The Effect of Surface Orientation on Delay Time of Bubbles from Artificial Sites during Nucleate Boiling

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Jakob (*5*) observed that nucleate-boiling bubbles from the same nucleation site grow and detach and that time elapses before the appearance of the next bubble. He postulated that this waiting period, or delay time, was equal to the time required for the bubble to grow and detach. Later investigations (*4, 6*) have found that the delay time is not necessarily equal to the period of growth and detachment.

Theoretically, no correlation has accurately predicted delay time. Zuber (*10*) states that the delay time is a function of the local heat flux, of the characteristics of the cavity and of the surface, and of the hydrodynamic conditions which exist. If so, delay time would be difficult to predict since even the basic nucleation process and existing flow regimes are not clearly defined and understood.

Experimentally, several observations show how bubble behavior is affected when delay time varies. These observations can be summarized by referring to Figure 1.

The rapid temperature drop ($A - B$) occurs during the rapid initial growth of the bubble (*1, 2*). The bubble then necks down and detaches at point C. The time interval from C to D would represent a short delay time and would result in a small, spherical bubble. A longer delay time, $C - E$, would result in a larger, more hemispherical bubble (*2, 6*). These experimental results indicate that delay time is an important variable in nucleate boiling.

This investigation was initiated after an unpublished experimental observation by Johnson and Mesler while boiling from artificial nucleation sites. If the surface with an artificial site was boiled in the vertical position, the bubbles were large and hemispherical and caused large surface-temperature fluctuations. However, if the same surface was boiled horizontally, the bubbles were small and spherical and caused only small surface-temperature variation. Comparison of these observations with the results of Hospeti and Mesler and of de la Pena, Johnson, and Mesler indicated that the change in surface position had caused a variation in delay time.

The purpose of this study was to determine whether the above effect of surface position on delay time was reproducible and, if so, to explain this behavior.

Experimental Apparatus

The usual problem in photographing boiling bubbles at a given area on a boiling surface is that other bubbles obstruct the view. For this reason, a boiling surface was designed which maximizes the heat flux in the center of the surface. The higher heat flux increases the probability of the formation of a single bubble column, which then can be clearly photographed. This design also reduces bubble formation at the boundary between dissimilar materials. Such boundaries seem to provide numerous good sites; however, with the edge of the metal surface somewhat cooler, bubbling from this interface was minimized. Figure 2 is a sketch of the boiling surface. The surface was Nichrome, the lead-ins were copper, and the assembly was molded in epoxy (Stycast 2,651 mm.).

Other surfaces used early in the investigation contained fast-response surface thermocouples as described in reference (*7*) However, the mating of the thermocouple with the surface cannot be perfect. Because the resulting imperfections could result in "unknown" artificial sites, uncertainty was introduced when a comparison of the results from natural and artificial sites was attempted. The surface described in Figure 2, therefore, was considered more desirable even though the surface temperature could not be determined.

The original experimental observation by Johnson and Mesler occurred while they were boiling from an artificial site which was mechanically drilled 0.0016 in. in diameter and several diameters deep. However, as such small holes are difficult to drill, we used the following technique to produce the artificial sites in the boiling surface.

The point of a sewing needle was sharpened until it was observed under a microscope to be conical, uniformly tapered, and less than 1 mil at the tip. The needle was then lowered into the surface with a drill press, without rotation, until the hole was about 2 mils across at the surface. From the geometry of the needle and observation under a microscope, the cavities produced seemed to be conical, circular at the surface with a 2-mil diameter, and 3 and 4 mils deep. The needle was not deformed, and the hole in the surface caused

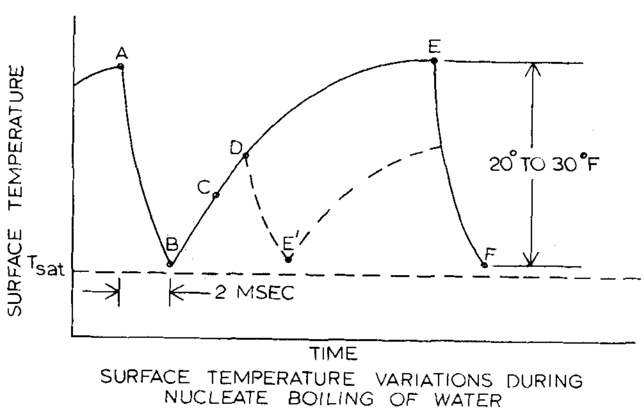


Fig. 1. Surface temperature variations during nucleate boiling of water.

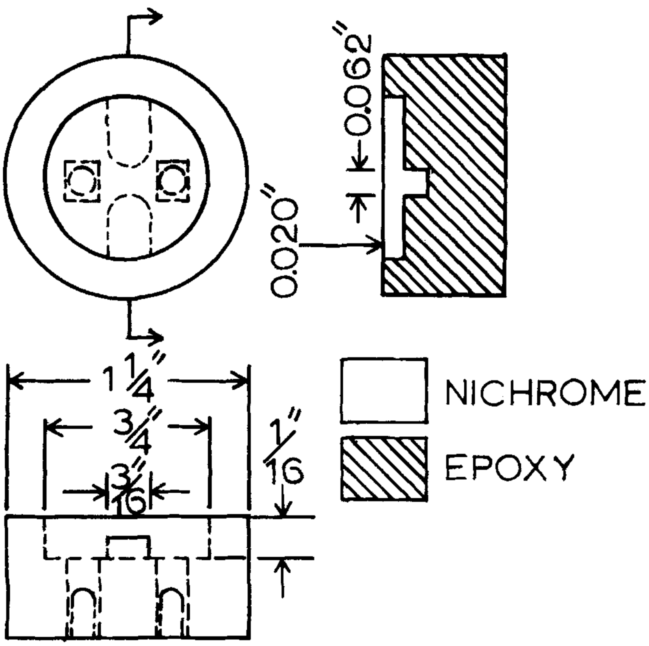


Fig. 2. The boiling surface (not to scale).

no noticeable ridging of the surrounding metal.

The boiling vessel was an aluminum tank 14 by 14 by 6 in. which had two 6-in.-diameter glass windows for lighting and photography. The tank was equipped with copper power leads, a reflux condenser, and immersion heaters which kept the water at saturation temperature.

Direct current was used to heat the boiling surface by resistance heating. An a-c rectifier which is internally regulated provided the necessary power.

The high-speed motion pictures were taken with a Fastax WF-17 camera operating at approximately 4,000 frames/sec. The delay times were determined with a timing light, which is an integral part of the camera. Figure 3 is a schematic diagram illustrating the experimental equipment.

EXPERIMENTAL PROCEDURE

Two boiling surfaces were constructed on the basis of the design described in Figure 2. Surface I did not have an artificial nucleation site, and the bubbles photographed were from natural sites produced by normal polishing. This surface was boiled in both positions with two polishes: 0.05 micron and 240 grit. An artificial site was placed in the center of Surface II. This surface was polished to 0.05 micron only, and bubbles were photographed with the surface in both positions.

The boiling surface was prepared as described previously, attached to the power leads, and placed in the boiling vessel in a fixed orientation. Early in the investigation it was realized that clear pictures were most difficult to obtain while the surface was in the vertical position. Any side bubbles which formed on the lower half of the surface would rise and obstruct the view. Consequently, attempts were made to obtain data in this position first. If the results were satisfactory, the the surface was then placed horizontally and the experiment repeated.

The boiling vessel was filled with demineralized water, brought to saturation temperature, and both water and surface were boiled together several hours for degassing prior to each experiment in either position. The current through the surface was then regulated until a single, stable bubble column was formed. The bubble column was considered stable when there were no noticeable periods during which bubble activity ceased.

The timing marks were generated at 1-msec. intervals. The pulse generator and pulse shaper were turned on and allowed to stabilize before the motion pictures were taken.

Extension tubes were used to obtain the desired magnification. The lenses used had a focal length of 2 in., and a 2-in. extension tube was used for most films. This combination results in a magnification of 1. The proper *f*-stop setting to obtain proper illumination of the bubbles was quickly determined by trial and error. With the two boiling surfaces, a total of nine films were taken.

DISCUSSION OF RESULTS

While a surface is boiling horizontally, the time at which a bubble detaches is easily determined. However, when it is boiling vertically, the bubbles tend to slide up the surface, and so in this position the contact period was considered ended when the bubble no longer covered any of the surface area under the bubble during its initial rapid growth. This choice was arbitrary, but it was a convenient and systematic criterion to determine delay time. The delay times and contact periods were read directly from a film reader, and the results from typical films are entered in Table 1.

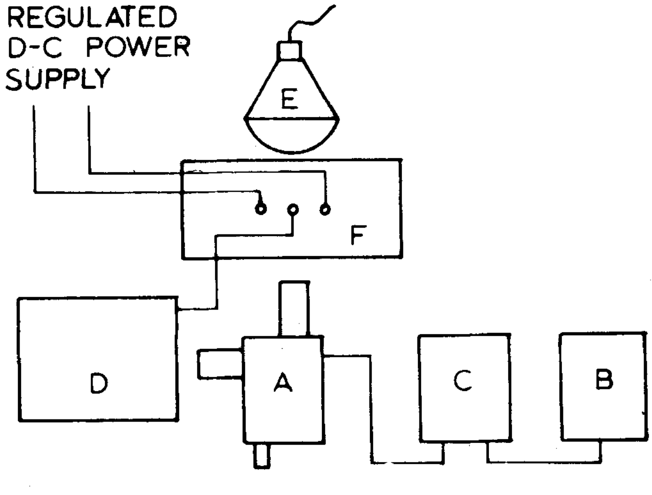
Other data for both Surfaces I and II are entered in Table 2. Since the cross section of the boiling surface was nonuniform, the absolute heat flux was not determined. However, relative heat flux was calculated on the assumption that it was proportional to the square of the current through the surface.

Since the results were also photographic, sketches of

Table 1. Contact and Delay Time in Milliseconds for Bubbles Shown on Films Identified in Table 2

Film 1		
1	—	32
2	365	33
3	74	31
4	133	31
5	78	32
Film 2		
1	—	19
2	65	22
3	73	21
4	100	18
5	88	20
6	54	20
7	68	20
8	61	21
9	52	21
10	62	21
11	70	20
Film 3		
1	—	25
2	435	15
3	138	12
4	76	16
Film 4		
1	—	14
2	59	13
3	78	10
4	50	14
5	57	11
6	60	8
7	47	9
8	49	11
9	51	11
10	50	11
11	57	13
12	62	10
13	61	12
14	70	15
Film 5		
1	—	29
2	140	33
3	43	28
4	42	34
5	75	30
6	64	29
7	49	32
8	59	35
9	50	33
Film 7		
1	0**	17
2	0	18
3	0	15
4	0	*11
5	0	17
6	0	*11
7	0	17
8	0	*8
9	0	15
10	0	*6
Film 8		
11	0	13
12	0	*3
13	0	*11
14	0	14
15	0	*3
16	0	*12
17	0	15
18	0	*3
19	0	15
20	0	10

* Bubble coalesced with previous bubble.
** Less than 0.25 msec.



LEGEND

A - FASTEX HIGH SPEED CAMERA
B - PULSE GENERATOR
C - PULSE SHAPER
D - OSCILLOSCOPE (WHEN USED)
E - 750 WATT LAMP
F - BOILING VESSEL (SEE FIG 2)

Fig. 3. Schematic diagram of experimental equipment.

typical bubble growth and detachment are shown in Figures 4 through 8. These sequences were reproduced from the actual films. For the growth time included with each bubble sequence, zero time was assumed to be the frame before the appearance of the bubble. A discussion of these film sequences follows.

Surface I (No Artificial Cavity)

For the 0.05-micron polish, the bubbles formed in both the horizontal and vertical positions were similar in size and shape. They were large, hemispherical bubbles preceded by large delay times, and typical examples are shown in Figures 4 and 5.

The unusually large, nearly hemispherical bubbles deserve some explanation. The results of Long and Berenson as stated by Zuber (*10*) show that when compared to a rough surface a smooth surface requires a higher average surface temperature to transfer the same heat flux. The

TABLE 2. DATA FOR SURFACES I AND II

Polish	Orientation	Film	Typical bubble, Fig.	Relative heat flux*
SURFACE I			(Natural site)	
0.05 micron	Vertical	1	4	2.50 Q(II)
0.05 micron	Horizontal	2	5	1.80 Q(II)
240 grit	Vertical	3	6-b	1.09 Q(II)
240 grit	Horizontal	4	6-a	1.09 Q(II)
SURFACE II			(Artificial site)	
0.05 micron	Vertical	5	7	2.46 Q(II)
0.05 micron	Vertical	6		2.23 Q(II)
0.05 micron	Horizontal	7	8	1.00 Q(II)
0.05 micron	Horizontal	8		1.00 Q(II)

* Based on lowest heat flux for Surface II.

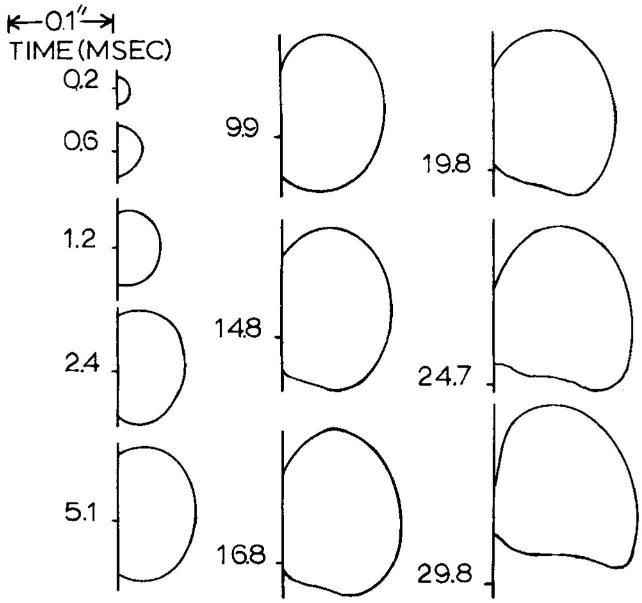


Fig. 4. Bubble forming on Surface I (vertical-0.05 micron polish-delay time: 78 msec) Film 1.

results of Hospeti and Mesler (*2*) indicate that bubbles which are large, nearly hemispherical, and preceded by long delay times originate at a relatively high initial surface temperature. Thus, the large, hemispherical bubbles were likely the result of the very smooth 0.05-micron polish, and it would seem that the surface temperature before bubble formation must have been relatively high.

For the 240-grit polish, again the bubbles formed in both positions were similar. However, on the rougher polish the bubbles were smaller and more oblate, as shown in Figure 6.

The delay times observed for both polishes varied statistically somewhat, which agrees with the results of Hsu and Graham (*4*). It should be noted that in the vertical position a higher relative heat flux was required to produce a bubble column. The delay times observed were also longer and more random. These effects in the vertical

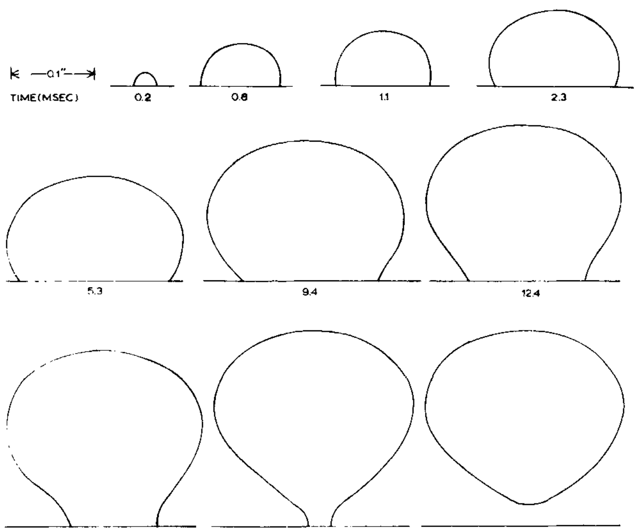


Fig. 5. Bubble forming on Surface I (horizontal-0.05 micron polish-delay time: 70 msec) Film 2.

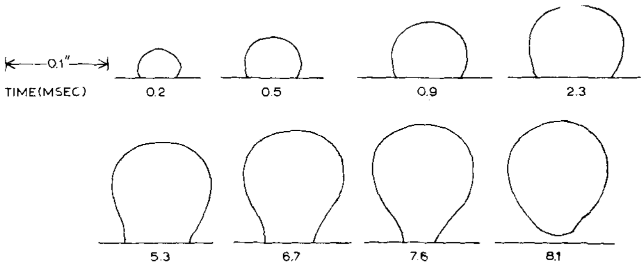


Fig. 6a. Bubbles forming on Surface I (240 grit polish) horizontal, delay time: 60 msec Film 4.

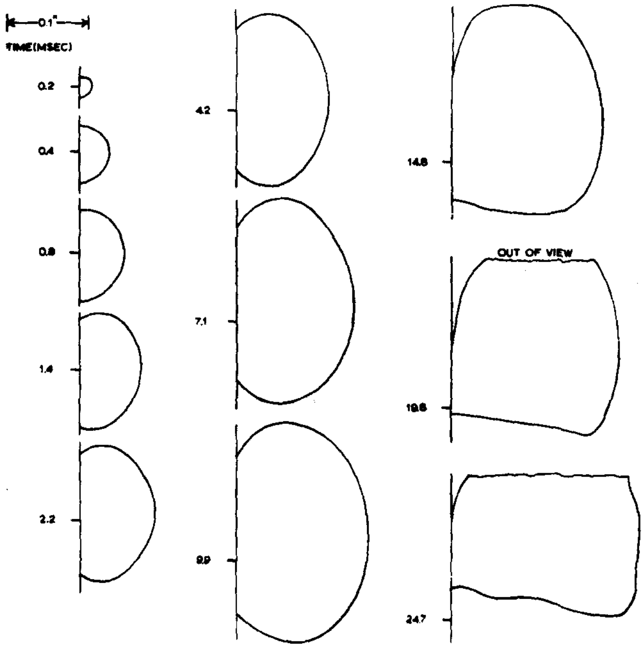


Fig. 7. Bubble forming on Surface II (vertical-artificial site-delay time: 50 msec) Film 5.

position were thought to be the result of the hydrodynamic boundary layer which develops on a heated vertical flat plate. This hydrodynamic boundary layer, and the resulting liquid velocity, could affect the surface-temperature behavior by increasing convective heat transfer.

Surface II (Artificial Site—0.05-Micron Polish Only)

Surface II was similar to Surface I except that an artificial nucleation site was formed in the center of the surface.

In the vertical position the bubbles were similar in size and shape to those formed on Surface I (see Figures 4 and 7). The delay times and contact period were also comparable.

In the horizontal position, however, unusual results were observed. Initially, as current was applied, several large bubbles formed over the site. Suddenly, a high-frequency column of small bubbles would form and the heat flux could then be reduced without causing the site to become unstable. Photography revealed that small, spherical bubbles were forming with little or no delay time (less than 0.25 msec.). A segment of one film is shown in Figure 8.

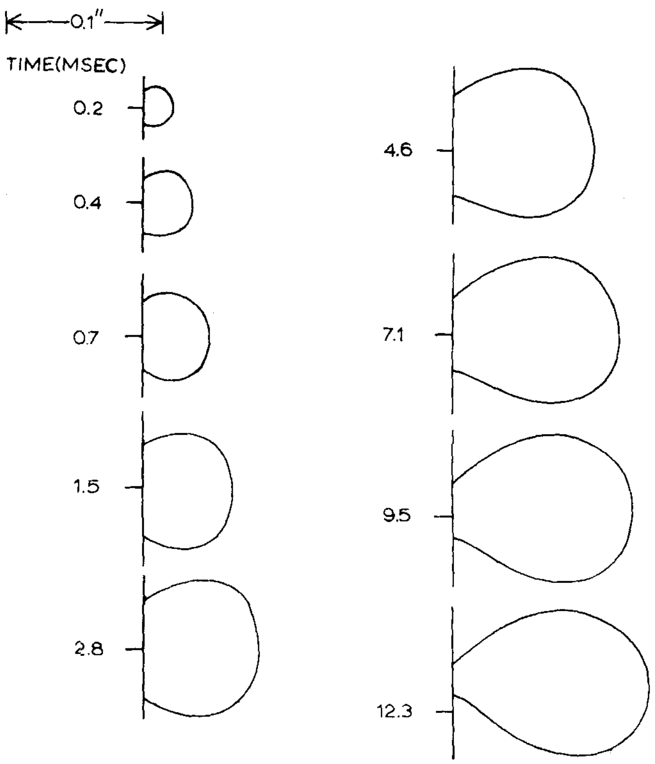


Fig. 6b. Bubbles forming on Surface I (240 grit polish) vertical, delay time: 138 msec Film 3.

The significance of this discovery becomes more apparent after one reviews recent results of other investigators. Yatabe and Westwater (9) apparently boiled from a vertical surface with artificial cavities and observed varying delay times. Howell and Siegel (3), when boiling on a horizontal surface with artificial sites, reported that the delay time was always zero, because vapor remained in the cavity from which the next bubble would grow. However, no emphasis was placed on surface position in either of these reports.

It is also important to note that in the above investigations the cavity size and shape were varied. The results of these investigators, then, support the results obtained in this report beyond the special type of artificial site used here. The site used here was conical and approximately 2 mils at the surface, and the sites of Howell and Siegel were cylindrical and varied in diameter from 0.0038 to 0.0413 in. and in depth from 0.010 to 0.030 in. The cavities of Yatabe and Westwater were reentrant and also varied in size and shape.

EXPLANATION OF RESULTS

The unusual effect of surface position on delay time of bubbles from an artificial site was reproducible. Consequently, it becomes necessary to explain why the effect should be so pronounced. A reasonable explanation was found by analyzing the difference in detachment caused by a change of surface position.

Horizontally, the bubbles neck down symmetrically about the nucleation site when detaching. In the vertical position, due to buoyancy, the bubbles tend to slide up the surface. A sketch illustrating this change in detachment is shown in Figure 9(a). The two methods of detachment result in a variation in the conditions imposed on the vapor in the cavity. In the horizontal position the vapor remaining in the cavity cannot escape after the bubble breaks off. Vertically, however, the vapor in the cavity has a path into the bubble as the liquid-vapor interface moves across the cavity opening. This path is shown in Figure 9(b).

The fact that a change in orientation of the surface will change the thermal-boundary-layer behavior simply can-

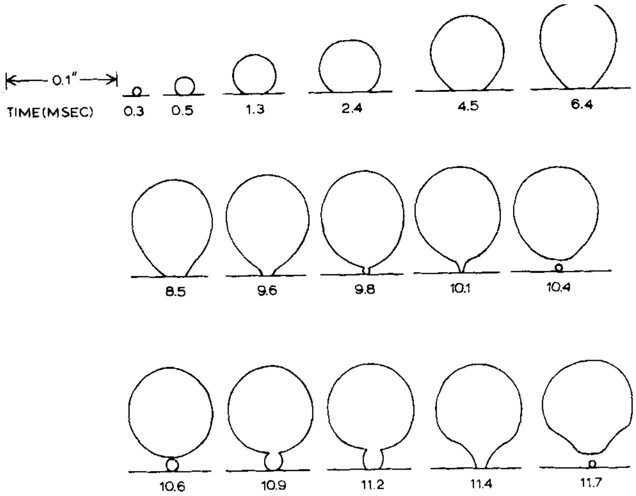


Fig. 8. Bubble forming on Surface II (horizontal-artificial site)Film 7.

not account for the unusual effect observed here. This is evident since the effect on natural sites was found to be slight. The influence of the thermal-boundary-layer behavior should not be greatly changed by forming an artificial site in the surface.

The fact that natural sites are not greatly influenced would indicate that cavity size could be the controlling factor. As cavity size decreases, the time required for the vapor-liquid interface to move across the cavity opening would decrease correspondingly. Therefore, for very small cavities, liquid inertia could delay penetration of the liquid into the cavity until the interface has passed.

However, to actually test the effect of cavity size on the unusual effect of orientation observed, unusual experimental capabilities would be necessary. Cavities which range in diameter from 0.001 in. to 0.01 micron should be formed on a surface which is smoother than 0.05 micron. Experimental equipment to do this is unavailable to the authors at this time.

Either by the above mechanism or for an unknown reason the cavity when in the vertical position apparently fills with liquid either partially or completely. Even with reentrant cavities a substantial part of the vapor could be displaced, although some portion will remain trapped. With the cavity partially filled with liquid, the site would become much less active, since the radius of any of the remaining vapor nuclei would be greatly reduced. The

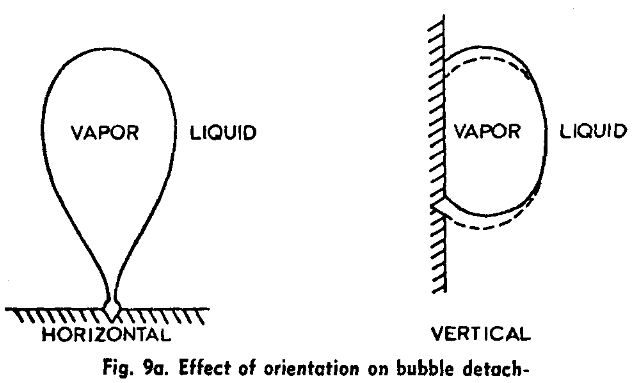


Fig. 9a. Effect of orientation on bubble detachment.

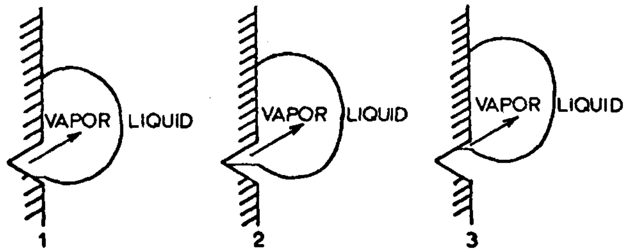


Fig. 9b. Vapor path into the bubble in the vertical position.

smaller nuclei would require a higher superheat to cause bubble growth (8) and, consequently, cause a longer delay.

CONCLUSIONS

1. A change in surface position, from horizontal to vertical, affects the delay time of bubbles from an artificial site. In a horizontal position small, spherical bubbles were formed with little or no delay time (less than 0.25 msec.). With the surface vertical, large, hemispherical bubbles were formed after long delay times (40 to 70 msec.).
2. The effect of surface position on delay time for natural sites is slight when compared with that for artificial sites. Generally, on a vertical surface a larger variation in delay time occurs and a higher heat flux is required to cause a stable bubble column.
3. The observations of other investigators who have studied boiling from artificial sites agree with the results of this report. However, the position of the surface was not considered important in these other investigations. Since bubble size and shape change as delay time varies, surface position must be considered when one is boiling from artificial sites.

ACKNOWLEDGMENT

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