Nucleate Boiling Site Activation by Vapor Injection

M. D. WITZKE, J. E. SCHROEDER,
J. E. SGHEIZA, and J. E. MYERS

Department of Chemical and Nuclear Engineering,
University of California
Santa Barbara, CA 93106

In a related paper, Myers (1985) proposed that, in the chaotic mixture of vapor and liquid in a boiling system, bubbles in the range of 10 to 100 microns in diameter (hereafter called microbubbles) could be carried by downward currents of liquid into the superheated region near the boiling plate and serve as nucleation sites. If the microbubble size and the amount of superheat were to meet certain criteria, bubble growth would occur and the location would for an instant appear to be a nucleation site. Work by Bankoff (1958) has shown that, depending on the contact angle between liquid, solid, and vapor and on the geometry of the cavities and protuberances on the heater surface, certain locations on the solid surface are capable of trapping vapor and becoming boiling sites. Should these surface conditions be sufficiently favorable, the site would continue to generate bubbles and would appear as a long-term nucleation position. If the surface conditions were less favorable, the growth and departure of a few bubbles or even a single bubble might be the end of the particular event.

An extension of the hypothesis would be that by increasing the number of bubbles in a system some might be of an appropriate size to qualify as microbubbles, with the possibility that some of these would recirculate to the boiling surface and form additional nucleation sites. This work represents an attempt to give some experimental support for this hypothesis. The population of persistently active nucleation sites present in a boiling system was determined both with and without the presence of artificially introduced microbubbles. Other variables studied included the effect on the nucleation site density of heat flux, pool depth, length of run, and the location of the microbubble-injection sparger.

APPARATUS

The apparatus used in all but the final part of this study consisted of a square, stainless steel vessel (15.2 cm × 15.2 cm) with a height of 25.4 cm. Boiling took place on a 0.00254 cm horizontal sheet of stainless steel that served as the bottom of the vessel. Two copper electrodes, 0.1 cm thick and 1 cm wide, were soldered to the bottom of the boiling plate for a length of 10 cm. They were 8.4 cm apart. Power was supplied from a 50 amp, 220 V outlet to an EMI DC power supply, Model SCR 10-500. Further details of the apparatus are provided in an earlier paper by Sgheiza and Myers (1985) and in works by Witzke (1977) and Sgheiza (1981).

The nucleation sites on the boiling surface were identified using an infrared scanning camera (Inframetrics, Inc., Model 209A) to display the thermal radiation pattern on the underside of the heater plate while water was boiling on its upper surface. As explained by Sgheiza and Myers, the presence of a bubble nucleating and growing on the upper surface produces a cool spot on the lower surface. This can be detected by the scanning camera and displayed as a dark spot on the screen of the special cathode-ray tube attached to the camera. Actual locating of the sites was done by taping a piece of clear acetate sheet over the cathode-ray tube picture screen and blacking out the nucleation sites one by one with black acetate marker until all had been counted. This method called for judgment as to what did and did not constitute a nucleation site. The majority of sites were unambiguously located, but at high heat fluxes clusters of nucleation sites made identification difficult.

The bubble injection tube was a horizontal stainless steel tube with an O.D. of 0.635 cm and a wall thickness of 0.0127 cm. The end of the tubing within the boiler was blanked off and bubbles were formed by forcing steam out of ten holes drilled horizontally in the tubing. These holes were approximately parallel to the heating surface and were drilled, five on each side of the tubing, with a drill bit 0.035 cm in diameter. The first hole was drilled 2.54 cm from the end of the tube; others were located at intervals of 1.27 cm. Steam for the microbubbles was generated by boiling distilled water in a 1 L Erlenmeyer flask on a hot plate at a rate of 5.9 g/min. This was held constant for all runs in which steam injection took place and amounted to 5 to 10% of the rate of steam generation in the main boiler.

RESULTS

The initial nucleation site studies involved a determination of the site population on the boiling plate as a function of heat flux with and without the injection of microbubbles into the system. At the start of each run the boiler was filled with 2.5 L of distilled water. Power was supplied at a level of 4.7 W/cm^2 until the liquid was brought to its saturation temperature. The system was then operated at a maximum heat flux of 41.3 W/cm^2 for 3 h before any data were taken. This was done in an attempt to avoid the hysteresis effects reported by Myers and Katz (1953).

The choice of variables for each run in a sequence of runs was chosen by lot. Once the conditions of plate voltage and microbubble injection for a specific run had been met, 10 min was allowed for the system to adjust to these conditions before a site count was taken. When a site count had been completed a new set of variables was chosen and the process was repeated. No two counts were made on any one day under the same conditions of plate voltage and microbubble injection without first repositioning the camera under the boiling plate so that a new part of the boiling surface could be examined. A new piece of acetate was used for each count and these were held for final tabulation until all the counts had been completed. Thirty counts were done at each of the eight plate voltages used, 15 counts during which microbubbles were not injected into the system and 15 counts during which microbubble injection took

Correspondence concerning this paper should be directed to J. E. Myers.

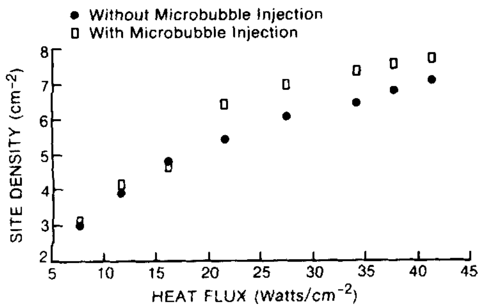

Figure 1. Nucleation site density as a function of heat flux.

place. The actual counting of nucleation sites was done after all 240 runs leading to Figure 1 had been completed. Each data point in this figure represents the arithmetic average of the 15 separate counts. It is evident that site density increases with heat flux and it also appears that the injection of microbubbles produces an increase in site density. This increase was tested statistically and found to be significant at the 95% confidence level for all heat fluxes above 20 W/cm^2. The average increase was 14%. The increase in site concentration with increasing heat flux without bubble injection corresponds to results reported by Sgheiza and Myers (1985). The results obtained with bubble injection indicate that the addition of the bubbles has a small but definite effect on site concentration.

An earlier study by Robinson and Katz (1951) studied the effect of injecting superheated Freon 12 from a sparger underneath horizontal tubes in pool boiling on the surfaces of the tubes. Their results, reported in terms of boiling heat transfer coefficients plotted vs. temperature difference driving force, showed increases in boiling coefficients up to 100% at a driving force of 4°C, but found that the increase was only about 20% at Δt = 8°C. Robinson and Katz attributed the increase in performance to the increased turbulence produced in the system by the injected vapor. All their results were at heat fluxes below 10 W/cm^2. The holes in the sparger at which their vapor bubbles were formed had a diameter of 0.10 cm, in contrast with a hole diameter of 0.035 cm used in the present work. These differences, plus the different geometrical arrangements of the two systems, limit the inferences that can be drawn for the present work from that of Robinson and Katz.

The results of a study of the effects of time and microbubble injection are shown in Figure 2. Site counts were made over a period of 16 h, with microbubble injection occurring from the eighth to the twelfth hours. The results show an increase of site density during the first 2 h of boiling, similar to that reported by Sgheiza (1981). Injection of microbubbles starting at the eighth hour caused an increase in site density of about 15%. Stopping the injection after 12 h caused site density to fall back to the level observed before injection. A similar test carried out at a higher heat flux (34.2 W/cm^2) showed similar results (Witzke, 1977).

All results reported above were made with the steam injection tube located 2.54 cm above the heater surface. Tests made with the bubble injection from the tube located at 3.8 and 5.1 cm above the heater showed no significant change in site density from the results obtained with the tube at 2.54 cm. Tests were also made at three different heat fluxes with and without the tube present but showed no effect of the presence of the tube. Finally, tests were made to see if depth of liquid had any effect on the concentration of sites. The depth of liquid in all previous runs was 11 cm. For this series, the depth was varied from 5 to 12.7 cm. No effect of depth was observed for heat fluxes of 16.1 and 21.5 W/cm^2, with and without bubble injection.

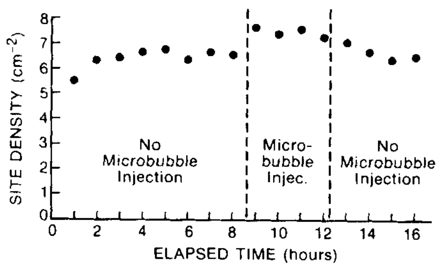

Figure 2. Variation in nucleation site density with elapsed time, with and without microbubble injection. Heat flux = 27.5 W/cm^2.

Vapor Entrainment by Plunging Jets

An alternative method of introducing bubbles into a liquid is by vapor entrainment with a plunging jet. Lin and Donnelly (1966) studied entrainment of air into 12 different Newtonian liquids and determined minimum velocities for gas entrainment. Their technique was employed in a portion of the present work (Schroeder, 1979) to see if bubbles entrained from the steam phase by jets of water at the saturation temperature had an effect on nucleation site concentration. Injection of liquid at 20–40 cm^3/s produced site density increases in the range of 15 to 30% over boiling without injection. However, the limited results indicated no effect of jet flow rate on site density. In the heat flux range studied (15–30 W/cm^2) the percentage increase seemed to be smaller at the higher heat flux. Experiments in which the liquid was injected from beneath the surface of the pool produced no change in site concentration, showing that the momentum of the plunging jet by itself had no effect on boiling.

CONCLUSIONS

Experiments were carried out to test the hypothesis that adding microbubbles to a boiling system would increase the concentration of nucleation sites on a boiling surface. No effect was found at heat fluxes below 20 W/cm^2, but at higher heat fluxes the injection of microbubbles brought about an average increase of 14% in site concentration. A test of 16 h duration, during which site concentration increased when microbubble injection was started at the eighth hour and decreased when the bubble injection was stopped at the twelfth hour, added further evidence of the validity of the hypothesis.

ACKNOWLEDGMENT

The National Science Foundation provided support for part of this work under grant ENG 75-06560.

LITERATURE CITED

Bankoff, S. G., "Entrapment of Gas in the Spreading of a Liquid over a Rough Surface," *AIChE J.*, **4**, 24 (1958).

Lin, T. J., and H. G. Donnelly, "Gas Bubble Entrainment by Plunging Laminar Liquid Jets," *AIChE J.*, **12**, 563 (1966).

Myers, J. E., "Short-Lived Sites in Nucleate Boiling," *AIChE J.*, **31** (1985).

———, and D. L. Katz, "Boiling Coefficients Outside Horizontal Tubes," *Chem. Eng. Progr. Symp. Ser. No. 5*, **49**, 107 (1953).

Robinson, D. B., and D. L. Katz, "Effect of Vapor Agitation on Boiling Coefficients," *Chem. Eng. Progr.*, **47**, 317 (1951).

Schroeder, J. E., "Transient Nucleate Boiling Site Activation by Vapor Injection," M.S. Thesis, Univ. of California, Santa Barbara (1979).

Sgheiza, J. E., "Behavior of Nucleation Sites in Pool Boiling," Ph.D. Thesis, Univ. of California, Santa Barbara (1981).

———, and J. E. Myers, "Behavior of Nucleation Sites in Pool Boiling," *AIChE J.*, **31** (1985).

Witzke, M. D., "Nucleate Boiling Site Formation from Microbubbles," M.S. Thesis, Univ. of California, Santa Barbara (1977).

Manuscript received Apr. 30, 1984; revision received July 17 and accepted July 23, 1984.