Paramagnetic liquid bridge in a gravity-compensating magnetic field

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Magnetic levitation was used to stabilize cylindrical columns of a paramagnetic liquid in air between two solid supports. The maximum achievable length to diameter ratio $R_{\max}$ was $\sim(3.10\pm0.07)$, very close to the Rayleigh–Plateau limit of π. For smaller R, the stability of the column was measured as a function of the Bond number, which could be *continuously* varied by adjusting the strength of the magnetic field.
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INTRODUCTION

Liquid bridges supported by two solid surfaces have been attracting scientific attention since the time of Rayleigh[1] and Plateau. For a cylindrical bridge of length L and diameter d, it was shown theoretically that in zero gravity the maximum slenderness ratio $R[\equiv L/d]$ is π.[1] 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. Theoretical studies have discussed the stability and possible shapes of axisymmetric bridges.[2–6] Experiments in reduced gravity have also focused on these issues. Experiments typically are performed in either a Plateau tank, in which the bridge is surrounded by a density-matched immiscible fluid,[7–9] or in a space-borne microgravity environment.[10] It has been shown, for example, that the stability limit R can be pushed beyond π by using flow stabilization,[6] by acoustic radiation pressure,[7,9] or by forming columns in the presence of an axial electric field.[8] In this paper we report on 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 $B\equiv g\rho d^2/4\sigma$, 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 ($MnCl_2\cdot 4H_2O$), 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 $U=-\frac{1}{2}\chi H^2$, and the force per unit volume is $-\nabla U$. To compensate gravity it is required that $\frac{1}{2}\chi\nabla H^2_{\text{comp}}\approx\rho g$, where H_{comp} corresponds to the magnetic field whose gradient just compensates gravity. For ∇H^2 larger or smaller than $2\rho g/\chi$, 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.

EXPERIMENT

An electromagnet fitted with special Faraday pole pieces was used to produce ∇H^2 uniform to approximately 6% over the length of a 1-cm-long column. In order to determine the field profile, a Bell model 9000 Gaussmeter utilizing a Hall effect probe was used to measure H_x as a function of vertical position z (see Fig. 1) along the symmetry plane ($x=0$) of the magnet. For all practical purposes, the field profile is translationally invariant along the y-axis, and therefore the y coordinate does not enter into the problem. Experimental values of both H_x and the product $H_x\partial_z H_x$ are shown as functions of z in Fig. 2. Note that along the plane $x=0$ the z-component of field H_z vanishes, although a small component of H_z exists for $x\neq0$. This small component may give rise to a slight distortion of the cylinder perpendicular to its symmetry axis, and will be discussed below. Nevertheless, over the small diameter of the columns $H_z\partial_z H_z$ remains small, and ∇H^2 is dominated by $H_x\partial_z H_x$; we shall therefore consider the z-component of force to be $\chi H_x\partial_z H_x$.

Manganese chloride tetrahydrate was obtained from Aldrich Chemicals and used as received. A high-concentration mixture of 62.5 wt. % $MnCl_2\cdot 4H_2O$ in distilled water was prepared. By weighing a known volume of the mixture, its density was determined to be $\rho=(1.45\pm0.01)\ \text{gm cm}^{-3}$. The surface tension σ in air was measured to be $(116\pm6)\ \text{ergs cm}^{-2}$ by the pendant drop method.[11,12] To establish a confidence level for this technique, the measurements were repeated with both pure water and glycerol, where the measured values of σ were found to scatter within ±5% of accepted values in the literature.

Figure 1 shows a sketch of the apparatus. Two $\frac{1}{2}$-in.-diameter 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 adjust-