Marangoni Flow: An Additional Mechanism in Boiling Heat Transfer

Absract. *Experimental results indicate that extensive liquid circulation can be established by surface tension gradients near bubbles attached to heated surfaces. This circulation can contribute significantly to the high rate of heat transfer observed under boiling conditions.*

Our experiments with bubbles on a heated surface show that a gradient of surface tension resulting from temperature differences around the bubble produces a very significant flow of liquid that can help to explain the high fluxes obtained in boiling heat transfer.

The motion of liquid surfaces under the influence of surface tension gradients has been known for over 100 years and is sometimes referred to as the Marangoni effect (*1*). Scriven and Sternling (*2*), for example, studied the problem of liquid convection resulting from surface tension gradients at a liquid/gas interface. The fluid-flow driving force developed by surface tension at an interface is proportional to the surface tension gradient, that is, change of surface tension with position. The surface tension gradient can be established in a number of ways; however, in heat transfer it most commonly results from a temperature gradient. Temperature gradients exist around bubbles during the boiling process, thus some liquid flow should be expected, but the key question is whether the effect is important in the mechanism of boiling heat transfer.

The extensive studies (*3*) of nucleate boiling heat transfer made during the past few years have resulted in a considerably increased understanding of the boiling process, but some important questions remain to be answered. One of the more important of these questions concerns the detailed mechanism by which heat is transferred from the heating surface to the boiling liquid. Moore and Mesler (*4*) postulate that the vaporization of the microlayer of liquid beneath a growing bubble is a primary factor in the high heat fluxes associated with boiling. Gunther and Kreith (*5*) have shown that the net amount of heat transferred as latent heat of bubbles is negligible in comparison with the overall convection component. However, the generally accepted explanation for the high boiling heat transfer rates has to do with the intense bubble-produced agitation of the liquid layer immediately adjacent to the heating surface. It is felt that the extremely rapid bubble growth and attendant departure from the heating surface serves to produce a high degree of liquid turbulence at the heating surface, thus resulting in high rates of heat transfer. An apparent paradox arises in the cases of boiling under low or zero gravity conditions and boiling on surfaces facing downward. In both situations high rates of heat transfer can be obtained even though bubbles do not always leave the heating surface.

To help answer the above question we constructed an experiment that permitted us to observe the liquid flow around bubbles under conditions in which boiling was not taking place and also under low heat flux boiling conditions. The flow pattern was indicated by small particles suspended in the liquid. The particles, which have the same density as the liquid, are approximately 10^{-4} cm in diameter and become quite visible when observed through a microscope under illumination by collimated light against a dark background. The liquid was heated on the top and cooled at the bottom, and in all cases the bubbles were on the underside of the heater.

Temperatures were measured by thermocouples embedded in the heating and cooling surfaces. The liquid was reagent grade *n*-butyl alcohol in all experiments discussed here, although similar results are obtained for methanol, carbon tetrachloride, and distilled water.

Boiling was started at the heater surface by slowly increasing the heater temperature. The liquid flow patterns were more readily observed when boiling was moderately vigorous but not so violent that the viewing area was completely filled with bubbles. When boiling was established, we consistently observed a streamline type of flow and a

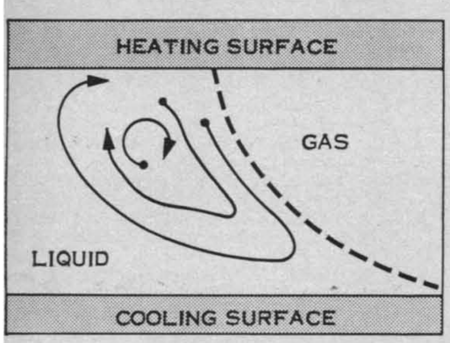


Fig. 1 (left). Marangoni flow pattern near the surface of the bubble shown below. (below left) Marangoni flow near the bubble surface with a temperature gradient of 50°C/cm; exposure time, ½ second.

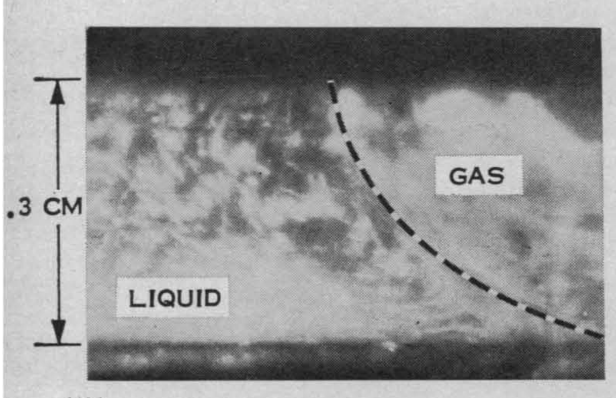
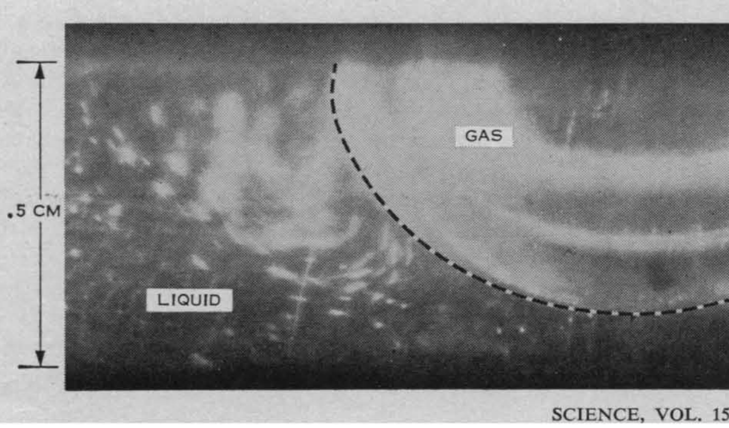


Fig. 2 (below right). Marangoni flow at a bubble surface with a temperature gradient of 20°C/cm; exposure time, ½ second.



rapid circulation of liquid around the bubbles. The general flow pattern is shown in Fig. 1 (left).

The liquid moved along the heated surface toward the bubble from all sides, and then traveled downward around the bubble periphery and was exuded downward in a stream from the bottom extremity of the bubble.

In larger apparatus the stream of liquid leaving the bubble surface has been observed to reach a length of 5 cm. The bubbles in this case were formed in highly subcooled liquid and were observed by 8000-frame-per-second photography to have a constant volume and to be non-oscillating over a time period of a minute or more.

As new bubbles grew at the preferred nucleation sites, they very quickly established the same characteristic liquid flow pattern. The velocity of the liquid around the bubble was of the order of 1 to 2 cm/sec when vigorous boiling was occurring. At lower boiling rates the liquid was not pushed away from the bubble so vigorously; rather, there was a tendency to produce rotating vortices near the heating surface. The bubbles were not observed to move downward from the heating surface, nor were they observed to oscillate, but on the contrary they maintained a stable shape for a number of seconds. Some of the bubbles could be observed moving along the heating surface, and a tendency for the bubbles to move toward each other was apparent.

Observations of a large number of stable, nongrowing air bubbles under nonboiling conditions show that the characteristic liquid flow patterns are essentially identical to those observed for vapor bubbles obtained under boiling conditions. Figures 1 and 2 show typical liquid flow patterns around stable air bubbles that were placed on the heating surface. The photographs are time exposures, so the illuminated particles appear as streaks indicating flow streamlines. These air bubbles reached their stable shape essentially immediately after the temperature gradient was established, and maintained this shape for periods often exceeding 2 minutes.

An additional observation showed that when two air bubbles were placed on the plate in the vicinity of one another they tended to coalesce in a manner similar to that observed for vapor bubbles. The reason for the coalescent tendency became obvious when we observed the liquid flow patterns around the bubbles.

The liquid between the bubbles becomes quickly heated because of the increased thermal mixing in that region, thus a horizontal temperature gradient is established. The horizontal temperature gradient and attendant horizontal surface tension gradient result in liquid flowing generally from the hotter toward the colder region, with a resultant bubble motion in the opposite direction.

The net result of the Marangoni flow around bubble surfaces significantly contributes to the convection of liquid away from the heated surface. Thus the Marangoni flow serves as a primary factor in the heat transfer mechanism for those situations in which bubbles remain on the heating surface for a relatively long period of time. As such, it may replace or supplement the currently recognized mechanism of liquid agitation resulting from bubble formation and separation from the heating surface.

From the identical flow patterns observed around the surfaces of air bubbles and boiling-produced vapor bubbles, it can be concluded that Maragoni liquid flow will occur around any bubble located in a temperature gradient.

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References and Notes

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Brightness Distributions of Radio Sources at 2-Centimeter Wavelength

Abstract. *Maps have been made of the 2-centimeter brightness distribution of M17, Cassiopeia-A, Taurus-A, and Orion nebula with a resolution of 2.3 minutes of arc, revealing several newly resolved features. M17 is a double thermal source. Some structure appears in Cassiopeia-A, including a suggestion of a ring shape. Taurus-A exhibits a brightness map similar to that obtained in earlier low-frequency results. The central part of Orion nebula is circularly symmetric to a high degree of accuracy.*

The newer instruments for the study of the continuum radiation from discrete radio sources are designed to increase the resolution and to extend the observable radio-frequency spectrum. Data obtained with these instruments can be used to test current theories of the origins and radiating mechanisms of H_{II} regions and supernova remnants within the galaxy, and to find out more concerning extragalactic emitters of radio waves. We report the observations on mapping of four bright sources at a wavelength of 2 cm, using the 2.3-minute-of-arc beam of the 36-m parabolic reflector at the Haystack Research Facility.

The tuned radio frequency receiver amplified and detected signals in a passband from 2.0 to 1.875 cm (15 to 16 Ghertz). The equivalent temperature of the noise power generated by the receiver was about 1500°K, which resulted in a fluctuation of the output that was equivalent to 0.04°K rms for the 8-second integration time used. The two-dimensional smoothing process reduced the fluctuation from the receiver output to much less than 0.01°K. This uncertainty was negligible compared with the systematic errors in aligning the scans and determining the baseline temperatures due to sky background, which are estimated to be ±.5°K peak and are clearly seen as a regular undulation in the lowest contours on several of the maps.

The antenna was on an altazimuth mounting and was pointed to follow and to scan celestial objects by means of a digital computer. The computer