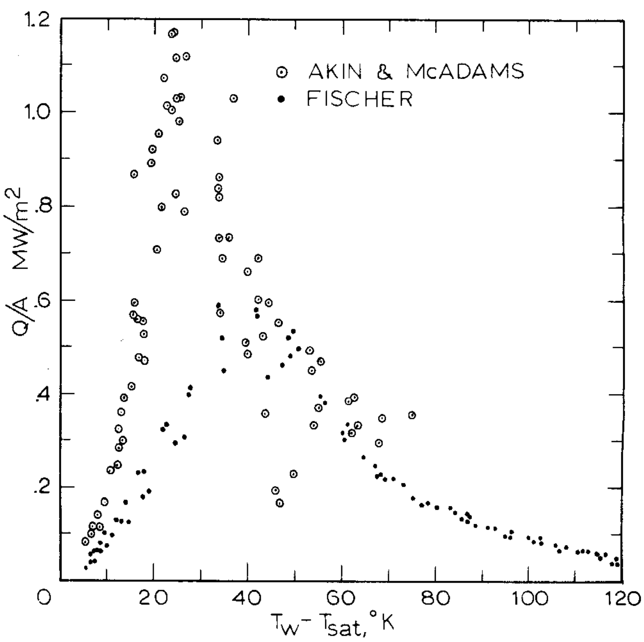


**Fig. 1. A comparison of steady-state boiling results of Akin and McAdams with transient results of Fischer.**

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There is no doubt boiling itself is a variable phenomenon. Bubbles characteristically appear at certain points. The scatter shown, even in the steady state results in Figure 1, reflects a randomness of the phenomenon. This randomness could contribute to surface temperature nonuniformity.

If we consider the evidence, it is only natural to expect some nonuniformity of surface temperature. If the surface is assumed uniform, then it must be shown to be so experimentally.

It is helpful to consider quantitatively the cooling of a typical body in a quenching experiment to examine the importance of timing. Within how short a time must the peak flux occur over the entire surface for results to be valid? Consider the use of the copper sphere used by Fischer.

The solution of the heat conduction equation for a body of uniform initial temperature and with the surface heat flux only a function of time is given by Duhamel's theorem as

$$\theta(r,t) - \theta_0 = \int_0^t \frac{Q(\lambda)}{A} \frac{\partial}{\partial t} \Theta(r, t-\lambda) d\lambda \qquad (1)$$

$\Theta$ is the change in temperature from a uniform initial temperature caused by unit heat flux from 0 to $t$ and is given by Carslaw and Jaeger for a sphere as

$$\Theta(r,t) = \frac{3t}{\rho c a} + \frac{5r^2 - 3a^2}{10ka} - \frac{2a^2}{kr} \sum_{i=1}^{\infty} \frac{\sin \frac{r\beta_i}{a}}{\beta_i^2 \sin \beta_i} e^{-\alpha \beta_i^2 t/a^2} \qquad (2)$$

$\beta_i$, $i = 1, 2, 3 \ldots$. are the positive roots of $\tan \beta = \beta$.

To simplify integration in Equation (1), consider the heat flux to be a stepwise function of time as was proposed by Stolz (1960):

$$Q(\lambda) \cong \sum_{n=1}^{N} Q_n \quad \text{where} \quad n - 1 = \frac{\lambda}{\epsilon} \text{ truncated} \qquad (3)$$

Then, by substitution in Equation (1)

$$\theta(r, N\epsilon) - \theta_0 = \int_0^t \sum_{n=1}^{N} \frac{Q_n}{A} \frac{\partial}{\partial t} \Theta(r, t-\lambda) d\lambda \qquad (4)$$

Moving the integral inside the summation, we get

$$\theta(r, N\epsilon) - \theta_0 = \sum_{n=1}^{N} \frac{Q_n}{A} \int_{(n-1)\epsilon}^{N\epsilon} \frac{\partial}{\partial t} \Theta(r, t-\lambda) d\lambda \qquad (5)$$

Integrating, we get

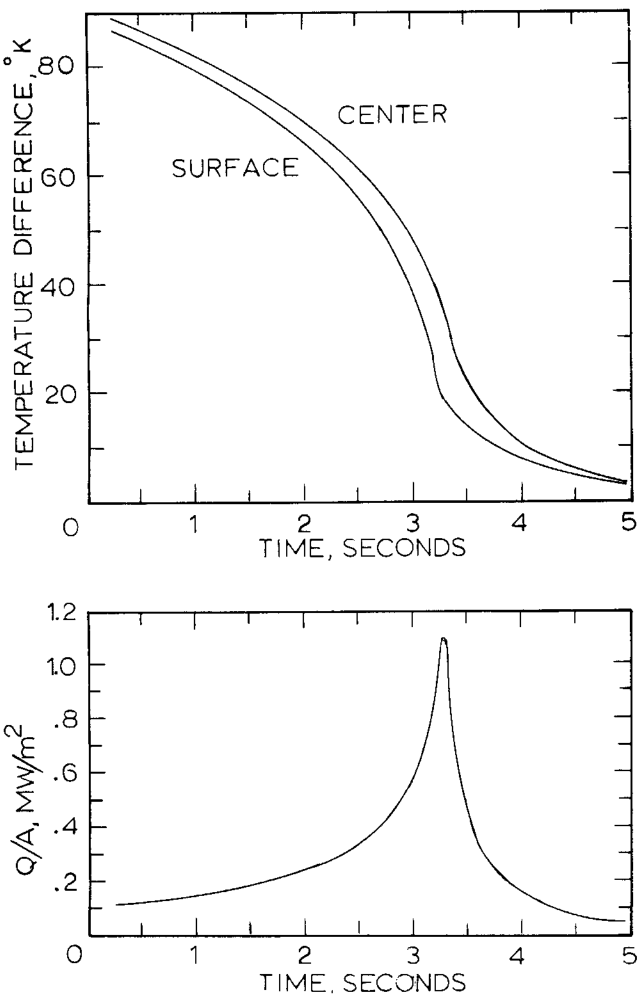


**Fig. 2. Calculated heat flux, center and surface temperatures of a copper sphere based on the results of Akin and McAdams.**

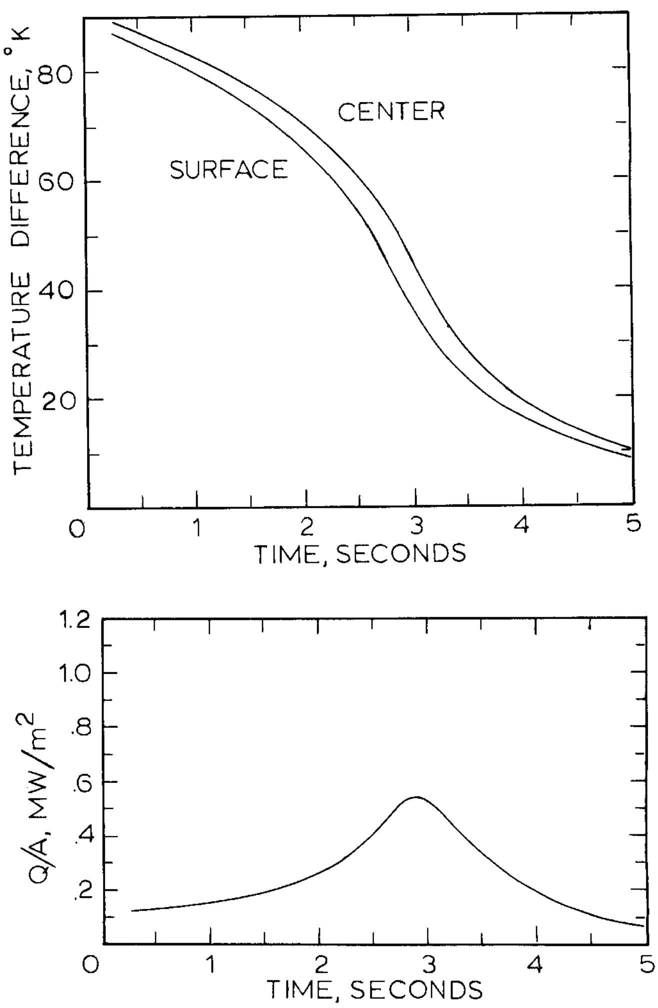


**Fig. 3. Calculated heat flux, center and surface temperatures of a copper sphere based on the results of Fischer.**

$$\theta(r, N\epsilon) - \theta_0 = \sum_{n=1}^{N} \frac{Q_n}{A} \Theta[r, (N - n + 1)\epsilon] \quad (6)$$

This equation was evaluated in time steps with a computer program requiring that the heat flux at each step satisfy the relation between heat flux and surface temperature as determined by either the steady state or transient experiments. Initial temperature was arbitrarily taken as 90°K above saturation, and time increments were 0.05 s. Higher initial temperatures or shorter time increments did not significantly affect the results of the calculation.

Shown in the upper graph of Figure 2 are the results of a calculation of the center and surface temperatures of the sphere using a curve drawn through the results of Akin and McAdams to relate heat flux to surface temperature. The center temperature differs from the surface temperature by as much as 14°K at about 3¼ s. Shown in the lower graph in Figure 2 is the heat flux as a function of time. The heat flux rises to a peak, and the peak has a duration of less than 1 s between 2½ and 3½ s.

To examine the transient cooling experiment, a similar calculation was made using a curve drawn through Fischer's results. At the higher temperature differences, the curve was drawn to coincide with the steady state results. Results of calculation with this curve are shown in Figure 3. These results naturally show a slower rate of cooling, and the heat flux exhibits a longer and lower peak.

Suppose the local heat flux peak occurs first at one location and rapidly spreads. The entire surface experiences the peak heat flux within a short interval. One means of assessing the effect of this on the transient cooling rate is to compute an average of the heat flux over the interval and take this for the average heat flux over the surface at that instant. The heat fluxes given in Figure 2 were thus averaged over intervals of 1 and 1.5 s, and the average heat fluxes obtained are shown in Figure 4. The peak heat fluxes for the two average curves are 0.5 and 0.6 MW/m$^2$, while the peak heat flux in Figure 3 is 0.54. Averaging the peak flux calculated from steady state boiling results over an interval of 1.0 to 1.5 s, we obtain a peak heat flux similar to that reported in Fischer's quenching experiment. Thus, the lower peak heat fluxes calculated in Fischer's quenching experiments could be indicating that an interval of 1 to 1.5 s is required for the entire surface to experience a local peak heat flux rather than a difference in the peak heat flux from steady state experiments. Without a simultaneous measurement of surface temperature at several locations, it is not possible to resolve this question.

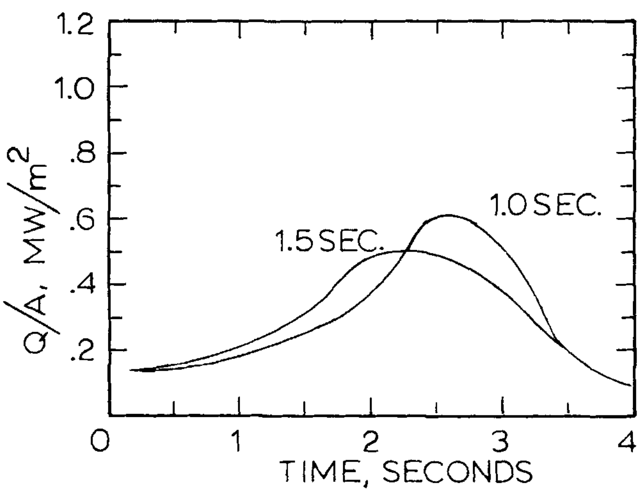


**Fig. 4. Heat fluxes from Fig. 2 averaged over intervals of 1.0 and 1.5 seconds.**

Fischer's experiment is considered here as a convenient example of several other experiments that have been reported. The same comments apply to these other experiments. A uniform surface temperature is assumed, but information is not presented in justification. The significance of the evidence of nonuniformity which is sometimes reported seems to be neglected. There is a lack of discussion of the error that might be involved if uniformity of surface temperature does not exist, or how uniform the temperature should be to justify the assumption.

Lack of uniform surface temperature in quenching is a distinct possibility, and evidence of it exists. The possible error in interpreting results from quenching experiments has been shown. Until additional experiments demonstrate that surface temperatures are sufficiently uniform, it appears wise to reserve judgment on previous quenching experiments which report a peak heat flux in boiling but which do not demonstrate surface temperature uniformity.


## ACKNOWLEDGMENT

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## NOTATION

- $a$ = radius of sphere, m
- $A$ = area, m$^2$
- $C$ = heat capacity, J/kgK
- $k$ = thermal conductivity, W/mK
- $N$ = last time increment number
- $Q$ = heat flow, W
- $r$ = radius, m
- $t$ = time, s

### Greek Letters

- $\alpha$ = thermal diffusivity, m$^2$/s
- $\epsilon$ = time increment, s
- $\lambda$ = time in convolution integral, s
- $\rho$ = density, kg/m$^3$
- $\theta$ = temperature, °K
- $\Theta$ = Equation (2)

### Subscripts

- $0$ = initially
- $n$ = time increment number

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