Short-Lived Sites in Nucleate Boiling

An hypothesis is proposed to explain the origin of short-lived sites observed in nucleate pool boiling. Conditions are postulated under which microbubbles might circulate into the superheated liquid region and serve as the source of these nucleation sites. Consequences of this possible mechanism are examined for explanations of hysteresis effects and scatter of results in boiling research.

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SCOPE

Although nucleate boiling is a common method of heat transfer in the chemical process industry, the design of nucleate boiling heat-transfer equipment is still largely based on performance data. This is at least partly because there is no generally accepted theory concerning the mechanism of nucleate boiling. As new facts about nucleate boiling have emerged, new mechanisms have been proposed. In this paper, previously reported studies on the active lifetimes of nucleate boiling sites, combined with observations on other boiling phenomena by various authors, lead to a theory on the origin of short-lived nucleate boiling sites. If this theory is correct it might help explain the origin and behavior of all nucleate boiling sites and thus lead to a general theory on the mechanism of nucleate boiling.

CONCLUSIONS AND SIGNIFICANCE

It is proposed that nucleation on or near a heated surface in pool boiling results from the downflow of bubbles carried by currents of liquid in the pool. To be carried downward a bubble needs to be sufficiently small that the downward drag of the liquid exceeds the buoyancy of the bubble. On the other hand, the bubble needs to be sufficiently large to be thermodynamically stable so that it does not collapse because of surface forces. Some of these recirculating microbubbles may enter the thermal boundary layer near the heater surface and serve as short-lived boiling sites, producing only a brief burst of bubbles. However, if the burst of bubbles originates near a cavity of suitable geometry on the surface of the plate, sustained boiling might occur at that site for the duration of that particular boiling run.

This theory would explain why the concentration of nucleation sites is a function of degree of superheat, why many more cavities than nucleation sites are found on metal plates used for boiling, and why hysteresis effects are observed when boiling heat fluxes are changed in experiments. It would also imply that the geometry of the boiling pool might be more important than previously thought and thus be the cause of much of the scatter in results reported by various authors.

INTRODUCTION

In the last thirty years numerous papers on the role of nucleation sites in boiling have appeared, including several which described novel techniques for locating and counting these sites (Clarke et al., 1959; Gaertner and Westwater, 1960; Kirby and Westwater, 1963; Heled and Orell, 1967; Raad and Myers, 1971; Sgheiza and Myers, 1977; Sgheiza, 1981). Although most reported counts have been of the total number of sites active during a run rather than the number active at any given time, the paper by Raad and Myers (1971) describes measurements of the actual lifetimes of active sites. They report that for the system studied some sites seemed to remain active almost indefinitely while others produced bubbles for a fraction of a second and then became dormant. The number of these temporarily active sites was not negligible and at any instant generally exceeded the number of seemingly permanently active sites.

The presence of these short-lived sites can be observed from above the heater surface in many boiling systems at low to moderate heat fluxes. However, their inclusion in most numerical counts of active sites is not likely because of their extremely short duration. Most observers doing visual counts during boiling would probably ignore them. The extent of their contribution to the total heat flux is not known, but in view of their numbers might be significant.

The origin of short-lived sites is the subject of an hypothesis presented in this paper. The existence of these short-lived sites may have little to do with the origin and presence of the long-lived or "permanent" sites, but a connection can be inferred and that will also be presented. This theory may also be used to explain other phenomena observed in studies of nucleate boiling.

The hypothesis derives from the likelihood that in the chaotic mixture of liquid and rising bubbles in a boiling system, a wide range of new bubbles, i.e., those not formed at the heating surface, is spawned. Some of these may be formed by coalescence and thus be larger than those rising directly from the heating surface. Others, which might be smaller, may be formed as the larger bubbles break through the upper surface of the liquid (Bergman and Mesler, 1981). Mesler and Mailen (1977) have shown, for example, that vapor bubbles venting through a falling liquid film cause nucleations to occur downstream from the original vapor bubbles; they attribute these nucleations to small bubbles formed during the original venting. Still another possible source of small bubbles may be entrainment in vortex rings produced by drops of liquid falling back into the pool (Carroll and Mesler, 1981). If the size range of new bubbles extends down to diameters of 10 to 100 microns, the possibility exists that downflowing currents of liquid could carry these small bubbles (microbubbles) into the region of superheated liquid near the plate. Should the amount of superheat and the microbubble size meet certain well-established criteria, bubble growth would then occur and that location would for an instant appear as a nucleation site. To continue this reasoning, if the conditions at the solid-liquid interface are unfavorable to the establishment of a permanent site, the growth and departure of a single bubble may be the end of that particular event. However, as will be discussed later, Bankoff (1958) has shown that depending on the geometry of the cavities and protuberances on a heater surface and the contact angle between liquid, solid, and vapor, certain locations on a solid surface are capable of trapping vapor and possibly becoming boiling sites. Other locations may form unstable sites, and still others no site at all. Three possibilities thus exist for a microbubble suddenly carried into the superheated liquid layer. The unstable sites may function briefly and be the short-lived sites reported by Raad; the stable sites may be added to the number of already-operating stable long-term nucleation positions; finally, the completely unfavorable sites may generate a single bubble which would depart with no further consequence.

ANALYSIS

We shall consider a hypothetical system boiling under steady conditions with a certain concentration of permanently active nucleation sites on the heater surface. The possible presence of short-lived sites will be ignored at first. By postulating a mechanism for fluid motion in the column, the maximum diameter of a microbubble which could be carried downward to the heater surface will be determined. All smaller bubbles can be carried downward, possibly into the superheated layer. Then, for a given amount of superheat in the fluid adjoining the heater surface, the minimum diameter can be determined at which a microbubble would grow. If the maximum diameter of the descending bubble exceeds the minimum diameter of a bubble which will grow in the superheated layer, this establishes a range within which microbubbles could serve as the source of new nucleation sites.

The fluid motion is approximated as follows: A flat, horizontal heater surface is covered with n permanently active nucleation sites per unit area. At each of these sites there rises a column of spherical bubbles with a uniform diameter D, forming with a constant frequency of f bubbles/s and rising with a steady vertical velocity U. The vertical distance between adjacent bubble centers in a bubble column is U/f. The volume of liquid directly between two adjacent bubbles in a column of bubbles amounts to

$$\frac{\pi D^2}{4}\frac{U}{f} - \frac{\pi D^3}{6} \qquad (1)$$

while the volume of both gas and liquid directly between any two adjacent bubble centers, when expressed entirely as an equivalent volume of liquid, is

$$\frac{\pi D^3}{6}\frac{\rho_v}{\rho_l} + \frac{\pi D^2}{4}\frac{U}{f} - \frac{\pi D^3}{6} \qquad (2)$$

The first term in this expression represents the volume of liquid necessary to produce a vapor bubble of diameter D. For most systems this is negligible in comparison with the difference in the other two terms which represents the volume of liquid in the column between two bubble centers. The bubbles and the liquid between vertically adjacent bubbles are assumed to be rising with a uniform velocity U.

The total volumetric rate of ascending liquid per unit area of heater surface is

$$\left(\frac{\pi D^2}{4}\frac{U}{f} - \frac{\pi D^3}{6}\right) fn \qquad (3)$$

and since this liquid must descend through the area not covered by columns of rising bubbles, the descending bulk velocity of liquid toward the plate is

$$\frac{\left(\frac{\pi D^2}{4}\frac{U}{f} - \frac{\pi D^3}{6}\right) fn}{1 - \frac{n\pi D^2}{4}} \qquad (4)$$

This is also the velocity of ascent in a stagnant liquid of the largest microbubble which would not rise through the descending liquid.

The size of microbubbles under consideration is small enough that the ascent velocity of these bubbles in a stagnant liquid can be represented by the Stokes law expression

$$\frac{D_m^2(\rho_l - \rho_v)g}{18\mu} \qquad (5)$$

Equating expressions 4 and 5 and neglecting ρ_v we get

$$(D_m)_{\max} = \left[\frac{18\mu f n}{\rho_l g}\left(\frac{\frac{\pi D^2}{4}\frac{U}{f} - \frac{\pi D^3}{6}}{1 - \frac{n\pi D^2}{4}}\right)\right]^{1/2} \qquad (6)$$

The quantity $(D_m)_{\max}$ is the diameter of the largest microbubble that will not rise through the descending liquid. All smaller microbubbles will be carried downward toward the heater surface; all larger bubbles will rise.

Only a few of these descending microbubbles will probably become immersed in the superheated layer and not all of those will grow even if immersed. The smallest bubble that will grow is given by the expression

$$(D_m)_{\min} = \frac{4\sigma T_s}{\lambda \rho_v \Delta T} \qquad (7)$$

Thus, the range of microbubbles that might be carried downward into the superheated liquid on the heater surface and might grow therein is given by Eqs. 6 and 7.

From a theoretical standpoint, if the liquid phase is at the saturation temperature, spherical bubbles of all sizes should tend to collapse. However, the bulk of the liquid is usually slightly superheated and, in any event, the time of immersion of most bubbles is short so that the collapsing of many bubbles large enough to be visible to the eye is not evident. The rate of collapse of smaller bubbles would partly determine whether any survived long enough to be carried into the superheated liquid and whether they were still of sufficiently large diameter to reverse the collapse and start growing once in the region of superheat.

NUMERICAL EVALUATION

A small amount of experimental data is available for evaluating the range of microbubbles which might grow in a boiling system. Kurihara (1956) and Roll (1962) both did nucleate boiling studies

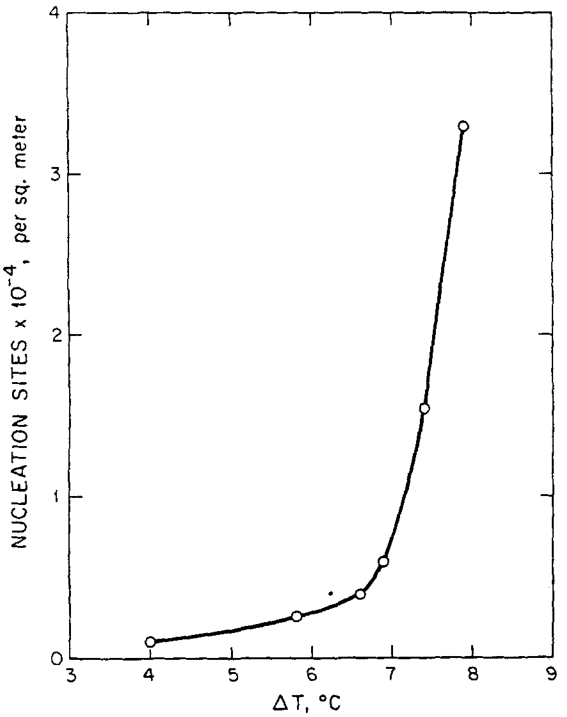

Figure 1. Concentration of nucleation sites vs. superheat for water at atmospheric pressure.

using a horizontal copper surface as a heater. (See also Kurihara and Myers, 1960; and Roll and Myers, 1964). Both studies included data taken using water boiling at atmospheric pressure on a surface polished with 0-grade emery paper. Kurihara reported the nucleation site concentration data given in Figure 1. Roll reported measurements of bubble volume, and delay and growth times of bubbles from which bubble frequency can be calculated. Roll's data varied considerably so averages have been taken for use here. For example, his measured bubble volumes generally ranged from 30

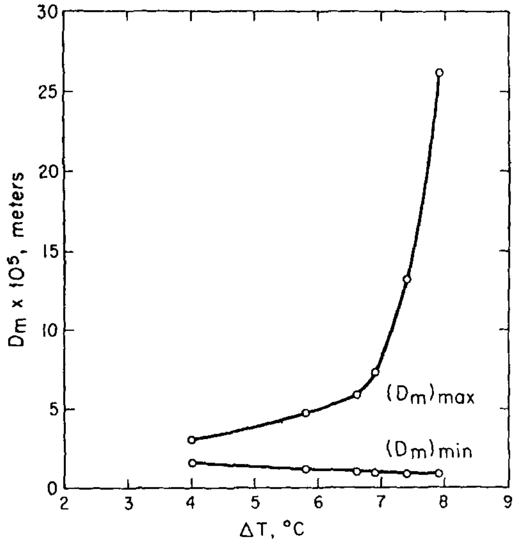

Figure 2. Range of microbubble diameters for growth in water boiling at atmospheric pressure.

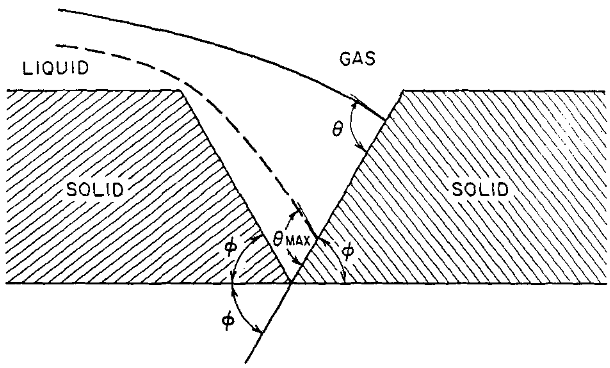

Figure 3. Displacement of liquid from a groove by an advancing gas phase.

to 90 mm^3; we will use 60 mm^3. Delay times ranged from 0.017 to 0.052 s; we will use 0.035 s. Growth times were between 0.008 and 0.015 s, for an average of 0.011 s. The sum of average delay and growth times is 0.046 s which corresponds to a bubble frequency of 22 bubbles/s. The results are from 12 nucleation sites.

The velocity of rise of bubbles was calculated from the equation

$$U = \left(\frac{4gD}{3C_D}\right)^{1/2} \tag{8}$$

using drag coefficients from a plot of C_D vs. Reynolds number. For the bubble diameter used here (4.9 mm) the Reynolds number is 2,500 and the terminal velocity U = 15 cm/s. At 22 bubbles per second, this fixes the center-to-center bubble spacing in a column at 6.9 mm. The use of the above values for D, U, and f in Eq. 6, along with the physical properties of water at 100°C and the nucleation site concentration values (n), gives the values for $(D_m)_{max}$ shown in Figure 2. Again, using the physical properties of water at 100°C, values were determined from Eq. 7 for $(D_m)_{min}$ and are also plotted in Figure 2.

RESULTS AND DISCUSSION

The plot of D_m vs. ΔT (Figure 2) shows that the size range of microbubbles which might recirculate and grow is extremely narrow at ΔT = 4°C but is approximately eighteen times larger when ΔT increases to 8°C. This is still a comparatively small temperature driving force for nucleate boiling; the nature of the function suggests that at higher values of ΔT the possibility of bubble growth from recirculated microbubbles is considerably greater. Unfortunately, Raad's observations of lifetimes of active sites were all made at one heat flux (27,100 W/m^2) so no experimental evidence is yet available that higher heat fluxes (and consequent higher values of ΔT) would provide an increase in the concentration of short-lived sites.

As mentioned earlier, the possibility exists that the sudden growth of a microbubble entering the superheated layer could cause the establishment of a long-lived boiling site which would persist for the duration of the heating run. The criteria for displacement of liquid from a groove by an advancing gas phase have been examined by Bankoff (1958), who considered the necessary conditions for trapping gas in a groove by an advancing liquid front. What concerns us here is the possible displacement of the liquid phase from the groove by a gas phase which might then serve as a long-lived site for production of bubbles. With reference to Figure 3 it can be seen that when the contact angle θ exceeds 2ϕ, an advancing gas front would occupy the entire cavity. Such a gas-filled cavity

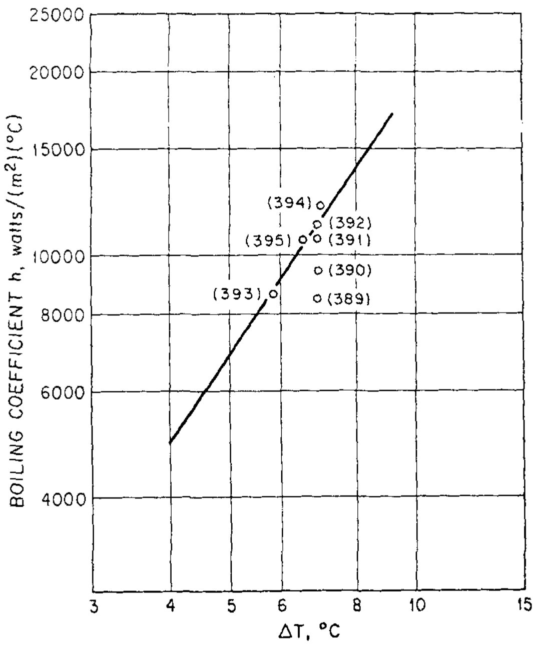

Figure 4. Effect of surface conditioning on boiling coefficients.

could presumably serve as a reservoir for formation of an unlimited sequence of bubbles.

From the preceding discussion, a mechanism emerges which could explain the existence of a range of nucleation site lifetimes. A single microbubble penetrating the superheated layer adjacent to the heater surface might simply grow and depart without further consequence. On the other hand, it might in its growth displace the liquid from a suitable adjacent cavity and produce a more or less permanent boiling site. As Bankoff has shown, some sites exist in which the gas in the cavity could be easily dislodged by more liquid; these would act as a source of bubbles for only a brief time. On the other hand, those sites from which the gas could not be easily dislodged could become permanent sites for the duration of the run.

Microscopic study of twenty actual nucleation sites was reported by Clark et al. (1959). Thirteen were identified as nearly-circular pits in the metal surface. Three were on scratches, three occurred at the boundary between the heater and surrounding plastic sealant, and one was on a speck of dirt. These sites were identified on a surface boiling at low heat fluxes.

One characteristic of boiling performance which could be explained by the tendency toward development of these secondary nucleation sites is that of hysteresis. Various delay phenomena in boiling have been labeled hysteresis effects. One in particular was noted by the author during boiling of propane on a horizontal copper tube; the results are in Figure 4, taken from Myers and Katz (1953). The straight line represents reproducible performance from a number of runs in which data were taken only after a period of four to five hours of boiling. On the other hand, the points designated by numbers 389 to 395 represent a particular set of consecutive runs one hour apart taken during continuous boiling with only a short warm-up period before the first run. The boiling coefficients show a steady climb to run 392, following which reproducible data could be obtained for both increasing and decreasing heat fluxes. One possible explanation is that the initial group of nucleation sites became gradually augmented by additional sites produced as a result of recirculated microbubbles. The same phenomenon was noted by the authors in the boiling of n-butane, but not with Freon 12, methyl chloride, or sulfur dioxide.

If hysteresis is the result of microbubble recirculation causing additional nucleation sites, it would seem to depend not only on the contact angle of the boiling fluid but also on the flow pattern of liquid in the boiling vessel. This would depend on the geometry of the vessel containing the liquid and on the shape and size of the heater surface. If such is the case, it might well explain why investigators in the past have often been successful in correlating their own boiling results for a variety of fluids studied in one particular boiling apparatus, but have had little success in correlating the results of others who studied the same fluids in a different vessel. This has been suggested in a recent paper by Morford and Messina (1982).

SUMMARY

Consideration of the possible origin of short-lived sites observed in nucleate boiling has led to a prediction of the approximate size range of microbubbles which might be carried downward into and grow within the superheated liquid layer on a heater surface. For water boiling at atmospheric pressure, the useful size range is very narrow at $\Delta T = 4°C$ but is many times greater at $\Delta T = 8°C$. If microbubbles do survive during downflow to get into the superheated layer they might provide merely a single bubble or, if they displace liquid from a cavity, a short burst of bubbles. If the cavity is of suitable dimensions, however, the site might be stable enough to provide a source of bubbles for as long as the boiling run continues. Such a mechanism would be a possible explanation for certain observed hysteresis effects in boiling and also for the wide variation of boiling results obtained by different investigators.

ACKNOWLEDGMENT

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NOTATION

C_D = drag coefficient
D = bubble diameter
D_m = microbubble diameter
f = bubble frequency
g = acceleration due to gravity
n = concentration of nucleation sites
T_s = liquid saturation temperature (absolute)
ΔT = liquid superheat
U = bubble velocity

Greek Letters

θ = contact angle
λ = latent heat of vaporization
μ = liquid viscosity
ρ_l = liquid density
ρ_v = vapor density
σ = surface tension
ϕ = inclination of groove wall with horizontal

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