Nucleation Studies in Pool Boiling on Thin Plates Using Liquid Crystals

TED RAAD and JOHN E. MYERS

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

Studies of the mechanism of nucleate boiling have been hampered by the difficulty of determining the location and number of nucleation sites. Visual counting is possible at relatively low heat fluxes, and studies using this technique have been reported by Westwater and Santangelo (*11*), Jakob (*4*), Corty and Foust (*2*), and Kurihara and Myers (*6*). The accuracy of this method is satisfactory when only a few sites are active; however, at heat fluxes of interest in most boiling systems the passage of bubbles through the liquid obscures the view of the boiling surface, particularly when the surface is flat. An indirect method of identifying nucleation sites, used by Gaertner and Westwater (*3*), consisted of electroplating during boiling. The boiling surface was plated during boiling and active boiling sites identified as pinholes which could be counted after removing the boiling electrolyte. Still another new technique was tested by Kirby and Westwater (*5*) who used a boiling surface composed of borosilicate glass coated on one surface with an electricity-conducting, transparent coating. Thus, boiling occurring on the upper surface of this plate could be recorded photographically from below.

None of the methods described above permits reliable locating and counting of nucleation sites on a flat metallic plate when boiling pure liquids at moderate-to-high heat fluxes. The technique used in the present study (*8*) has been tested on a limited basis and is suggested as one which might be suitable in this range. Briefly, the system employed liquid methylene chloride boiling in an open vessel, in which the bottom consisted of a thin, horizontal stainless steel sheet heated by an electric current. The underside of the stainless steel plate was coated with a thin layer of cholesteric liquid crystals which exhibited color fluctuations in the temperature range of the nucleating bubbles. Because of the thinness of the plate, the temperature fluctuations on the upper (boiling) surface around the nucleation sites produced corresponding variations on the underside of the plate causing color changes of the liquid crystals. These fluctuating color patterns were recorded on motion-picture color film which, after development, was projected and examined. Circular color pattern characteristics of nucleation sites were identified and counted, which made possible brief studies of the effects of such variables as surface roughness, aging, and heat flux on the concentration of active sites on the boiling surface.

Ted Raad is with Chevron Research Company, Richmond, California 94802. Correspondence concerning this communication should be addressed to John E. Myers.

EXPERIMENTAL APPARATUS

The boiler used in this study consisted of a square vessel made of ⅛-in. stainless steel, 10 in. high and 6 in. wide. The plate on which boiling took place was 0.001-in. thick, type-302, full-hard, stainless steel. This plate was attached to the vessel, sealed, and insulated by means of a brass frame ⅜-in. thick, asbestos gaskets 1/16-in. thick, and two transite frames 13/32-in. thick. Two copper electrodes, 1/32-in. thick and 9/16-in. wide, were soldered to the bottom side of the boiling plate for a length of 4 in. They were 3.25 in. apart. Power was supplied from a 50-amp. 220-volt outlet to a Westinghouse alternating current arc welder transformer, type WT-46. A 3-in. by 3-in. area of the underside of the plate was coated with a mixture of cholesteric liquid crystals on a black background.

The only liquid boiled in the experiment was methylene chloride (Mallinckrodt) which had a boiling point of 39.8°C. and a density of 1.315-1.321 g./ml. at 25°C. The color changes of the liquid crystals were photographed on Kodak Ektachrome 7242 film with a Bolex 16 mm. Rex camera, equipped with an F 2.4 Pan-Cinor "70" lens. A 1-plus close-up lens was attached to the Pan-Cinor lens. All the film was taken at 64 frames per sec. with a lens opening of F 2.8. Illumination was provided by two new G.E. Photo EBV lamps with a color temperature rating of 3,200°K. The color patterns on the developed film were analyzed using a stop-action projector.

The liquid crystal coating employed was a mixture of VL 401-R and VL 401-L manufactured by the Vari-Light Corporation of Cincinnati, Ohio. The two materials were mixed to obtain a color response according to a mixing graph obtained from the supplier (*1*). The irridescent color change for these mixtures is exhibited over a narrow temperature range said to be approximately two centigrade degrees. Upon cooling through this range, the sequence of colors starting from colorless is from blue to red and back to colorless. Thus, blue color represents higher temperatures than red. Since the colors observed were from scattered incident light, it was recommended that they be observed from a black background. Thus, a coating of black, water soluble paint was applied to the underside of the boiling plate prior to applying the liquid crystal coating.

RESULTS

Because of the exploratory nature of the project, several aspects of boiling nucleation were studied briefly to determine the applicability of the technique. One immediate result was confirmation of the notion that the portion of the plate beneath a growing bubble is a "cold spot" rather than a "hot spot". Bubble sites showed colors ranging from red on the inside to blue on the outside in accordance with the conclusions of Moore and Mesler (*7*), Roemer (*9*), and Roll and Myers (*10*).

A question much debated is whether the length of time a system has boiled will have an effect on the number of active nucleation sites. Experiments were run at heat fluxes of 8,600, 12,000, and 24,500 B.t.u./(hr.)(sq. ft.) and counts of active sites made at times of 15, 60, 90, and 120 min. after start of boiling. No significant change in the number of sites was found to occur as a function of time. The number of sites observed did, however, increase with heat flux. The average concentration of sites ranged from 340/sq. ft. at 8600 B.t.u./(hr.)(sq. ft.) to 820/sq. ft. at 24,500 B.t.u./(hr.)(sq. ft.).

Another variable frequently studied is the effect of surface roughness on boiling. It is generally found that boiling coefficients are higher for rough surfaces than for smooth ones. In these studies a 3-in. by 3-in. area on the stainless steel boiling surface was prepared by wrapping emery paper on a hand sander and rubbing 10 strokes in one direction and then 10 strokes at 90° until the surface was considered reproducible. Three grades of emery paper were used, ranging from fine to coarse. In contrast to what was expected, the surface polished with the finest paper showed approximately twice as many active sites as the surface polished by the coarse paper, and the medium-polished surface had the fewest sites of all three. All runs were made at a heat flux of 8600 B.t.u./(hr.)(sq. ft.).

The final study made was one in which the length of time of active boiling from specific sites was studied. As was anticipated, a small number of sites remained active almost indefinitely, while others produced bursts of bubbles and then became dormant. One aspect that seemed particularly interesting was that the concentration of permanently active sites seemed about the same for all three degrees of surface roughness described above. However, the fine surface appeared to have a much larger number of short-term sites than the coarser surfaces.

CONCLUSIONS

One important conclusion from the studies described above was that the concept of temperature of the boiling surface is rather illusory. Motion picture photographs of the liquid-crystal color changes showed the boiling plate to be swept by convection waves and spotted with numerous temperature patterns resulting from nucleation. It would seem difficult to say how a meaningful average surface temperature might be determined. The main results of the study indicate that a variety of long-standing problems in nucleate boiling can be investigated using the thin plate technique described above.

ACKNOWLEDGMENT

Initial work on the project involved use of infra-red photography in attempts to determine temperature patterns on the underside of the thin boiling surface. When these methods met with little success, Professor R. B. Roemer of the Department of Mechanical Engineering at UCSB suggested the use of liquid crystals for temperature indication. His valuable suggestion is gratefully acknowledged. Valuable assistance was also provided by J. Leaman and W. Swalling of the Learning Resources department of the University of California, Santa Barbara.

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Two-Variable Distillation Control: Decouple or Not Decouple

ANTONI NIEDERLINSKI

Politechnika Slaska, Gliwice, Poland

Luyben (*1*) presented an exhaustive study of a noninteracting two-variable distillation control system. The aim of this communication is to draw attention to possible advantages of another control structure serving the same purpose.

The designer of a two-variable control system usually has the option between a noninteracting and interacting design. The former is the more celebrated in the technical literature. A number of methods have been developed, based either on the transfer-function approach (*2*) or state-space approach (*3*), which result in a control system noninteracting with respect to only set point changes. This property has some undeniable advantages for multivariable servosystems where set points are variable, but seems to