An Experimental Study of Surface Cooling by Bubbles during Nucleate Boiling of Water

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By using a special surface thermocouple Moore and Mesler have measured large temperature fluctuations during nucleate boiling of water on chromel P surface. They found that the temperature dropped 20° to 30°F. in about 2 msec. but required 10 to 20 msec. to recover. They have postulated that the surface was cooled during initial bubble growth by evaporation of a microlayer into the bubble. To test this hypothesis a technique was developed to photograph a bubble growing from an artificial site as the surface temperature was measured.

Temperature fluctuations were recorded on an oscilloscope which automatically triggered the bubble photographs by means of a time delay unit and flash tube. Photographs of bubbles were taken at 1 μsec. exposure time and ranged from about 10 μsec. after the start of the temperature drop to about 1 msec. before the start of another cycle. The photographs show that the surface cools during bubble growth and recovers during bubble departure.

A recent paper by Moore and Mesler (*1*) reported rapid drops in surface temperature during the nucleate boiling of water. Although a hypothesis was advanced to account for the drops, no experimental attempt was made to relate the temperature drops to the behavior of bubbles. This study was begun to obtain data on the relation.

Moore and Mesler observed temperature drops of 25°F. occurring in 2 msec. at heat fluxes of 135,000 B.t.u./hr. sq. ft. and above. At this high rate the boiling surface is so filled with bubbles that it is impossible to see what any individual bubble is doing.

To relate the bubble behavior to the temperature it was believed necessary to get isolated bubbles to grow near the surface thermocouple so the bubble could be photographed as the temperature was being recorded. To accomplish this the heating surface was first highly polished to minimize bubbling everywhere on the heating surface. An artificial site was then introduced close to the thermocouple to support bubbling there. This technique produced temperature drops when bubbling was occurring at the site near the thermocouple. The temperature drops were smaller than those reported by Moore and Mesler but were otherwise similar.

The surface thermocouple indicated its temperature on an oscilloscope connected to a variable time delay unit which in turn fired a flash tube illuminating the bubble. With cameras focused on the oscilloscope face and the bubbling site it was possible to record both the surface temperature and the state of the bubble at one instant during the temperature record.

EXPERIMENTAL EQUIPMENT

The experimental equipment consisted of a surface thermocouple mounted in a vertical boiling surface, an electrical power supply, a potentiometer and oscilloscope, a time delay unit, an electronic flash tube, and two cameras. Figure 1 depicts a schematic diagram of the equipment.

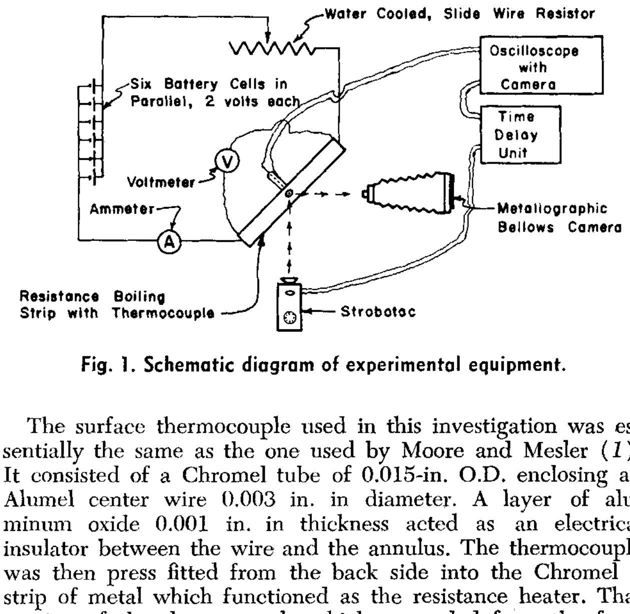

Fig. 1. Schematic diagram of experimental equipment.

The surface thermocouple used in this investigation was essentially the same as the one used by Moore and Mesler (*1*). It consisted of a Chromel tube of 0.015-in. O.D. enclosing an Alumel center wire 0.003 in. in diameter. A layer of aluminum oxide 0.001 in. in thickness acted as an electrical insulator between the wire and the annulus. The thermocouple was then press fitted from the back side into the Chromel P strip of metal which functioned as the resistance heater. That portion of the thermocouple which protruded from the front face (the boiling surface) of the Chromel P strip was then removed so that the end of the thermocouple was flush with the boiling surface. A junction was then created on the end of the thermocouple on the boiling surface.

Two types of resistance boiling strips were used in the investigation. The strip used to obtain a majority of the data was similar in design to that used by Moore and Mesler (*1*) but with less epoxy resin on the reverse side. The plastic was used primarily to support and protect the thermocouple and

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not to insulate the reverse side of the boiling strip. Two problems were encountered with boiling strips of the initial design. First bubbles that formed on the bottom edge of the strip during boiling would rise in front of the boiling surface. Hence the nucleation site under observation would be obscured. Second after several experimental runs a small crack developed at the metal and plastic interface. This crack afforded an excellent place for nucleation to occur. These cracks not only produced bubbles which obscured the artificial nucleation site but afforded such excellent nucleation sites that several boiling strips were found to cease boiling on the flat surface and to boil only from the cracks. A second type of boiling strip was designed to eliminate the plastic to metal interface. The new design (2) was found to perform as desired and was used to obtain part of the data.

A cathode-ray oscilloscope with a preamplifier indicated the temperature fluctuations sensed by the surface thermocouple. This A.C. type of preamplifier allows the rapid temperature changes to be sensed but does not permit absolute temperatures to be determined. The temperature traces were recorded with a camera. All displays could be simultaneously viewed and photographed.

An average absolute surface temperature was determined as follows. With a potentiometer the thermocouple voltage was measured with the current flowing first one direction through the strip and then in the opposite direction. These readings did not agree because the current through the strip caused a small voltage drop across the thermocouple junction. This voltage drop was cancelled by averaging the two readings.

A wave-form generator and a pulse generator composed the time delay unit. The wave-form generator was triggered at the beginning of the oscilloscope trace to generate a sawtooth wave form. The pulse generator was set to generate a pulse at a preselected point on the sawtooth wave form. This generated pulse was used to trigger the electronic flash tube.

A simple metallographic bellows camera photographed the bubbles as they grew on the vertical surface. The axis of the camera made an angle of 14 deg. with a normal to the surface. A magnification of twelve was obtained on all bubble negatives.

The boiling strip was held by two brass electrodes. The complete assembly was then contained in a vessel with water. Power for boiling was furnished by six 2-v. battery cells connected in parallel. The voltage drop across the boiling strip was varied by use of a water cooled slide wire resistor. Additional heat was furnished by a laboratory hotplate to keep bulk water always at saturation temperature during all experimental work.

The actual section of the boiling strip which experienced boiling during a run was that portion located between the holding bars. The section was 1¼ in. in length, ¼ in. in width, and 1/16 in. in thickness. The area available for boiling heat transfer was determined by measuring the exposed surface of the boiling strip. This area included the front face, two sides, and the portion of the reverse side not covered with epoxy. The area was calculated to be 0.50 sq. in. ± 5%.

To reduce the number of natural sites on a boiling strip that would support bubbling the boiling strip was polished with 240, 360, 400, and 600 grit paper and then on a polishing wheel with alpha alumina and gamma alumina. This produced a boiling strip with mirror smoothness. An artificial nucleation site was introduced in the center Alumel wire of the thermocouple by pricking the surface with a sharpened needle.

Several methods were used in an attempt to create a thermocouple junction on the surface of boiling strips. The only successful ones were vapor plating and deforming the metal by scratching the surface so that the Alumel center wire contacted the Chromel P annulus.

Since the temperature indicated by a thermocouple is the average temperature over the complete thermocouple junction, an attempt was made to restrict the junction for this investigation. Although Moore and Mesler used the complete annulus as a junction for their work, the junction for this investigation was limited to less than 0.002-in. arc of the annulus by vapor plating and to less than 0.001-in. arc by scratching. In vapor plating the junction was limited by masking all of the surface

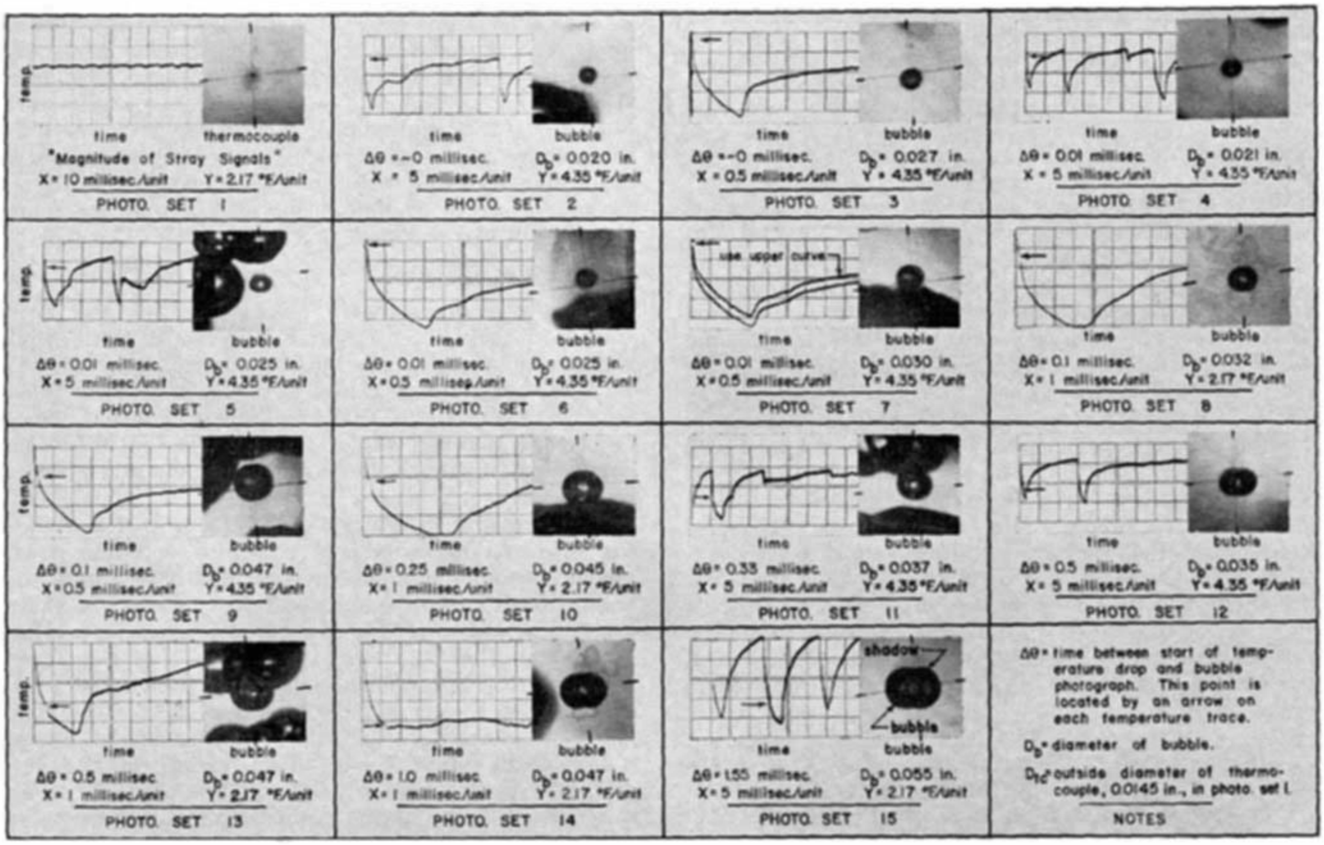

Fig. 2. Photographs of bubbles growing from nucleation site during cooling of surface.

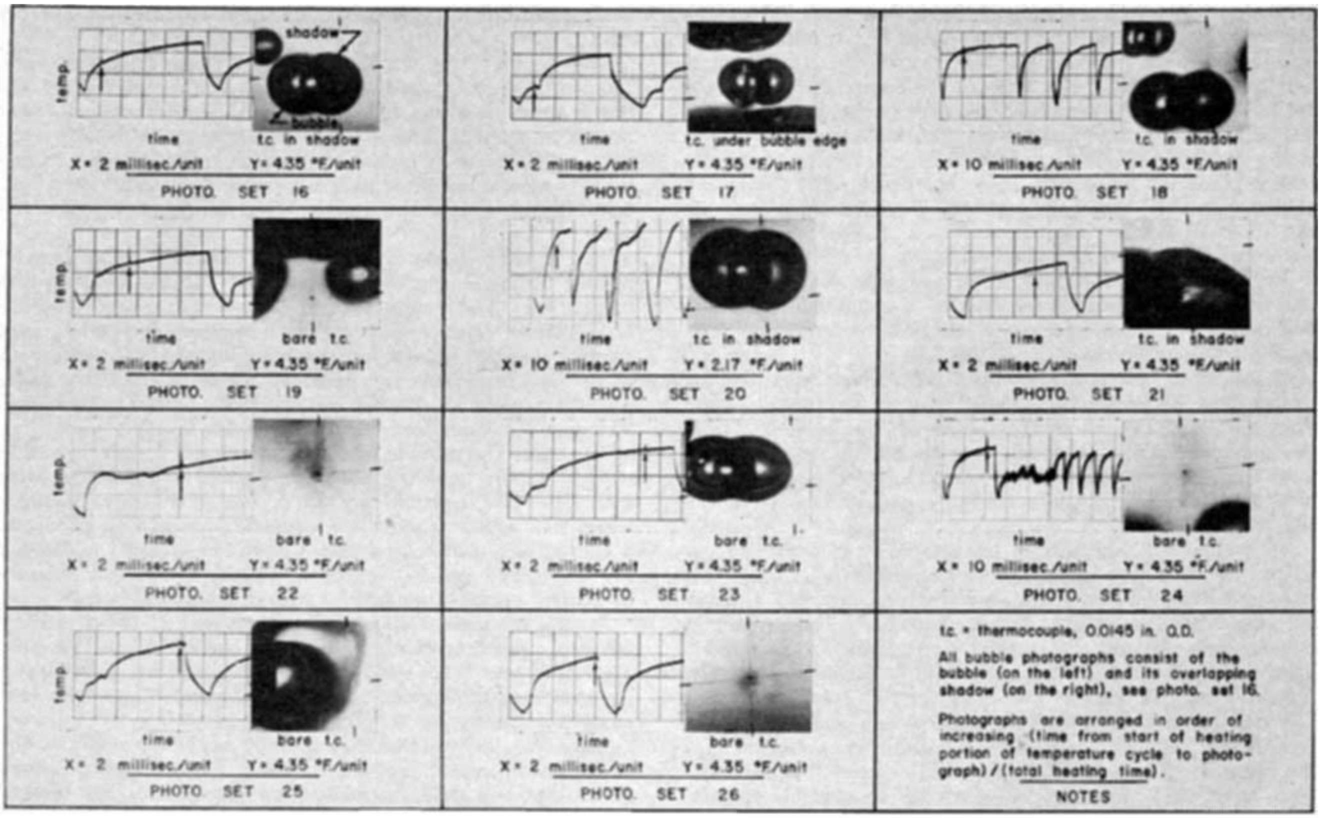

Fig. 3. Photographs of bubbles departing from nucleation site during heating of surface.

except that desired for the junction. The scratching method resembled the method used by Moore and Mesler, but only one small sliver of metal was forced by needle point from the center wire across the oxide layer to contact the annulus and form the thermocouple junction; in the method of Moore and Mesler many slivers formed the junction. Hence the junction was kept small, and the surface of the boiling strip remained smooth. Extreme care was taken to assure that junctions were formed only on the boiling surface and not below the surface.

PROCEDURE

Water at atmospheric pressure was used as the boiling medium for all tests. Before any data were obtained during a run, the water was degassed by boiling for a couple of hours. It was also found necessary to degas the boiling strip. The oscilloscope was adjusted to trigger on either the rapid temperature drop or the relatively slow temperature rise of the cyclic fluctuations. Usually the rapid drop portion of the fluctuations was used to trigger the oscilloscope, but the slow temperature rise portion was also used to obtain a few photographs. Many photographs obtained with this technique were not useable. Extraneous bubbles in the boiling liquid would sometimes obscure the nucleation site under observation, while at other times the oscilloscope would trigger on an undesired portion of the trace.

To facilitate the location of the thermocouple and artificial nucleation site (in the center of the thermocouple) a set of scribe marks were engraved in the metal surface. Since they reproduced lightly in some bubble photographs, a short line on the edge of the photographs was used to accent them.

RESULTS

Photographs taken during the rapid temperature drop are presented as a series in Figure 2, while those taken during the slower temperature rise are shown in Figure 3.

The temperature and time at which each bubble photograph was taken is marked by an arrow on the temperature traces. On the original oscilloscope photographs the time of bubble exposure was indicated by a discontinuity in the temperature trace. The oscilloscope trace would jump vertically off scale and remain off scale during the discharge of flash tube which lasted 1.2 μsec. The trace then returned to its normal path of indicating surface temperature. This discontinuity consisted of a gap in the trace followed by a spike as the beam returned. Photographs of Figure 2 prominently show the gap, while those of Figure 3 show the spike. At all times this discontinuity was found to occur at the time preselected on the pulse delay unit.

Cooling of Surface

Many photographs were obtained during the rapid cooling portion of the temperature cycle. All photographs not ruined by extraneous bubbles obscuring the view or by faulty operation are shown in Figure 2, while pertinent data are tabulated in Table 1. Bubble diameters, times, and temperatures in Tables 1 and 2 were obtained from enlarged photographs. Heat flux values were determined by measuring the electrical current flowing through the boiling strip and the voltage across the strip. The area of the strip was measured and combined with the power measurements to calculate an average heat flux to an estimated $\pm$ 15%. It is emphasized that these Q/A values are average values for the entire strip and not local values at the nucleating site.

To interpret the bubble photographs it is necessary to recognize that each photograph shows both the bubble and its shadow. Since the field of vision with the camera was so small (about one-eighth of an inch in diameter) and the exposure time only 1.2 μsec. the only way to obtain enough light with the available flash tube was to use direct reflection of the light from the boiling surface. This created the shadow.

TABLE 1. DATA FOR PHOTOGRAPHS TAKEN DURING COOLING OF BOILING SURFACE

Photo set No.	$\Delta\theta_c$, msec.	$\Sigma\theta_c$, msec.	ΔT, °F.	ΣT, °F.	D_b, in.	$T_{avg.}$, °F	Q/A, B.t.u./(hr.)(sq. ft.)
1	—	—	—	—	—	213.0	0
2	0	2.2	0	10.9	0.020	218.7	29,400
3	0	1.3	0	18.7	0.027	220.8	51,300
4	0.01	1.7	1.1	8.0	0.021	218.0	23,100
5	0.01	2.5	1.3	10.8	0.025	217.5	21,600
6	0.01	1.57	1.0	19.1	0.025	220.7	50,500
7	0.01	1.62	1.0	17.0	0.030	220.7	50,500
8	0.1	3.5	2.2	10.0	0.032	—	19,400
9	0.1	1.45	6.2	18.9	0.047	220.7	50,500
10	0.25	4.5	2.2	9.8	0.045	—	20,500
11	0.33	2.7	5.7	10.7	0.037	218.1	22,400
12	0.5	1.0	6.4	8.0	0.035	217.9	23,100
13	0.5	2.2	5.7	8.7	0.047	—	20,500
14	1.0	1.0	7.8	8.3	0.047	—	20,700
15	1.55	4.7	7.2	9.3	0.055	217.3	19,200

Photo set 1 shows the thermocouple and scribe marks with no bubbles, while the temperature trace shows the magnitude of stray signals picked up by the oscilloscope to be less than 0.01 mv. or 0.2°F. Photo sets 2 through 15 were taken at various times after the start of the cooling period. The times range from approximately 0 to 1.55 msec., while the bubble grows from 0.02 to 0.055 in. in diameter. The one fact which stands out in Figure 2 is that only very early in the temperature drop is the bubble very small. The bubbles become larger at later times, but the growth rate appears to vary from one bubble to the next.

Even with an exposure time of 1.2 μsec., the bubble photographs in the first few photo sets of Figure 2 appear blurred. This is caused by the extremely fast, initial growth rate of the bubbles. A safe estimate as to the actual time between the start of the temperature drop and the bubble photographs shown in photo sets 2 and 3 is less than 10 μsec. The initial bubble diameter growth is 0.02 in. for the first 10 μsec. This rate corresponds to a 10% gain in diameter while the bubble photograph was being exposed.

An appreciation of the difficulty of obtaining photographs of small bubbles is obtained by noting that the initial rate of cooling, as measured from enlargements, is 0.7°F./10 μsec. If the surface temperature before dropping rises just 0.7°F. above the triggering level, it is 10 μsec. after the drop begins before the earliest bubble picture can be taken.

Heating of Surface

Photographs obtained during the slow temperature rise portion of the temperature cycle are shown in Figure 3, while Table 2 contains the pertinent data for the photographs.

In analyzing the bubble photographs a shadow hides some details, but it is still evident that bubbles leave the boiling surface in the early stages of the heating portion of the temperature cycle. Photo sets 16 and 17 show none of the thermocouple, but if an estimate is made as to where the bubble edge is located in the shadow, it is seen that the scribe marks locate the thermocouple partly under the bubble and partly in the shadow. The thermocouple is only partially visible in photo sets 18, 20, 21, 25, but clearly it is in the shadow and not beneath the bubble. Photo sets 19, 22, 23, 24, and 26 certainly indicate that the bubble has departed from the thermocouple. Although it is evident that the bubble leaves in the early stages of the temperature recovery, it is not apparent exactly what the bubble is doing at the instant the temperature begins to rise.

Photo set 26 is of special interest. The bubble photograph was taken within 0.2 msec. of the next temperature drop, and no bubble is evident on the artificial site. This also indicates that initiation of bubble growth must correspond to the temperature drop.

DISCUSSION OF RESULTS

Moore and Mesler postulated that the temperature drops were caused by the evaporation of a microlayer underneath the bubble. The results of this study are consistent with the hypothesis, since they show that the surface is cooled as the bubble grows and that there is no cooling where there is no bubble. The present study does not indicate the reason the cooling stops so suddenly, but neither does it dispute the hypothesis that the cooling ceases because the surface beneath the bubble has dried off.

TABLE 2. DATA FOR PHOTOGRAPHS TAKEN DURING HEATING OFBOILING SURFACE

Photo set No.	$\Delta\theta_h$, msec.	$\Sigma\theta_h$, msec.	$\Sigma\theta_t$, msec.	$\Sigma\theta_c$, msec.	$T_{avg.}$, °F.	Q/A, B.t.u./(hr.)(sq. ft.)
16	1.48	10.9	12.6	1.7	218.4	25,300
17	1.36	8.4	9.4	1.0	218.5	26,700
18	9.0	34.4	35.6	1.2	217.6	21,000
19	4.3	11.7	13.6	1.9	219.3	32,800
20	7.0	13.8	15.4	1.6	217.5	20,800
21	4.96	9.5	11.1	1.6	218.2	24,800
22	8.8	—	—	—	219.0	29,700
23	11.6	14.0	—	2.4	218.0	24,000
24	18.2	22.0	24.0	2.0	216.6	16,700
25	9.2	9.7	12.0	2.3	218.1	24,500
26	6.6	6.8	8.6	1.8	218.7	27,300

Since bubble growth rate varies from bubble to bubble, it is not possible by the present method to determine how bubble growth rate varies with the surface temperature. This will require obtaining several bubble photographs during any one temperature drop.

CONCLUSIONS

The following conclusions have resulted from this study.

1. The bubble behavior is consistent with the microlayer vaporization hypothesis of Moore and Mesler. A bubble growing on a surface removes heat very rapidly, a bubble departs from its nucleation site as the surface temperature increases, and the sudden temperature drop corresponds to the initiation of bubble growth.
2. No significant cooling is apparent as liquid returns to the surface during bubble departure. Such cooling is predicted by many hypotheses concerning nucleate boiling.

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NOTATION

D_b = diameter of bubble, in.

D_{tc} = outside diameter of chromel annulus for thermocouple, in.

Q/A = heat flux, B.t.u./(hr.) (sq. ft.)

$t.c.$ = thermocouple

X = horizontal coordinates of oscilloscope trace, time, msec.

Y = vertical coordinates of oscilloscope trace, temperature, °F.

T_{avg} = average temperature of nucleation site or thermocouple temperature, °F.

Greek Letters

ΔT = temperature drop from start of cooling cycle to taking of bubble photograph, °F.

ΣT = total temperature drop from start of cooling cycle to end of cooling cycle, °F.

$\Delta\theta_c$ = time from start of cooling cycle to taking of bubble photograph, msec.

$\Delta\theta_h$ = time from start of heating cycle to taking of bubble photograph, msec.

$\Sigma\theta_c$ = total time from start of cooling cycle to end of cooling cycle, msec.

$\Sigma\theta_h$ = total time from start of heating cycle to end of heating cycle, msec.

$\Sigma\theta_t$ = total time of complete temperature cycle, msec.

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Vapor-Liquid Equilibrium Determination by a New Apparatus

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The prediction of the vapor-liquid equilibria of nonideal systems continues, despite the considerable fundamental research on the interaction between molecules, to be a rather elusive goal. Recourse to experimental measurement will undoubtedly be required for the foreseeable future in order to provide the mass of data necessary for engineering calculations. Such measurements, if they are of sufficiently high accuracy, will also serve the more important function of providing a basis for the development and evaluation of theories describing the liquid state.

Although the vapor-liquid equilibria of mixtures can be obtained by a variety of experimental methods, for example the measurements of the vapor pressure of solutions of known compositions and temperatures as described by Van Ness and Ljunglin (8), direct measurement of the x-y-T-P data by means of equilibrium stills retains considerable appeal particularly for mixtures more complex than the binary. A summary of the types, construction, and capabilities of the many stills which have been used is provided by Hala et al. (3). Although a number of the devices are reported to be quite precise and reliable, they suffer the drawbacks of rather complex construction or difficult experimental requirements. This study was directed to the development and evaluation of an apparatus which would hopefully surmount these objections without sacrificing the accuracy of the measurements.

Previous studies in vapor-liquid equilibrium in this laboratory had led to the development of a modification of the Gillespie apparatus. Although this modified equilibrium still described by Landwehr et al. (7) had achieved most of the desired objectives, two undesirable features which it shares with the large majority of existing devices deserved further consideration.

The first of these was concerned with the vapor condensate sampling cell which was of the conventional overflow design. The vaporization of liquid at the liquid-vapor

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