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BEHAVIOR OF FLUIDS IN A WEIGHTLESS ENVIRONMENT

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ABSTRACT

Fluid behavior in space differs markedly from that in a gravity-dominated environment. This must be considered for all fluid usage, whether for vehicle operations or payload experiments. Numerous investigations have shown that the behavior of fluids in a low-g environment is controlled primarily by surface tension forces. Certain fluid and system characteristics determine the magnitude of these forces for both a free liquid surface and liquid in contact with a solid. These characteristics, including surface tension, wettability or contact angle, system geometry, and the relationships governing their interaction, are discussed. Various aspects of fluid behavior in a low-g environment are then presented. This includes the formation of static interface shapes, oscillation and rotation of drops, coalescence, the formation of foams, tendency for cavitation, and diffusion in liquids which were observed during the Skylab fluid mechanics science demonstrations. Liquid reorientation and capillary pumping to establish equilibrium configurations for various system geometries, observed during various free-fall (drop-tower) low-g tests, are also presented. Several passive low-g fluid storage and transfer systems are discussed. These systems use surface tension forces to control the liquid/vapor interface and provide gas-free liquid transfer and liquid-free vapor venting.

INTRODUCTION

Fluid behavior in space is controlled by surface tension forces which are generally insignificant in a gravity dominated environment. Basic phenomena such as buoyancy, settling, convection, mixing and diffusion are considerably different when gravity is not present. The reaction rates for many processes may be altered. These, and other differences in behavior, may offer advantages in conducting biological experiments. For example, longer residence times are available for oxygen bubbles in contact with immiscible substrates, and strong shear forces induced by agitation in liquid media can be eliminated. The lack of significant buoyancy forces, on the other hand, may introduce certain handling concerns such as the separation and control of liquid and vapor. An understanding of how surface tension controls fluid behavior in low-g is thus needed in planning any experiments where liquids will be interacting with gases and surfaces.

A discussion of fluid and system characteristics that determine the magnitude of the surface tension forces is presented in this paper. Examples of surface tension dominated behavior illustrating some of the basic phenomena are available from both drop tower and Skylab fluid mechanics demonstrations. The separation of liquid and vapor by surface tension forces to accomplish low-g storage and transfer is presented as a practical application of the basic principles to a real system.

FLUID CHARACTERISTICS

The shape of a gas-liquid interface in low-gravity (gravity forces are negligible) is determined solely by capillary forces. The Young-Laplace equation relates liquid surface tension and the curvature of the interface to the pressure differential between the gas and liquid,

$$P_L - P_G = \sigma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{1}$$

where the subscripts L and G refer to the liquid and gas respectively, σ is the surface

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tension, and R_1 and R_2 are the radii of curvature of the interface. The radii of curvature are considered positive when their center of curvature is within the liquid. The sum of the reciprocals of the radii, $(1/R_1 + 1/R_2)$, is referred to as the curvature of the interface[1].

Under static conditions, the pressure of the gas in contact with the liquid is uniform over the entire liquid surface. An equilibrium interface will be established when the pressure in the liquid is also uniform and the pressure differential defined by equation (1) is a constant. If the pressure difference is constant, then the curvature must also be uniform over the entire surface.

Considering a globule of liquid in low-gravity, not in contact with any surface, the requirement of uniform curvature can only be satisfied if both radii of curvature are equal. The globule then has the form of a sphere, with the radii of curvature equal to its radius. Equation (1) simplifies to:

$$P_L - P_G = \frac{2\sigma}{r} \tag{2}$$

where r is the radius of the sphere. The pressure within the drop of liquid is greater than that of the surrounding gas by an amount that is directly proportional to the surface tension and inversely proportional to the radius of the drop. The same holds true for a bubble surrounded by liquid except that the pressure within the gas is greater than that in the liquid.

When the liquid is in contact with a surface, the determination of the interface becomes more complex. The curvature of the surface will still be a constant, but the two radii of curvature will vary over the surface. The liquid-to-solid contact angle θ is a boundary condition that must be satisfied. This is the angle formed between the liquid and the surface, measured within the liquid.

Variations in σ due to temperature and in σ and θ due to contamination, dissolved pressurant, and liquid purity will affect interface shape. The value of contact angle primarily depends on the liquid surface tension and the solid boundary surface energy. The latter can be expressed as a so-called "critical surface tension." If the liquid surface tension is less than the critical value, the contact angle is zero. If the surface tension is a greater than the critical value, the cosine of the contact angle is a linear proportion to the difference between the liquid and the critical surface tensions. Clean metal surfaces have high critical surface tensions and most liquids will completely wet them. Maintaining a contaminant-free surface is difficult to achieve in practice, however. Most monolayer contaminant films (except fluorocarbons) have critical surface tensions between 20 and 45 dynes/cm[2, 3]. This is also true of plastics. Water, with its high surface tension of 72 dynes/cm, will have high contact angles on these surfaces. A contact angle of 33.5° is shown in Figure 1.

Very few liquids (other than liquid metals) have a higher surface tension than water. Since water has such a high surface energy, it is readily contaminated and a considerable lowering of the surface tension takes place[4]. Contaminants that lower the surface tension of a liquid are referred to as surface active agents. A small amount of a surface active agent will impose its low surface tension on a liquid of much higher surface tension. As the concentration of the impurity is increased the surface tension of the solution decreases until it becomes saturated. Further addition of the impurity does not cause any change in surface tension[5]. For example, adding soap of the type used on Skylab to water, in approximately the concentrations used in the demonstrations, reduced the surface tension to 20 dynes/cm[6].

While the Young-Laplace equation can define more than one interface for any given set of conditions, the equation for surface energy defines the preferred configuration. A stable interface shape is achieved when the surface energy is a minimum. In simplified form, surface energy is defined by

$$S.E. = \sigma_{LV} (A_{LV} - A_{SL} \cos\theta) \tag{3}$$

where A is area and LV denotes liquid-vapor and SL denotes solid liquid. A capillary area can be defined as

$$A_C = A_{LV} - A_{SL} \cos\theta \tag{4}$$

for any given interface. Then surface energy can be further simplified to

$$S.E. = \sigma_{LV} A_C \tag{5}$$

Again consider a free-floating globule of liquid. The surface energy will be a minimum when the capillary area, which is the area of the liquid-vapor interface in this case, is a minimum. This occurs when the globule assumes a spherical shape, again confirming the static shape for a liquid drop.

The capillary area is reduced when a liquid drop contacts a solid surface. Therefore, contact with a surface is a preferred equilibrium configuration for a liquid drop. This decrease in surface energy accounts for the adhesiveness of a liquid on a surface. Energy must be added to remove a drop from a surface.

The equilibrium interface configuration is established by the mechanism of surface-tension-driven flow, termed capillary pumping. Liquid will preferentially orient within a container by capillary pumping if the system is in a low-g environment[7]. The geometry can be modified by compartmentation in one area of the tank such that a lower characteristic dimension results. This reduced length can be provided by a vane structure (surface tension device). The device can reduce the pressure of liquid adjacent to and within the device to a value lower than the pressure of liquid located away from the device. The low-pressure region will be created when the device causes the curvature of the interface about the device to be large (small radius of curvature) in comparison to the curvature of the liquid elsewhere in the tank. The pressure difference will have an effect only if the two liquid volumes are in communication. Under near-zero-g conditions, spreading of the liquid as it wets the tank walls will usually bring the liquid into communication with the surface tension device. If this is not possible, some sort of communication channel must be provided.

With a communication path provided, liquid will be transferred, as shown in Figure 2, until the curvature of the interface throughout the tank is the same, i.e., pressure is uniform. The surface tension device is designed so the curvature of the interface remains high until the device has filled with liquid. In comparison, liquid in contact with only the tank wall has a relatively low curvature.

For a spherical gas-liquid interface with liquid in contact with a surface, equation (2) becomes

$$P_G - P_L = \frac{2\sigma}{r} \tag{6}$$

This pressure differential can be related to a dimension (other than the radius of curvature) such as the pore radius R and a second parameter, the liquid-to-solid contact angle θ. This is done by introducing the relationship between R, θ, and r as shown in Figure 3. Then

$$P_G - P_L = \frac{2\sigma}{r} \cos\theta \tag{7}$$

A final criterion for determining interface stability is the Bond number (Bo), a dimensionless ratio of acceleration forces to capillary forces[8]

$$Bo = \frac{\rho a L^2}{\sigma} \tag{8}$$

where L is the characteristic system dimension. The liquid/gas interface is stable in a cylindrical tank or circular pore when $Bo \leqslant 0.84$. The critical Bo for square weave screen is 0.45[8]. Surface tension forces become significant, producing highly curved interfaces, for Bo in the range of five or below. The interface is essentially flat for $Bo \geqslant 50$[9]. Other scaling parameters, such as the Weber, Froude, and Reynolds numbers, are applied when liquid flow is involved[8].

LOW-G FLUID MECHANICS

The above described characteristics of fluid behavior in a low-g environment have been demonstrated in space and in simulated low-g environments on earth. These experiments illustrate the basic phenomena of low-g fluid mechanics. A number of fluid mechanics science demonstrations were performed on Skylab. While these demonstrations did not follow rigorous experimental protocols, they did provide interesting demonstrations of basic phenomena, some of which had not been previously observed[6].

Skylab Fluid Mechanics Demonstrations

The following are examples of fluid mechanics demonstrations performed aboard Skylab to illustrate low-g fluid behavior.

Static Interface Shape.- Surface tension and contact angle work together, as discussed previously, to yield the static shape of a gas/liquid interface in low-g. It was demonstrated that a free floating drop of water assumes a spherical shape, as shown in Figure 4. Due to disturbances induced in forming the drop and the relative acceleration of the Skylab and the drop, a completely static interface was difficult to form. Before the lightly damped oscillations ceased, the drop impacted a surface.

The astronauts found that these difficulties could be overcome by placing the drop on a thread. For the drop sizes used (30 to 100 cc), the thread retained and centered the drop. An evaluation of the data showed that the thread had a significant effect on the damping of the drop oscillations and caused a distortion of the drop shape (~ 5% elongation along the thread axis)[6].

When the drop was in contact with a larger surface like a straw, the surface influence was stronger and the equilibrium interface shape positioned the drop tangent to surface. On a large flat surface, the contact angle became a significant factor in establishing the interface shape, as illustrated in Figure 5. Water was the liquid for all these demonstrations, giving contact angles ranging from 30 to 90 degrees, depending on the surface material. A liquid with a lower surface tension would wet these surfaces and give somewhat different interface shapes[6].

Oscillating Drop.- Drops were oscillated in their basic first and second modes. Surface tension is the restoring force that sustains the oscillation. Opposite sides of the drop were pulled by rods to induce oscillation. A thread was again used to initially stabilize the drop. Measured oscillation frequencies were found to correlate well with theory. Damping of the oscillation was found to be at least an order of magnitude greater than predicted by theory due to the presence of higher modes of oscillation (a result of the method of inducing oscillation) and the damping effect of the thread[6].

Coalescence.- Coalescence depends upon the interaction of two liquid interfaces when they meet. Depending upon the angle of incidence and relative velocities, the drops can bounce off one another or combine. Momentum effects can cause them to separate again.

Drops were impacted by holding one drop stationary on a thread and maneuvering the second drop onto a collision course. Drops ranging from 1.8- to 5.2-cm diameter could be observed as they coalesced. The drops were colored differently so the rate of mixing (found to be fairly slow) could be observed. The coalescence observed in Skylab was consistent with available theory[6].

Rotating Drop.- When a liquid drop is rotated, centrifugal and surface tension forces balance to produce the resulting interface shape. This was the most unique demonstration performed on Skylab. Such a test was not previously feasible because of the long low-g period required and the need to manipulate the drop. Available theory predicts a completely different result, but does hint that other results may be possible.

When rotated at low rates, the drop has a watermelon shape. At higher rates, it pinches off, assuming a peanut shape, as shown in Figure 6. If the rate is increased further, an equilibrium shape cannot be achieved and the drop divides into two drops[6].

Immiscible Liquids.- A dispersion of two immiscible liquids can be formed if they are strongly mixed. If the densities of the two liquids are different, the dispersion will quickly separate in one-g. When gravity forces are small, the mechanism for separation of a dispersion is very different. One liquid can separate from the other only by coalescence of the finely divided drops. If drops of one liquid do come into contact and do coalesce, separation can proceed at some slow rate.

An experiment using various proportions of oil and water was performed to examine this phenomena. The two liquids were separated centrifugally and then mixed by shaking. They were observed for a period of 10 hours to see if any separation could be observed. Only a "cellular structure that grew coarse" could be observed[6]. On Earth, the two liquids completely separate in less than 10 seconds[10].

Ice Melting.- This demonstration provided an indication of the influence of a low-g environment on the mechanisms of heat transfer[6]. Instead of draining away as it does in one-g, the liquid surrounded the ice, acting to insulate it from the surrounding air. It took 190 minutes for the ice to completely melt to a liquid drop in low-g. The ice melted in 130 minutes in the same experiment on earth[11].

Since convection is thought of as being driven by buoyant forces, conduction and radiation heat transfer are usually presumed to be the means of heat transfer in low-g. While not established from this experiment, convection could still be a mechanism of heat transfer in low-g. Convection can be driven by surface tension forces (Marangoni flow) since gradients in temperature along an interface also produce gradients in surface tension[12]. Thermoacoustic effects, mechanical vibrations, electric and magnetic fields, concentration gradients and chemical potentials are also possible mechanisms for convective heat transfer in low-g[13].

Cavitation.- A bubble within a liquid can oscillate in much the same manner as a liquid drop oscillates. Both hydrodynamic and surface tension forces act at the surface of the bubble. If the magnitude of the hydrodynamic forces exceeds the surface tension forces at some point on the surface, the bubble can become unstable and collapse upon itself. Each time an unstable drop collapses a jet of liquid forms that shoots across the bubble.

This phenomena was demonstrated on Skylab in the following manner. A bubble was formed inside a drop such that only a thin film separated them at one area on the surface. When the surface was touched with a plunger, the bubble ruptured. While the source of the instability of the bubble was not a hydrodynamic force, the resulting collapse was the same as cavitation. A jet of liquid shot out of the drop at the point the bubble had been ruptured, as shown in Figure 7. As the velocity of the jet decreased, surface tension forces acted to retract part of the jet back into the drop, while some of the jet pinched off into additional drops[6].

Drop Tower Testing

Drop tower test facilities have been extensively employed to investigate some of the basic low-g fluid behavior. Although limited by relatively short test times, on the order of 2 to 5 sec, they do provide a quite accurately controlled acceleration environment (acceleration range between 10^{-5} and 10^{-1} g)[14]. Examples of interface shapes within containers and liquid motion resulting in reorientation within a container are presented below.

Capillary Pumping and Interface Shapes.- Liquids are usually stored in a container and the shape assumed by the liquid/vapor interface is important to the draining or filling of the container in low-g. The tank shape and any internal structures influence the interface shape. Differences in capillary pressure will cause liquid to be transferred from a region of low curvature to a region of higher curvature, as discussed previously. This capillary pumping establishes the equilibrium interface shapes. Interface shapes and pumping rates have been established for numerous geometries[7]. As an example, orientation of small liquid volumes by various vane configurations is shown in Figure 8. Orientation of the liquid in a bare tank is shown in the upper left hand corner. Liquid positioning with each of the five different vane devices, however, is such that gas-free liquid could be supplied to an outlet located at the 6 o'clock position.

Liquid Motion.- Disturbing forces acting on a container can cause the liquid within to reorient. A small lateral acceleration component will make the liquid flow along one side of the tank as it reorients. In a tank with a smooth interior wall the flow adheres to the tank wall continuing past its final equilibrium position. A typical example is shown in Figure 9[15]. As the liquid began to move, the liquid interface remained relatively flat so the motion appeared as a rotation of the interface about its center. Very little splashing of the liquid occurred during the reorientation. Once the leading edge of the flow reached the tank dome, the liquid interface began to acquire some curvature. The liquid overshot its final equilibrium position, continuing around the tank and recirculating some of the liquid. Baffles or surface tension device structure will breakup this recirculation and speed the achievement of its new static position. Baffles do induce turbulence and produce gas bubbles within the bulk liquid however.

STORAGE AND TRANSFER

Operation of passive devices for the storage and transfer of liquid in low-g illustrates a practical application of the previously described, surface tension dominated, behavior. Devices are available to handle a wide range of fluids such as alcohols, freons, propellants and cryogens[16,17]. Configurations differ because of varied functional requirements; however, the operational principle for each system relies on the relatively small pressure differential that exists across any curved gas/liquid interface due to intermolecular forces. Liquid surface tension and ullage pressure support are used to passively provide near-instantaneous, gas-free liquid expulsion on demand.

In general the surface tension devices are divided into two categories: devices that use fine-mesh screen for liquid orientation and control and those that use sheet or vane-type structures. The characteristic dimension, pore size, is the significant parameter that differentiates between the two categories. The vane devices with larger characteristic pore dimensions operate only in low acceleration environments on the order of 10^{-3} g or less, depending on the size of the tank or container. Fine-mesh screen devices, by virtue of very small pore sizes and small radii of curvature, can provide retention and control of large liquid masses over a wide range of spacecraft accelerations. The small capillary pressure differences that exists at the screen pores must balance or exceed the sum of other pressure differences tending to breakdown the passively-controlled liquid/gas interface. Premature interface breakdown reduces the quantity of gas-free liquid that can be expelled from the tank. During storage with no liquid outflow the capillary pressure difference must exceed the hydrostatic head supported by the screen. Additional losses which must also be balanced by the capillary pressure difference are introduced with a flowing system.

For applications requiring a screen system, there are two categories of devices: total communication systems and partial retention or trap systems[18]. Trap devices are screen reservoirs which position only a small percentage of the total liquid load over the outlet. Total communication devices are composed of screen liners or individual liquid supply channels which are in continuous communication with the bulk liquid. An example of a total communication channel device is shown in Figure 10. If the tank is large, on the order of 3 feet and greater, or the acceleration is relatively large, the tank can be compartmented so that the hydrostatic head to which any segment of the device is exposed is reduced. A schematic of such a device is shown in Figure 11.

An example of a device which uses vanes to orient propellants for gas-free liquid expulsion in a very low-g environment is provided by Martin Marietta Viking 1975 Orbiter propellant tankage[19]. The surface tension propellant management device (PMD) orients the liquid over the tank outlet so that a bubble-free supply of propellant is available to the rocket engines. Ullage control is provided by the PMD for liquid-free gas venting of the tank during all maneuvers of the vehicle following separation from the Centaur upper stage. During spacecraft cruise and immediately before engine burns, the PMD orients the propellant symmetrically about the tank centerline to enhance spacecraft pointing accuracy during engine firings.

A schematic of the propellant management device is shown in Figure 12. The primary elements of the PMD were the vane assembly, the communication channel assembly, and the mounting cap assembly. The vane assembly, shown in Figure 13, consisted of a hollow central tube or standpipe to which twelve 6Al-4V titanium sheet vanes were attached. A communication channel was positioned along the wall to provide for the capillary pumping of the propellants from the top to the bottom of the tank during low-g. Cleaning of the PMD and the inside of the tank was important to assure near-zero contact angles between the propellants and metallic surfaces.

The efficient transfer of liquid from one tank to another in a weightless environment is primarily dependent on the initial liquid/vapor interface shapes and their locations in both the supply and receiver containers, and the flowrate of the transfer. Liquid/vapor separation and control is required in the supply container to accomplish gas-free liquid flow from the container. Several kinds of devices are available for accomplishing expulsion from the supply container including the previously discussed passive surface tension devices, positive expulsion devices such as bladders and metal diaphragms, and bellows.

The particular device selected depends upon factors such as fluid compatibility, cycle life, expulsion efficiency, cost. etc.

Pressure control in the receiver tank during filling is a key design consideration. When small quantities of liquid and small containers are being used, evacuating the container to achieve transfer is a rather simple approach. On a larger scale, structural considerations and/or vaporization of the liquid usually rule out this method of transfer. For a high vapor pressure fluid or a cryogen the receiver container must be vented during the transfer, and the location of the gas must be carefully controlled.

An example of evacuating one container to achieve transfer in a low-g environment was demonstrated during the Skylab missions[6]. A sample of blood was drawn in a large syringe and transferred to an evacuated bottle. The pressure within the bottle was selected so that the addition of a given volume of blood reduced the pressure differential between the syringe and bottle to zero.

The needle of the syringe was inserted into the bottle, piercing a diaphragm. It extended part way into the bottle. Blood immediately began to transfer from the syringe to the bottle, since the bottle was at a pressure somewhat below ambient. As the flow of liquid began, a drop could be observed forming at the tip of the syringe. No turbulence or geysering of the blood was observed. The drop continued to expand until it contacted the wall of the bottle. At this point there was a volume of liquid, located near one end of the bottle, dividing the gas into two separate volumes. The interface on each side of the liquid volume moved toward the ends of the bottle compressing the two gas volumes as the transfer continued. The volume of gas near the diaphragm of the bottle was the smaller of the two. Each volume was at the same pressure with the liquid acting as a piston between them. Some pressure was applied to the plunger of the syringe to achieve complete transfer of the liquid.

The transfer of liquid from one tank to a second vented tank in a weightless environment was demonstrated by the crew of Apollo 14[20]. Two surface-tension baffle designs were incorporated in separate tanks of a scale-model liquid-transfer system with each tank being used alternatively as the supply and reciever tank. A sketch of the tanks is presented in Figure 14. One tank contained a standpipe-liner baffle structure consisting of a perforated standpipe located over the drain/fill port and a wall-liner spaced a fixed distance away from the tank wall. The second tank contained a curved-web baffle structure consisting of three circular perforated plates nested around a small feeder capillary section. The curved web baffles are arranged off-center such that the cross-sectional area between baffles increases gradually from the feeder section towards the opposite end of the tank. This arrangement tends to retain the bulk liquid adjacent to the feeder.

Testing was performed to determine the ability to achieve gas-free outflow from the supply tank and orderly inflow into the receiver tank with gas located at the tank vent and liquid at the fill port. Gas-free liquid was transferred to and from either baffled tank to within 2 percent of the liquid available for transfer and the receiver tank vent remained in contact with gas. Transfer between unbaffled tanks was included for comparison and gas ingestion occurred when less than 12 percent of the supply tank volume had been delivered. At the termination of transfer liquid had ingested into the receiver tank vent.

CONCLUDING REMARKS

The parameters that govern fluid behavior in a weightless environment have been partially characterized and verified by ground and orbital testing. Because the environment, geometry, and fluids of interest influence this behavior and also differ from system to system, each new application must be evaluated to assure that the desired performance is achieved. Early assessment of fluid behavior and control for each experiment is required. One-g bench and/or drop tower testing can provide verification prior to orbital operation.

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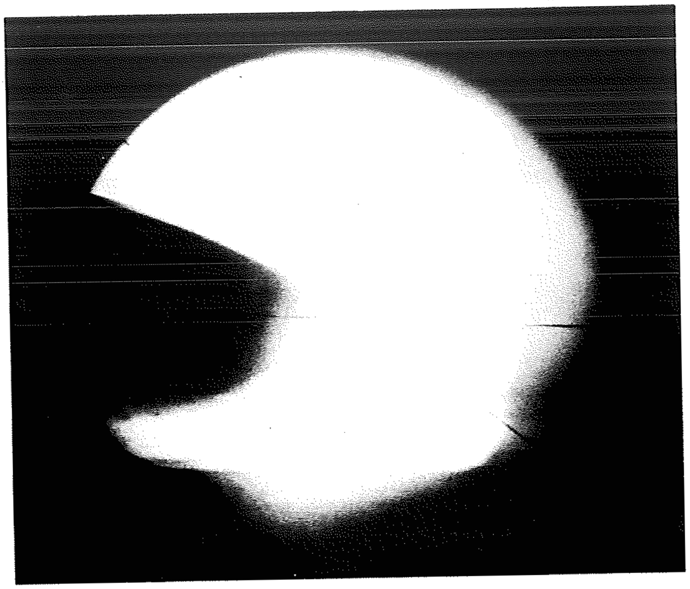


Figure 1.- 33.5° contact angle of a drop on a contaminated surface.

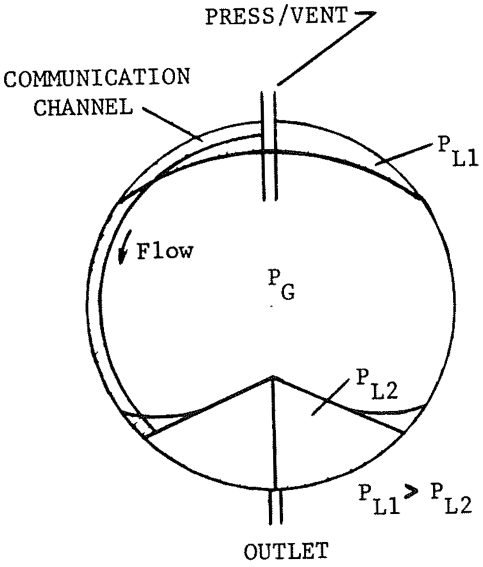


Figure 2.- Capillary pumping with a vane surface-tension device.

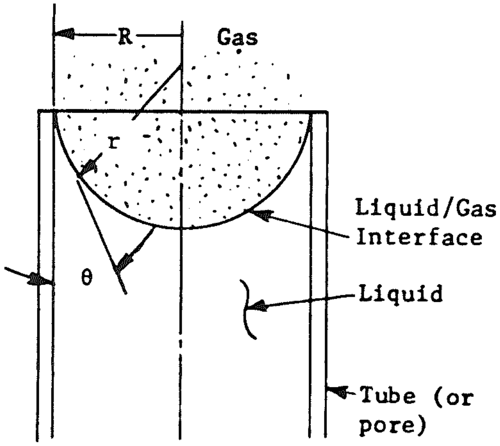


Figure 3.- Liquid/gas-interface shape in a pore.

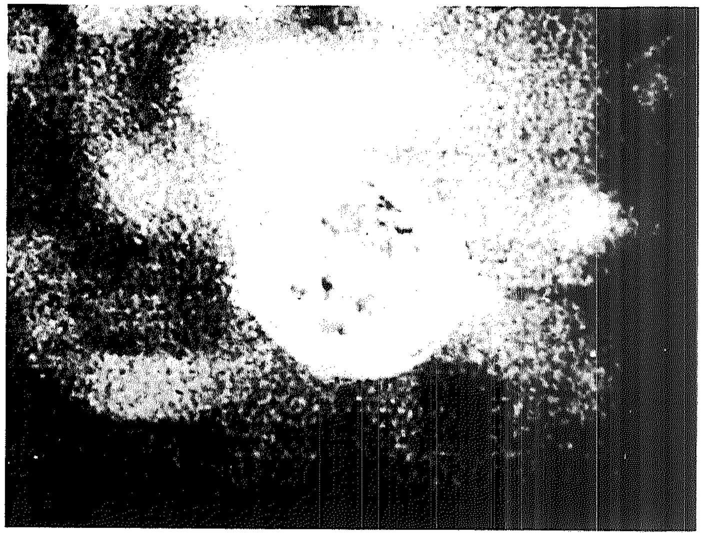


Figure 4.- Free-floating water drop.

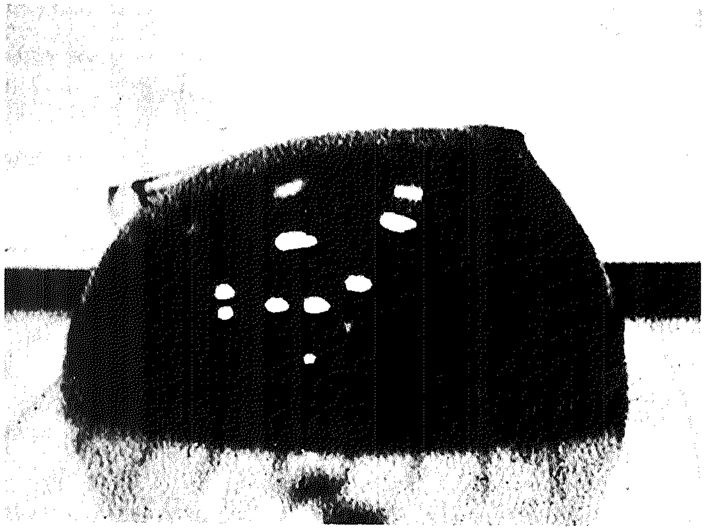


Figure 5.- Water drop on a flat surface (tube freely resting on drop surface).

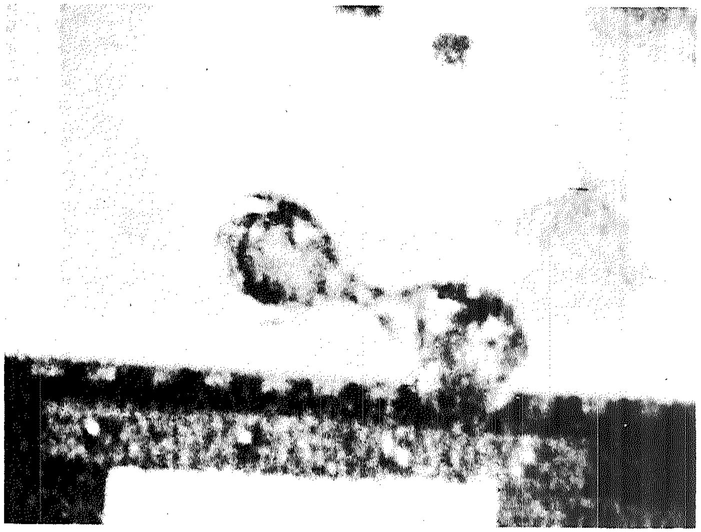


Figure 6.- Peanut shape assumed by a rotating drop.

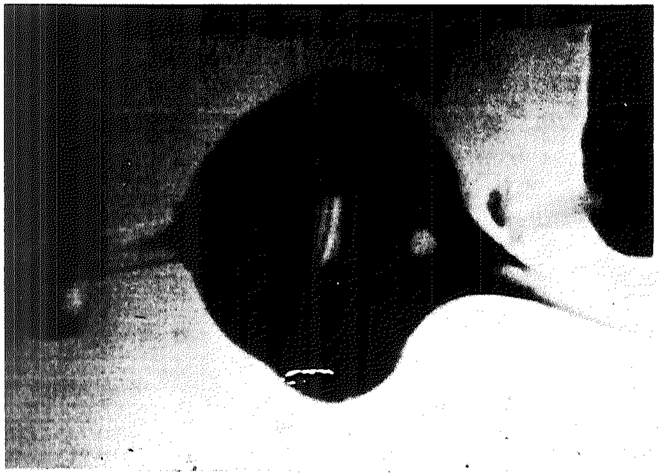


Figure 7.- Bubble collapse showing liquid jet leaving the drop.

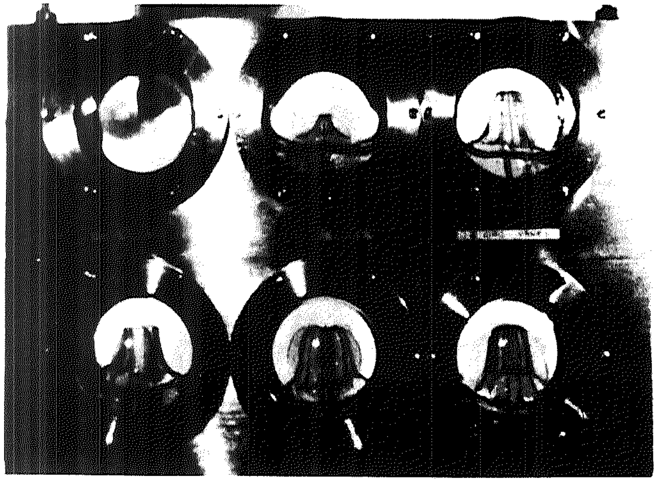


Figure 8.- Liquid orientation in low-g for various vane configurations.

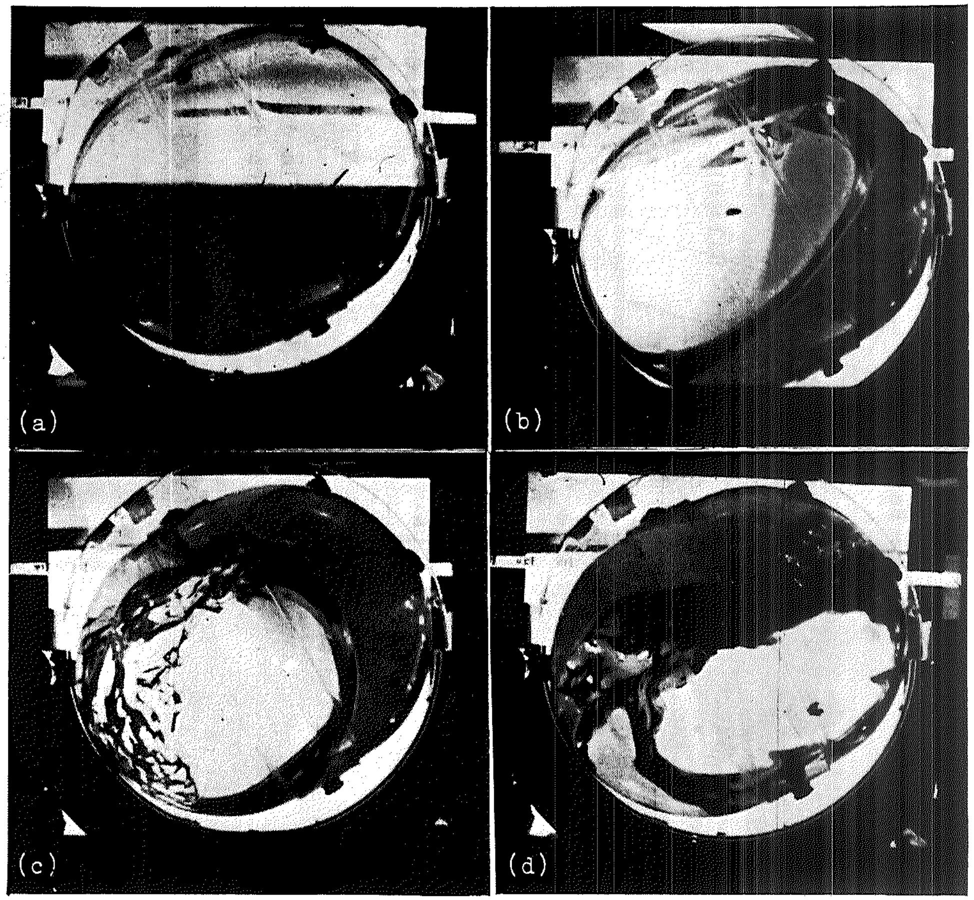


Figure 9.- Reorientation in cylindrical tank with off-axis acceleration.

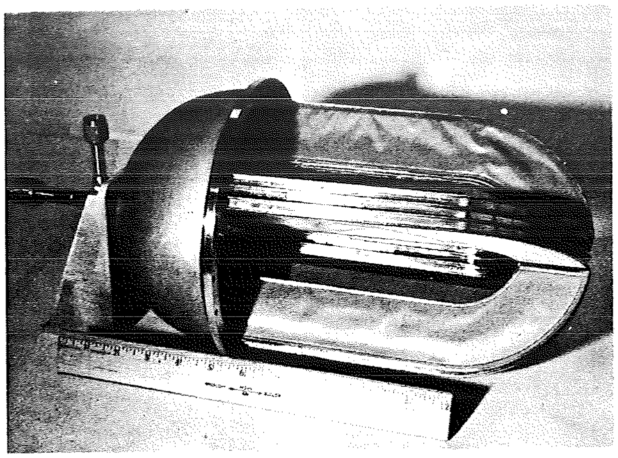


Figure 10.- Total communication screen device.

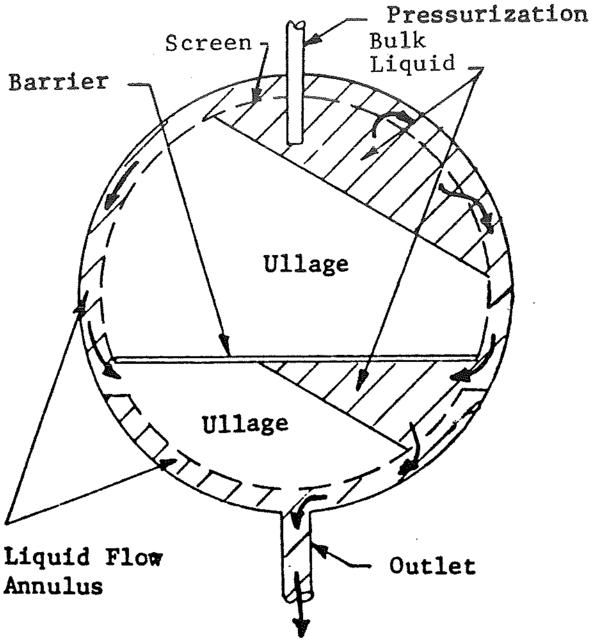


Figure 11.- Schematic of a compartmentalized screen device.

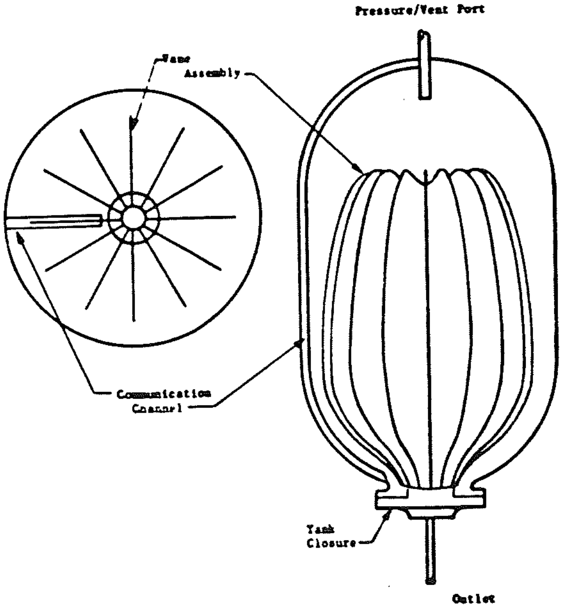


Figure 12.- Schematic of the Viking orbiter 1975 propellant management device.

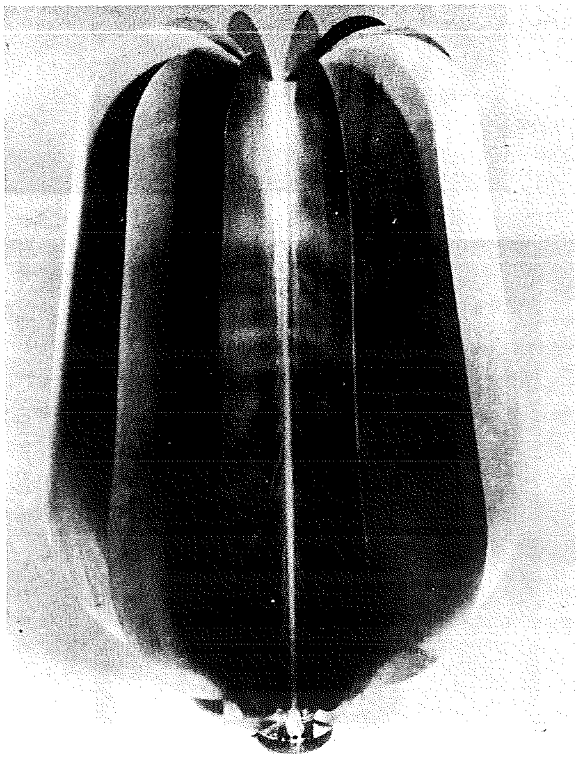
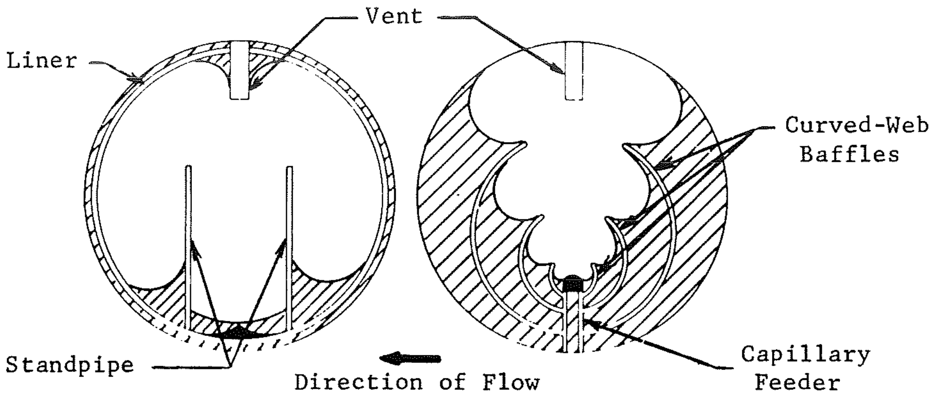
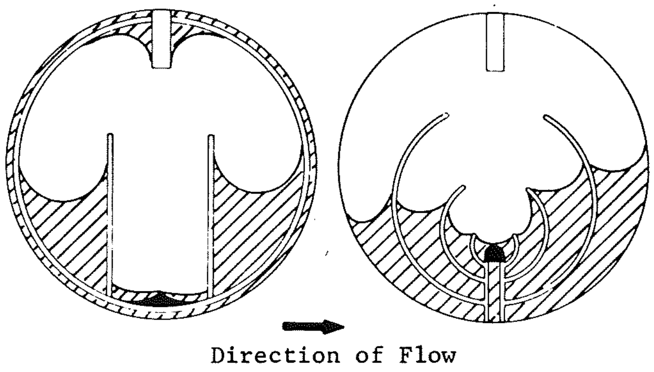


Figure 13.- Photograph of the Viking orbiter 1975 vane structure.



(a) Filling of standpipe.



(b) Standpipe section nearly empty.

Figure 14.- Apollo 14 fluid transfer with baffled tanks (ref. 20).