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Novel method for measuring surface tension

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ABSTRACT

It is shown that the observed geometry of an electrostatic deformation of a liquid surface can be used for the measurement of surface tension. Based on simulations and measurements, an empirical formula for the relation between the shape of the deformation and the surface tension is derived and discussed. A novel method for high resolution measurements of the surface tension using interferometry of an electrostatically deformed liquid surface is presented and investigated.

1. Introduction

The shape of a liquid interface is defined by the forces acting on the liquid and can be deformed by an electrostatical force. This phenomenon has been used to characterize properties of liquids including deformation profiles through the observation of the liquid surface with a microscope [1]. The use of an alternating current at frequencies too high for the liquid surface to follow has been used to measure surface tension, interfacial tension, and viscosity by measuring the time constants of transient behavior [2]. Another method of measurement involving the transient behavior of the liquid uses the deflection of a beam of light by the deformed liquid surface [3–5]. However, the measurement of transients involves obvious drawbacks and the measurement of the shape of a liquid surface by adjusting a microscope is not very precise. In the present work we offer a novel method to easily and robustly measure the surface tension of a liquid.

Several established methods for the measurement of the surface tension of a liquid already exist, each having certain advantages and disadvantages. The capillary rise method is very simple, but requires fairly large liquid volumes and that the materials used are thoroughly cleaned, as do the Wilhelmy plate and du Noüy ring methods. The latter two methods measure the force of the liquid surface exerted on a plate and ring, respectively, which also requires large amounts of liquid and involves the use of a precision scale. The pendant drop and sessile drop methods, on the other hand, only require minute amounts of liquid as the surface forces will cause small volumes to have a spherical shape that is distorted by the effect of gravity. The surface tension can then be calculated from certain parameters or the entire profile of the drop or bubble by an algorithm. However, manual calculations suffer from low accuracy while automated systems can cost up to \$100,000 [6,7].

The method proposed here has no requirements regarding the materials or liquids used and does not involve any moving parts. The calculation of the surface tension from the measurement data is similar to the pendant/sessile drop method, inasmuch that the surface tension is computed by an algorithm, but involves the measurement of only a single parameter that is determined with high precision through interferometry.

2. Theory

There are three forces acting on each element of the liquid surface:

- electrostatic force,
- surface tension, and
- gravity.

The equilibrium situation in which all forces cancel each other is described by:

$$F_{elec} - F_{grav} - F_{surface} = 0 \quad (1)$$

Electrostatic deformation can be caused by a flat electrode positioned parallel to the liquid surface. The electric field at the surface of the liquid created by applying a voltage to an electrode above the liquid is oriented perpendicular to the surface. The gravitational

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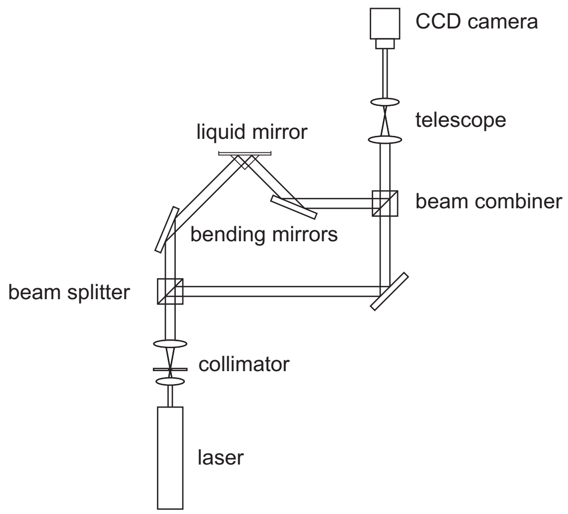

Fig. 1. Experimental setup for measuring the deformation of the electrostatically deformed liquid surface.

force acts only in the vertical direction pulling the liquid down while the only force having a horizontal component is the surface tension which results in a smoothing of the surface deformation.

Without surface tension there is no horizontal component and the surface deformation would be a column of liquid with the footprint of the shape of the electrode rising out of the liquid. With infinite surface tension the electrostatic force would have to pull up the liquid over the entire surface of the liquid container. These two extremes show that the width of the induced surface deformation depends both on the geometry of the electrode and on the surface tension of the liquid, making this method suitable for measuring surface tension. Further analysis of the geometry indicates that a higher surface tension pulls up more liquid outside the footprint of the electrode making the actual width of the deformation also dependent on the gravitational force, i.e. the density of the liquid.

From an analysis of the units it is expected that the width of the induced deformation, w, is given by the formula:

$$w = a + b \cdot r + c \cdot \sqrt{\frac{\gamma}{\rho \cdot g}} + \text{higher orders}(r, \rho, \gamma) \quad (2)$$

with r the radius of the electrode, γ the surface tension, ρ the density of the fluid, g the gravitational constant, and a, b, and c constants to be determined. The constants themselves may be functions of r and ρ. The term $\sqrt{(2 \cdot \gamma)/(\rho \cdot g)}$ is called the capillary constant and indicates the length scale on which effects of surface tension will be comparable to effects of gravity [8].

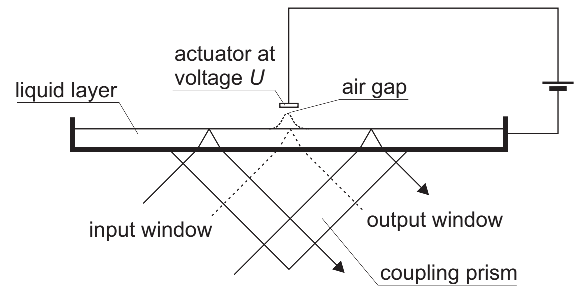

Fig. 2. The liquid mirror device.

3. Method

An interferometer (Fig. 1) including a liquid mirror based on total internal reflection [9] is used for the observation of the deformation of the liquid surface. A collimated laser beam is split into two paths, one of which is coupled into the liquid container. The light enters the metal container through a transparent coupling prism mounted into a window in the bottom of the container (Fig. 2). The beam is reflected by the liquid surface by total internal reflection and coupled out of the container by way of the same coupling prism. The beams are then recombined to form an interference pattern showing the shape of the surface. Above the liquid surface an electrode structure is positioned to which a voltage can be applied while the metal container remains at ground potential. When no voltage is applied the liquid is flat (Fig. 3, left), while a voltage applied to the electrode induces a surface deformation (Fig. 3, right).

The amplitude and width of the deformation can be determined with high resolution from the interferograms.

Measurements with an electrode structure and a thin metal rod shown in Fig. 4 were performed on glycerin and water at different distances between the electrode and the liquid surface. In order to validate the measurement method extensive simulations were carried out.

4. Simulations

The shape, u, of the deformation of the liquid surface, in the assumption of some nonzero conductivity of the liquid, is described by a differential equation that can be solved numerically [9]:

$$\frac{\varepsilon\varepsilon_0 U^2(x,y)}{2d^2} - (\rho g - k)u - \gamma\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) = 0 \quad (3)$$

with ε the dielectric constant of the gas filling the gap, U the electric potential, d the distance between the electrode and the liquid surface, ρ the density of the liquid, g the gravitational constant, k

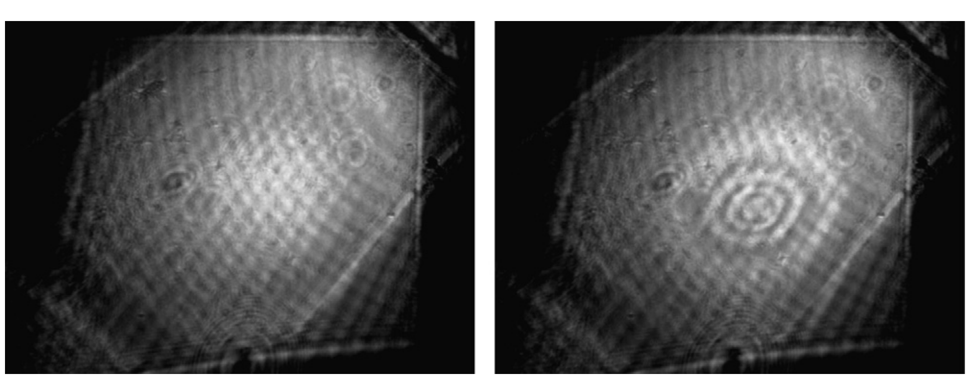

Fig. 3. Flat liquid surface (left) and an electrostatically deformed liquid surface (right).