Paramagnetic Liquid Bridge in a Gravity-Compensating Magnetic Field*

Milind P. Mahajan, Mesfin Tsige, P.L. Taylor, and Charles Rosenblatt
Department of Physics
Case Western Reserve University
Cleveland, OH 44106-7079

Liquid bridges supported by two solid surfaces have been attracting scientific attention since the time of Rayleigh and Plateau. For a cylindrical bridge of length *L* and diameter *d*, it was shown theoretically that in zero gravity the maximum slenderness ratio *R* [•••*L/d*] is π. The stability and ultimate collapse of such bridges is of interest because of their importance in a number of industrial processes and their potential for low gravity applications. In the presence of gravity, however, the cylindrical shape of an axisymmetric bridge tends to deform, limiting its stability and decreasing the maximum achievable value of *R*. It has been shown, for example, that the stability limit *R* can be pushed beyond π by using flow stabilization, by acoustic radiation pressure, or by forming columns in the presence of an axial electric field. In this work, we describe experiments in which magnetic levitation was used to simulate a low gravity environment and create quasi-cylindrical liquid columns in air. Use of a magnetic field permits us to continuously vary the Bond number

$$B \quad \frac{g\rho d^2}{4\sigma}$$

, where *g* is the gravitational acceleration, ρ is the density of the liquid, and σ is the surface tension of the liquid in air. The dimensionless Bond number represents the relative importance of external forces acting on the liquid column to those due to surface tension. Our central result is that in a large magnetic field gradient we could create and stabilize columns of mixtures of water and paramagnetic manganese chloride tetrahydrate ($MnCl_2 \quad 4H_2O$), achieving a length to diameter ratio very close to π.

The principle of magnetic compensation of gravity is straightforward. For a material of volumetric magnetic susceptibility χ in a magnetic field H, the energy per unit volume is given by U = -_χH^2, and the force per unit volume is -MU. To compensate gravity it is required that

$$?\chi \quad H^2_{comp} \quad \rho g$$

, where H_{comp} corresponds to the magnetic field whose gradient just compensates gravity. For H^2 larger or smaller than 2ρg/χ, the liquid will rise or sag in the column, ultimately causing the column to collapse if H^2 deviates too significantly from its gravity-compensating value. Thus the effective force on the column may be controlled by varying the current in the magnet.

Two aluminum rods were machined to have cylindrical tips at their ends that are d = 0.32 cm diameter and 1.27 cm long. The pair was placed vertically in the magnet at x =0, such that the small tips faced each other. The upper rod was attached to a precision micrometer to facilitate adjustment of its position along the z-axis relative to the lower tip. The lower tip was placed at this position so that the center of the liquid column would be at the approximate maximum in $H_x f_z H_x$. A boroscope attached to a CCD camera was positioned along the y-axis to view the liquid bridge, and the images were recorded with a video cassette recorder. The magnetic field was adjusted so that H^2 approximately corresponded to H^2_{comp}, and liquid was injected into the gap. The upper tip was then translated upward using the micrometer, thereby creating a liquid cylinder between the two tips. For the longest cylinders (0.8 < L < 1.0 cm), the shape of the cylinder was found to be extremely sensitive to magnetic field: We found that if $H_x f_z H_x$ were to deviate from 2.57 x 10^7 G^2 cm^{-1} [defined as $(H_x f_z H_x)_{comp}$] by more than 1%, a noticeable bulge in the cylinder would appear near the top (for too large a field) or the bottom (for too small a field). Thus, knowing the density

---

* Based on project *Determination of the Surface Energy of Smectic Liquid Crystals From the Shape Anisotropy of Freely Suspended Droplets*

ρ and $(H_x f_z H_x)_{comp}$, we were able to extract the volumetric magnetic susceptibility of the water/salt mixture (per cm^3) $\chi = \dfrac{\rho g}{(H_x f_z H_x)_{comp}} = (5.54 \pm 0.05) \times 10^{-5}$.

For our experiment the Bond number B must be redefined to include the effects of the magnetic field, *viz.*,

$$B \quad \frac{(\rho g - \chi H_x f_z H_x) d^2}{4\sigma}.$$

Columns of a given slenderness ratio *R* were created and stabilized in a magnetic field gradient, such that $(H_x f_z H_x)_{comp} = 2.57 \times 10^7\ G^2\ cm^{-1}$; this corresponds to B = 0. Then B was varied either positively or negatively by decreasing or increasing the magnetic field from its value H_{comp}. For a given *R* there was some maximum and minimum field, corresponding to a negative and positive Bond number, beyond which the column could no longer be sustained and catastrophically collapsed. Our results for the stability limits (maximum Bond number for a given *R*) are in good agreement with the predictions of Coriell *et al.* [*J. Colloid Int. Sci.*, 60, 126 (1977)].

Unlike experiments in density-matching fluids, the magnetic approach facilitates measurements of the fluid in an air environment, as well as a *continuous* change of Bond number by varying the magnetic field. Studies of smectic liquid crystalline bridges are currently underway. These exhibit interesting behavior and much higher stability because of their viscoelastic properties, including shear-thinning and the existence of a yield stress.