# ELECTROHYDRODYNAMIC STABILITY OF A LIQUID BRIDGE - THE 'ALEX' EXPERIMENT

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## I. RESEARCH OBJECTIVES

G. I. Taylor's[2] leaky dielectric model describes electrohydrodynamic fluid motion driven by strong electric fields. We carried out microgravity experiments aboard the space shuttle Columbia during the LMS Mission in the summer of 1996 to test that theory. Our experiments dealt with the electrohydrodynamic stability of liquid bridges.

## II. BACKGROUND

Electrical forces can be used to manipulate fluids by controlling the shape of an interface or exerting a body force on bulk liquid. For example, liquids can be pumped or sprayed by an appropriately shaped electric field. For apolar liquids (such as organic compounds) where the conductivity is low, relatively high field strengths (1000 V/cm) are needed. Controlling the flow of liquids in micron-scale devices is also a rapidly emerging technology*. Here, the design of small scale fluid circuits depends, in part, on understanding the electrical forces and their relation to fluid motion; there are many other applications of electrohydrodynamics. Hence the need for a reliable, well-tested theory for designing apparatus. The current theory, the leaky dielectric model, was invented by G. I. Taylor[2] in the 1960's, but very few quantitative tests have been carried out[3]. We used a liquid bridge as a venue for our experiments. One reason for choosing the bridge configuration is it's simple geometry. In addition, studying the electrohydrodynamic stability enabled us to probe aspects of the theory which had not been previously accessible.

A liquid bridge is a column of liquid pinned to a flat plate at each end (figure 1). Over a century ago, Plateau found that a neutrally buoyant bridge is stable to small perturbations as long as its length, L, is less than it's circumference, $\pi d$ ($2a = d$, the diameter). Thus, for stability $L/d < \pi$. Interfacial tension plays a dual role. With short bridges, small perturbations are smoothed by the action of interfacial tension. Longer bridges become unstable, also due to interfacial tension. All this derives from the amount of new surface created by a perturbation relative to that in the base configuration. Electrical forces have profound effects. Charging the bridge to bring it to a high potential makes it more unstable since the radially directed electric field opposes surface tension. Conversely, a field aligned with axis of the bridge may stabilize it. The mechanism depends on the presence or absence of free electrical charge.

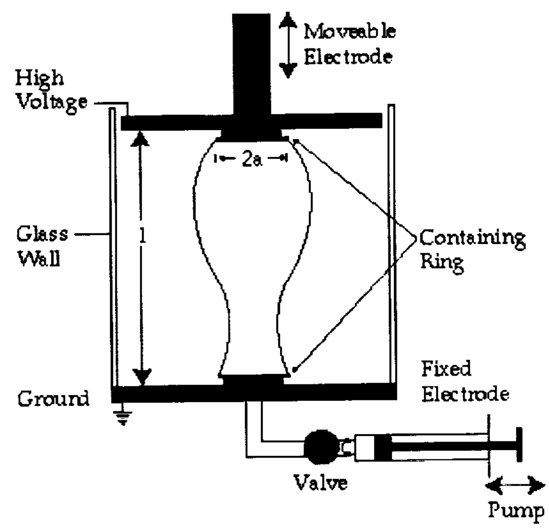



Figure 1. Schematic diagram of a liquid bridge, including features for altering the volume and imposing an electric field.

Fluid bodies composed of perfect dielectric liquids can be maintained in deformed states without motion. A perfect dielectric drop deforms into a prolate spheroid in an applied field and electrical stresses balance interfacial tension on the (static) deformed interface. Non-cylindrical equilibrium bridge configurations are possible, e.g., bridges stressed by an axial field. Bridges with $L/d > \pi$ can be stabilized, up to a point; stability derives from the arrangement of polarization charge induced on the interface.

A leaky dielectric material[1,2] behaves like a dielectric with a small conductivity. In such materials, free charge is transported by ion migration and these liquids behave as Ohmic conductors. The behavior of leaky dielectrics is quite different from perfect dielectrics because free charge congregates at interfaces due to the steep gradients in electrical properties. Thus, in contrast to the situation with a perfect dielectric, the deformation of droplet placed a steady field depends

* A recent newspaper article [*U. S. 1*, January 29,1997] reports work at Orchid Biocomputer, a company founded by the Stanford Research Institute and SmithKline Beecham on a technology for carrying out a multitude of chemical reactions on a microchip. Fluid management is by electrohydrodynamic pumping.

on the delicate balance of electrical, interfacial tension *and* hydrodynamic forces. A droplet of one fluid suspended in another may deform into a prolate spheroid whereas an oblate deformation ensues upon reversing the arrangement of fluids. Here the deformation and shape are dynamic.

A liquid bridge offers an excellent venue for studying electrohydrodynamic stability since its location is fixed by the pinned contact lines (c.f., figure 1). Following the motion of a droplet is more difficult due to translation in the applied field[4]. Buoyancy plays a major role in studying phenomena with free surfaces and, in terrestrial environments, often necessitates the use of an isopycnic system with a matrix fluid surrounding the fluid body of interest. Since interfaces play major roles in electrohydrodynamics this complicates matters greatly. For example, the influence of the electrical properties of both fluids and the interface must be understood, especially processes whereby charge crosses the interface. In our LMS experiment we avoided such problems by using a gas, sulfur hexafluoride - $SF_6$, as the matrix fluid. At the conditions of the experiment $SF_6$ behaves as a (very low viscosity) perfect dielectric gas. Neutrally buoyant liquid bridges may take on any one of three configurations: cylindrical, amphora (vase-like), or separated into two drops. In this experiment, the transitions between these three configurations were studied.

In our experiments the behavior of a given bridge is governed by two dimensionless groups: These are: the aspect ratio, $\beta = L/d$ and $\Delta = a\varepsilon\varepsilon_o E^2/\gamma$ which is the ratio of stabilizing electrical forces to destabilizing interfacial tension forces. The new symbols are: $\varepsilon$, the dielectric constant of the bridge fluid; $\varepsilon_o$, the permittivity of free space; E, the field strength; and $\gamma$, the interfacial tension. The other parameters are ratios of mechanical and electrical properties which are fixed for a given fluid pair.

## III. APPARATUS

The LMS experiment ALEX, an acronym for **A** Liquid **E**lectrohydrodynamics e**X**periment, was sponsored by NASA and the European Space Agency (ESA) with Daimler-Benz Aerospace as the prime contractor. Two Italian companies, Ferrari Engineering and Laben, were responsible, respectively, for the mechanical design and fabrication and electrical design, fabrication and integration. Trek Engineering (USA) built the high voltage power supply. Two test containers - TC4A & TC4B were manufactured and used in the Bubble, Drop & Particle Unit (BDPU), under the overall supervision of ESTEC, the scientific and technological arm of ESA. An especially noteworthy aspect of the experiment is that only 18 months elapsed between the science concept review and the flight aboard the space shuttle Columbia. During the LMS Mission, ALEX was operated by remote control from the Marshall Space Flight Center, Huntsville, Alabama. The success of the experiment demonstrates it is possible to carry out meaningful experiments within a short time span.

### *Test Container Configurations*

Each test container was equipped with a carousel apparatus housing three test cells. One test cell in each container contained a 2-phase mixture, similar to that used in terrestrial experiments to serve as a tie-in to ground-based work. The other two cells contained a single liquid to be suspended as a bridge in $SF_6$, a high field strength dielectric gas. Five of the six cells were operated successfully. In the other cell, a 2-phase cell, the bridge spilled from the retainer rings intended to hold the column in place. Nevertheless, useful video data were obtained. Overall, nearly 20,000 video images were acquired to depict various stages of the behavior of bridges in both dc and ac fields. Analysis of the images was carried out using image analysis software developed by MARS, an ESA subcontractor. Following the mission, the hardware was recalibrated to verify the data. None of the important calibrations changed, indicating that data collected during the mission are reliable.

### *Experiment Sequence*

The liquid bridge electrohydrodynamic experiments were conducted in a dynamic mode. For the two-phase experiments, experience with previous ground studies provided an estimate of the electric fields necessary for stability. However, since there was no theory or experimental data for single-phase configurations, the electric fields necessary for stability were determined via trial and error in flight. Thus, changes in the configuration were not pre-programmed, but determined based upon the progress of the experiment.

Before a stability experiment was performed, it was necessary to form a liquid bridge. In the two-phase experiments, a short bridge (~1 mm) was created when the TC was filled prior to the launch. For the single-phase experiments, the bridge was built in orbit to avoid spilling fluid from the containing rings during the launch. The first step was to inject a drop of fluid into the containing ring on the fixed electrode. Then the movable electrode was positioned 1.5 cm above the fixed electrode and 12 kV applied. At this field strength (8 kV/cm), the drop is pulled into a shape known as a Taylor cone. Electrical forces cause fluid to be ejected from the tip of the cone towards the movable electrode where it collects inside the containing ring on the electrode. As fluid was transferred from the fixed electrode containing ring, additional fluid was added until the movable electrode containing ring was filled and a drop of fluid visible. Then the voltage was removed and the electrodes brought together until the drops on the containing ring touched and coalesced. From this point, the single- and two-phase experiments proceeded in essentially the same fashion. The aspect ratio of the bridge was changed by moving the electrode and injecting or withdrawing fluid into the bridge at the appropriate volumetric rate so that a perfect cylinder was formed. At the outset, the aspect ratio was increased until it was close to the Plateau limit, $\pi$, and the bridge volume checked to ensure that the configuration was cylindrical. Fluid was added or withdrawn as necessary. Then the stability of the bridge at an aspect ratio just below $\pi$ was investigated.

Next, the aspect ratio was increased using an electric field to maintain a stable configuration. Commands were sent in real time to increase the field since the field needed for stability was not known *a priori*. Once the desired aspect ratio was achieved, the electric field could be raised or lowered in small steps to examine the transitions from cylinder to amphora and the pinch-off point. Between voltage steps, the bridge was allowed to assume a steady state configuration. After the pinch-off point was identified, the voltage could be increased to re-establish the bridge. Then, further increases in the field allowed the sequence of configurations leading to a perfect cylinder to be re-studied. Configurations were analyzed in real time using the image analysis program developed by MARS.

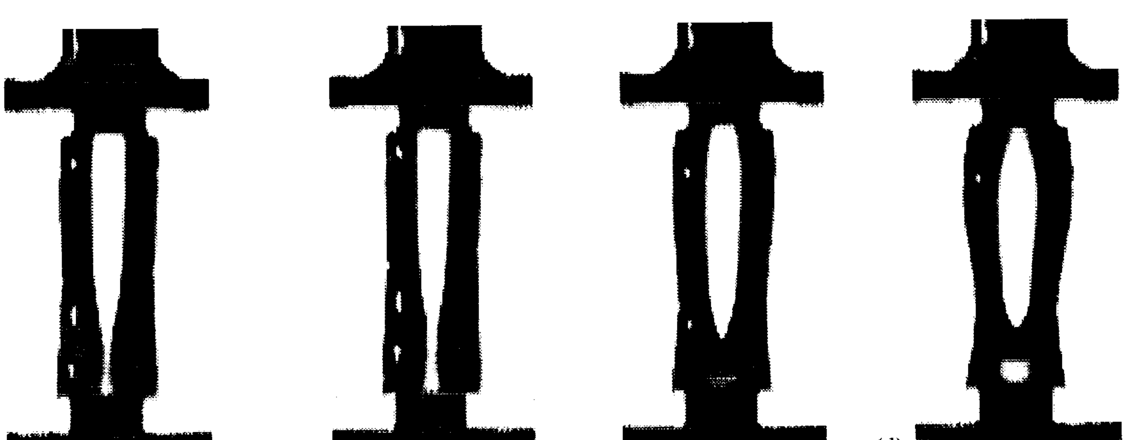
The image analysis algorithm produced digitized images and, from the edge coordinates, a trace of the bridge could be reconstructed. The edge coordinates were also used to calculate the Fast Fourier Transform (FFT) of the shape and minimum and maximum diameters. The processes of digitization and edge detection proceeded at a rate of 2 to 10 images per second.

It was important to observe a sequence of "equilibrium" bridge shapes to identify the various configurations (cf. Figure 2). Once a steady state configuration was established, the voltage was changed and shape changes monitored by following the evolution of the FFT coefficients and maximum or minimum diameter. A steady state configuration was defined as one which did not change during a certain period. Once steady state is achieved, the voltage was changed again and the process repeated.

Following the mission, all the image analysis was repeated in a more deliberate fashion. First, the telemetry data recorded in the ECIO data file was examined to determine when "events" occurred during the experiment. Events include changes in voltage, frequency, aspect ration, cell rotation, or pumping. The ECIO file was use instead of the MMI files saved during the mission since they include all of the LOS data. Next, the HRM data was reformatted and saved as a series of TIFF images which were then analyzed with a modified version of the MARS Image Analysis Software. The HRM data was used over the live video recordings since it has an accompanying time stamp allowing for the synchronization of the images with the MMI data. Over 17,000 images from the HRM data were analyzed in the previously described fashion.

The experiments conducted during the LMS mission examined the stability of six different liquid bridges for AC and DC fields. A total of 41 different experiments were conducted in two test containers, TC 4A and TC 4B, during two separate on-line periods. The experiments involved the effects of DC and AC field levels and frequencies on the stability of bridge with different aspect ratios. Sixteen experiments were conducted the first night, and 25 the next. Each test container had two single-phase and one two-phase liquid bridge experiment. Selected results are described in the following sections.

Other than an accidental camera dislocation and a minor problem with a limit switch, the test containers and BDPU hardware performed flawlessly. Also the support teams performed magnificently. Support in the POCC by Dornier, MARS, Alenia, Teledyne Brown, NASA, and ESA was invaluable to the success of our experiment. An additional support team made up of engineers from Laben and Ferrari were on hand in Italy but were not utilized extensively during the mission -- a testament to the job done prior to the



(a) (b) (c) (d)

Figure 2: Deformation of a castor oil bridge in $SF_6$ with a decreasing electric field.
Electric field parameter: (a) = .4, b = .25, = .24, = ..

launch in fabricating and filling the test containers.

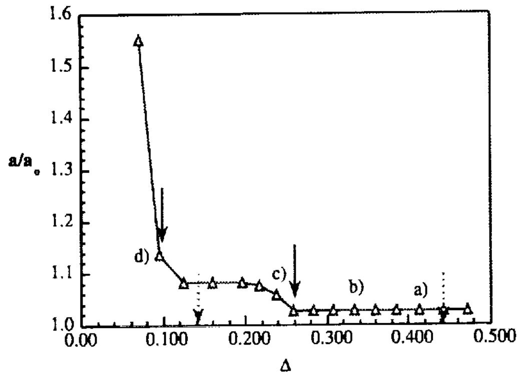



Figure 3: Maximum bridge radius - electric field parameter relation for a decreasing field. Points correspond to configurations noted in figure 2.

## IV. COMPARISON OF FLIGHT AND GROUND-BASED RESULTS

With the two-phase system, transitions from cylinder to amphora and the pinch-off point were found to agree closely with the results of Sankaran and Saville[4] after taking account of the difference between the properties of the two system. The transition from cylinder to amphora occurred at $\Delta = 0.195$, and pinch-off at $\Delta = 0.057$ at $\beta = 3.36$. This compares to the values of $\Delta = 0.18$ and 0.03 reported by Sankaran and Saville[4] for the transition and pinch-off points respectively. This agreement between μ-g and 1-g experiments validates the performance of the flight system for steady fields.

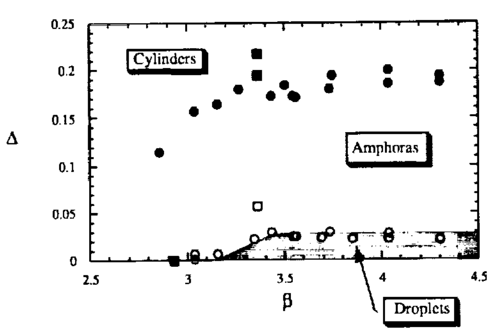



Figure 4: A comparison of flight and ground-based results in a two-phase system. ● & ○ - terrestrial experiments; ■ & ❑ - μg experiments.

## V. COMPARISON BETWEEN THEORY AND EXPERIMENT

At the time of the experiment the leaky dielectric model had not been used to predict the behavior of a pinned bridge. Since that time, C. L. Burcham has completed calculations[5] to predict the stability of a liquid, leaky dielectric bridge in a dielectric gas. Some results are shown in figure 5.

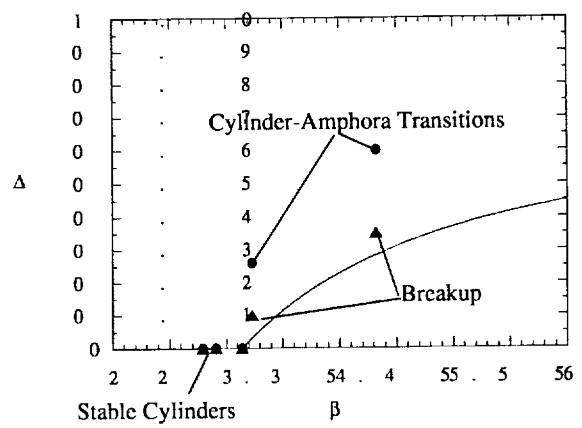



Figure 5: Comparison between theory and experiment The solid line is the theoretical demarcation between stable and unstable cylindrical bridges.

As the figure indicates, theory and experiment disagree. The reasons for this are not yet understood. One possible mechanism is surface conduction, which is not part of the theory presented here. A liquid-gas interface would amplify effects of this sort.

## VI. SUMMARY & CONCLUSIONS

The ALEX apparatus performed as designed and produced a considerable amount of useful data. The primary goal, to provide data to test the leaky dielectric model in the liquid bridge configuration, was achieved.

## VII. ACKNOWLEDGMENTS

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