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USE OF AN ELECTRIC FIELD TO ATTAIN A ZERO-GRAVITY LIQUID-VAPOR INTERFACE CONFIGURATION UNDER ONE-GRAVITY

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1968

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ABSTRACT

An experimental investigation was conducted to determine the feasibility of attaining a zero-gravity configuration of a liquid-vapor interface at one-gravity by means of a transverse electric field. The results indicate that the behavior of the interface depends on the tank material, tank diameter, liquid properties, electric field, and electrode configuration. The proper choice of these parameters deformed the interface as in a reduced gravity environment.

INTRODUCTION

The NASA-Lewis Research Center is currently conducting a study of the various problems associated with the behavior of liquid rocket propellants in space vehicle tanks while exposed to weightlessness. When a liquid-vapor system is subjected to weightlessness, a finite time is required for the interface to reach its equilibrium configuration (ref. 1). This is called the formation time. For example, the formation time for a liquid in a 20-centimeter-diameter tank is about 3 seconds. Most of the fluid behavior studies have used free-fall through heights of less than 100 feet to produce the weightless environment. Thus, the environment is limited to less than 2.5 seconds. Tanks with diameters larger than 20 centimeters must be excluded from these programs because of the long formation time. Any means of shortening the formation time or producing the equilibrium interface while in one-g would be an advantage.

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An experimental investigation was, therefore, performed to determine the feasibility of using the dielectrophoretic effect to cause the interface (under one-gravity) to attain its weightless equilibrium configuration. The use of a dielectrophoretic force to position fluids has been proposed for many applications (ref. 2), including slosh control (ref. 3), vapor ingestion control (ref. 4) and liquid orientation (ref. 5). The authors suggest that this method might be useful to increase the capabilities of current research facilities by permitting the use of larger diameter tanks in fluid behavior studies. The work most closely related to this application has been reported by Sumoto (ref. 6) where the rise of liquid dielectrics up a vertical electrode was observed.

The purpose of this report is to present the results of a photographic study of the behavior of the liquid-vapor interface under one-gravity when subjected to a transverse electric field. The special case of fluids with 90 degree contact angles has been excluded. Transparent tanks (borsilicate glass and acrylic plastic) with internal diameters from 1.27 to 3.81 centimeters were used. Three electrode shapes were used. The liquid dielectrics were water, 70% water-30% ethanol mixture, Freon TF, FC-43 (a proprietary fluorocarbon solvent), peanut oil, carbon tetrachloride and silicone oil.

APPARATUS AND PROCEDURE

A schematic drawing of the apparatus used in this investigation is presented in figure 1. The experimental tank was suitably mounted and illuminated to allow a 16-millimeter high speed motion picture camera to photograph the behavior of the liquid-vapor interface during application of the electric field. The applied voltage to the tank was obtained from a high voltage power supply (adjustable from 7 to 40 KVDC and current limited to 1 ma) and was measured with an electrostatic voltmeter with a range of 0 to 50 KVDC.

The tanks used in this study were fabricated from acrylic plastic tubing and precision-bore borosilicate glass tubing. The internal diameter (D) of the tanks ranged from 1.27 to 3.81 centimeters in 0.635-centimeter increments. The top and bottom of each tank consisted of an electrode-stopper which provided a liquid seal and established the electric field shape. All tanks had an over-all length of 20.32 centimeters. A schematic drawing of the three electrode-stopper configurations used is presented in figure 2 and a typical tank assembly is shown in figure 3.

The pertinent physical properties of the seven test liquids used in this study are given in table I. The values listed were obtained from standard references except those for the fluorocarbon solvents which were obtained from unpublished NASA data. The liquids were either analytic reagent grade or, in the case of Freon TF precision cleaning grade. All liquids had a static contact angle very near to zero degrees on the tank walls with the exception of water and acrylic plastic where the contact angle is nominally 50 degrees.

Prior to sealing the tank ends with electrode-stoppers, the tanks were thoroughly cleaned in the Zero Gravity Facility's Cleanroom (fig. 4). Contamination of the liquid and the tank walls which could alter the surface tension or electrical conductivity (ref. 7) was carefully avoided. The glass tanks were cleaned with chromic acid, followed by an ultrasonic cleaning in a detergent-water colution, rinsed with a distilled water-ethanol solution, and dried in a warm air-dryer. The acrylic plastic tanks were cleaned in a similar fashion; however, the chromic acid cleaning was omitted. The tanks were rinsed with test liquid, filled to the desired liquid depth and sealed. The tanks were removed from the cleanroom and taken to the test area, placed in a support and the high-voltage wires were attached to the electrodes.

The behavior of the liquid-vapor interface during the application of the high voltage was recorded photographically. A digital clock and a scale with 0.1-centimeter divisions were placed alongside the tank to record the formation time and measure the displacement of the interface.

RESULTS

The eight configurations studied are listed in table II. Five tank sizes and both acrylic plastic and borosilicate glass were used. Because many parameters affected the liquid-vapor interface behavior, each combination of variables will be described and discussed briefly. This will be followed by a generalization in the next section.

The initial tests were made with flat upper and lower electrodes (fig. 2(a)). The average distance between the lower electrode and the interface (h as shown in fig. 3) was 13.0 centimeters. Application of 40 KV to the electrodes produced no visible effect on the Freon TF interface. The low electrical conductivity and dielectric constant of Freon TF did not produce enough surface charge accumulation with the 13.0-centimeter separation to move the interface. This separation was reduced to 4.7 centimeters and a liquid film similar to that reported by Sumoto (ref. 6) was formed on the wall. Flow took place between the upper electrode and the interface within this film (fig. 5). A sketch of the flow pattern is shown in figure 6. The flow velocity appeared to be high. The film thickness increased from a thin layer on the wall of the 1.27-centimeter tank to a relatively thick layer on the 3.18-centimeter tank wall. The film thickness was slightly thicker for the glass tanks than for the plastic tanks. Although reducing h caused formation of the liquid on the wall, it did not result in the desired interface curvature.

Increasing the dielectric constant by using water produced a different result with the glass tank than with the plastic tanks. The interface of the water in a plastic tank was characterized by waves (fig. 7). This was previously reported by Melcher in reference 8. The glass tanks had flow on the wall between the upper electrode and the interface (fig. 8). This resulted mainly from the difference in the wettability of water on these two materials. With the glass tanks the charge transfer and the resultant current flow caused by the streams of liquid on the wall was large enough to limit the maximum applied voltage between 14 and 19 KV.

To increase the wettability a mixture of 70% water and 30% ethanol (by volume) was used. The interface behaved similar to that of water in the plastic tanks, but was different in the glass tanks. The interface behavior was dependent on the diameter of the glass tank. For a small diameter (1.27 cm) the liquid formed a thin film on the wall. As the diameter increased to 2.54 centimeters streams were formed on the wall. For the largest diameter tested (3.81 cm), neither films or streams were encountered, but a wave motion was begun on the surface.

A fluorocarbon solvent with a relatively high viscosity was used to study the effect of increasing this property. The other properties of FC-43 were similar to those of Freon TF. The shape of the bottom electrode was changed to a point as shown in figure 2(a), while the top electrode was the previously used flat type. The pointed electrode permitted h to be small (3.2 cm) while maintaining the liquid depth to greater than 3 tank radii. The average depth was 13 centimeters. The electrical conductivity was so low that only a slight wave motion occurred at the interface.

The electrode configuration was changed to the pointed type at the top (fig. 2(b)) and the tubular type at the bottom (fig. 2(c)). Carbon tetrachloride was used with this configuration. The interface experienced a rapid wave motion and no streams or films formed on the wall. The combination of low viscosity and low electrical conductivity prevented formation of the desired interface curvature.

The field shape was changed by making both electrodes the pointed type and higher viscosity fluids were tested. For large diameter tanks with peanut oil, the interface behaved similarly with both the glass and plastic tanks. However, for the small diameter tanks the increase of the interface curvature was larger for the plastic tanks than for glass. At the maximum applied voltage the interface in the smaller diameter tanks had a depression that had a pulsating motion (fig. 9). This has been previously observed by Taylor and McEwan (ref. 9). As the tank diameter was increased, the depth of the depression decreased and a bulge was formed on the interface above the electrode (fig. 10). This has also been reported by Pohl (ref. 10). There appeared to be a high flow of liquid circulating within the bulge. The electric field from this combination of electrodes and fluid properties did not produce the desired interface curvature.

The electrode configuration was changed to a flat upper electrode (fig. 2(a)) and a pointed lower electrode (fig. 2(b)). The dielectric was changed to silicone oil. The interface behavior was better in the glass tanks than in the plastic ones and the desired curvature was attained in the smaller tanks (fig. 11). Increasing the tank diameter did not maintain the desired curvature.

DISCUSSION

Many parameters affect the behavior of the interface in an electric field. The most important of these are the electric field shape which results from the electrode configuration, the field strength produced by the applied voltage, the tank diameter and material, and the physical properties of the liquid. Because of the number and interaction of these parameters, only the general trends observed will be discussed.

The field strength and shape are of prime importance in this study. It was found that below a critical field strength (i.e., applied voltage) no change occurred in the interface. However, as the voltage was increased, the behavior of the interface changed greatly and the sequence of events was as follows. At low field strengths surface disturbances or depressions were seen or wave motion was begun. Increasing the field strength caused films of flow to occur on the wall above the interface. A further increase in the field strength increased the film thickness and flow within the film was begun.

The electrode configuration and the applied voltage determined the field strength and shape. An improper combination of electrode shapes caused undesirable effects such as the bulge formation on the interface or the depressions encountered. Proper alinement of the electrodes was required to prevent unsymmetric interface curvature. It was found that the distance between the interface and the lower electrode had a large effect on the interface behavior for strong dielectrics such as Freon-TF, FC-43 and carbon tetrachloride.

The liquid properties found to be of greatest importance in this study were the dielectric constant (related to the conductivity) and the viscosity. The strong dielectric liquids required a small distance between the interface and the upper electrode to affect the interface. Liquids with the highest viscosities (peanut oil and silicone oil) attain the largest interface curvature. The high viscosity precluded formation of films or streams on the tank walls as well as wave motion on the interface.

The tank size was limited to less than 2.5 centimeters because as the diameter was increased above this the interface began to oscillate instead of assuming the equilibrium configuration. The tank material was only of secondary importance and then was a function of the wettability by the test liquid. Only with silicone oil was the interface curvature greater for glass than for the plastic tanks.

CONCLUDING REMARKS

Qualitative results of the effect of various parameters on the behavior of a liquid-vapor interface under one gravity in a transverse electric field are presented. These parameters include the electric field, the electrode configuration, the tank diameter and material, and the properties of the fluid such as viscosity and conductivity.

An electric field can be used to induce curvature to a liquid-vapor interface under one-gravity only under very special conditions. The conditions required are tank diameters less than 2.5 centimeters, liquids with moderate viscosities and an electric field with a large strength and the proper shape.

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TABLE I. - SUMMARY OF LIQUID PROPERTIES

(Values Correspond to 20° C)

Liquid	Surface tension (N/mx10^2)	Density (kg/m^3x10^{-3})	Viscosity (N sec/m^2x10^4)	Dielectric constant
Water	7.28	1.00	1.0	81.0
70% water and 30% ethanol	3.24	0.94		
Carbon tetra-chloride	2.69	1.59	9.7	2.2
Freon-TF[a]	1.86	1.58	7.0	2.4
FC-43[b]	1.60	1.87	48.7	1.9
Peanut oil		0.92		3.1
Silicone oil		0.91		2.5

[a]Freon-TF: E.I. Dupont de Nemours and Co. registered trademark for a fluorocarbon solvent (trichlorotrifluoroethane).
[b]FC-43: Minnesota Mining and Manufacturing Co. registered trademark for a fluorocarbon solvent.

TABLE II. - SUMMARY OF TEST CONFIGURATIONS

Configuration number	Liquid	Upper electrode shape	Lower electrode shape
1	Freon-TF	Flat (fig. 2(a))	Flat (fig. 2(a))
2	Freon-TF	Flat (fig. 2(a))	Flat (fig. 2(a))
3	Water	Flat (fig. 2(a))	Flat (fig. 2(a))
4	70% water and 30% ethanol	Flat (fig. 2(a))	Flat (fig. 2(a))
5	FC-43	Flat (fig. 2(a))	Pointed (fig. 2(b))
6	Carbon tetra-chloride	Pointed (fig. 2(b))	Tubular (fig. 2(c))
7	Peanut oil	Pointed (fig. 2(b))	Pointed (fig. 2(b))
8	Silicone oil	Flat (fig. 2(a))	Pointed (fig. 2(b))

Tank diameters: 1.27, 1.91, 2.54, 3.18, 3.81 cm.

Tank materials: Acrylic plastic and borosilicate glass

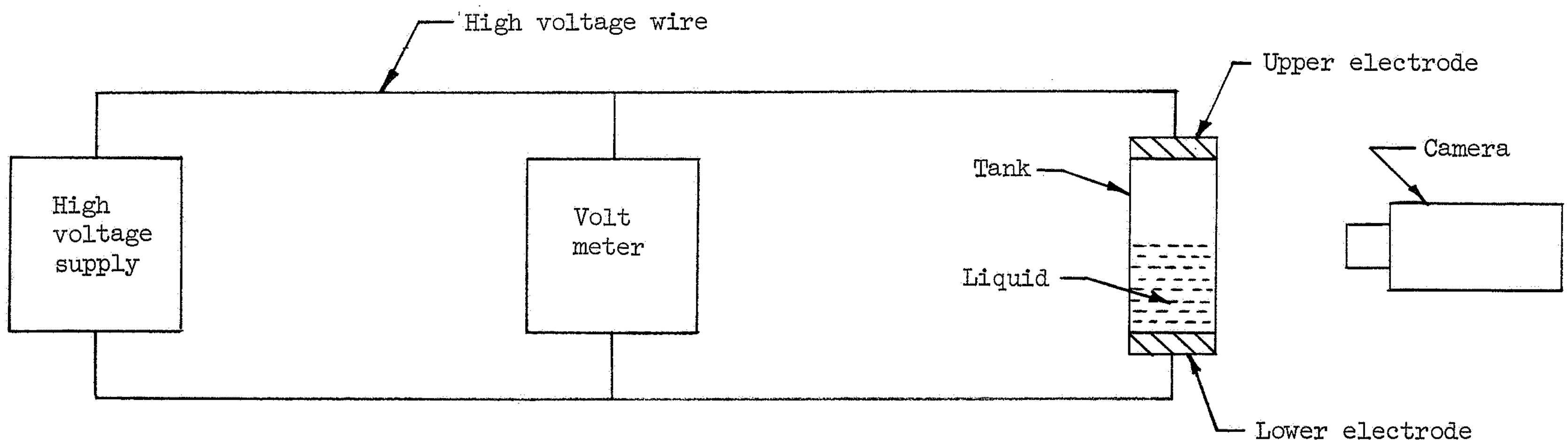

Figure 1. - Schematic of experimental layout.

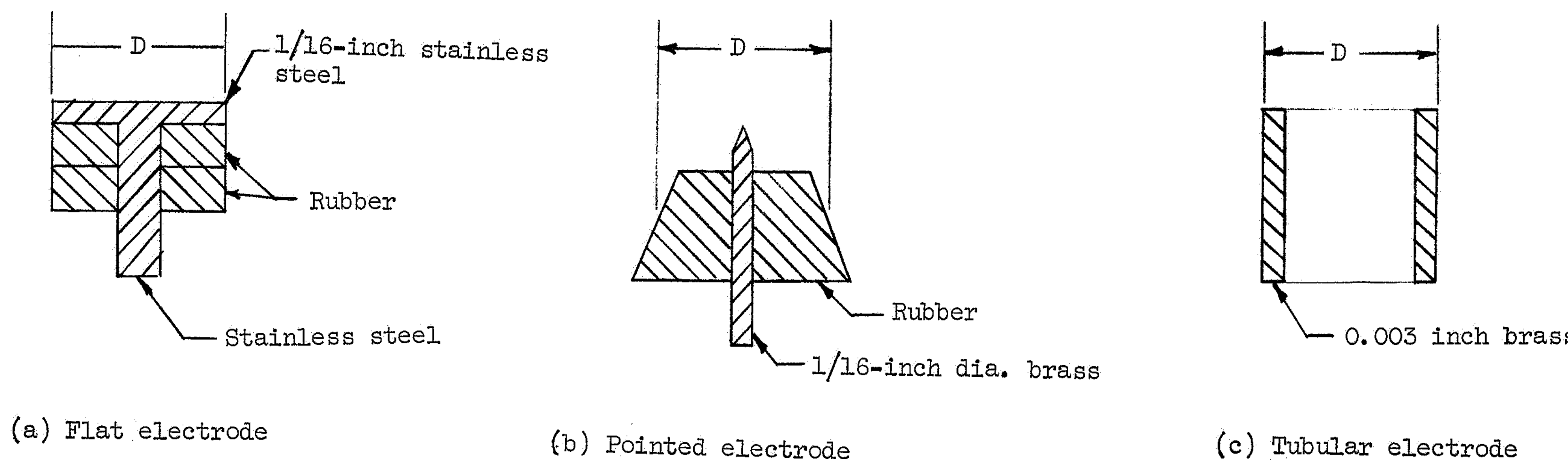

Figure 2. - Electrode designs.

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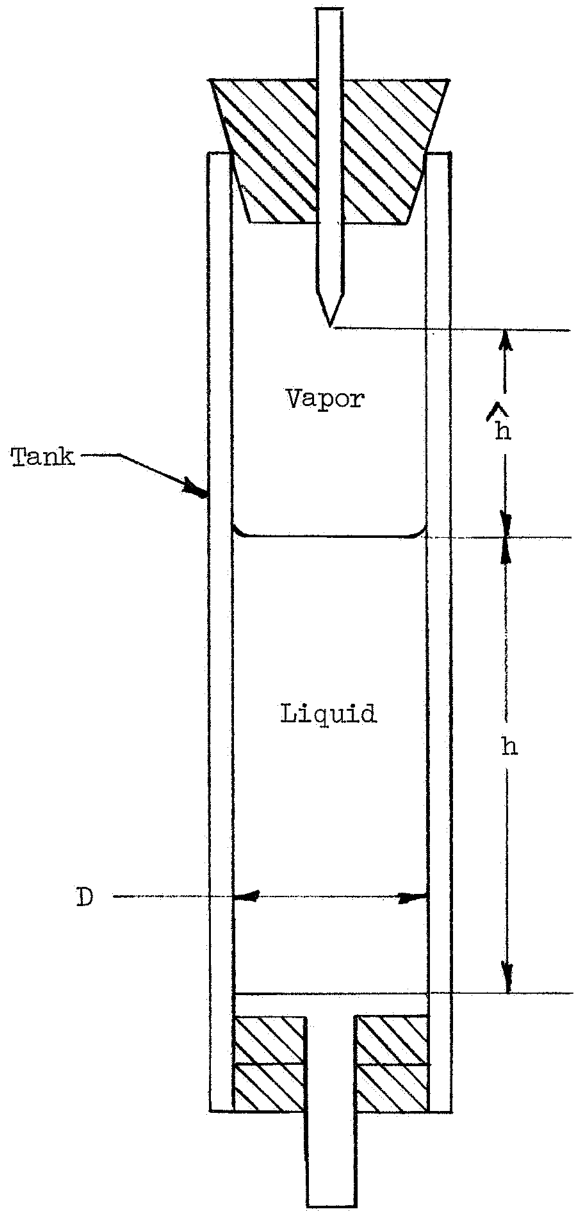

Figure 3. - Schematic of a tank with a flat lower electrode and a pointed upper electrode.

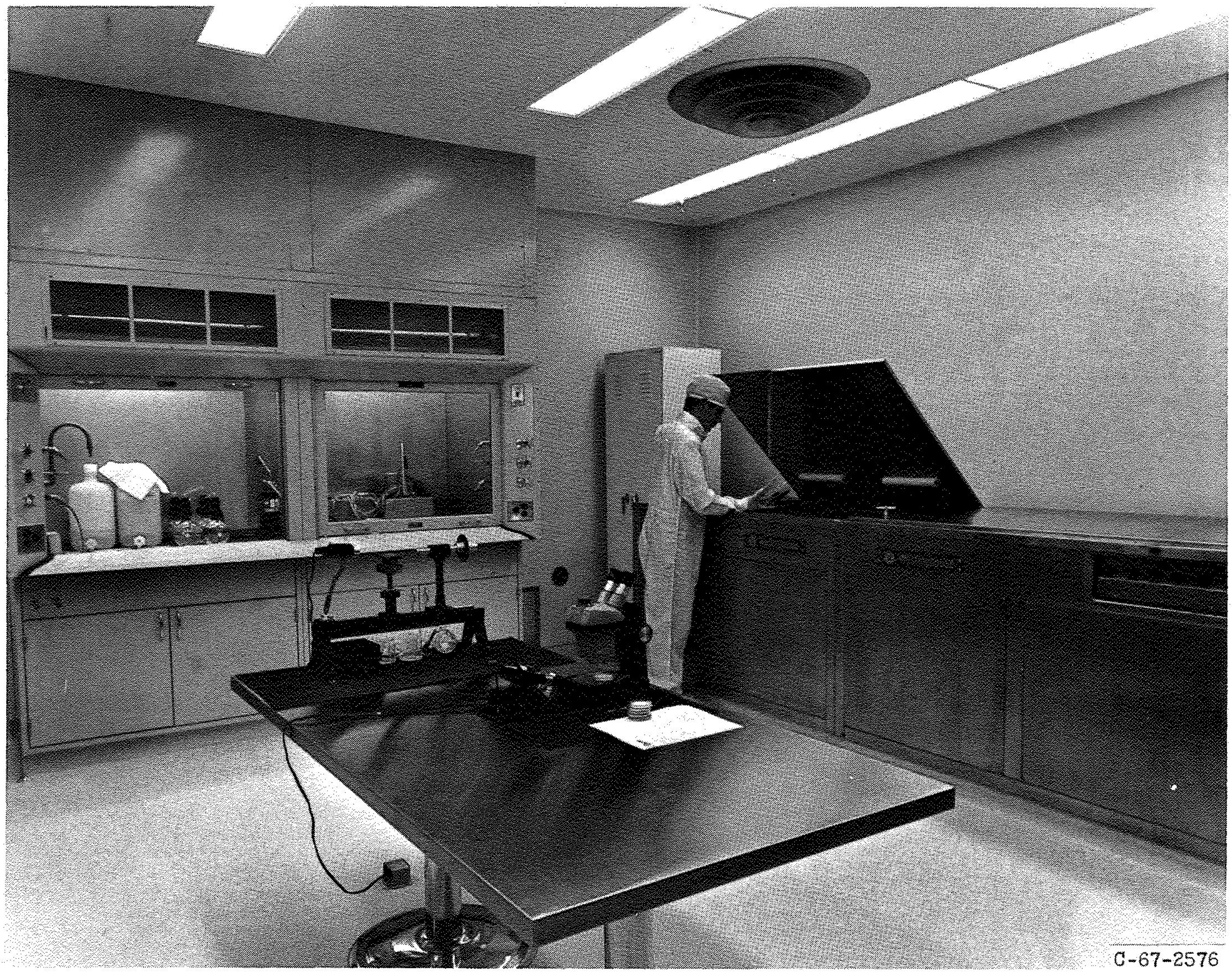

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Figure 4. - Cleanroom.

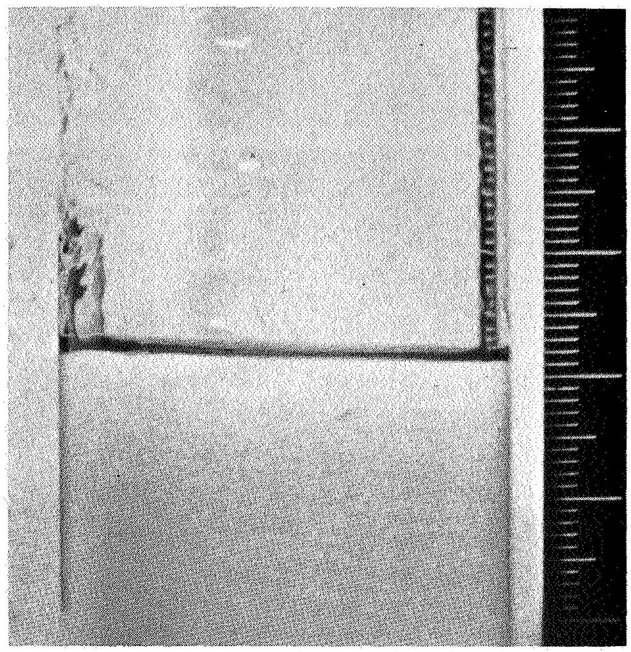

Figure 5. - Liquid film formed on a tank wall with freon TF and flat upper and lower electrodes.

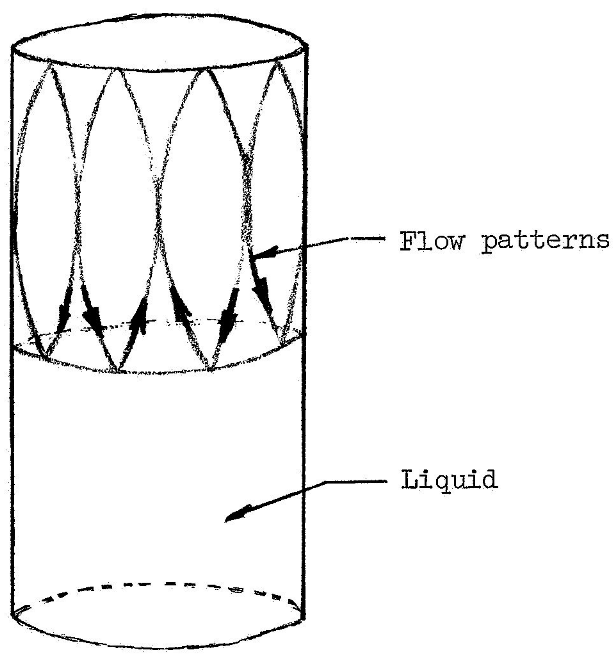

Figure 6. - Schematic of liquid motion on the inner tank walls (Front side shown only).

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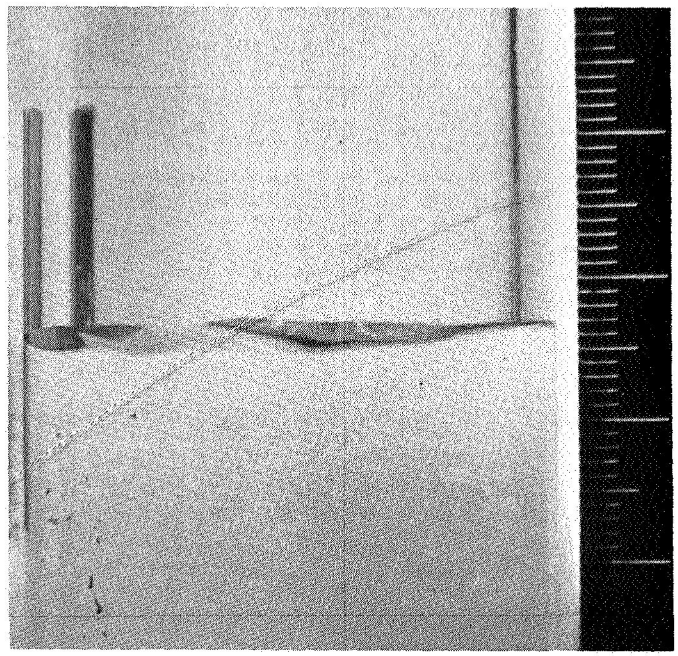


Figure 7. - Wave motion of the water interface in a plastic tank.

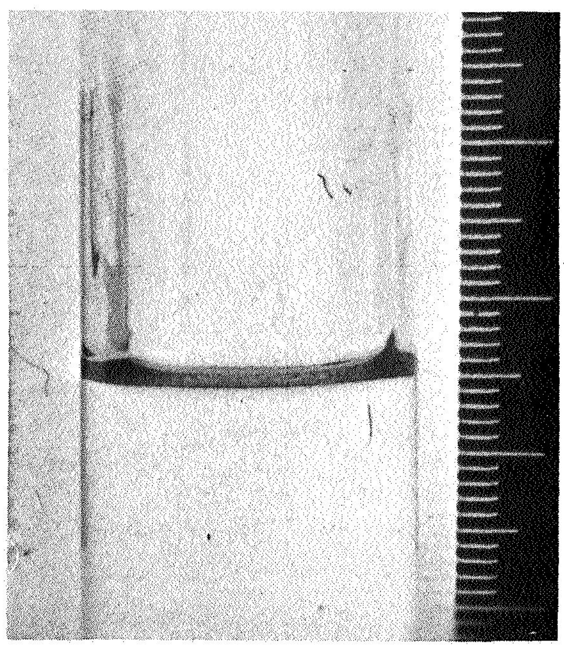


Figure 8. - Streams formed on a glass tank wall with water.

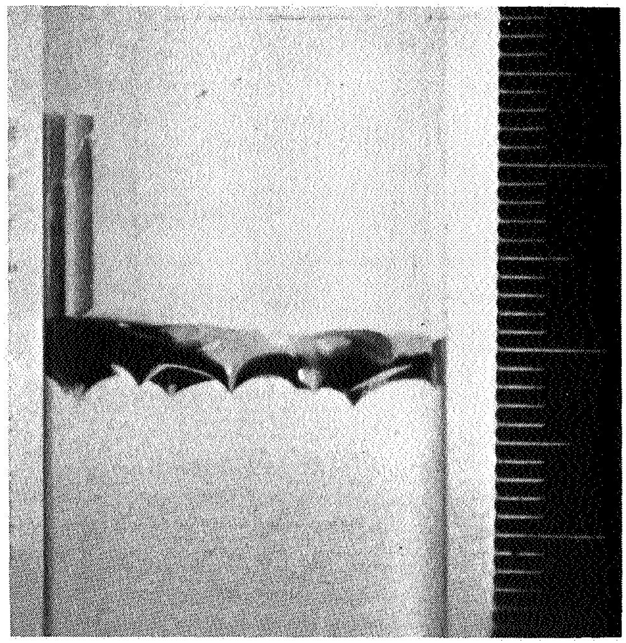


Figure 9. - Depressions formed at the interface of peanut oil with applied voltage 40 KV. Acrylic plastic tank diameter ≈ 1.91 cm.

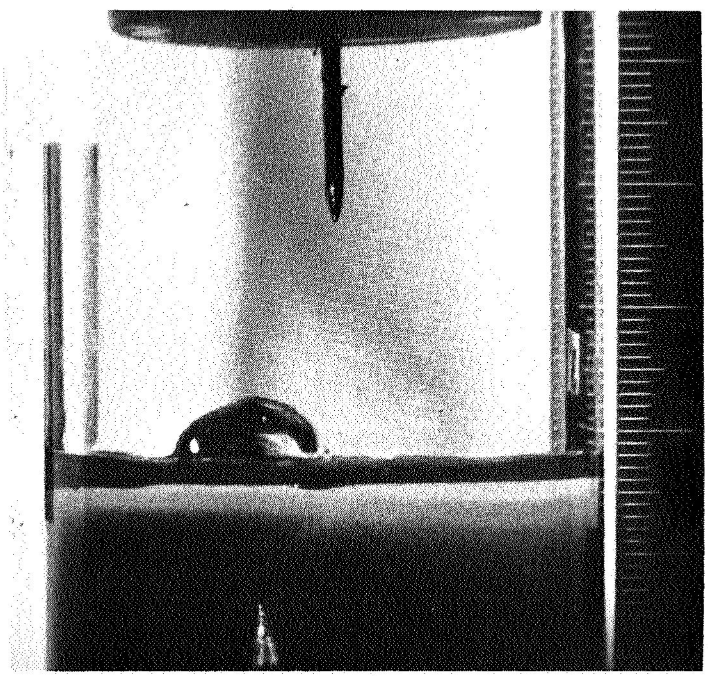
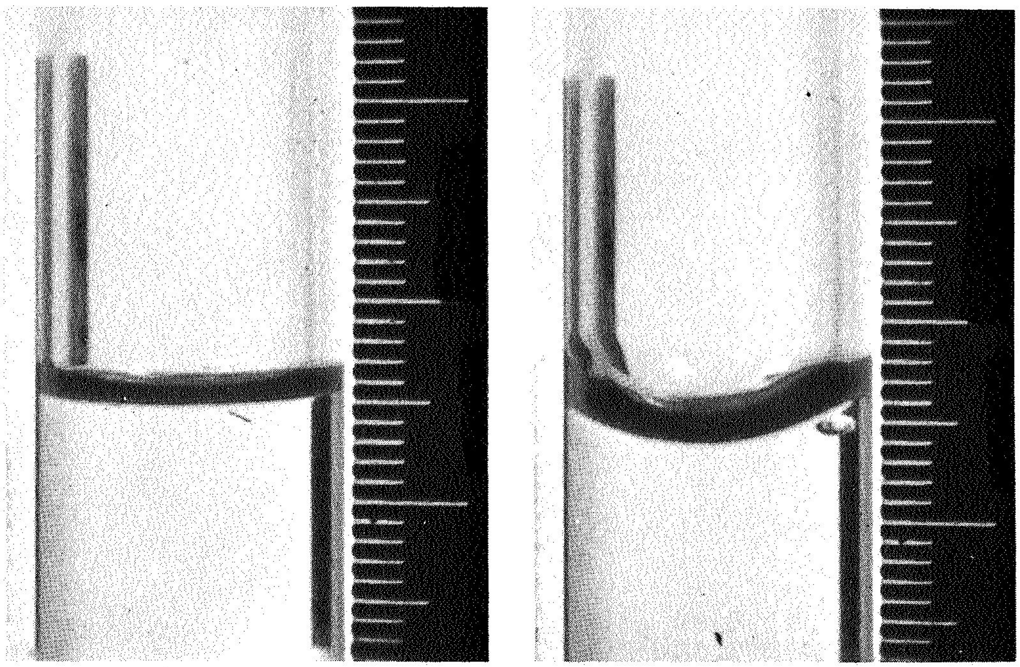


Figure 10. - Bulge formed on the interface of peanut oil in acrylic plastic tank with diameter of 3.81 cm. Upper electrode is shown at top.



(a) No electric field present. (b) Electric field present.

Figure 11. - Effect of an electric field on oil in 1.27 cm diameter tank.