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DIELECTROPHORETIC BAFFLING TO CONTROL VAPOR INGESTION IN WEIGHTLESSNESS

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16. Abstract

An experimental program was conducted in the Lewis Research Center's 2.2-Second Zero Gravity Facility to observe the effect of dielectrophoretic baffling on the vapor ingestion phenomenon. The study was conducted with flat-bottom right-circular cylindrical tanks in both normal gravity and weightlessness. Dielectrophoretic baffling had an insignificant effect on the vapor ingestion phenomenon in normal gravity. In weightlessness, the minimum liquid height with dielectrophoretic baffling was always smaller than the critical height without dielectrophoretic baffling. The use of dielectrophoretic baffling in weightlessness also increased the amount of liquid expelled before vapor ingestion. Effects of the electric fields associated with various electrode configurations are also discussed.

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SUMMARY

An experimental program was conducted to determine the feasibility, and to evaluate the merits, of dielectrophoretic baffling to control vapor ingestion during the draining of liquids in a weightless environment. The study was conducted with flat-bottom, right-circular, cylindrical tanks with dielectrophoretic baffling and mechanical baffling in both normal gravity and weightlessness. The weightless tests were conducted in the Lewis Research Center's 2.2-Second Zero Gravity Facility. A high voltage, as much as 27.5 kilovolts, applied to a pair of electrodes inside the test tanks produced the dielectrophoretic baffling effect. The mechanical baffling effect was produced by the same electrodes but with no applied voltage. A total of five different electrode configurations were tested. The test liquids were carbon tetrachloride and trichlorotrifluoroethane.

The test tanks were 4 and 8 centimeters in diameter and were fitted with cylindrical outlets concentric to the tank axis and equal to either one-tenth or one-twentieth of the respective tank diameters. Both the dielectrophoretic baffling and the associated mechanical baffling had an insignificant effect on vapor ingestion in normal gravity. In weightlessness, the minimum liquid height, defined as the lowest point on the liquid-vapor interface at the incipience of vapor ingestion, was measured. In the presence of dielectrophoretic baffling, this height was always smaller than the critical height without dielectrophoretic baffling. In weightlessness, the use of dielectrophoretic baffling also increased the amount of liquid expelled before vapor ingestion. The electrode configuration of a pair of parallel screens, which produced the largest region and the most uniform electric field above the tank outlet, was the most effective in increasing the amount of liquid expelled.

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INTRODUCTION

The NASA Lewis Research Center is currently investigating the fluid dynamic problems associated with the in-orbit transfer of liquids between tanker and receiver vehicles. Of significant importance to achieving a successful transfer is the minimization of the residual propellant in the tanker vehicle. Studies conducted to date in a zero-gravity (or weightless) environment (refs. 1 to 5) indicate that severe distortion of the liquid-vapor interface can occur during liquid outflow, resulting in high residuals at the time that vapor enters the tank outlet. It was established that the residuals could be reduced by pumping at low rates or by incorporating mechanical baffles near the tank outlet to delay the entrance of vapor into the tank outlet line. However, neither of these two methods of reducing residuals is completely satisfactory. Pumping at low velocities will increase the total time required to complete the transfer, and the baffling of the outlet will add a weight penalty to the overall system.

Another possible method of improving the overall in-orbit transfer process is dielectrophoretic baffling near the tank outlet to delay the ingestion of vapor into the outlet. Dielectrophoretic baffling should have the effect of stabilizing the liquid-vapor interface and thereby increasing the overall efficiency of the transfer process by impeding the entrance of vapor into the outlet line and thus reducing the residuals. References 6 to 10 present various aspects of this problem. However, at the present time, no zero-gravity data exist which permit the evaluation of the effectiveness of such a baffling technique.

This report presents the results of a study of the effect of dielectrophoretic baffling on vapor ingestion in both normal-gravity and weightless environments. The tests were conducted at the Lewis Research Center's 2.2-Second Zero Gravity Facility. The experimental containers were flat-bottom, right-circular, cylindrical tanks 4 and 8 centimeters in diameter. The bases of the tanks were fitted with cylindrical outlets that were concentric to the tank axis and equal to either one-tenth or one-twentieth of the respective tank diameters. The bases were also fitted with electrodes to which a high voltage was applied in order to produce the dielectrophoretic baffling. A total of five different electrode configurations were tested.

SYMBOLS

E electric field, V/cm

Fr Froude number, $Fr = Q_o^2/gR^5$

f arbitrary function of applied voltage

g acceleration due to gravity, 980 cm/sec^2

g_a ambient acceleration, cm/sec^2

h_{cr} critical height, cm

h'_{cr} critical height with electric field, cm

h_f final liquid height, cm

h_i initial liquid height, cm

h_{min} minimum liquid height, cm

h_{vi} vapor ingestion height, cm

K dielectric constant, $K = \epsilon/\epsilon_o$

N_e electric field number, $N_e = \dfrac{(\epsilon - \epsilon_o)E^2}{2\rho g_a h_{cr}}$

Q_o outflow rate, cm^3/sec

R tank radius, cm

R_F residual fraction

r_o outlet radius, cm

V_F volume change fraction, $V_F = (V_i - V_f)/V_i$

V_f final volume, cm^3

V_i initial volume, cm^3

V_o outflow velocity, cm/sec

v potential difference (applied voltage), volts

We Weber number, $We = Q_o^2/\beta R^3$

β specific surface tension, σ/ρ, cm^3/sec^2

ϵ electrical permittivity of test liquid, farad/cm

ϵ_o electrical permittivity of free space, 8.85×10^{-14} farad/cm

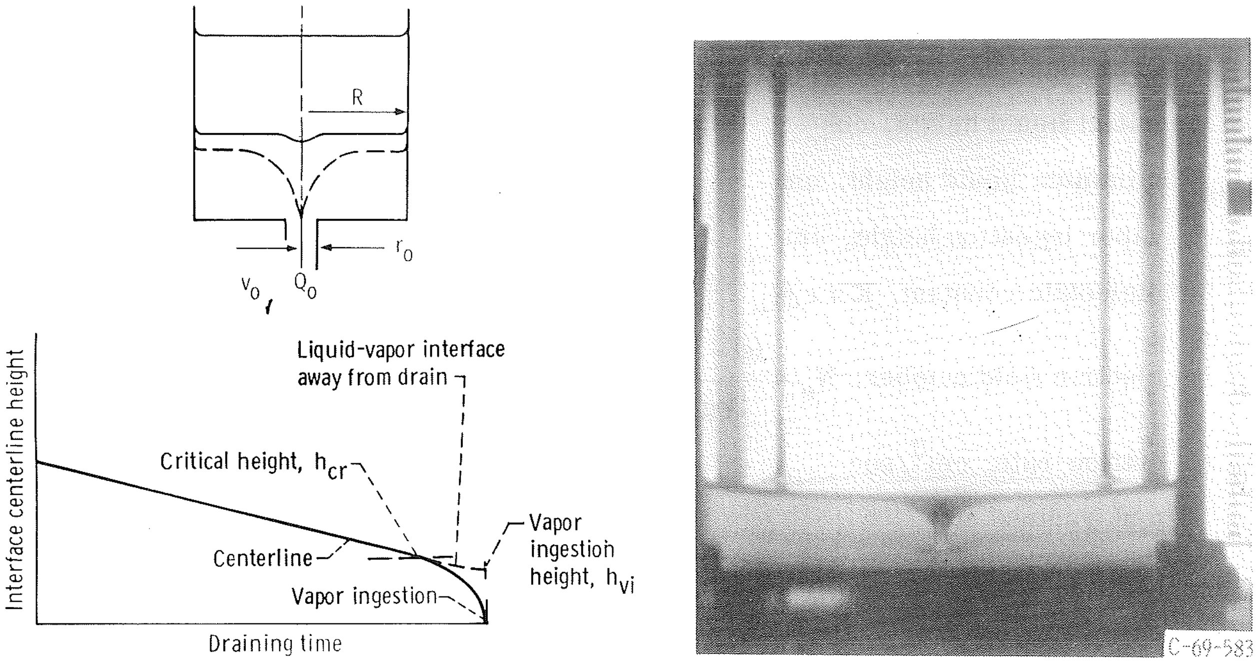
μ absolute viscosity, centipoise

ρ density, g/cm^3

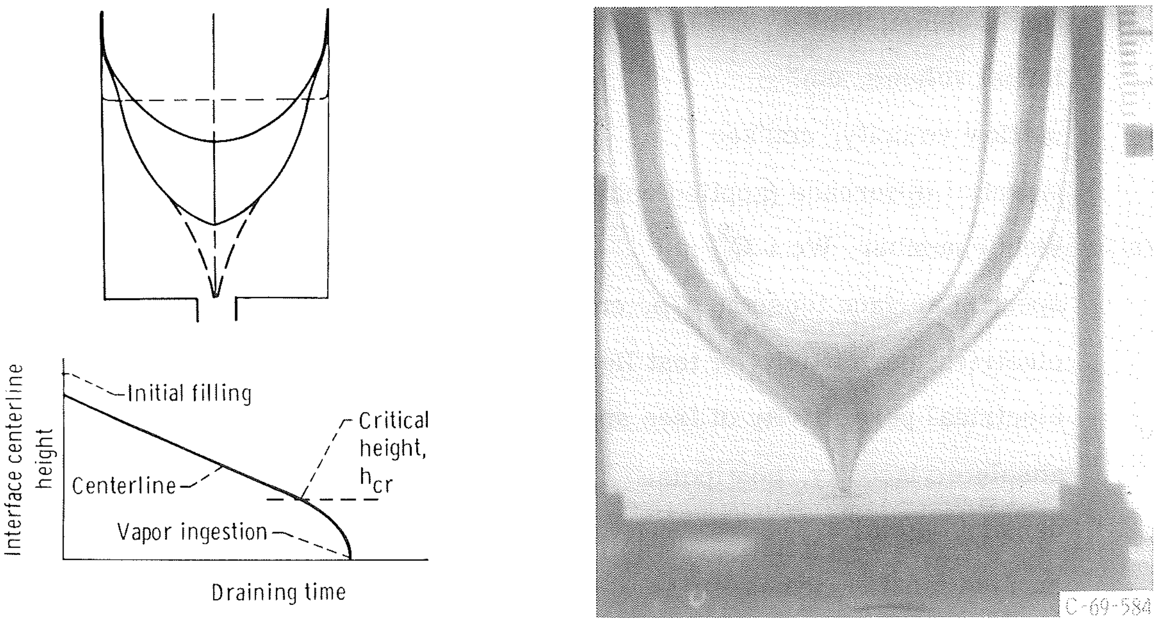
σ surface tension, dynes/cm

BACKGROUND

During draining at a constant rate from a partially filled tank, the liquid-vapor interface moves at a constant velocity until the time at which the center of the interface is



(a) Normal gravity.



(b) Weightlessness.

Figure 1. - Vapor ingestion in cylindrical containers with no outlet port baffling.

suddenly drawn toward the outlet. At this time, a dip in the liquid-vapor interface is formed and rapidly accelerates toward the outlet, followed quickly by the ingestion of vapor into the outlet line. This behavior was described in detail in reference 4 and is illustrated for both normal gravity and weightlessness in figure 1. The displacement-time graphs show the interface height as a function of draining time, while the sketches indicate the position and shape of the interface at various instances of time. The photographs show the instant of vapor ingestion.

In normal gravity (fig. 1(a)), the interface away from the drain is essentially flat even at the time of vapor ingestion. The displacement-time graph shows the constant draining velocity followed by the rapid acceleration of the interface centerline towards the outlet. The vapor ingestion height is defined as the flat interface height away from the drain at the time of vapor ingestion into the outlet. The analysis of reference 10 predicts that the vapor ingestion height in normal gravity is a function of the Froude number (the ratio of inertia to gravity forces). Both the experimental data of reference 10 and the data presented by Abdalla and Berenyi in reference 4 substantiate the correlation of vapor ingestion height with the outflow Froude number quite well. It can be concluded from the literature that the vapor ingestion phenomenon of low-viscosity liquids in normal gravity is fairly well understood.

The draining phenomenon in weightlessness, as shown by the displacement-time graph of figure 1(b), is similar to that in normal gravity. During draining, the interface on the tank centerline moves at a constant velocity until incipience of vapor ingestion and then accelerates into the outlet. Because the liquid-vapor interface is highly curved in weightlessness, the normal-gravity vapor ingestion height, which was based on a flat interface, cannot be used. The vapor ingestion height that was used in the weightless tests was based on the centerline height of the liquid-vapor interface at the incipience of vapor ingestion and is called the critical height. The experimental data of reference 4 correlate this critical height with the outflow Weber number quite well. A study (ref. 11) was conducted to test the effect of mechanical baffles on liquid residuals. In that study, the mechanical baffles were shown to be of some help, but they still resulted in high liquid residuals (as was the case with no baffles) at the time of vapor ingestion.

This present study, then, examines the effectiveness of an electric field in the tank to delay the time of vapor ingestion and thereby decrease the amount of liquid remaining in a tank after outflow in a weightless environment. Detailed results are given for one particular electrode configuration, and some limited data are included on various other electrode geometries.

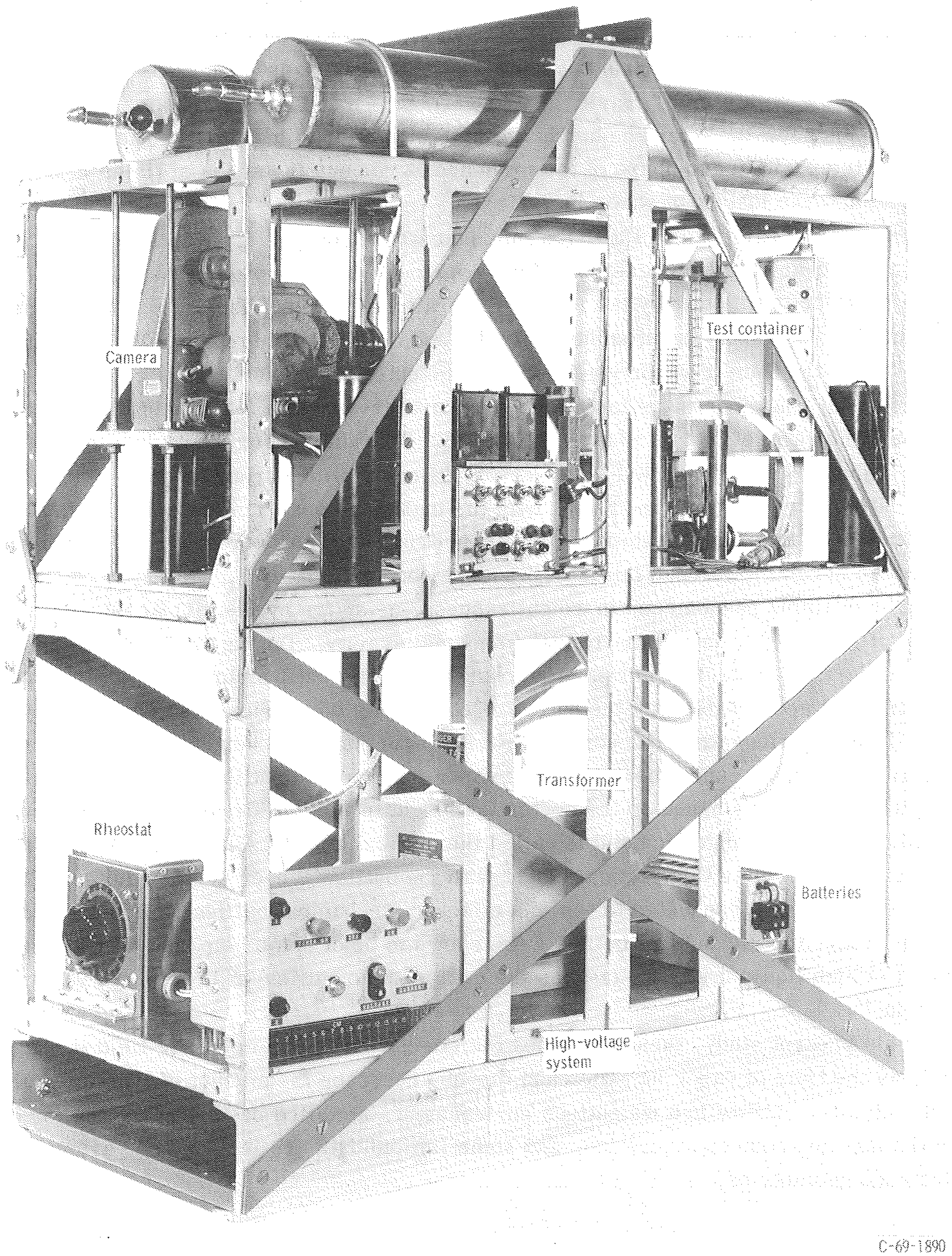


Figure 2. - Experiment package.

APPARATUS AND PROCEDURE

Test Facility

The experimental data for this study were obtained in the Lewis Research Center's 2.2-Second Zero Gravity Facility. A detailed description of the facility and its mode of operation may be found in reference 4. It consists basically of a drop tower in which experiments are conducted with the use of recoverable, freely falling experiment packages. A 2.2-second period of weightlessness is obtained in this facility.

Experiment Systems

The experiment package, shown in figure 2, is the same unit used in reference 4, with the addition of the high-voltage system. It consisted of an aluminum frame on

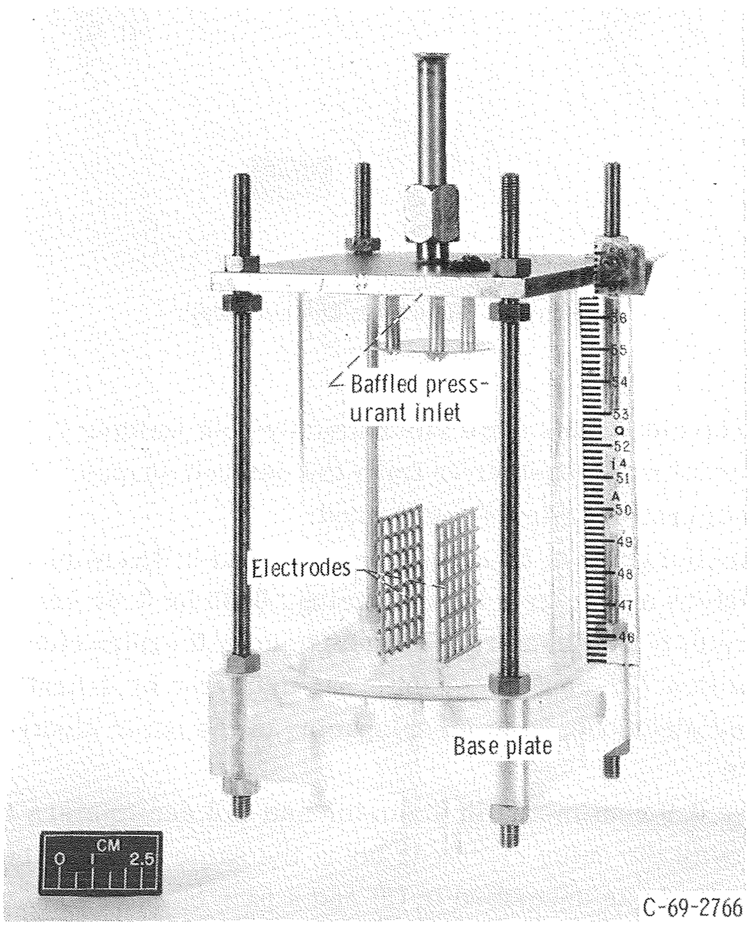


Figure 3. - Test container.

which were mounted the experiment tank, a pressurization and pumping system, a high-speed motion-picture camera, a high-voltage power supply, and auxiliary equipment such as batteries, timers, and a digital clock. This was a completely self-contained unit with no external connections during the weightless test drops.

Test containers. - The test containers, flat-bottomed, right-circular cylinders 4 and 8 centimeters in diameter, were also the same ones used in reference 4 but with modified outlet bases. As shown in figures 3 and 4, the outlet bases, machined from acrylic plastic, were fitted with O-ring seals and were used to support the electrodes. The outlet lines were concentric with the tank axes and equal to one-tenth or one-twentieth of the respective tank diameters.

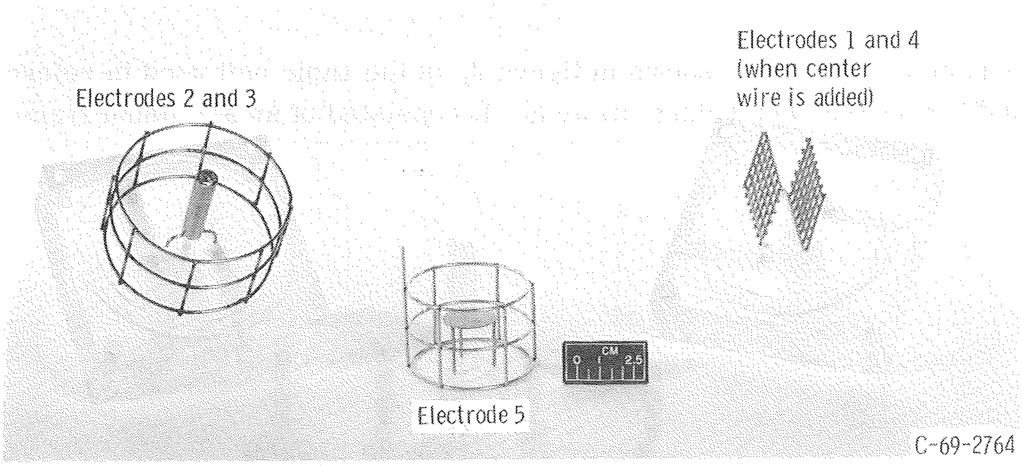


Figure 4. - Base plates with electrodes.

Electrodes. - The electrodes were fabricated by spot welding 0.16-centimeter-diameter stainless-steel wire together to form the desired shapes. A total of five different electrode configurations (fig. 4) were used:

(1) A pair of parallel grids 4.5 centimeters high and 3.2 centimeters wide placed 1.7 centimeters apart; grid mesh spacing, 0.65 by 0.65 centimeter

(2) A single wire 0.16 centimeter in diameter and 5.5 centimeters high for the inner electrode with a 7.3-centimeter-internal-diameter by 4-centimeter-high grid for the outer electrode; grid mesh spacing of the outer electrode, 1.6 by 2.8 centimeters

(3) A single wire 0.9 centimeter in diameter and 5.5 centimeters high for the inner electrode, with the outer electrode being the same as described in (2)

(4) An inner electrode as described in (2) and a pair of outer electrodes as described in (1)

(5) A circular disk 0.1 centimeter thick and 2.5 centimeters in diameter placed 0.8 centimeter above the outlet hole for the center electrode with a 5.2-centimeter-internal-diameter by 4-centimeter-high grid for the outer electrode; grid mesh spacing of the outer electrode, 1.7 by 2.7 centimeters

All electrode configurations were designed to have a minimal amount of blockage on the liquid flow.

High-voltage supply. - The high-voltage supply was designed to be simple, light-weight, compact, and sturdy enough to withstand numerous test drops with an average deceleration of 15 g's. A schematic of the high-voltage supply is given by figure 5. The high-voltage frequency of 400 hertz was chosen in order to prevent the accumulation of free charges on the liquid-vapor interface; that is, the frequency was much greater than the reciprocal of the relaxation times of the test liquids.

Test liquids. - The two tests liquids chosen for this study were carbon tetrachloride

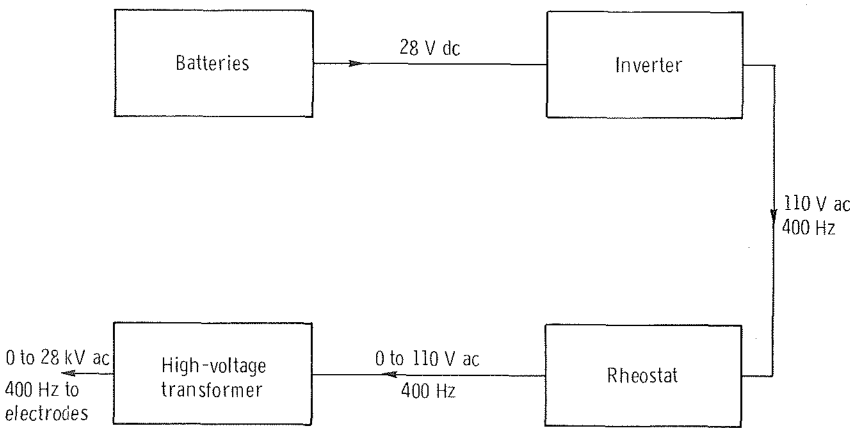


Figure 5. - Schematic diagram of high-voltage system.

TABLE I. - PROPERTIES OF TEST LIQUIDS

[Values correspond to 20° C; static contact angle with cast acrylic plastic in air, 0°.]

Property	Carbon tetrachloride	Trichloro-trifluoroethane
Surface tension, σ, dynes/cm	26.9	18.6
Density, ρ, g/cm^3	1.59	1.58
Specific surface tension, β, cm^3/sec^2	16.9	11.75
Viscosity, μ, cP	.97	.70
Dielectric constant, K	2.2	2.4

and trichlorotrifluoroethane. The physical properties of these two test liquids pertinent to this study, as obtained from standard references, are given in table I. The liquids were analytic reagent grade and precision cleaning grade, respectively. The liquids had a static contact angle on the tank wall of nearly zero degrees. To improve the quality of the photographic data, a small amount of dye was added to the test liquids. The addition of this dye had no measurable effect on the surface tension, density, and viscosity of the test liquids.

Test Procedure

The container was prepared and tests were conducted in a manner described in detail in reference 4. After proper cleaning of the test container, it was installed in the experiment package and filled with liquid to the desired level. The tank was then pressurized, and the liquid was drained by opening a solenoid valve downstream from the tank outlet. The motion of the liquid-vapor interface during outflow in normal gravity was photographically recorded to obtain a flow-rate-against-pressure calibration. From this, the desired flow rate in weightlessness could be obtained by setting the precalibrated pressure. Unlike the tests of reference 4, however, in this study it was necessary to obtain data both with and without the electric field. Data reduction, however, was accomplished in the same manner as described in reference 4; that is, by obtaining time-displacement plots of the centerpoint of the liquid-vapor interface. From these plots, data could then be obtained for vapor ingestion heights and draining times.

RESULTS AND DISCUSSION

Each data point for this study required four test runs. Tests at the same flow rate were performed in normal and zero gravity both with and without the applied high voltage. A complete set of data was obtained with the set of parallel-grid electrodes (fig. 3). The other electrode configurations were superficially examined for their effect on the interface shape during draining and on the amount of liquid residuals remaining in the tank.

Vapor Ingestion in Normal Gravity

No measurable effect on the vapor ingestion phenomenon as a result of the baffling was observed in normal gravity either with or without the applied high voltage (23.5 kV). The data were compared with the equation given in reference 4:

$$\frac{h_{vi}}{R} = 0.679(Fr)^{0.2} \quad (1)$$

As noted in reference 4, this equation is limited to liquids having low velocities and for $r_o/h_{vi} << 1.0$. The experimental results with the electrode grids both with and without the applied high voltage agree favorably with the empirical equation (1).

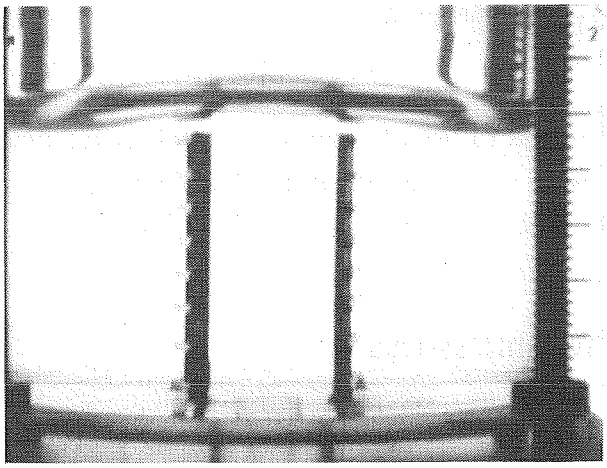
Vapor Ingestion in Weightlessness

Experimental data were obtained in weightlessness for the same range of variables as in normal gravity. Tests were conducted both with and without the applied high voltage.

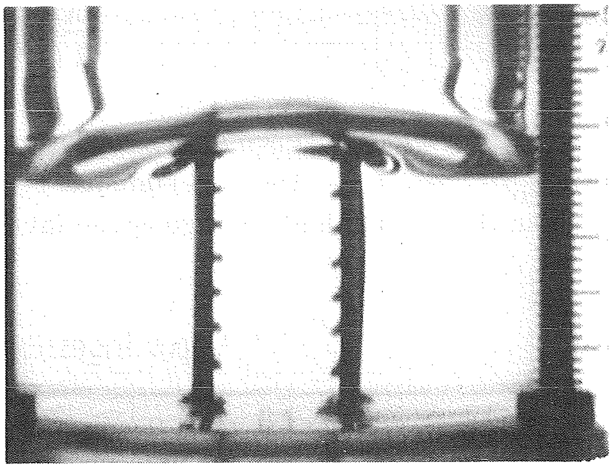
Effect of an electric field on initial interface shape. - In order to obtain a better understanding of the effect of dielectrophoretic baffling on the vapor ingestion phenomenon, the effect of the electric field on the initial interface shape in weightlessness was first investigated. The electric field set up by the electrodes inside the tank causes the liquid-vapor interface to assume various shapes. These shapes are functions of liquid properties, electrode shapes, applied voltages, and liquid levels (ref. 9). The investigation consisted of observing the formation of the interface shapes in weightlessness for different fillings of trichlorotrifluoroethane in an 8-centimeter-diameter tank fitted with parallel-grid electrodes at a potential of 23.5 kilovolts. These tests were then compared with the same tank-liquid configuration at 0 volts.

The results of this study are presented in figure 6. Even though the highest concentration of the electric field is below the interface, the fringe electric field has enough influence to flatten the interface. Figures 6(a) and (b) show that for liquid heights slightly greater than the electrode height, the interface is slightly convex. For liquid heights less than the electrode height, the space between the electrodes is filled with liquid and also some liquid is supported above the electrodes (figs. 6(c) and (d)). From figure 6(d), it is seen that the electrical pressure is strong enough to hold 0.4 centimeter of liquid above the top of the electrodes as well as 3.0 centimeters of liquid between the electrodes. Also, from figure 6(e), which gives the side view of the electrodes, it can be seen that the electrical pressure between electrodes is similar in the horizontal direction to that in the vertical direction. Note the liquid supported on the side of the electrodes by the fringe electric field. For comparison, note in figure 6(f) that with zero applied voltage no liquid rise occurs between the grids.

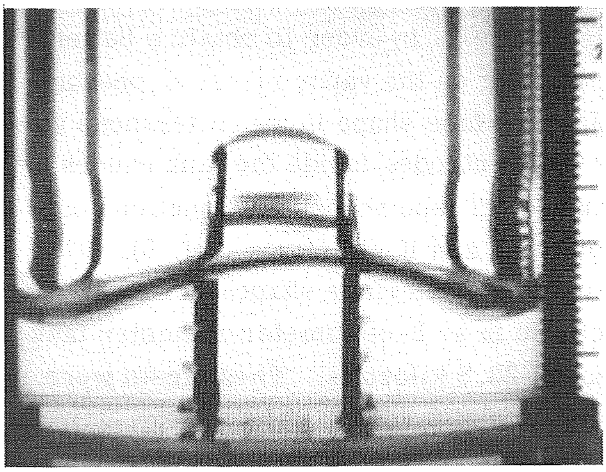
Generally, from all the data films with the various electrode configurations tested, it was noted that the electric field always caused the interface to be flatter than the no-



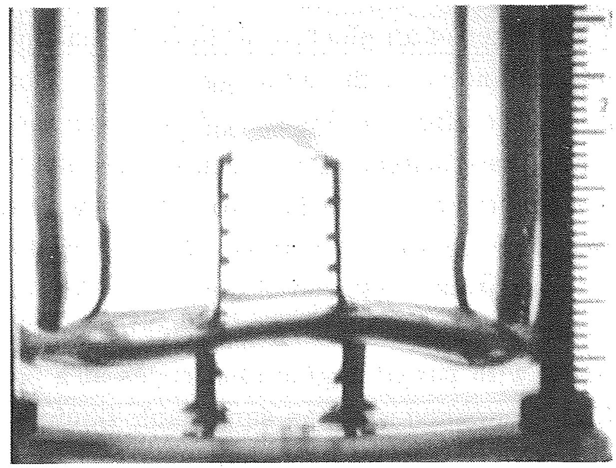
(a) Initial liquid height, 6 centimeters; voltage, 23.5 kilovolts.



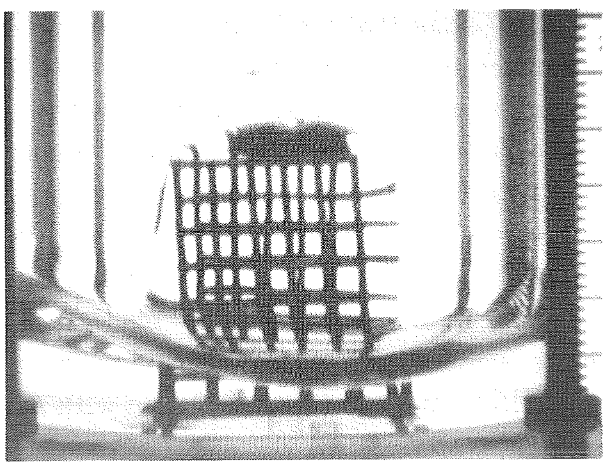
(b) Initial liquid height, 4.5 centimeters; voltage 23.5 kilovolts.



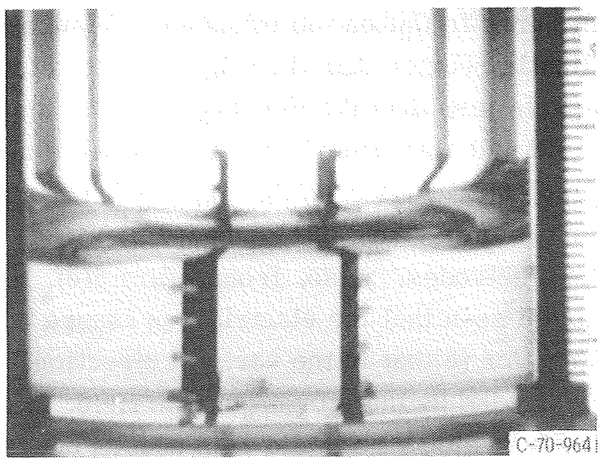
(c) Initial liquid height, 3.0 centimeters; voltage, 23.5 kilovolts.



(d) Initial liquid height, 2.0 centimeters; voltage, 23.5 kilovolts.



(e) Initial liquid height, 2.0 centimeters; voltage, 23.5 kilovolts (side view of grids shown in (d)).



(f) Initial liquid height, 3.0 centimeters; voltage, 0.

Figure 6. - Effect of electric field on liquid-vapor interface as function of filling level.

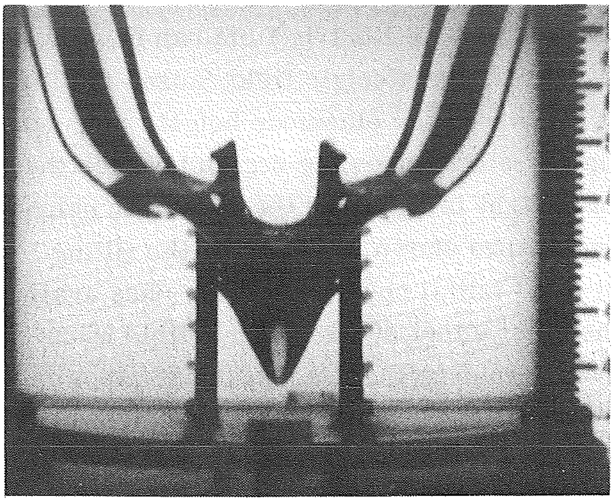
electric-field case. Therefore, it can be concluded that the electric field can have a large effect on the liquid interface in two ways. First, the electric field causes the interface to be flatter when the liquid height is greater than the electrode height. Second, in the case of parallel-grid electrodes, the electric field causes the region between the electrodes to be filled with liquid when the liquid height is less than the electrode height.

After examining the various initial interface shapes shown in figure 6, the filling level shown in figure 6(a) was deemed the most ideal initial condition (of the ones available) for the outflow test. This shape shows the least effect of the electric field when compared to a "no-field" zero-gravity liquid-vapor interface. Also, all past vapor ingestion studies were conducted with higher initial filling levels. Therefore, this initial condition (fig. 6(a)) makes comparisons with the existing studies more meaningful than any of the others shown in figure 6. However, in general, the time required for the interface to reach this static equilibrium configuration was too long to allow an outflow test to follow in the 2.2 seconds available. Therefore, the initiation of outflow was implemented at the time when the interface centerline reached a low point in its formation cycle. At this time, the interface centerline velocity was zero and the interface shape was slightly more concave than that shown in figure 6(a). This procedure was similar to that of reference 4.

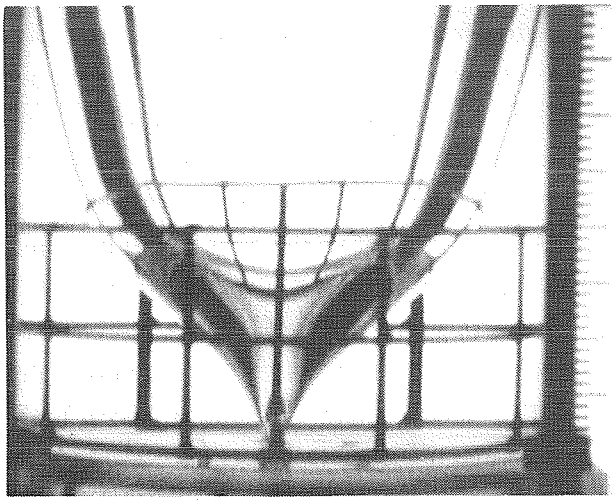
Effect of electrodes with no voltage on vapor ingestion. - For all draining tests (both with and without applied voltage), the tanks were filled to a height of 6 centimeters for the tests in weightlessness. Upon entering weightlessness, the initially flat interface became curved and, as described in the preceding paragraph, outflow was initiated from this curved interface and allowed to proceed to the point of vapor ingestion. The interface in the presence of mechanical baffling (i.e., the electrodes with no voltage applied) at the time of vapor ingestion is shown in figure 7 for the various electrode shapes examined.

Representative draining curves obtained from the motion pictures and giving the interface centerline height as a function of draining time are presented in figure 8 for the 8-centimeter-diameter tank with a 0.8-centimeter-diameter outlet. In this figure, draining curves for three electrodes are compared with the no-electrode case. Each of these outflow tests was conducted at a constant flow rate from a constant initial volume; however, note that the draining time has increased with the use of any electrode. In addition to increasing this draining time, electrodes 1 and 4 have also held up the interface center point at the initiation of outflow. Both of these factors have a tendency to increase the amount of liquid that may be drained before vapor ingestion.

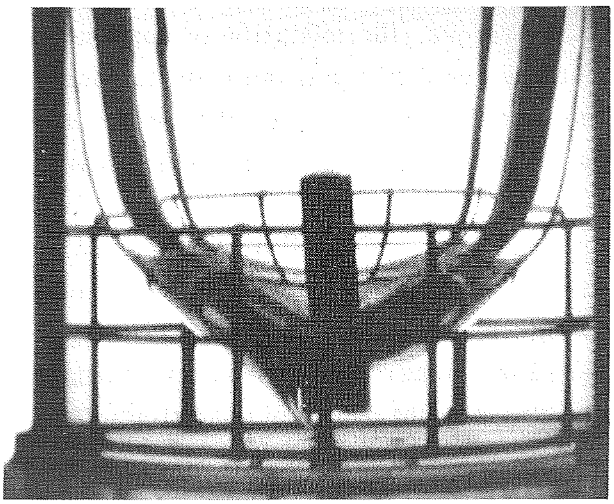
Also note that with electrode 1 the draining curve tends to be more nonlinear than with electrodes 4 and 5. One reason for this curvature in the presence of some baffles may be explained as follows: From the data film, it is seen that the liquid tends to "hang-up" between the tank wall and the electrodes; hence, in order to maintain the conservation of mass (i.e., the continuity equation for the liquid), the interface center-



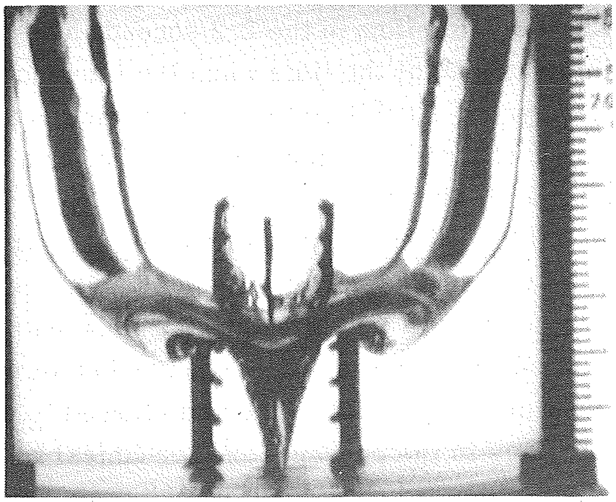
(a) Electrode 1.



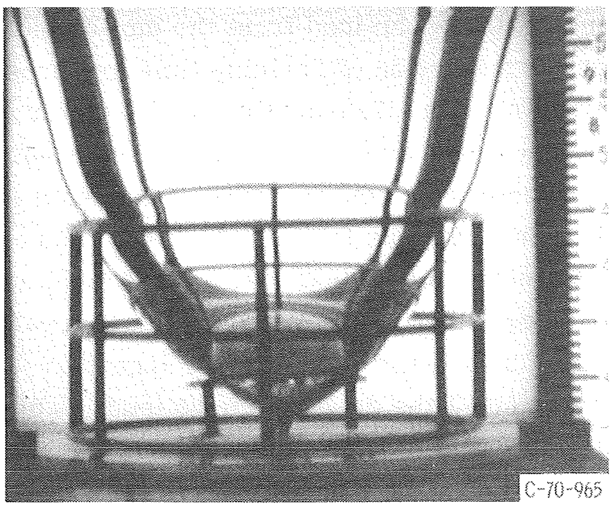
(b) Electrode 2.



(c) Electrode 3.



(d) Electrode 4.



(e) Electrode 5.

Figure 7. - Vapor ingestion in weightlessness with mechanical baffles. No applied voltage.

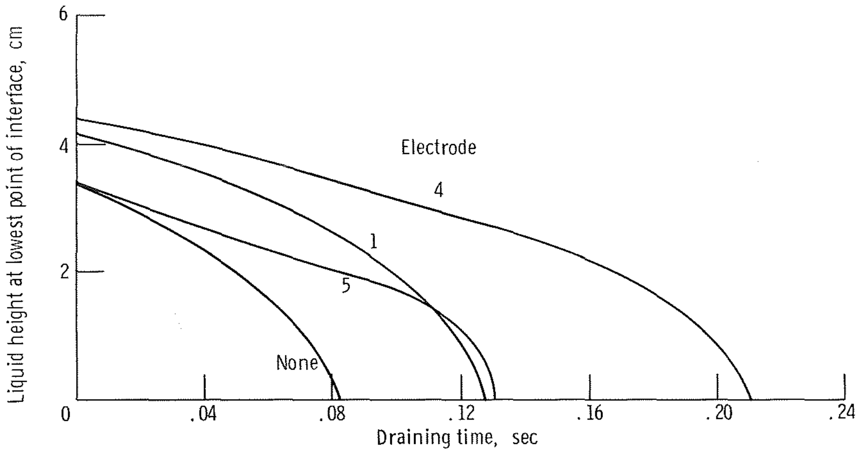


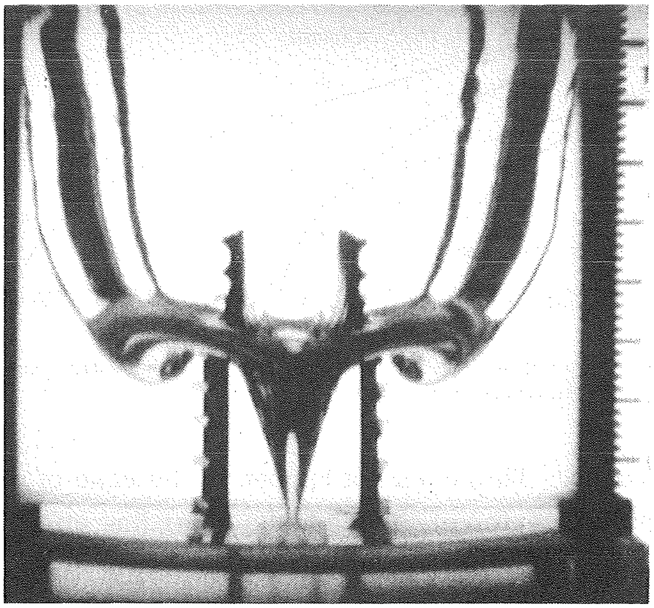
Figure 8. - Effect of electrodes on draining curves (with no applied voltage). Constant flow rate, 420 cubic centimeters per second.

line velocity had to increase. This does not happen in the case of electrodes 4 and 5 because with these designs the center electrode has a retarding effect on the centerline velocity and, consequently, liquid is drawn in from the areas closer to the wall.

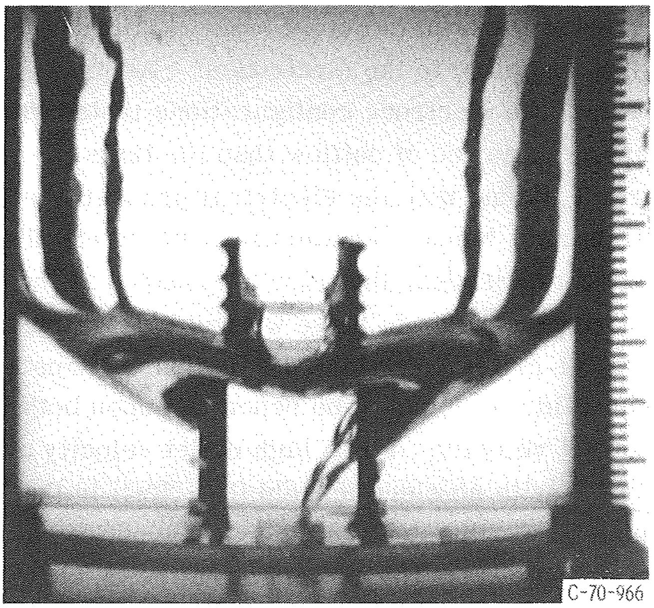
Effect of electrodes with applied voltage on vapor ingestion. - For every data point obtained with mechanical baffling (the electrodes) for a given set of parameters, one or more data points for the same set of parameters were obtained with dielectrophoretic baffling (i. e., with a voltage applied to the electrodes). As previously mentioned, the electric field associated with the electrode configurations tested always caused the interface to be less curved at the initiation of outflow than the tests in weightlessness with no field. This flatter interface, along with the electrical pressure between the electrodes, increased the draining time and, hence, the amount of liquid expelled in all cases tested. Except for the parallel-grid electrodes, the interface shapes at the time of vapor ingestion with an electric field were similar to those without an electric field (see figs. 7(b) to (d)). For the parallel-grid electrodes, the interface shape at the time of vapor ingestion with an electric field was found to be dependent upon both the magnitude of voltage applied and the outlet velocity. For a high outlet velocity and low voltage, vapor ingestion was similar to that with no electric field (fig. 7(a)) in that it occurred along the centerline of the tank (fig. 9(a)). However, for a low outlet velocity and a high voltage, vapor ingestion began away from the centerline of the tank (fig. 9(b)).

Effect of variable applied voltage. - The effect of the electric field on the interface prior to the initiation of outflow has been discussed previously. Hence, this section is concerned only with the effect on the vapor ingestion phenomenon observed when the electric field strength is increased by raising the voltage applied to the parallel grids.

For this set of tests, the outflow of trichlorotrifluoroethane from the 8-centimeter-diameter tank with the 0. 8-centimeter outlet was studied. In all cases, the initial liquid



(a) Voltage, 17 kilovolts.



(b) Voltage, 23.5 kilovolts.

Figure 9. - Vapor ingestion in presence of electric field.

height was 6 centimeters and the outlet velocity was 834 centimeters per second. A total of six different voltages ranging from 0 to 27.5 kilovolts was tested. The findings of importance from these tests are as follows: First, for voltages equal to or less than 17 kilovolts, vapor ingestion occurred along the tank axis, as shown in figure 9(a). However, for voltages greater than 17 kilovolts, vapor ingestion began away from the tank axis, as shown in figure 9(b). Second, as the electric field strength was increased, the duration of the draining time was increased, as evident from the draining curves of figure 10. Also, as in the case with mechanical baffling, the draining curves with dielectrophoretic baffling were not linear. Third, as the electric field strength was increased, the interface height at the initiation of outflow increased because the electric field caused the interface to become flatter, as previously mentioned. This is evident from the higher initial point (on fig. 10) for the higher voltages.

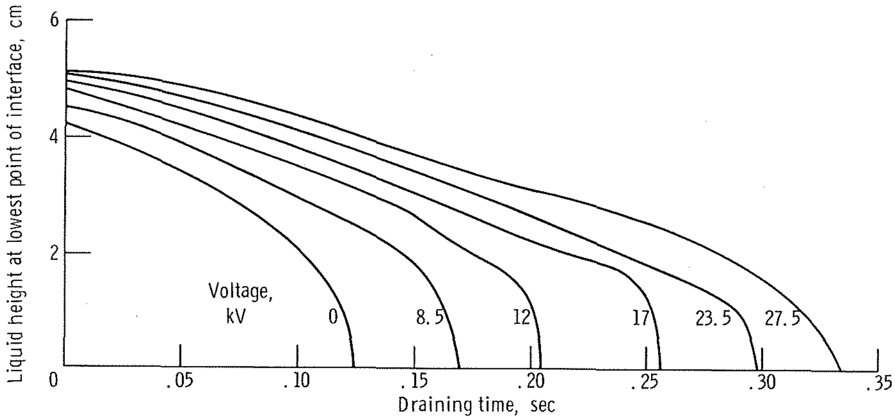


Figure 10. - Effect of applied voltage on draining curves (with parallel-grid electrodes) for a constant outflow rate.

Weber number scaling with dielectrophoresis. - A correlation with a form of the Weber number (the ratio of inertia to surface tension forces) was attempted. Because it was difficult to define the critical height accurately from the nonlinear draining curves and because in some tests vapor ingestion began away from the centerline of the tank, an accurate correlation of the experimental data with the Weber number (as presented in ref. 4) was difficult to make. The attempt that was made is presented here. Beginning with the Weber number correlation given in reference 4, the critical height (in the absence of an electric field) is given as

$$\frac{h_{cr}}{R} = 0.355\ We^{0.125} \tag{2}$$

As a result of these present studies, it has been observed that the critical height in the presence of an electric field h'_{cr} or the minimum height h_{min} is always lower than the corresponding critical height h_{cr} without the electric field. This observation leads to a modified form of equation (2) for the case of the applied electric field, as follows:

$$\frac{h'_{cr}}{R} = 0.355\ We^{0.125}(1.0 - f) \tag{3}$$

where f is an arbitrary function of the applied voltage.

A log-log plot of equation (3) assuming values of f of 0.2, 0.4, 0.6, and 0.8 gives a series of straight lines all of which are parallel to the $f = 0$ line of reference 4 (see fig. 11). The data obtained for the parallel-grid electrodes at 23.5 kilovolts are also presented in figure 11. When vapor ingestion began away from the centerline of the tank, the minimum interface height was used instead of the critical height. As this figure shows, the critical heights (or the minimum interface heights) with an electric field lie on a straight line of $f = 0.4$. The form of equation (3) is, therefore, a valid representation of the effect of the electric field.[1]

Volume change fraction. - For discussion purposes, the definitions of the volume change fraction and residual fraction are introduced. By definition, the volume change fraction is equal to the initial volume minus the final volume, divided by the initial volume. The volume change fraction is related to the residual fraction defined in reference 4 as follows:

$$V_F = \frac{V_i - V_f}{V_i} = 1.0 - R_F \tag{4}$$

Values for V_F were easily calculated from the data obtained from the draining curves. With the outflow rate obtained from the normal-gravity tests and with the

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[1]Lubin and Hurwitz (ref. 10) have suggested that the function f should take the form

$$N_e = \frac{(\epsilon - \epsilon_0)E^2}{2\rho g_a h_{cr}}$$

The data presented herein for the case of zero gravity and 23.5 kV do not fit this format.

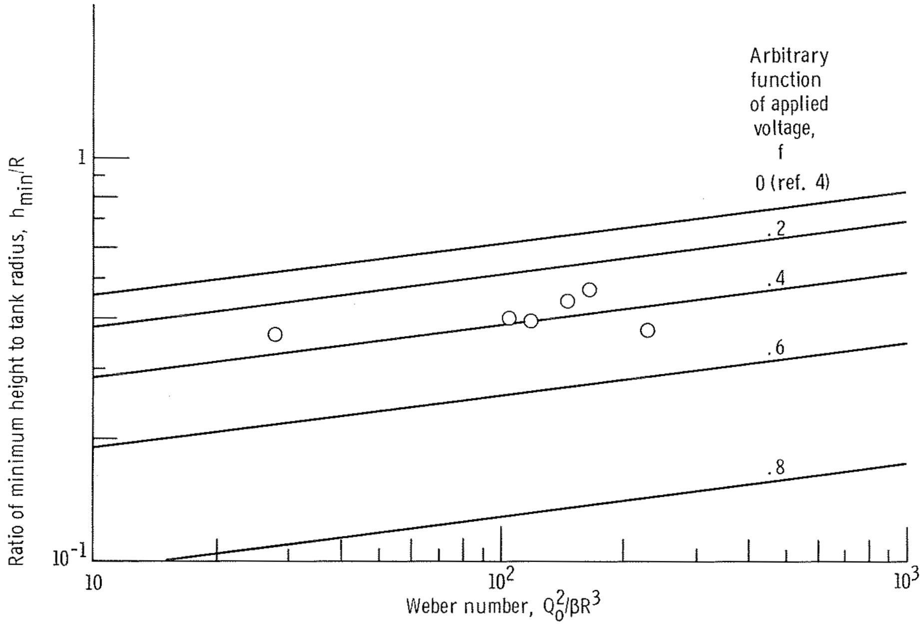

Figure 11. - Minimum height as function of Weber number with dielectrophoretic baffling (with parallel-grid electrodes).

draining time in weightlessness, the amount of liquid expelled (the volume change) was given as the product of the outflow rate and the draining time in weightlessness. (The final volume may then be obtained by subtracting the volume change from the known initial volume.) The volume change fraction provides a convenient means of evaluating the effectiveness of baffling. For example, with the data obtained from this program for the 8-centimeter-diameter tanks fitted with parallel-grid electrodes, the volume change fraction with dielectrophoretic baffling and with mechanical baffling is given in figure 12 as a function of the Weber number. Data obtained with no baffling resulted

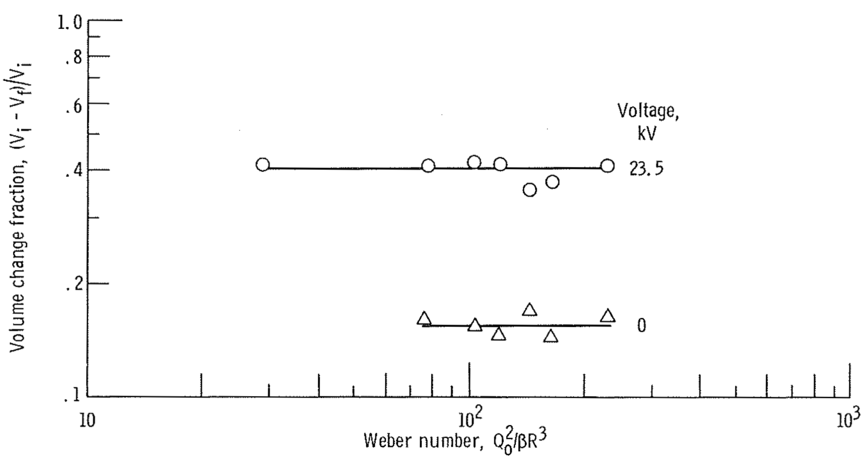

Figure 12. - Volume change fraction as function of Weber number with mechanical and dielectrophoretic baffling (with parallel-grid electrode 1).

in a volume change fraction of the same order of magnitude (0. 11) as the 0-kilovolt cases. (Recall that the baffling tested had no effect on the vapor ingestion in normal gravity; and, hence, a plot of the volume change fraction as a function of the Froude number in normal gravity is not presented.)

From figure 12 it is evident that dielectrophoretic baffling is much better than mechanical baffling alone. For the range of parameters tested, dielectrophoretic baffling increased the volume change fraction approximately $2\frac{1}{2}$ times.

Effect of variable voltage on volume change fraction. - In order to observe the dependence of the amount of liquid expelled on the electric field strength, the volume change fraction was plotted as a function of the applied voltage (fig. 13). From this fig-

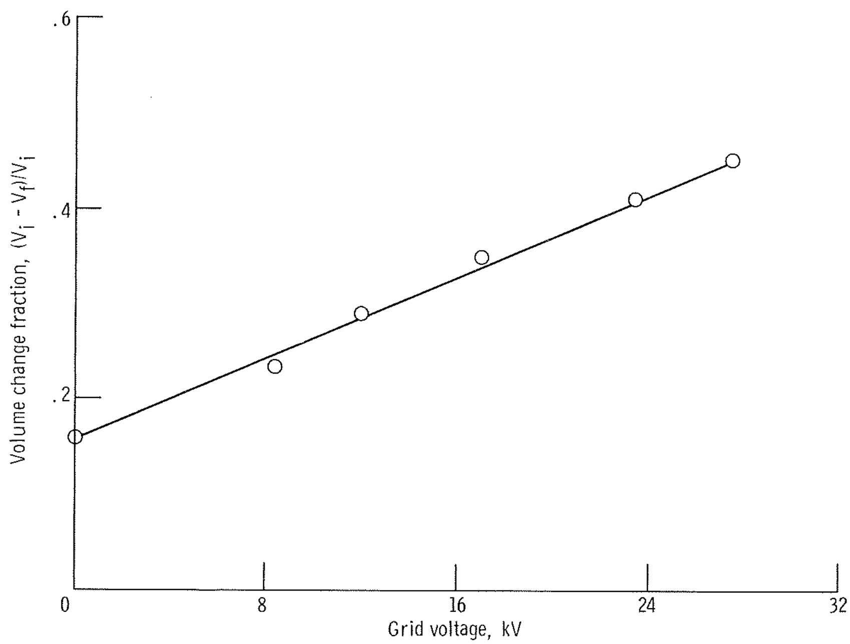

Figure 13. - Effect of grid voltage on volume change fraction (with parallel-grid electrodes).

ure the advantage of a large electric field strength is clearly established; that is, an increase in applied voltage produces an increase in the volume change fraction. In addition, it can be observed from figure 13 that, over the range tested for this electrode configuration, the volume change fraction varies linearly with the electric field and not with the second power as predicted by reference 10. Also, the dependence of the volume change fraction on the electric field was independent of whether the vapor ingestion began on the tank centerline or away from the electrode grid.

Effect of electrode configuration. - Because the dielectrophoretic baffling effect was obtained by applying a high voltage to a pair of electrodes, it is obvious that the electrode configuration is important. As previously mentioned, the electrodes acted as mechanical baffles and showed an effect on the vapor ingestion phenomenon in weightlessness. Also, it was noted that all electrode configurations tested caused the interface to be flatter prior to outflow if an applied voltage was present.

However, only the detailed results obtained with the parallel grids have been discussed so far. Hence, in this section, the effects of the remaining four electrode configurations are given. At this point, it should be stated that the parallel grids were the original design and, hence, were tested more extensively than the other four electrode configurations. The testing of the other electrode configurations was limited to obtaining their effect on the draining time in order to help establish guidelines for the design of better electrode configurations.

An unlimited number of electrode configurations are possible. However, the electrode configurations described here have been chosen to minimize two weaknesses of the parallel-grid electrodes: the occurrence of interface breakdown away from the tank axis and eventually vapor passing through the grids (fig. 9(b)), and the occurrence of vapor ingestion along the tank axis (fig. 9(a)) at low values of applied voltage and high outlet velocities.

Hence, with the purpose of overcoming these weaknesses of the parallel-grid electrodes, the design of the four electrode configurations was based on the combination of mechanical and dielectrophoretic baffling. In particular, the circular-grid concentric with the disk (fig. 4) was chosen in order to take advantage of the disk holding up the interface centerpoint. The remaining designs (i. e., a circular grid concentric with a center wire (fig. 4) and a center wire between the parallel grids) were chosen in order to take advantage of the center wire holding up the interface centerline by means of surface tension. The results obtained from testing these four electrode configurations are given in a plot of the volume change fraction as a function of the Weber number in figure 14. As shown in figure 14, the volume change fractions with the other mechanical baffles are larger than the average volume change fraction with parallel grids at zero kilovolt. However, the most significant result from figure 14 is the fact that a voltage applied to the parallel-grid electrodes resulted in a larger average volume change fraction than for the other four electrode configurations with an applied voltage.

A study of the data films revealed why these four electrode configurations did not perform as well as expected. Briefly, their faults can be explained as follows: First, the center-disk electrode inside the circular grid was too thin, which concentrated the effect of the high-strength electric field over a narrow horizontal region. Also, the disk was too low because, by the time the low point of the interface reached the region of high electric field, it was moving so fast that the inertia of the moving liquid was much larger than what the electric field could support. Second, both the wire in between the parallel-grid electrodes and that concentric with the circular grid were of such small diameter that the extent of the region of high electric field near the tank outlet was too

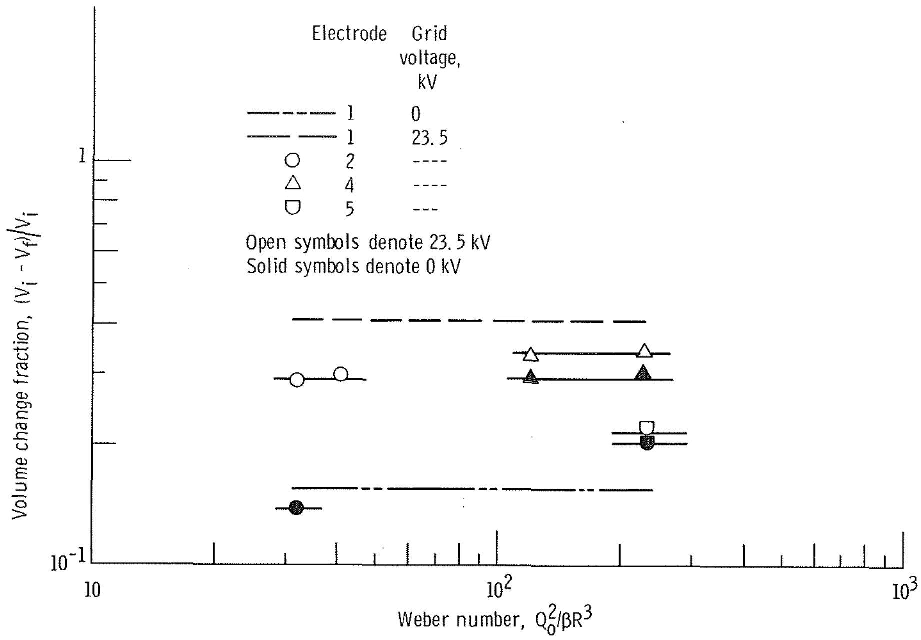

Figure 14. - Effect of electrode configuration on volume change fraction.

small. In this context, note how a larger center wire increased the volume change fraction (fig. 14). Third, the larger circular grid (which was almost the same diameter as the tank diameter) caused the electric field to extend over the entire tank cross-sectional area so that the electric field was trying to support the entire liquid interface. However, because the applied pressure was larger than the electrical pressure, vapor ingestion occurred in a relatively short draining time.

The results from other tests not shown in figure 14 are in accord with the third finding in the preceding paragraph. In these tests, trichlorotrifluoroethane was drained at 762 and 1055 centimeters per second from a 4-centimeter-diameter tank fitted with a 0.4-centimeter outlet and parallel-grid electrodes that covered 26 percent of the tank cross-sectional area. An average increase of only 29 percent occurred in the volume change fraction when 23.5 kilovolts were applied to the electrodes.

From the preceding results, the following guidelines for an electrode configuration can be made: First, the electrodes should be higher than the interface height at the time of incipience of vapor ingestion. Second, the horizontal extent of the electric field should be larger than the tank outlet diameter. Third, in view of these guidelines and from previous considerations, vapor ingestion may still occur both from on the tank axis or away from the tank axis.

SUMMARY OF RESULTS

An experimental program was conducted in order to evaluate the merits of dielectrophoretic baffling for the control of vapor ingestion during outflow of liquids in weightlessness. The study was conducted with 4- and 8-centimeter-diameter flat-bottom, cylindrical tanks in both normal gravity and a weightless environment. The tests were conducted in the Lewis Research Center's 2.2-Second Zero Gravity Facility. The test liquids were carbon tetrachloride and trichlorotrifluoroethane. A high voltage, as much as 27.5 kilovolts, applied to various pairs of electrodes inside the test tanks produced the dielectrophoretic baffling effect. A total of five different electrode configurations was tested. Results were obtained over a range of outlet sizes, flow rates, and initial liquid heights. For the ranges investigated, the results may be summarized as follows:

1. Neither the dielectrophoretic nor the mechanical baffling had any effect on vapor ingestion in normal gravity. Vapor ingestion in normal gravity agreed with a previous analysis predicting a Froude number correlation.

2. In weightlessness, the presence of dielectrophoretic baffling affected the liquid-vapor interface shape before and during outflow from the tanks.

3. In weightlessness, the minimum liquid height, defined as the lowest point on the interface, was always smaller with dielectrophoretic baffling than the critical height without dielectrophoretic baffling.

4. The use of dielectrophoretic baffling significantly increased the amount of liquid expelled in weightlessness before vapor ingestion.

5. Over the range of voltages tested, the amount of liquid expelled varied linearly with the applied voltage.

6. The electrode configuration which determines the strength and the shape of the electric field had a very significant effect on the vapor ingestion phenomenon.

7. A pair of parallel-grid electrodes, which produced the largest region and the most uniform electric field above the tank outlet, was the most effective configuration of those tested for increasing the amount of liquid expelled in weightlessness.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 1, 1970,
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