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Electrowetting — From statics to dynamics

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ABSTRACT

More than one century ago, Lippmann found that capillary forces can be effectively controlled by external electrostatic forces. As a simple example, by applying a voltage between a conducting liquid droplet and the surface it is sitting on we are able to adjust the wetting angle of the drop. Since Lippmann's findings, electrocapillary phenomena – or electrowetting – have developed into a series of tools for manipulating microdroplets on solid surfaces, or small amounts of liquids in capillaries for microfluidic applications. In this article, we briefly review some recent progress of fundamental understanding of electrowetting and address some still unsolved issues. Specifically, we focus on static and dynamic electrowetting. In static electrowetting, we discuss some basic phenomena found in DC and AC electrowetting, and some theories about the origin of contact angle saturation. In dynamic electrowetting, we introduce some studies about this rather recent area. At last, we address some other capillary phenomena governed by electrostatics and we give an outlook that might stimulate further investigations on electrowetting.

Contents

Abbreviations: AC, alternating current; DC, direct current; EWOD, electrowetting on dielectric; HD, hydrodynamic (model); MK, molecular kinetic (theory); A, area (m^2); C, capacitance per unit area (F/m^2); E, electric field strength (V/m); F, force (N); H, drop height (m); H^*, characteristic drop height (m); L, characteristic length (m); L_C, capillary length (m); R, drop wetting radius (m); R^*, characteristic drop radius (m); R_0, initial drop radius; T, absolute temperature (K); U, contact line velocity (m/s); U^*, characteristic contact line velocity (m/s); V, voltage, applied potential (V); V_S, saturation voltage (V); V_{th}, threshold voltage (V); V_{eff}, effective voltage (V); c, coefficient; d, thickness (m); f, frequency (Hz); f_0, molecular jump frequency (Hz); f_C, critical frequency (Hz); g, gravitational acceleration (m/s^2); k_B, Boltzmann constant; l, slip length (m); t, time (s); α, wetting exponent; γ, surface tension (N/m); γ_{LS}, liquid–solid interfacial tension (N/m); γ_{SV}, solid–vapor interfacial tension (N/m); ε, relative permittivity; ε_0, free space permittivity; λ, molecular displacement (m); μ, viscosity (Pa s); θ_{eq}, equilibrium contact angle; θ, contact angle; θ_A, advancing contact angle; θ_R, receding contact angle; $\Delta\theta$, contact angle hysteresis; ρ, density (kg/m^3); σ, conductivity (S).

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1. Introduction

Wettability is a key parameter to describe the chemical–physical properties of a surface and is usually characterized by a very simple method: measuring the angle of contact – or wetting angle – of a droplet of a test liquid with the surface. Triggered by many industrial applications, such as coating, printing, cleaning, or friction and wear control, many chemical or physical methods have been developed to control the wettability of surfaces [1–3]. Eventually, lyophilic, superlyophilic, lyophobic and superlyophobic surfaces can be fabricated in laboratory by modifying the surface chemistry and introducing multiscale physical roughness [1–3]. Such surfaces maintain their wetting properties over some time, but do not allow for an active control of their wettability after being manufactured. In practical applications, however, active control of the wettability is more attractive. Indeed, smart approaches such as thermal tuning [4,5], optical switching [6], as well as electrostatic controlling of contact angles [7,8] have been developed. Among them, the electrostatic method is the most popular one due to its real-time actuation, fast response, long term reliability, and good stability of the actuation.

During his works, Lippmann found that applying a voltage between mercury and aqueous electrolytes allowed for controlling the position of the mercury meniscus in a capillary. In 1875, he was probably the first to report this *electrocapillary* phenomenon, which is at the foundations of electrowetting [9]. He further proposed a physical model and developed a number of applications. Later, Möller [10], Frumkin et al. [11], Gorodetskaya and Kabanov [12], Smolders [13], and Nakamura et al. [14] conducted contact angle measurements at the mercury/metal-electrolyte interfaces. They found that the contact angle decreased with applied potential, and argued that the decrease of contact angle was due to the change of interfacial energy [10–15]. However, Lippmann's discovery and the other works did not attract much attention until the 1980s, when the term *electrowetting* was coined and proposed for designing display devices [16,17]. Since then, electrowetting started to develop rapidly and nowadays it has been successfully applied in areas like lab-on-chip systems [18–20], adaptive optical lenses [21], electronic display technology [17,22], or mixing in microfluidic channels [23,24]. In principle, electrowetting can be applied to drops sitting on a bare electrode, or on thin dielectric layer on top of an electrode. However, most of the recent electrowetting studies and applications are carried out on dielectric, giving rise to the definition of *electrowetting-on-dielectric* (EWOD).

In this review, we focus on the latest progress on some fundamental aspects of electrowetting. In Section 2, we give a short description of the basics of static and dynamic wetting. Section 3 is devoted to static electrowetting. We will discuss the basic phenomena in DC and AC electrowetting, as well as the contact angle saturation (CAS) phenomenon. In Section 4, recent results about fast and low speed electrowetting will be presented. Finally, we briefly address some other interesting capillary phenomena governed by electrostatics.

2. Wetting fundamentals

2.1. Contact angle and contact angle hysteresis

2.1.1. Contact angle

When a liquid drop is brought into contact with a solid surface, the drop spreads on the surface to minimize the free energy of the system. Eventually, the drop comes to rest on the surface in a minimum energy state. If the drop size, R_0, is smaller than the capillary length, L_C, e.g. $R_0 \ll L_C = \sqrt{\frac{\gamma}{\rho g}}$, with γ and ρ respectively the surface tension and the density of the liquid and g the acceleration due to gravity, the gravity does not distort the spherical drop shape and can thus be neglected [25]. This condition is usually satisfied in all published electrowetting studies. For chemically and physically homogenous surfaces, the drop in equilibrium adopts a spherical cap shape, as shown in Fig. 1. The equilibrium contact angle, θ_{eq}, near the contact line is determined by the interfacial tensions, γ_{LV}, γ_{LS}, and γ_{SV} at the liquid–solid–vapor interfaces.

$$\cos\theta_{eq} = \frac{\gamma_{SV} - \gamma_{LS}}{\gamma} \tag{1}$$

Usually, γ_{LV} is denoted as γ for brevity. The above equation is called *Young*'s equation, in honor of Thomas Young who expressed it with words in his work published in 1805 [26]. Young's equation can be derived either from a mechanical perspective [1,3] or from a thermodynamic perspective [27]. θ_{eq} is a useful parameter to characterize the wettability of surfaces, as one can easily relate the contact radius R to θ_{eq} with

$$R = R_0 \sin\theta_{eq} \left[\frac{4}{\left(1 - \cos\theta_{eq}\right)^2 \left(2 + \cos\theta_{eq}\right)} \right]^{1/3}. \tag{2}$$

Taking the limit as $\theta_{eq} \to 0°$, we find $R \to \infty$ which means the liquid tends to wet the surface completely. While if $\theta_{eq} \to 180°$, we obtain $R \to 0$, which reflects that the surface repels the liquid extremely.

2.1.2. Contact angle hysteresis

Natural surfaces are decorated with physical roughness or chemical moieties. The physical or chemical heterogeneity of surfaces leads to deviations of the contact angle from the one predicted by Young's equation. Pinning of the contact line of a wetting/dewetting drop due

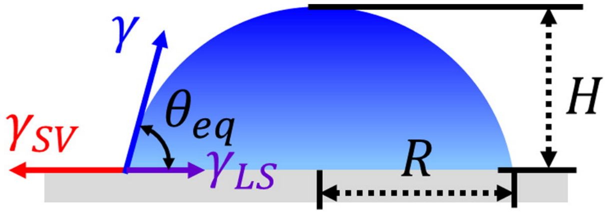

Fig. 1. Sketch of a drop sitting on a solid substrate in equilibrium.

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