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Electrostatic cancellation of gravity effects in liquid mixtures

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We point out that a spatially varying electric field can be used to cancel the effect of gravity in liquid mixtures by coupling to the different components' permittivities. Cancellation occurs if the system under consideration is small enough. For a simple "wedge" electrode geometry we show that the required system size and voltage are practical, and easily realizable in the laboratory. Thus this setup might be a simple alternative to other options such as the space shuttle, drop-tower, or magnetic levitation experiments.

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The gravitational force brings about unwanted effects in many experiments where phase transitions are studied. Buoyancy effects in liquid mixtures and colloidal suspensions, for example, become increasingly important close to the critical point. A common approach to negate gravity is to use a rocket, a plane, or a drop-tower facility [1]. The space shuttle is an expensive and risky alternative which becomes less and less obvious. A second approach consists of using magnetic levitation to compensate gravity forces [2]. In this case, too, the experimental setup, based on a superconductor, is complicated and expensive.

We propose here an alternative based on negating gravity forces by using electrostatic forces in a wedge geometry. We consider for simplicity a binary mixture of two liquids A and B with dielectric constants ε_A and ε_B and densities ρ_A and ρ_B, respectively. The critical exponents, after the gravity effect had been negated, are the same for all systems in the same (Ising) universality class. The coupling of the gravitational force to the densities of the two liquids contributes a free-energy density

$$F_g = [\rho_0 + (\rho_A - \rho_B)\phi]gh. \tag{1}$$

Here, g is the gravitational acceleration, ϕ is the local A-component mixture composition $(0<\phi<1)$, h is a height above some fixed reference, and the mixture density $\rho(\phi)$ is given by a linear relation, $\rho(\phi)=\rho_0+(\rho_A-\rho_B)\phi$.

As pointed out before [3,4], a field varying like $E\sim\sqrt{h}$ is needed to cancel gravity, because in this case $E^2\sim h$ is linear, just like the gravitational field. On the other hand, E^2 always varies linearly if the spatial extent under consideration is small enough, and here we suggest one geometry where the linear dependence on the spatial coordinate can be used in a practical device.

The liquid mixture should be confined in an apparatus consisting of two "wedge"-shaped electrodes, see Fig. 1. The electric field then couples to the different dielectric constants of the components and can counteract gravity. In a uniform medium, the electric field **E** points in the azimuthal direction and its amplitude is

$$E = V/\theta r, \tag{2}$$

where θ is the opening angle of the wedge, r is the distance from the origin, and V the potential difference between the two plates. The electrostatic contribution to the free-energy density of the mixture is given by $F_{\mathrm{es}}=-\frac{1}{2}\varepsilon\mathbf{E}^2$. For small density variations, as is relevant close to a critical point, one can expand $\varepsilon(\phi)$ to linear order in ϕ: $\varepsilon=\varepsilon_0+(\varepsilon_A-\varepsilon_B)\phi$.

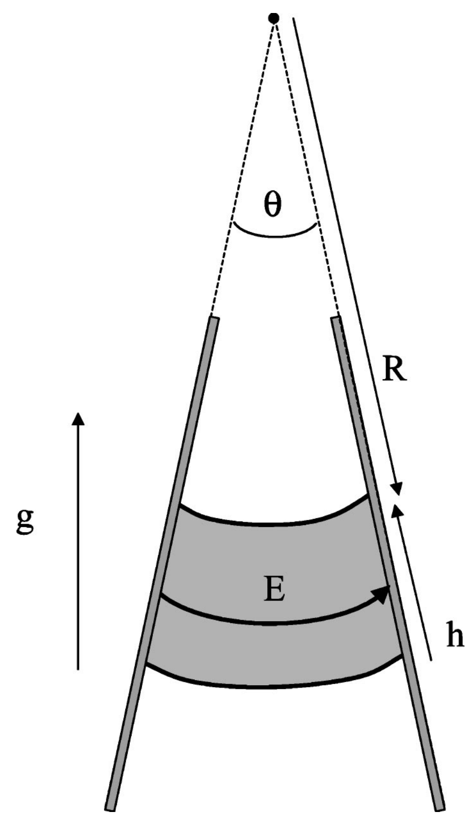

FIG. 1. Illustration of the suggested geometry. Two flat electrodes with voltage difference V are tilted with an angle θ. In the mixture (shaded region), situated at distance R from the imaginary meeting point, the field $E=V/\theta r$ is azimuthal. $h\ll R$ is the height above a fixed reference point. The setup shown assumes $\rho_A>\rho_B$ and $\varepsilon_A>\varepsilon_B$, otherwise it should be turned upside down.

In equilibrium, density variations will be azimuthal (they will depend on r only), since any deviation from such a density profile costs energy [5,6]. In this case, the solution of Laplace's equation for the field is still $E=V/\theta r$. In the experiment, the system should be confined to a small region whose extension is much smaller than R and the angle θ should be small. In this case it is possible to expand r around R and obtain the electrostatic contribution to the free energy

$$F_{\mathrm{es}} \simeq -[\varepsilon_0 + (\varepsilon_A - \varepsilon_B)\phi]\frac{V^2}{\theta^2 R^3}h + \text{const.} \quad (3)$$

Hence, considering terms linear in ϕ in Eqs. (1) and (3), one finds that the electrostatic and gravitational free-energy densities exactly cancel throughout the whole sample volume if

$$(\rho_A - \rho_B)g = (\varepsilon_A - \varepsilon_B)\frac{V^2}{\theta^2 R^3}. \quad (4)$$

Let us examine the numerical values of the parameters required for this method to work. For concreteness we consider a methanol-cyclohexane mixture, where the density difference is $\rho_A - \rho_B \simeq 130\ \mathrm{kg/m^3}$, and the permittivity difference is $\varepsilon_A - \varepsilon_B \simeq (31.6\times 8.9)\times 10^{-12}$ F/m. At a voltage of $V=100$ V and opening angle $\theta=5°$, we find that $R=1.4$ cm. This value of R means that the system itself (with dimensions $h \ll R$) cannot be larger than a few millimeters. However, decreasing the opening angle to 1° and increasing V to 500 V shows that R is much larger, $R=12$ cm, allowing for a correspondingly larger system size. The corresponding fields for the two cases above are $E=V/\theta R = 8.1\times 10^4$ V/m and $E=2.4\times 10^5$ V/m, well below dielectric breakdown. At these rather low fields, the field-induced shift of the critical temperature is found to be negligible (smaller than 4×10^{-5} K) [7,8].

The device proposed by us can thus be easily realized in the laboratory. In order to avoid problems of charge injection it would be advisable to use moderate frequency ($\gtrsim 1$ kHz) ac fields. The device suggested (and other geometric variants) has many advantages over airborne and magnetic devices; the most obvious ones are the simplicity and small price of the setup.

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