How the liquid contact angle saturates by the electrowetting effect

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Abstract – We present a rigorous analytical analysis of the electric force at a perfectly conductive wedge formed by the wetting angle of a liquid droplet on an insulated electrode using the Maxwell stress tensor, which leads to a macroscopic explanation of the contact angle saturation phenomenon in electrowetting [1, 2]. The electrowetting effect is nowadays being widely used as a liquid actuation mechanism in a wide range of microfluidic applications such as lab-on-a-chip systems in medicine [3], variable focus lens in electro-optical devices or in display technology [1, 2]. This actuation mechanism relies on the precise manipulation (change) of the liquid wetting angle using the electric force, and is limited by the still not fully understood saturation phenomenon.

When applying a voltage on the perfectly conductive droplet placed on an insulated counter electrode the resulting electric forces will be confined to the immediate tip of the droplet wedge, as schematically illustrated in Fig. 1. These electric forces tend to drag the droplet over the hydrophobic dielectric causing a deformed liquid surface with a decreased contact angle. Due to an asymmetrically applied voltage (e.g. right electrode is activated) the resulting force direction can be specifically controlled and consequently the resting droplet can be set in motion. This actuation principle forms the basis of several electrowetting manipulation operators such as the droplet creation from a reservoir of a liquid, the transport, splitting and merging [1, 2].

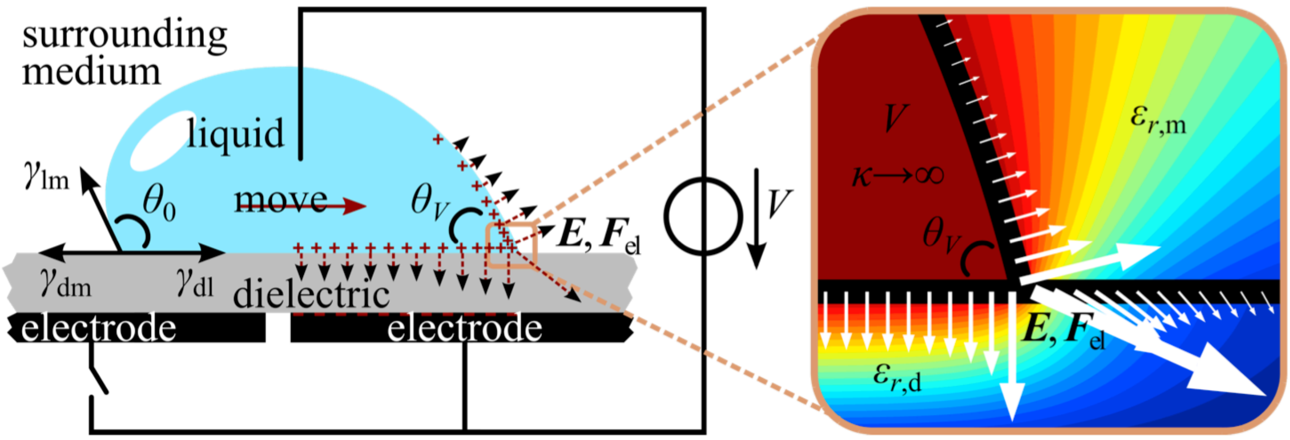

Fig.1: Scheme of the droplet transport between two electrodes. When the right electrode is activated, the estimated electric forces concentrate in the vicinity of the right-hand triple point of the perfectly conductive droplet. This specific asymmetric distribution of forces causes the directed motion of the droplet with the decreased right contact angle.

The tip of the droplet wedge is represented by the triple junction (also called *triple point*) of the three adjacent phases: conductive liquid, dielectric solid and surrounding medium. Forces acting solely on the triple point while being described by corresponding interfacial tensions together with a shear force define the realm of the conventional approximate Young-Lippmann law [1, 2]. In this context, the voltage dependent contact angle becomes the major parameter for the resulting drag force and can theoretically reach 0° by a sufficiently high voltage. In practice, however, the electrically manipulated contact angle saturates (despite further increasing voltage) to a certain value, which lies between 30° and 80°, depending on specific properties of the electrowetting-system. This effect of the contact angle saturation at a minimal angle (yielding maximal drag force) is still under considerable debate relating its origin to various microscopic but rather disconnected mechanisms [4, 5]. In contrast, our macroscopic analytical explanation of the contact angle saturation – based on the 2D vectorial analysis of the actuation electric forces on the liquid surface – has the potential to predominate the microscopic ones due to emergent theoretical electrostatic field singularities in the triple point [6, 7].

We calculated the electric and displacement field on the droplet surface (wedge) as well as in a close radial neighborhood around the triple point relying on their well-known fractional order local dependence. With these field vectors, the estimated electrostatic pressure (N/m^2) on the liquid droplet could be determined using the Maxwell stress tensor together with renormalization techniques. It is shown, that the vector orientation of the electrostatic pressure in the singular triple point together with the adjacent much weaker ones are strongly dependent on the droplet contact angle as well as on the permittivities of the dielectric and the surrounding medium. Depending on these parameters, the horizontal component of this resulting pressure changes direction (zero crossing) at a certain contact angle, whose value is in the range from 10° to 82°. Below this zero crossing angle the electrostatic pressure – with a negative horizontal component – no longer antagonizes the Laplace pressure of the liquid droplet. Consequently, any droplet deformation is inhibited and thereby the decrease of the contact angle, rendering this limiting value to contact angle saturation. In addition, it was found that voltage levels and thickness of the dielectric layer have no direct influence on the direction of the electrostatic pressure but rather on its magnitude and thus the steepness of the zero crossing, respectively. In summary, these analytical results suggest that the cause of the contact angle decrease as well as of its saturation lies in the angle- and permittivity-dependent vector orientation of the resulting electrostatic pressure on the droplet.

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