A DISCUSSION OF LABORATORY METHODS OF SIMULATING LOW-GRAVITY FLUID MECHANICS

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FRANKLIN T. DODGE

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ABSTRACT

Methods of simulating the behavior of liquids in a low-gravity environment by experiments in Earth based laboratories are discussed, with an attempt made to point out the advantages and limitations of each. Two promising methods are indicated: small models, and magnetic fluids. It is concluded that these methods should be developed further, not only to complement orbital experiments but also to give preliminary data at low cost.

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I. INTRODUCTION

The behavior of liquids subjected to greatly reduced body forces has become an area of active interest, especially as concerns those parts of the behavior that pertain to the design of space vehicles. In hydrodynamic systems that operate independently of the linear acceleration of the vehicle (for example, closed loop flow systems), the magnitude of the body forces is of little or no consequence. But when the liquid possesses a free surface, as does the liquid fuel in a rocket tank, the body forces (i.e., the "weight" of the liquid) induced by the linear acceleration of it as a whole are usually predominant in controlling the location of the liquid in its container and in determining the motion of the liquid. Consequently, when the linear acceleration and the body forces are very small, such liquids tend to act in a manner that is considerably at variance with that which prior experience might lead one to expect. This is because other small forces, which are usually negligible when the body forces are large, become important here. Any kind of force whose magnitude is independent of gravity* thus might be considered important in low-gravity fluid mechanics. Two examples are: interfacial forces between the liquid and its vapor or the ullage gas; and small body-like forces that are caused by rotations of the spacecraft.

Vehicles used for deep-space probes are in an almost zero-gravity environment for an extended period of time. Because of this, the designer must be able to determine under low-gravity conditions such things as the location of the fuel in the tanks when an engine must be restarted, the length

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*The word "gravity" will be used as a short synonym for the phrase "linear acceleration of the liquid as a whole."

of time it takes for transient motions to decay after the engines are shut down and the forces exerted on the tanks during this period, the magnitude of the slosh-induced forces and moments during low thrust midcourse maneuvers, and the behavior of boiling vapor bubbles when their buoyancy is small. Nonetheless, experimental data for these kinds of phenomena are currently not abundant -- for the obvious reason that a low-gravity laboratory is not available on Earth. Until such time as fluid mechanics experiments become possible in vehicles in space, therefore, one must rely on low-gravity simulations in the laboratory.

Low-gravity simulation is feasible because, as in other physical problems, it is the magnitude of various dimensionless products of the dimensional variables that govern the fluid's behavior; therefore, even though the magnitude of the gravity field cannot be changed on Earth, it is sometimes possible to manipulate the other variables that enter the dimensionless groups so that the groups as a whole take on the proper low-gravity magnitude. Alternatively, by using such techniques as drop towers or certain other laboratory methods, the net body forces in the liquid can be made to approach zero.

It is beyond the scope of this report to enumerate every possible dimensionless group that should be simulated in a true "low-gravity" experiment; Saad and DeBrock [1]* give an account of the manner in which the dimensionless parameters may be formed and evaluated as to the role each plays in determining liquid behavior. In any given situation, the experimenter

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*Numbers in brackets refer to the References at the end of this report.

must decide in advance what parameters are important and design his experiments accordingly. Nonetheless, some of the parameters that seem to be important in most low-gravity problems are:

(1) Bond number, $N_{Bo} = \frac{\Delta\rho \cdot a \cdot L^2}{T}$ ($\Delta\rho$ is the change in density from the liquid to the gas across their common interface. Here, a is the magnitude of gravity, L is a pertinent length dimension, and T is the interfacial tension between the liquid and the gas). N_{Bo} is an indication of the size of capillary or surface tension forces compared to gravity or body forces. $N_{Bo} < 1$ is the regime of capillary dominated (low gravity) fluid mechanics, while $N_{Bo} >> 10$ indicates the high-g regime. The Bond number, for example, plays an important role in differentiating between ordinary high-g and low-g free surface motions and in predicting whether a vapor bubble will break up into smaller bubbles.

(2) Weber number, $N_{We} = \frac{\rho V^2 L}{T}$ (V is a characteristic velocity). It gives an estimate of the relative importance of inertial forces and capillary forces; for $N_{We} >> 10$, capillary forces influence the dynamic behavior only slightly.

(3) Solid-liquid-gas contact angle θ_c. The angle at which the liquid meets the tank walls at liquid-tank-gas intersections under low-gravity conditions largely determines whether the liquid free surface will be nearly flat or highly curved. The change in θ_c as the free surface moves, called contact angle hysteresis, is also an important variable because the amount of hysteresis strongly affects the total energy dissipation during the motion.

(4) Reynolds number, $N_{Re} = \frac{\rho L^{3/2} a^{1/2}}{\mu}$ (μ is the dynamic viscosity). N_{Re} determines when viscous forces are important.

(5) Froude number, $N_{Fr} = V^2/gL$. The Froude number indicates the ratio of inertia forces to gravity forces. It generally is an important scaling parameter in motions of a liquid possessing a free surface when gravity is present.

Other parameters that may be needed in special situations are the cavitation parameter, $\frac{p - p_v}{\rho La}$ (p_v is the vapor pressure of the liquid), and the compressibility parameter, $\frac{K}{\rho La}$ (K is the bulk compressibility). A variety of other parameters can also be formed [1].

The purpose of this report is to describe laboratory techniques of duplicating the actual low-gravity values of the above parameters, especially the Bond number, by adjusting the values of the other variables that enter into the definitions of them. Some of the methods described already have been used, others are still in the evaluation stage.

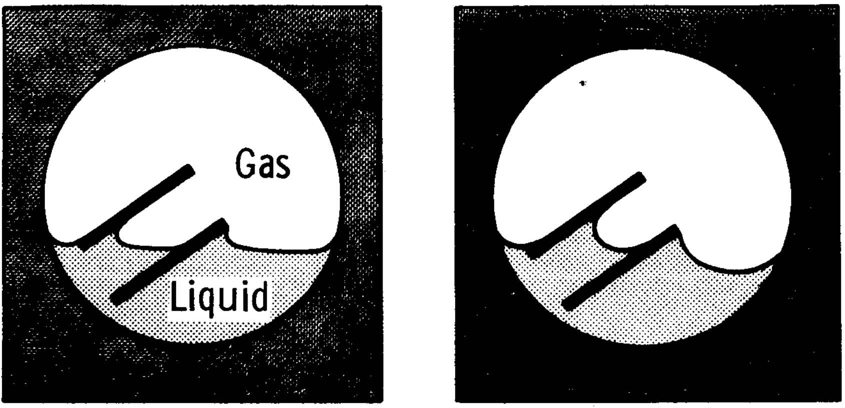
II. DISCUSSION OF SIMULATION METHODS

Perhaps the most popular method of simulating a low-gravity environment, at least in point of the amount of data generated, is the use of drop towers, in which the entire fluid mechanics experiment is allowed to fall freely for distances on the order of hundreds of feet. During the free-fall period, the effective gravity acting on the experimental package can be as low as 10^{-5} of standard gravity, g_o, or as high as 0.1 g_o, depending on the drag shield arrangements and auxiliary thrusters (References [2] through [5] are typical of the many kinds of published experimental investigations).

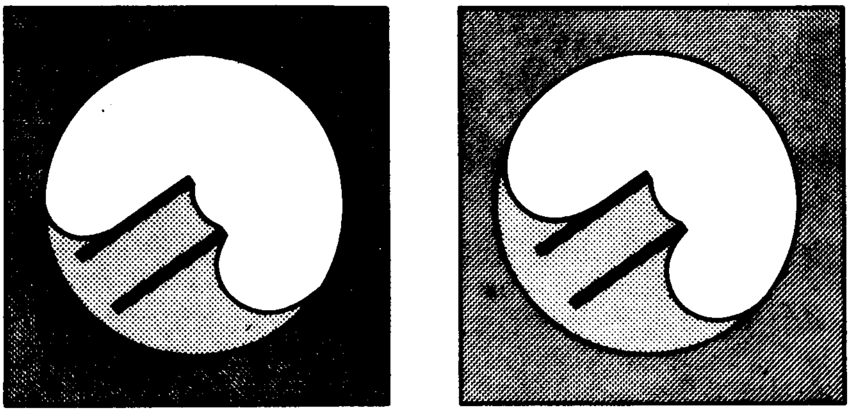
The drop-tower method has the obvious advantage that it is able to give an actual duplication of a low-gravity acceleration. This allows a great deal of flexibility in choosing values for the other scaling parameters, and thus generally results in a good overall modeling of full-scale phenomena. The disadvantages are that all the observations of the falling experimental package must be made remotely and that the duration of time in which the experiment must be conducted is quite short. In particular, the short length of testing time makes it difficult to arrange for the initial transients upon entering the weightless state to decay in time for other phenomena to be studied. Thus, for example, it is nearly impossible to carry out a study of steady-state low-gravity sloshing or to get a complete picture of everything that occurs during reorientation of the liquid. Nonetheless, valuable information has been obtained, especially for the more fundamental aspects of low-gravity fluid mechanics.

On the other hand, it is not necessary to use a drop-tower to study the hydrostatic configuration of the liquid, since it is determined only by the magnitude of the Bond number (based on a characteristic dimension of the free surface), the value of the contact angle θ_c, and the geometry of the container. The only one of these parameters that is difficult to scale properly is the Bond number, since if small values of $\Delta\rho \cdot aL^2/T$ are desired, it is usually necessary to use containers of small dimensions. One way to circumvent the small tank handicap has been devised by Olsen [6]. By containing the liquid between two very closely spaced glass plates (a "Hele-Shaw cell") such that the thickness of the liquid layer is thin compared to its other linear dimensions, the glass plates can be tipped almost to the horizontal without "spilling" the liquid. Since the effective gravity acting on the liquid is $g_o \times \sin \phi$, where ϕ is the angle of inclination of the plates from the horizontal, the Bond number can be varied by varying ϕ. Nearly zero gravity is obtained when the plates are nearly horizontal. Thus, reasonably large values of L may still yield small values of N_{Bo}. Figure 1 (see next page), adapted from photographs in [5], shows some of the results of this apparatus in simulating the effectiveness of a standpipe in retaining the liquid in one end of the tank.

If the Bond number, the contact angle, and geometric similarity are used as scaling factors, Olsen's simulator gives an exact representation of the hydrostatic liquid configuration in two-dimensional tanks and a fairly good approximation for three-dimensional axisymmetric tanks. The simulator has the advantage of giving a wide range of values of N_{Bo} with the same tank and same fluid. However, because of the large viscous forces induced by fluid motion in the narrow space between the plates, the simulator appears to be



Bond number:	375	47
Angle of inclination	0.84×10^{-1} rad	1.1×10^{-2} rad
Tank diameter	12.7 cm	12.7 cm



Bond number	3.95	~0.22
Angle of inclination	0.89×10^{-3} rad	$\sim 5 \times 10^{-5}$ rad
Tank diameter	12.7 cm	12.7 cm

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Figure 1. Simulation of Free-Surface Retention by a standpipe at low gravities (Adapted from Ref. 5)

usable only in studying static configurations; that is, the Reynolds number would be too far out of scale for any dynamic simulation of full-size phenomena.

Another example of the same sort of simulation technique is the use of model tanks of extremely small size. The hydrostatic configuration of the liquid under low gravity is modeled by the Bond number, where now the pertinent linear dimension is related to the dimensions of the free surface; for example, in an axisymmetric tank, the proper L is the radius of the circular planform of the free surface. Thus, to achieve really small Bond numbers, containers of almost minute diameter must be used.* The simulation is exact, but quite elaborate optical techniques are necessary to measure the configurational parameters of the liquid [7, 8]. However, some relief on the tank size can be obtained by using two immiscible liquids whose densities are slightly different; by floating the lighter liquid on the heavier, the interface between the two is governed by the Bond number based on the difference in densities, rather than on the density of either one separately.† The heavier liquid will assume the correct hydrostatic configuration for this Bond number.

For moderately small Bond numbers, the dynamics of liquid motion can also be investigated with the aid of small models. In addition to geometric similarity and the Bond number and static contact angle criteria, the Reynolds number and the contact angle hysteresis should be modeled properly for an exact simulation of full-scale behavior. At this time, the exact requirements

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*If water is the contained fluid, the tank diameter for a given N_{Bo} is $d = 2(N_{Bo}T/\rho g)^{1/2} \approx 0.548\ (N_{Bo})^{1/2}$ centimeters.

†Using the same example as the previous footnote, the tank diameter is now given by $d = 0.548\ (N_{Bo}/\Delta\rho)$, where $\Delta\rho$, the density difference, is in gm/cm^3.

for scaling the contact angle hysteresis are unknown except when the hysteresis is zero, in which case the contact angle of the moving fluid is always equal to the hydrostatic fluid.* The Reynolds number similarity between model and full scale prototype also imposes a stringent requirement on the tank size since the Reynolds number increases rapidly with decreasing tank size. As an example, Figure 2 is a cross plot of Bond number, tank size, and logarithmic decrement for free surface sloshing, which illustrates this point. (The log decrement is computed from the formula $\delta = 8.34\,\nu^{1/2}d^{-3/4}g_o^{-1/4}$, which neglects any damping caused by a curved free surface or contact angle hysteresis.) Typically, the viscous damping in full-scale tanks is very small; therefore, one should try to hold the damping below, say, about 0.02 of critical, which corresponds to a logarithmic decrement of about 0.12. For decrements significantly larger than this, the viscous forces certainly would become too large to give a usable simulation. Thus, according to Figure 2, a Bond number of about 5 is just about the smallest one for which a liquid dynamic simulation can be achieved, at least using water as the test liquid. (Other liquids give results of this same magnitude.) For $N_{Bo} = 5$, the corresponding tank diameter works out to be about 1.2 cm; thus, no visual problems arise, but sophisticated dynamometers and electronic equipment are required to measure the dynamic parameters of the liquid motion [1, 9].

From the previous remarks, it can be concluded that a simulation of liquid dynamic behavior using small models can be successful only for

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*It has been conjectured that the hysteresis is indeed always zero if pure fluids and very clean, hard surfaced containers are used.

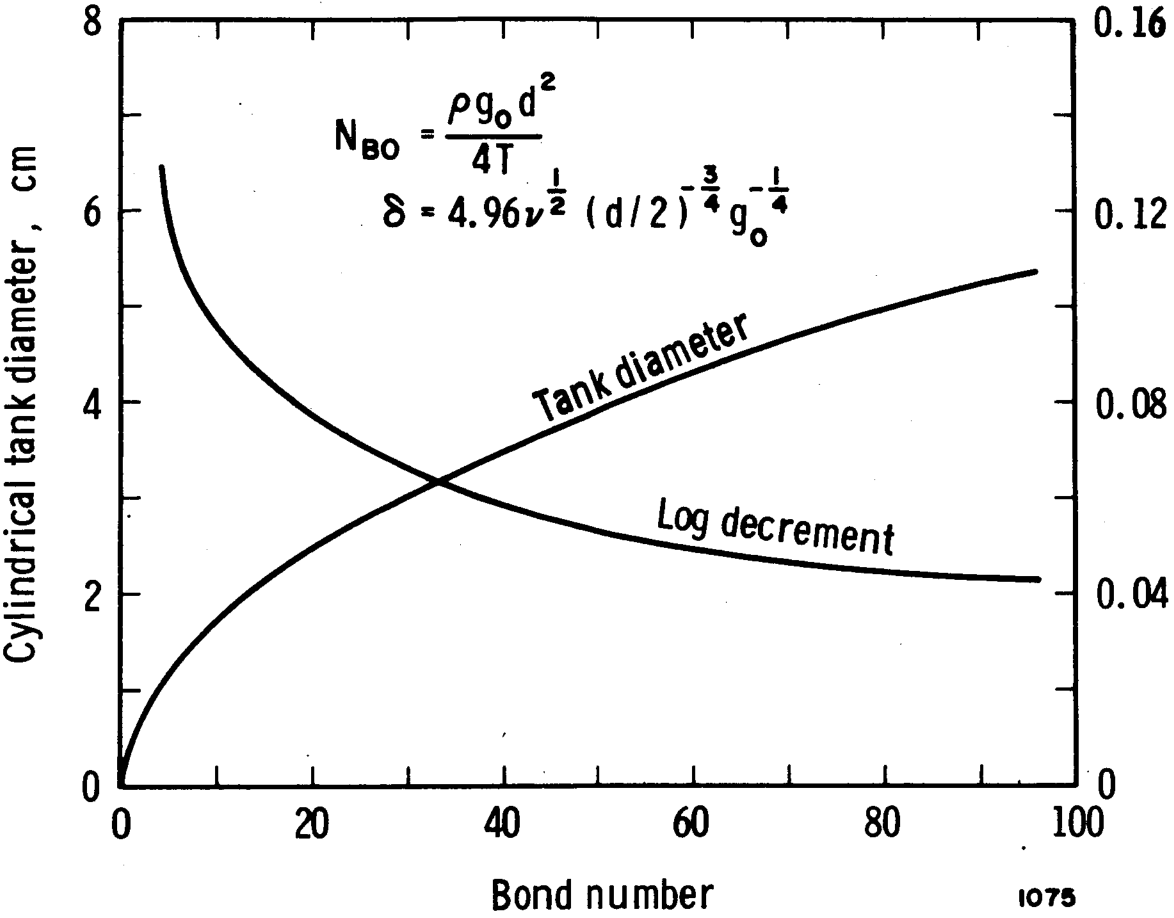

Figure 2. Tank diameter and log decrement for given Bond number, with water as test liquid, at standard gravity

$N_{Bo} \gtrsim 10$. While this encompasses most of the liquid propellant problems in orbiting vehicles near Earth, typical values of N_{Bo} for deep-space vehicles are at least one order of magnitude smaller than this. Nonetheless, it should be emphasized that much of the vexing behavior of the liquids in large propellant tanks (for which $N_{Bo} > 10$ in Earth orbit) can be studied with the aid of properly designed experiments with small models.

In order to extend more nearly to zero the range of obtainable Bond numbers, without a proportionate increase in the viscous stresses, the net body force acting on the fluid particles must be made smaller. Although drop towers are able to do this for short periods, other means of cancelling the gravitational body forces are needed for experiments requiring longer test periods. Body forces induced by electric, electromagnetic, and magnetic means have been suggested for this purpose.

Dielectrophoresis is the name given to the process in which very strong electric fields are used to induce body forces in a dielectric (i.e., poorly conducting) fluid [10, 11]. The magnitude of the induced force is proportional to the gradient of the square of the electric field; that is, $\vec{F} \propto \text{grad}\,(\vec{E} \cdot \vec{E})$. By establishing an electric field in the liquid such that $\text{grad}\,(\vec{E} \cdot \vec{E})$ is constant in space and of the proper direction, the gravitationally induced body force, ρg_o, may be partially or completely cancelled. The liquid, then, will react statically and dynamically the same as if the only body force acting were equal to the difference between the gravitationally and electrically induced body force; in short, a true low-gravity simulation is possible. There are, however, several disadvantages to this method. An ac electric field is required, because, with dc fields, a layer of electric charge is gradually deposited on the free surface*; since the charges are all of the same sign, they repel each other, causing an effect just the opposite of surface tension and tending to make the free surface break up. When ac fields are used, the accumulation of charge can be kept low enough so that no instability occurs; the electrically induced body force, however, varies in magnitude at twice the frequency of the electric field variation. Furthermore, specially designed electrodes are required to give electric fields having the proper gradient. But the most stringent requirement is the extremely large electric fields needed to give reasonable body forces. Because of the limitations of high voltage generators currently available, it seems that, even here, small models are required if large electric fields are to be generated.† Dielectrophoresis would appear, then, to have no real advantages for studying liquid dynamics, although it does hold promise for such phenomena as boiling heat transfer, where the buoyancy of the vapor bubbles must be made zero, or in other cases in which the body force really should be very small rather than merely small in comparison to other forces.

Magnetohydrodynamic cancellation of gravity forces is another technique that can be used [12]. In this method, the additional body forces are caused by the interaction of crossed magnetic and electric fields. One such arrangement is shown in Figure 3. The tank is rectangular, and its length into the paper is supposed to be much greater than L (i.e., the tank is essentially

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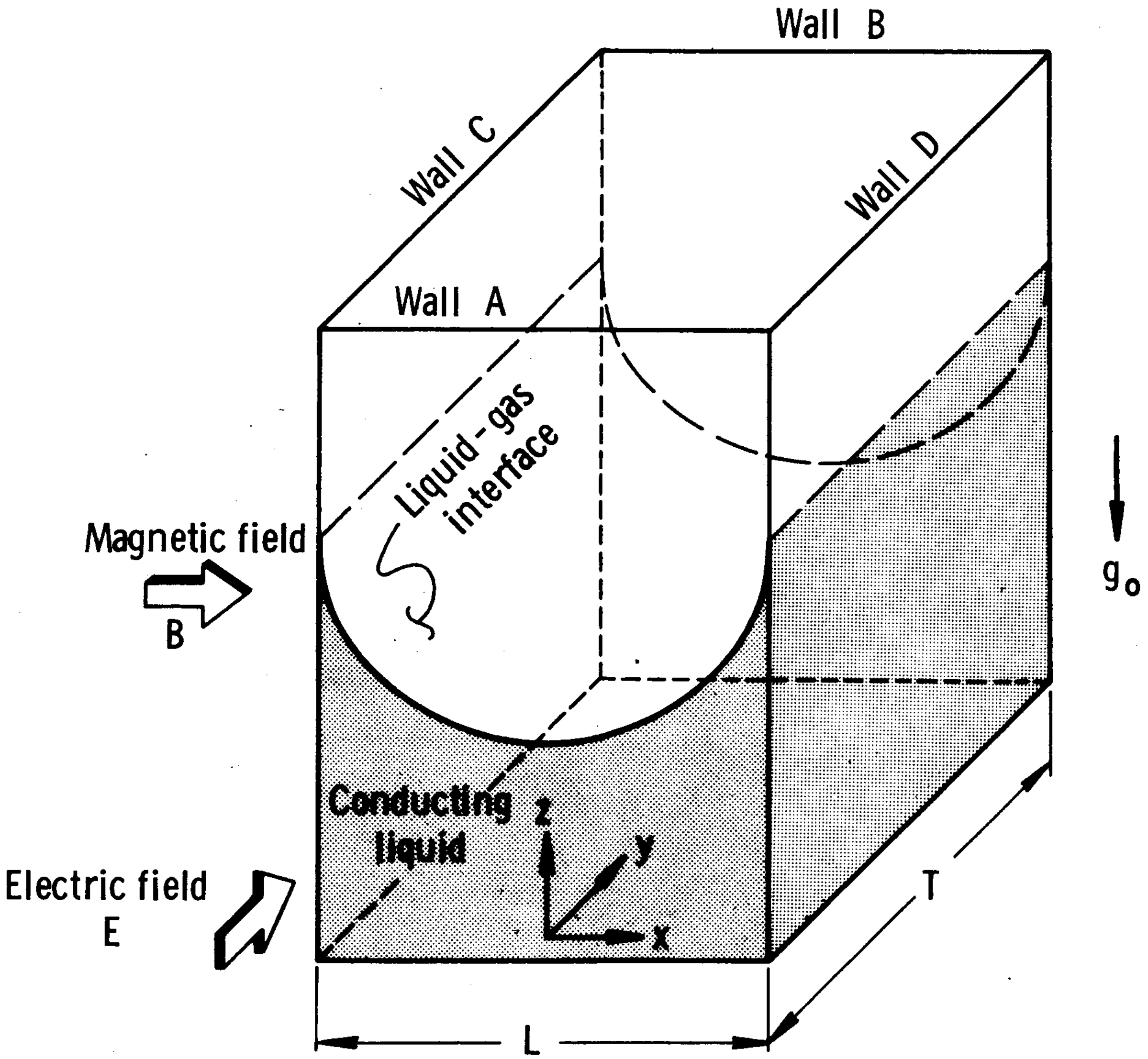
*No liquid is perfectly nonconducting. Thus, the applied electric field will cause some small current, which eventually results in an accumulation of charge at the free surface.

†The strength of the electric field is, roughly, equal to the applied voltage divided by the distance between the electrodes; thus, high fields require small models.



Walls A and B are conductive
Walls C and D are nonconductive
Note: $\frac{T}{L} \gg 1$

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Figure 3. MHD arrangement in rectangular tank

two-dimensional). The liquid is nonmagnetic and has a finite electrical conductivity, σ.

The net body force on a liquid particle is $-\rho g_o \vec{z} + \vec{J} \times \vec{B}$, where $\vec{J}$ is the current density and $\vec{B}$ is the magnetic field strength. If the fluid has a velocity $\vec{V}$, the current is $\vec{J} = \sigma(\vec{E} + \vec{V} \times \vec{B})$; except for small induced electromagnetic fields, the body force, then, is $[-\rho g_o + \sigma|\vec{E}||\vec{B}|]\vec{z} + \sigma(\vec{V} \times \vec{B}) \times \vec{B}$. By picking appropriate values of $\vec{E}$ and $\vec{B}$, the first term in the body force can be made as small as possible. Thus, for hydrostatic studies (i.e., $\vec{V} = 0$), a true low-gravity environment can be obtained. In dynamic studies, $\vec{V}$ is not zero (although if the excitation is in the x-direction, $\vec{V} \times \vec{B}$ is almost zero) and, thus, the influence of the small residual body forces should be evaluated.

It should be noted that both the magnetic field lines and the electric field lines should be straight and orthogonal to each other in the fluid if the electromagnetic body force is to be a constant and opposed to the gravitational body force. Now, the magnetic permeability of most conducting liquids is very close to that of air, and hence the magnetic field lines will remain straight regardless of the liquid's configuration. The electric field lines near the free surface, however, must bend around until the current is tangent to the free surface. Nonetheless, orthogonality can be closely approached in a two-dimensional situation by arranging the fields as shown in Figure 3. Unfortunately, this arrangement will not work in a three-dimensional case, so the magnetohydrodynamic technique appears to be most useful for two-dimensional geometries. One other drawback might be the necessity of cooling the liquid to dissipate the Joulean heat generated by the currents.

A third method of cancelling the gravitational body force is to use a magnetic fluid* in the presence of a suitably directed magnetic field. Papell and Faber [13] have employed such a method to study reduced-gravity boiling, with good results; the technique has also been described elsewhere [14, 15, 16, 17]. In this method, an ordinary fluid is made magnetizable by adding submicron size iron oxide particles to form a colloidal suspension; then, when in a magnetic field, a body force proportional to the gradient of the magnetic field is exerted on the fluid. If the fluid and its container are placed near the centerline of the core of a high quality solenoid-type electromagnet [13], the gradient of the magnetic field is constant and the magnetic body force induced in the liquid is also constant and can be directed so as to cancel, or partially cancel (depending on the strength of the field), the gravitational body force. Thus, here, as well as in the dielectrophoresis and magnetohydrodynamic techniques, an actual low gravity is created.

There appear to be no obvious disadvantages in the use of magnetic fluids, other than that the tank can be no bigger in diameter than about three inches, which is the core diameter of available large solenoid type electromagnets [13]. Since the magnetic field lines for such magnets run in the axial direction, any axisymmetrical or two-dimensional configuration can be used, in contrast to the magnetohydrodynamic technique; furthermore, the magnetic body forces induced by currently available magnets are sufficiently large to give true zero-gravity, in contrast to the small induced forces of

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*A more exact name is magnetizable fluid, since the fluid is not magnetic in the sense that it possesses a magnetic field.

currently available dielectrophoresis techniques. However, even in the best electromagnets, there is some variation in the magnetic field across the core diameter; the effect of this on the zero-gravity simulation needs to be assessed as well as possible anomalous surface effects that appear occasionally [14].

Other zero-gravity simulations are possible in special situations. Kana and Dodge [18] describe a method in which vapor bubbles appear to lose their buoyancy (i.e., are in zero-g) when placed in a pulsating pressure field. Kana and Chu [19] describe experiments in which neutrally buoyant bubbles are simulated by inflated balloons, counterweighted to cancel their buoyancy; this appears to be useful in preliminary studies of the behavior of vapor bubbles (or of the ullage bubble) in zero gravity. Saad and Debrock [1] have studied low-gravity liquid reorientation by using a particular form of free-falling liquid in conjunction with small diameter models.

Other simulation techniques will no doubt appear as research into zero-gravity fluid mechanics progresses, but the foregoing descriptions cover the most widely used methods currently being studied.

III. CONCLUSIONS

A number of techniques for simulating low-gravity fluid mechanics in a one-g environment have been described in this report. Except in a few instances, all the methods have in common the fact that only the liquid behavior is simulated; in those cases where the weight or density of the gas above the liquid is important, other simulation methods must be used. Furthermore, most of the remarks made apply only to situations in which the liquid behaves isothermally. It is possible, however, to simulate nonisothermal cases, such as heat transfer and stratification, by modeling the appropriate dimensionless parameters; for example, magnetic fluids [13] have been employed to study low-gravity boiling.

Two of the methods described appear to be the most promising ones for further work. Small diameter tanks give an adequate simulation of liquid dynamics in Bond number ranges greater than about ten; this method is fairly trouble-free and has been shown to be valuable in previous research [7 through 9]. The use of magnetic fluids can be used in the lower ranges of Bond numbers; this method has been employed previously in limited experiments [13 through 19] and is also the most practical way actually to cancel the existing gravitational body forces.

Certainly, these two laboratory techniques require further developmental work. But there are several reasons for pursuing this work. The cost of their development in relation to the development costs of orbital experiments, the only real alternative, is small indeed. Moreover, laboratory simulation experiments will be needed to guide orbital experiments, which are largely one-time-only affairs and which might not be designed properly without prior information. Likewise, a great deal of valuable information can be obtained by simulation experiments during the period before orbital experiments become practical. For these reasons, it seems that laboratory simulation methods will always be a needed tool in the investigation of low-gravity fluid mechanics.

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