A PHOTOGRAPHIC STUDY OF BUBBLE

BEHAVIOR IN A DIRECT-CONTACT BOILER

by

PAUL WILLIAM BORDLEY

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Signature of Author

Department of Nuclear Engineering
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Certified by

Mujid S. Kazimi
Thesis Supervisor

Accepted by

Chairman, Department Committee on Theses

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ABSTRACT

Boiling in a direct-contact heat exchanger was studied with high-speed movie photography. Measurements were made from photographs of bubble size and velocity. The liquids were freon-113 and water. The results were graphed, and a correlation was found between drop velocity and diameter, which corresponded to earlier data. Seidmann's relation of drop height versus time was found applicable. Drafting was found to be a very important consideration for the modeling of bubble behavior.

Thesis Supervisor: Dr. Mujid S. Kazimi

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FIGURES and TABLES

I. Introduction

High speed photography is a valuable tool in the investigation of short-lived and high speed phenomena. This paper gives some of the results of a photographic study of a direct-contact boiling heat exchanger system. This system was designed by Russell Smith for his Ph.D. thesis experiment, which was to determine the heat transfer coefficient in such a system (1). This study complements that work, in that through photography bubble behavior can be observed and quantified. In particular the bubble velocity dependance on bubble diameter is the focus of attention in this work.

Sideman and Taitel (2) in 1963 did extensive photographic studies of a pentane-water heat exchanger system. They were able to determine bubble velocities, shapes, positions, and vibration frequencies. This information was used to compute predictions for the heat transfer coefficients. They produced equations to predict drop velocity, area, and heat absorption.

Simpson, Beggs, and Nazir (3) used butane and brine in a similar experiment. They studied single drop/bubble behavior. They achieved quite excellent results in correlating bubble velocity and diameter. They derived better relations to explain bubble behavior than Sideman et al., using the earlier work as their guide. Simpson et al. found that at a critical diameter drop velocity abruptly becomes a new function. This change corresponds with the shape of the drop, which changes from an ellipsoidal shape to a cap shape quite abruptly.

Blair, Boehm, and Jacobs (4) constructed an apparatus very similar to the one used in this study. They used freon boiling in water. Their purpose was to be able to predict the relationship of the total heat transferred to a drop and the logarithmic temperature difference between the drop and its environment.

The works of Sideman et al. and Simpson et al. are similar to the work of this study. The principal difference is that they worked with single bubbles, while this work investigates similar effects with groups of drops. There are thus more factors involved, since the drops do interact. The difference in working fluids might be important, as pentane and butane are both less dense than water (and brine), while the freon used in this study has a specific gravity of 1.56. This would seem to require a much higher amount of vaporization for a given velocity. Blair et al. designed a very useful experimental apparatus with many features that were also incorporated into apparatus used for our investigation.

II. Experimental Apparatus

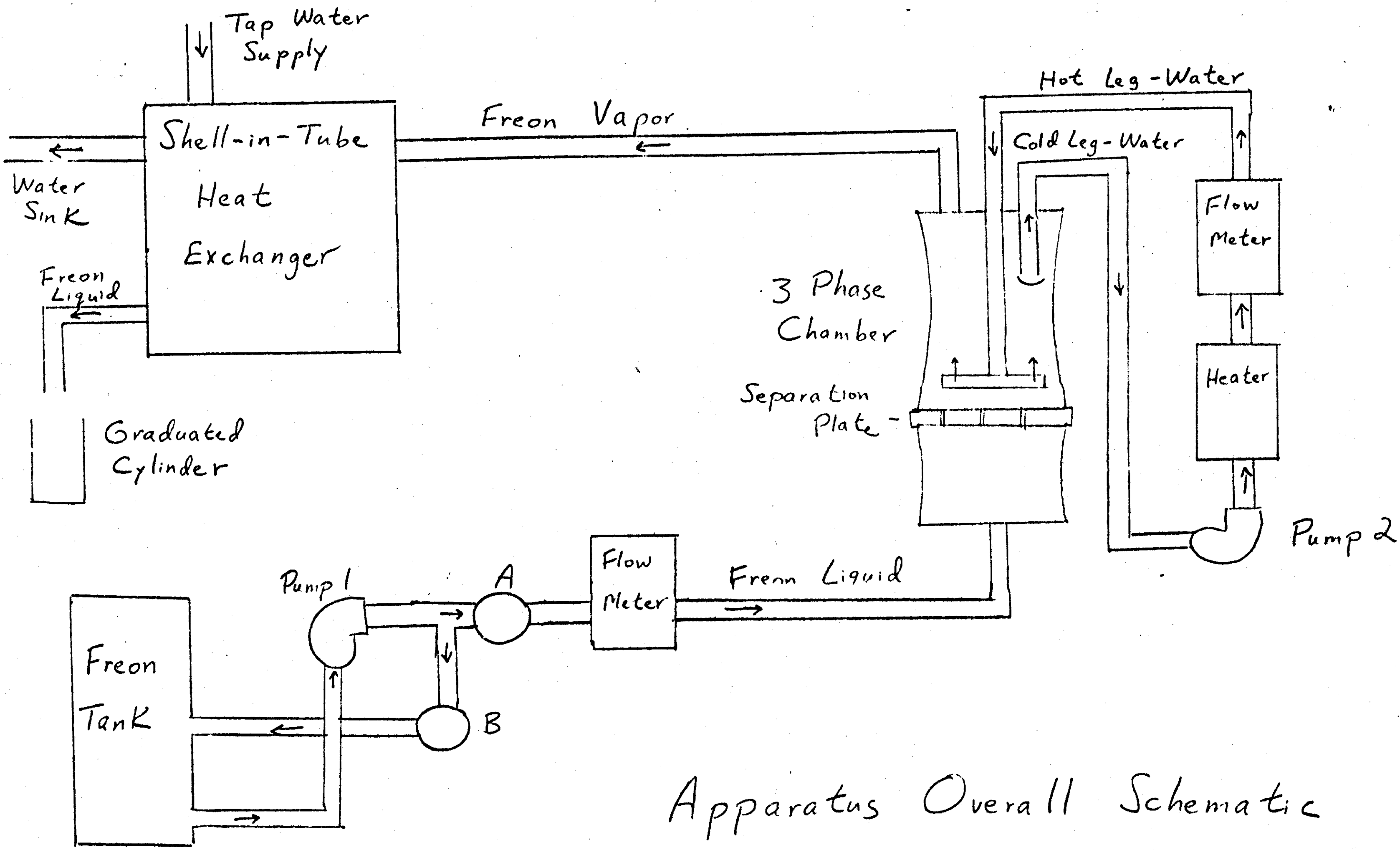
The apparatus propels a jet of trifluorotrichloro-ethane (freon-113) into a transparent vessel containing water which is at a temperature above the saturation point of freon-113. The apparatus allows the photographic study of the boiling process and the monitoring of flow rates and temperatures. A schematic diagram is shown in Figure 1.

The apparatus is divided into four systems: the water circulation loop, the freon circulation system, the three phase chamber, and the photographic system.

Water Circulation System

The water circulation loop maintains the water in the three phase chamber at a fairly uniform temperature which is chosen by the operator. The loop has the following components:

1. An 18 kilowatt heater. The heater maintains a constant water temperature between 65 and 500 degrees F., which is set by a thermostat.
2. Pump number 2. This is a 50 horsepower B & G rotary constant displacement pump. It provides a steady liquid flow of approximately 2.5 gal./min.



Apparatus Overall Schematic

Figure 1

at pressures between 14.7 and 150 psia.

3. Flowmeter. It measures flows between 0 and 8.9 gal./min. with an accuracy of +-0.05 gal./min.
4. Water outlet loop. This is a 0.5 inch diameter copper pipe formed into an 8 inch loop, with horizontal axes. Spaced at 1 inch intervals along the upper surface are 0.25 inch holes. This ring is 2 inches above the Kevlar plate.
5. Water intake. The intake is a 1 inch copper pipe opening 3 inches beneath the top of the three phase chamber. Vapor is inhibited from flowing into the intake with two devices. The first is a convex metal shroud mounted beneath the intake. The other is an aluminum plate which keeps freon flow away from the intake except for the upper two inches of water, where the plate ends. The flow of vapor into the intake is undesirable as it can lead to pump damage.

Freon Circulation System

Freon-113 is pumped into the three phase chamber at 65°F. It flows out of the chamber as vapor and is condensed in the heat exchanger. The components are:

1. Pump number 1. This is a heavy duty, explosion proof rotary pump which delivers a constant flow of 10 gal/min, part of which is fed into the three phase chamber.
2. Freon storage tank. This is a cylindrical steel tank, closed at both ends, 4 feet long and 1 foot in diameter, with a capacity of 30 gallons.
3. Flowmater. It has a measuring range of 0 to 1.0 gal/min, accurate to within ± 0.005 gal/min.
4. Control system. Since a constant displacement pump is used, flow must be varied by diverting a portion of the total flow. Valve A operates as an on-off switch. When closed, all freon flows through valve B and back to the storage tank. Valve B is the throttle. The flow rate is read from the meter, which is visible to the throttler.
5. Chimney. The chimney is a 4 inch pipe mounted at the top of the three phase chamber.
6. Heat exchanger. This is a three pass shell-in-tube device. The coolant for the system is tap water at 60 degrees F. The condensed freon-113 flows into a graduated cylinder, so that the amount that has flowed can be measured.

Three Phase Chamber

The twin chambers are open-ended pyrex cylinders, separated and sealed with Kevlar plates. The cylinders are narrower in the centers than at the ends. The maximum diameter is 9 inches, the minimum is 8 inches.

Holes of various sizes and configurations were drilled into the Kevlar separation plates. The plates used had three different hole sizes:

a) single center hole, 1.0 mm diameter

b) single center hole, 0.5 mm diameter

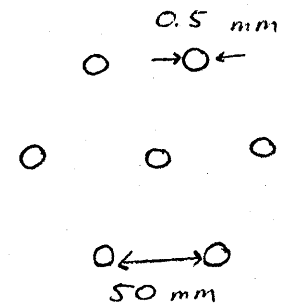
c) 7 holes, each 0.5 mm in diameter, arranged as shown in Figure 2.

Temperatures in the chamber are monitored by 4 thermocouples located at different axial positions, 2 inches radially from the pyrex outer wall. A fifth thermocouple is attached to the freon inlet pipe. (See Figure 3).

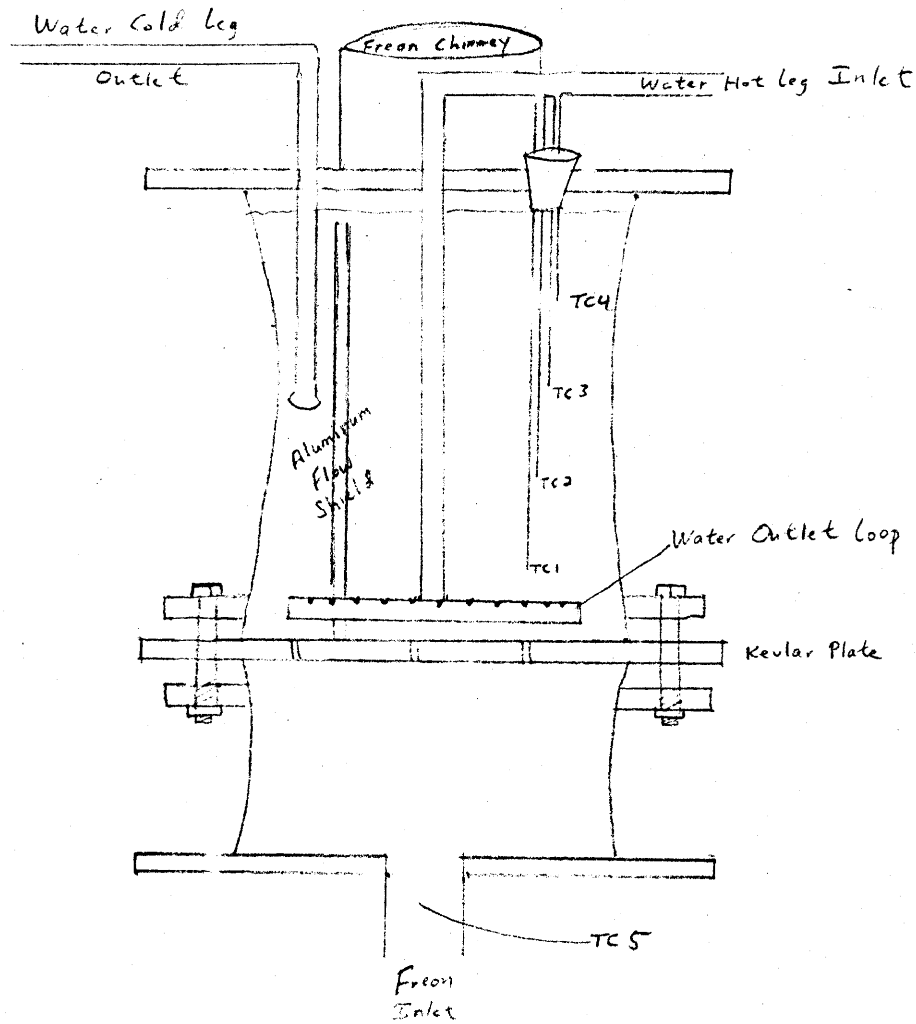
Photographic System

1. The camera. The camera is a Hy-Cam high speed movie camera. This camera operates at film speeds between 20 and 11000 frames per second. The camera was placed on a tripod 3.2 feet from the chamber.

Figure 2



Seven-Holed Separation Plate Pattern



Three Phase Chamber - Side View

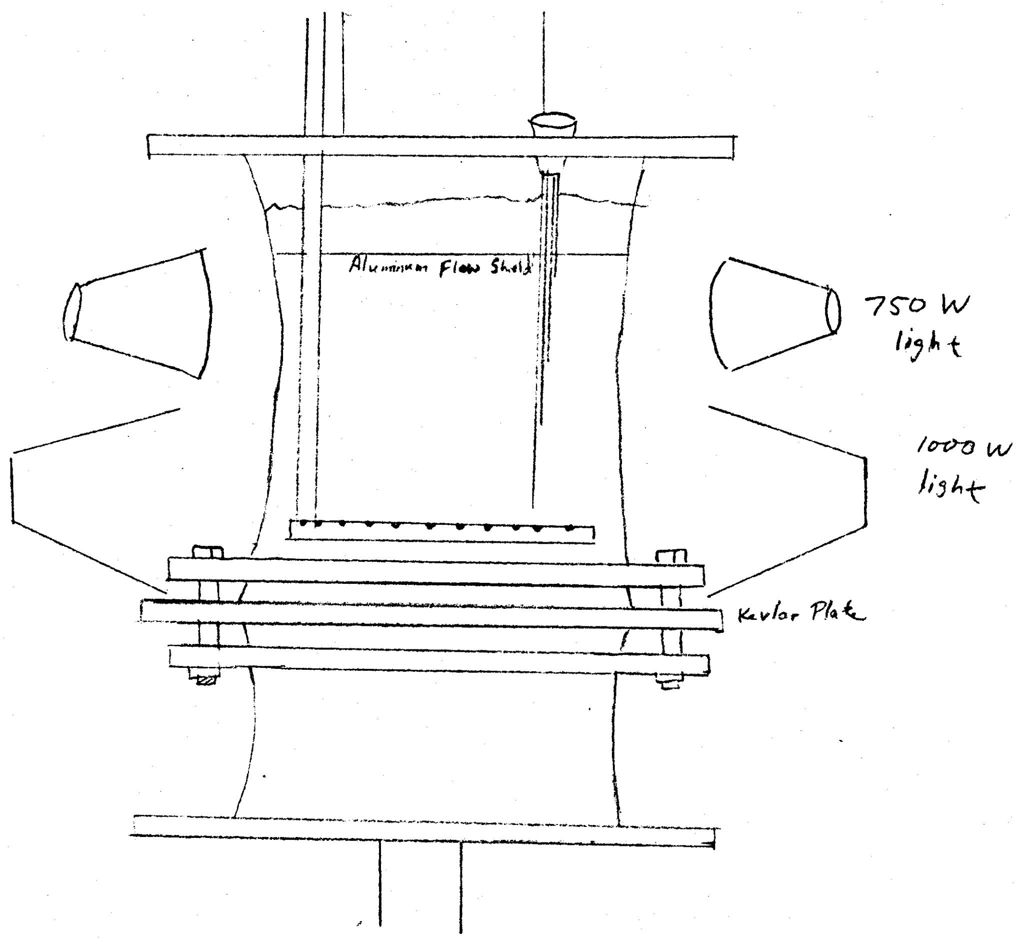
Figure 3

2. Film. Kodak 4-X reversal film 7277 was used. Film was exposed at rates of 1000 and 2000 frames per second, and f-stops of 5.6 and 3.0 were used, respectively.

3. Lighting. The chamber was side-lighted. Two 1000 watt Tote-A-Lites and two 750 watt lights were mounted symmetrically about 2 inches from the pyrex wall of the chamber (see Figure 4). These are continuous lights. They were only turned on shortly before a photographic run, as they produced inordinate amounts of heat. They were attached to nearby convenient piping.

Other Important Components

Thermocouple readings were continuously monitored by a Ramp Scanner and Processor. Readings were displayed continuously and recorded at arbitrary intervals.



Three Phase Chamber - Front View

Figure 4

III. Experiments

The same basic procedure was used for all the runs. Settings and some methods were changed as more experience was gained in the use of the apparatus. It was quickly found that under many conditions useful data could not be gotten.

Before the start of a run, the thermocouples were inserted into the chamber and the microprocessors were switched on. The water circulation pump and the heater were then started, and the chamber water temperature was increased from ambient to approximately 115 °F., which is 6 degrees below the saturation point of freon-113. The pump was allowed to come to full speed, which impels a flow of 2.5 gal/min. The heat exchanger tap water flow was opened, and the freon pump was started. Valve A was fully closed and valve B open, so that all the flow would be diverted back to the storage tank. When all components were operating smoothly, the water temperature was brought up above saturation to the desired temperature, the lights were turned on, and the valve line-up changed to induce the desired flow into the chamber. It was necessary to not turn the lighting on until just before the start of the run, as the lights operated at extremely high temperatures which tended to make the thermocouples read incorrectly. The camera could be operated when desired, having earlier been aimed and focused. The camera could only be operated for short periods of time because of the very high speed at which the film was run (100 feet of film was exposed in under 4 seconds. This high speed was considered necessary as vapor velocities could exceed 1200 cm/sec.

First run parameters are listed in Table 1.

The results from the first run were mixed at best. Columns of liquid freon-113 flowed into the chamber, and a significant amount vaporized and moved upward as bubbles, as desired. However there was a tendency for the freon to flow along the top of the separation plate and boil in other places. Additionally the camera speed, while high, was not fast enough to give clear data. Problems with the deposition of gas bubbles on the inside of the chamber pyrex wall also degraded the quality of the pictures.

Accordingly, changes were made before the next run. A new plate was made and installed. This plate incorporated a single 0.5 mm. hole. It was hoped that this plate would increase the velocity of the fluid jet, and decrease the amount of fluid flowing along the upper surface of the plate. The camera speed was increased to 2000 frames per second, and the chamber wall was cleaned immediately before the run, with the aim of improving picture clarity.

Lighting was not altered.

The photographs obtained were considerably improved. Clarity was excellent. The problem of freon flow along the plate instead of vertically was minimal. The film clearly showed the next problem to be overcome: too many bubbles were being formed, and there was too much turbulence in the chamber, so that the observed behavior was not interesting. Freon would leave the liquid jet, slow down, and coalesce at a level about 10 cm. above the separation plate. This coalesced bubble would then move up the chamber, and 10 cm. higher, would break up into many smaller bubbles. The turbulence, especially near the top of the chamber, destroyed any idea of obtaining explainable results.

The problem of bubble coalescence seemed to arise from two factors: the freon jet had a velocity near or greater than the terminal velocity of the bubbles, and the density of the bubbles caused drafting effects, wherein the lead bubble in a group would experience considerably more drag effects than the ones following it, so that the trailing bubbles moved at higher velocities and eventually caught up with and coalesced with the lead bubble. Lower flow rates were tried, though the apparatus is not designed for very low flow rates. It was found that even at low flow rates this early coalescence still occurred. Additionally, low flow rates brought back the problem of flow becoming horizontal along the plate. 0.5 mm. was the smallest practical hole that could be drilled into the separation plate. As single bubbles were not of interest in this study, the apparatus could not significantly be chahged. The solution to the problem was to abandon the idea of steady state flow and use a burst. This made it more difficult to photograph, as one could not be sure that what was being recorded would yield useful results. After a bit of practice, though fairly uniform bursts could be created. A second change made was to turn off the water circulation pump just before the start of the run. Considering the small amounts of freon being boiled as opposed to the quantity of water in the chamber, little change of temperature would be expected in the system during a run. The lighting could be left on for even shorter periods of time, as with no water circulation, the heat from the lamps proved to be very significant in altering the temperature distribution in the chamber.

The next run produced good results. Similar behavior to that found by Sideman and Taitel (2) in 1963 with pentane boiling through water was observed. The bubbles first assumed a spherical shape. They then soon became ellipsoids, with their major axes horizontal. At one position, the drops abruptly assumed a mushroom cap shape and remained in this shape for the remainder of their travel up the chamber.

In this run, an approximately 2 second burst was used, with a maximum flow rate of 0.25 gal/min. The seven holed plate was used. This allowed a smaller amount of flow to pass through a given hole than with the one hole system at a given flow rate of the system. It was found that weven holes were enough separated so that the flows through each did not interfere. See Table 1.

As mentioned before, this run finally gave useful results. The behavior of the bubbles in regard to their shape was classic. The success of this run can probably be attributed to these factors:

1. Water flow was cut off, making turbulence its minimum.
2. The flow rate was low.
3. The flow rate was not allowed to remain at a level where much coalescence would occur (though a few bubbles did combine due to drafting effects).
4. The operating procedure had become more streamlined through practice.

Table I

Experiment Parameters

Parameter	Run I	Run II	Run III
chamber water temperature, °F	135 *	138 *	131 *
freon entrance temperature, °F	65	65	65
freon flow rate, gal/min	0.1	0.1	0.25**
water flow rate, gal/min	2.5	2.5	0.0
plate	1-hole	1-hole	7-hole
hole size, mm.	1.0	0.5	0.5
camera speed, frames/sec	1000	2000	2000
camera f-stop	5.6	3.0	3.0

* Freon saturation temperature is 121 °F.

** This is not a constant flow rate, only the maximum.

IV. Results and Discussions

The parameters of boiling that can be measured through photography are: bubble size, shape, speed, and oscillation activity. The developed film was put into a microfilm reader and measurements were made from the projected image. The size of the projected image was about the same as the actual size of the chamber (image size was 0.9144 actual size). In this particular series of experiments the initial 5 centimeters of the chamber could not be observed due to the obstruction of the metal ring which held the two parts of the chamber together.

Sideman and Taitel (2) correlated bubble height with elapsed time of a bubble in the vessel. They report that for a pentane-water system that a graph of this relation should be a smooth curve, with no dependance on bubble mass. Their equation is

$$H - H_o = Bt^p$$

where

H = level of the drop

H_o = initial level

B and p are constants

t = elapsed time

The average value of p that they found was 1.16. In this experiment, a similar relationship was found (see Figure 5). The behavior does indeed follow the same equation near the bottom of the vessel. It would seem reasonable to assume that this variance is caused by the high initial velocity of the freon as it is injected into the upper chamber, and that this effect should die out later on. The outermost curves on the graph, the ones which differ the most from the average, are an unusual case, for these two bubbles were involved in a drafting situation. The trailing bubble rose very quickly, as it experienced less water resistance, and collided and coalesced with the lead bubble. In this study, the average value of p was found to be 1.0486. H was found to be 0.5 and B 274. Sideman and Taitel's equation becomes:

$$H - 0.5 = 274\ t^{(1.0486)}$$

These results agree quite well with the earlier ones.

The next relationship considered was velocity as a function of time. As can be seen from Figure 6 this relationship just does not seem to exist. There was too much variance between drops.

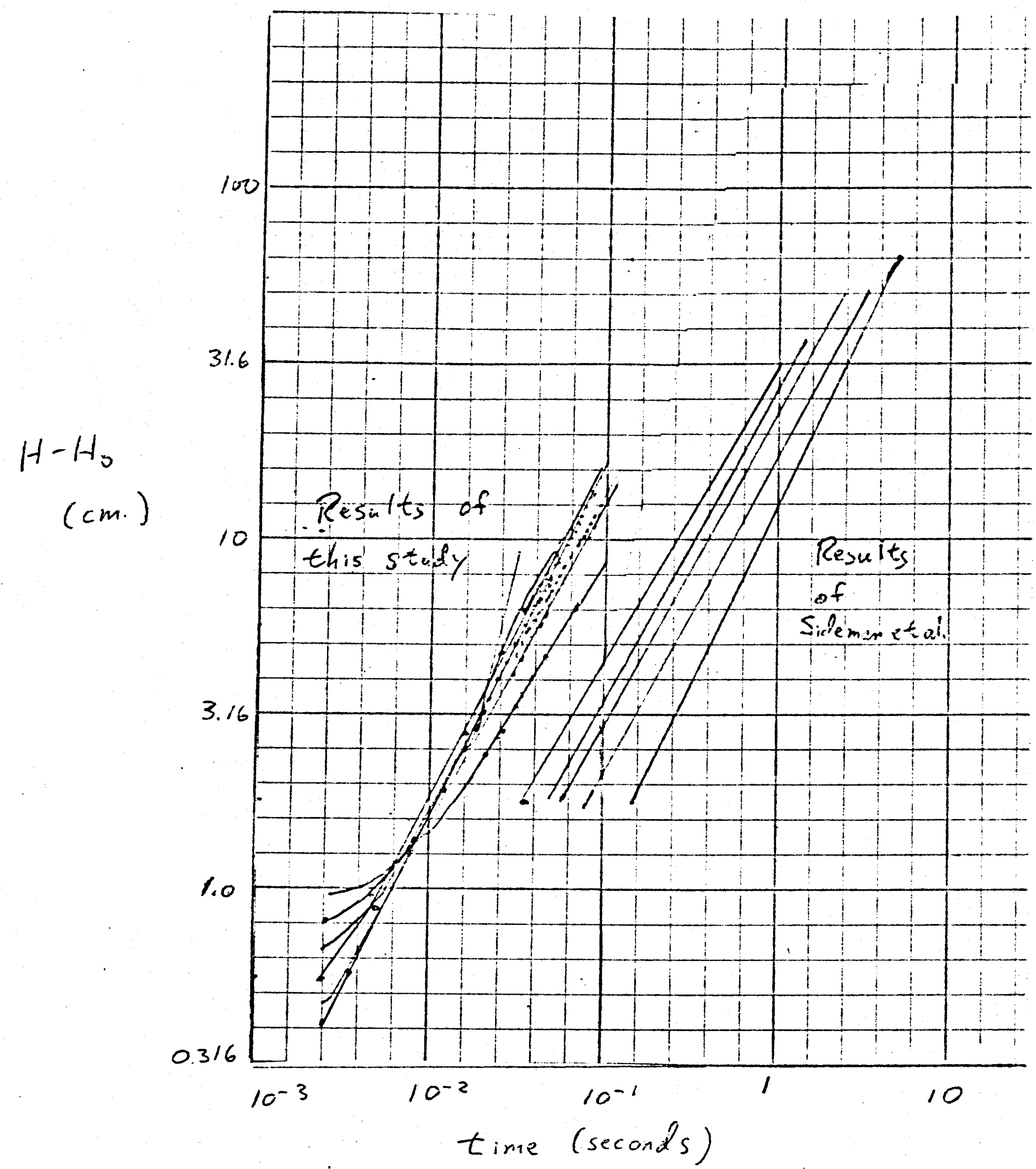
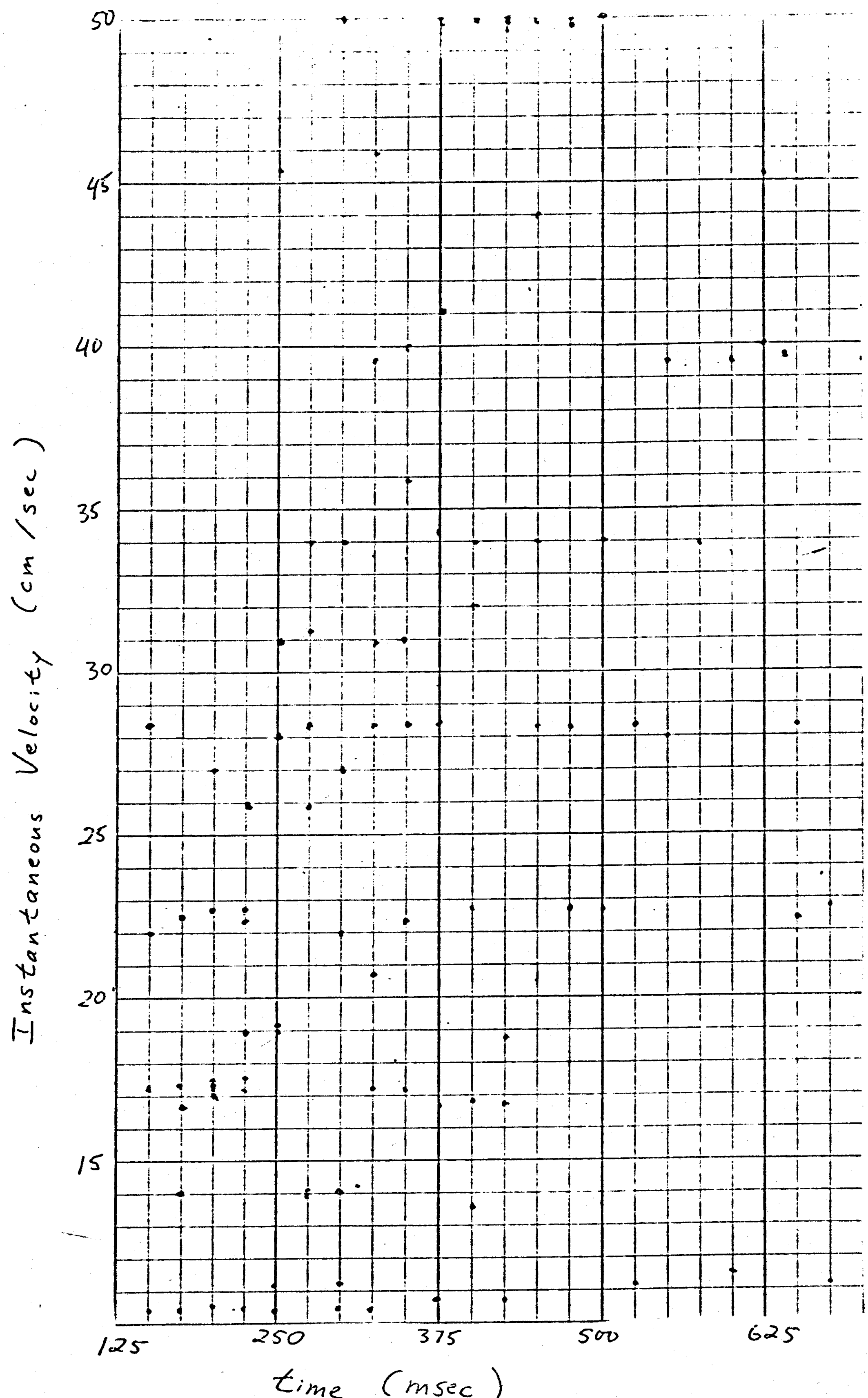

H - H₀
(cm.)
100
31.6
10
3.16
1.0
0.316
10⁻³
10⁻²
10⁻¹
1
10
time (seconds)
Results of this study
Results of Sideman et al.

Figure 5



50
45
40
35
30
25
20
15
Instantaneous Velocity (cm/sec)
125
250
375
500
625
time (msec)

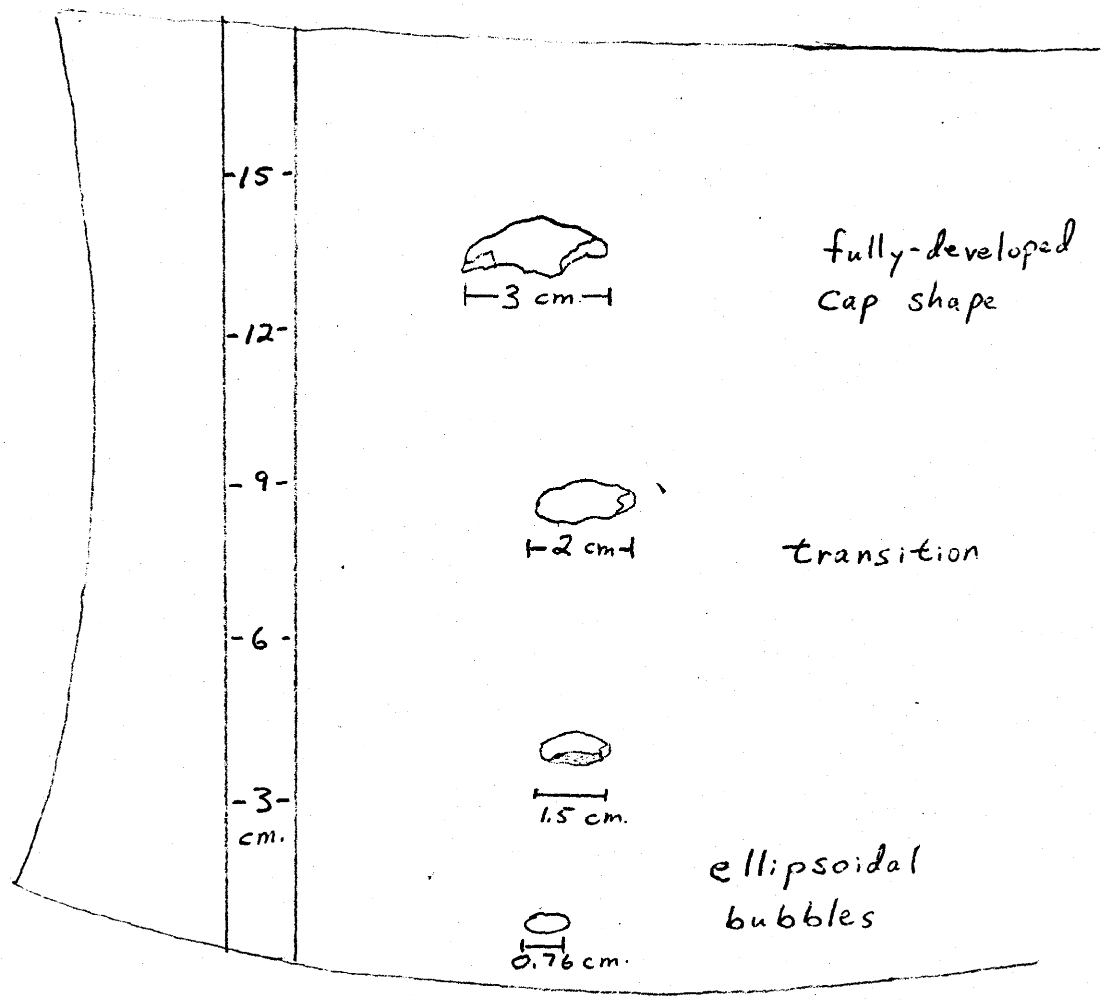
Figure 6

Velocity versus bubble diameter is a parameter which should be theoretically explainable. Simpson, Beggs and Nazir (3), using an apparatus with butane and brine, achieved very excellent results with such a correlation. However, data in this study show the bubble behavior to be much more random. This randomness could be attributable to some of these factors:

1. The bubbles were sent off in a burst, not as single bubbles, so drafting effects will be present.
2. Data was taken at very high speed, so short-lived phenomena would have significant effects.
3. Drops did not always travel vertically, so a false change in size would be recorded.

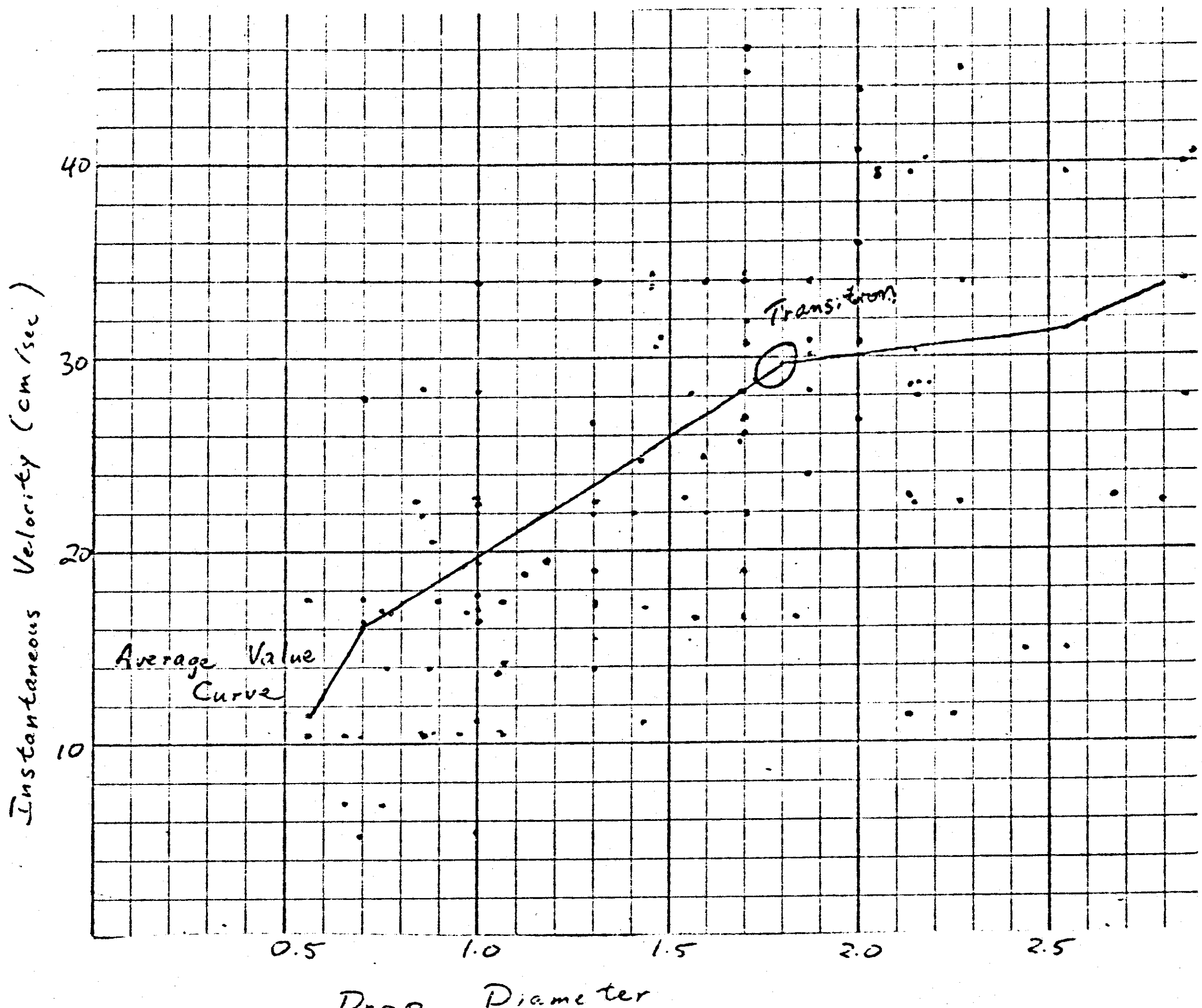
Since the elapsed time of the photographic runs was so short, it can be assumed that flow rate, initial drop size, and water temperature conditions remained constant. The entire cylinder of water was at a uniform temperature, at least as measured by the thermocouples. The graph of drop velocity versus drop diameter is shown in figure 8.

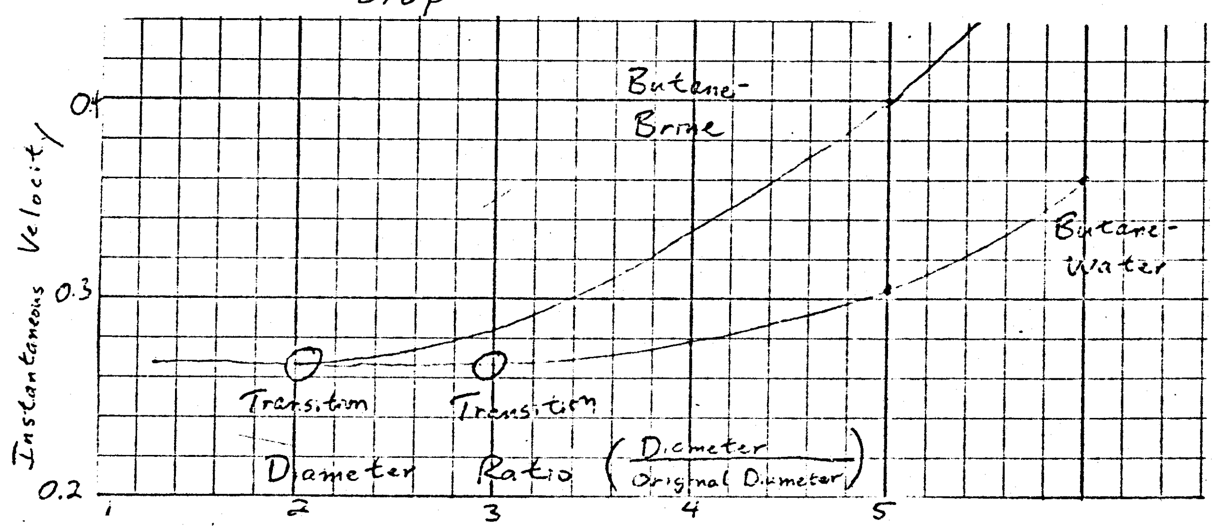
Drop shape changes dramatically as the drop evaporates. Upon injection, the drop is spherical. Soon, as evaporation commences, an ellipsoidal shape is formed. The ellipsoid oscillates and expands greatly horizontally. The lower side of the bubble is much darker than the upper part, which seems to indicate that the liquid does remain in the lower part of the bubble. This agrees with previous observations. When the horizontal diameter of the bubble becomes greater than 1.8 cm., the ellipsoid shape becomes unstable and the transition to cap shape takes place. This cap shape is retained as evaporation becomes complete and the bubble breaks the surface of the water. Typical activity in the chamber is shown in Figure 7.



Bubble Development

Figure 7





Results of Simpson et al.

V. Conclusions and Recommendations

High speed photography does give good results for this kind of experiment. The higher speeds used did show up more anamalous activity than did earlier work. This anamalous activity (random velocity peaks, apparent bubble shrinkage at some points), can partly be attributed to error, however much of it seems to come from interactions between bubbles. The drafting of one bubble to its predecessor is a significant factor in changing the velocity of the lower drop. The upper drop, which is usually larger, and hence moving at a higher rate of speed, greatly increases the speed of the lower bubble above the speed it would have if it were alone. 2 cm. seems to be the critical length between bubbles for significant drafting. If two bubbles are 2 cm. or closer, it is quite likely that the two will move together and coalesce. Still, there appears to be some drafting along the entire process for all bubbles.

Freon-113 does not appear to be the ideal working fluid for experiments of this type. The extreme density of this substance in the liquid phase causes operating problems with the apparatus. The flow of freon along the bottom of the separation plate creates random drops which get recorded. Freon also causes pump problems.

The velocity of a drop with respect to time appears to be a smooth function, with little dependance on the drop size and shape. However, there is some evidence of a transition with shape in the relation of drop velocity and size. See Figure 8. At the drop size where the transition to cap shape occurs (about 1.8 cm. diameter) there is a change in the velocity curve. This relationship is not well documented in this study as drafting and change in apparent size with radial displacement were important factors. If it is legitimate to average these effects out then there is an obvious transition.

For further investigation of bubble behavior in direct-contact boiling, I would recommend the use of different working fluids, changing to a fluid with a density more nearly that of water. Continued use of very high speed photography is warranted, as the data obtained is very precise. Drafting is an interesting effect, so future studies should use groups of drops, even steady state if flow rates can be well enough controlled. This should give more practical results than earlier single drop experiments.

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