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A methodology to determine the adhesion force of arbitrarily shaped drops with convex contact lines

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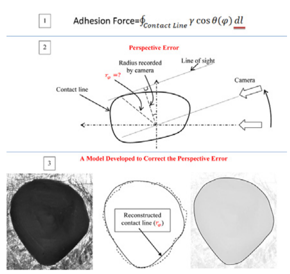
HIGHLIGHTS

- Model for measuring drop adhesion force was developed.
- No assumption for shape of contact line needed except convexity.
- No assumption for variation of contact angle along contact line is needed.
- New contact line model was experimentally validated.

GRAPHICAL ABSTRACT



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ABSTRACT

The adhesion force of drops deposited on smooth solid surfaces can be found by integration along the contact line of the liquid–vapor surface tension acting on an infinitesimal contact line element, projected on the substrate plane ($\gamma_{||}$). Approximate relations available in the literature are applicable only for drops with specific contact line shapes (*e.g.* circular, elliptical, parallel-sided, or contact lines with at least one axis of symmetry). However, in most applications drops are exposed to a combination of forces and the contact line may have any arbitrary shape. In this study, a model is developed to calculate the adhesion force of drops with arbitrary shape. The contact line shape and contact angle values are found using side view images taken at different azimuthal angles (around the drop). The model is applicable to drops of any shape, as long as contact line is convex, and takes into account the perspective errors during imaging.

1. Introduction

Drop removal from solid surfaces is a challenge in various areas such as aerospace [1], fuel cell technology [2,3], cleaning application [4], wind turbines [5], oil recovery [6,7], *etc.* The purpose of this study is to find a general relationship to measure the adhesion force between drops and solid surfaces. From an energetic perspective, adhesion is deemed to occur on the contact area (solid–liquid interface) of a drop and solid surface (Wenzel's and Cassie's theories). Adhesion force from a mechanical perspective manifests at the three-phase line, where liquid, air and solid phases meet [8–15]. The forces on the contact line are surface tension forces (*i.e.* forces operative at the interface in the tangential direction; these tensions are properties of the interface and a function of temperature [15]). The adhesion force which opposes the external force (*e.g.* gravity) can be found by integrating the surface tension forces along the contact line. This approach is an indirect approach as the adhesion

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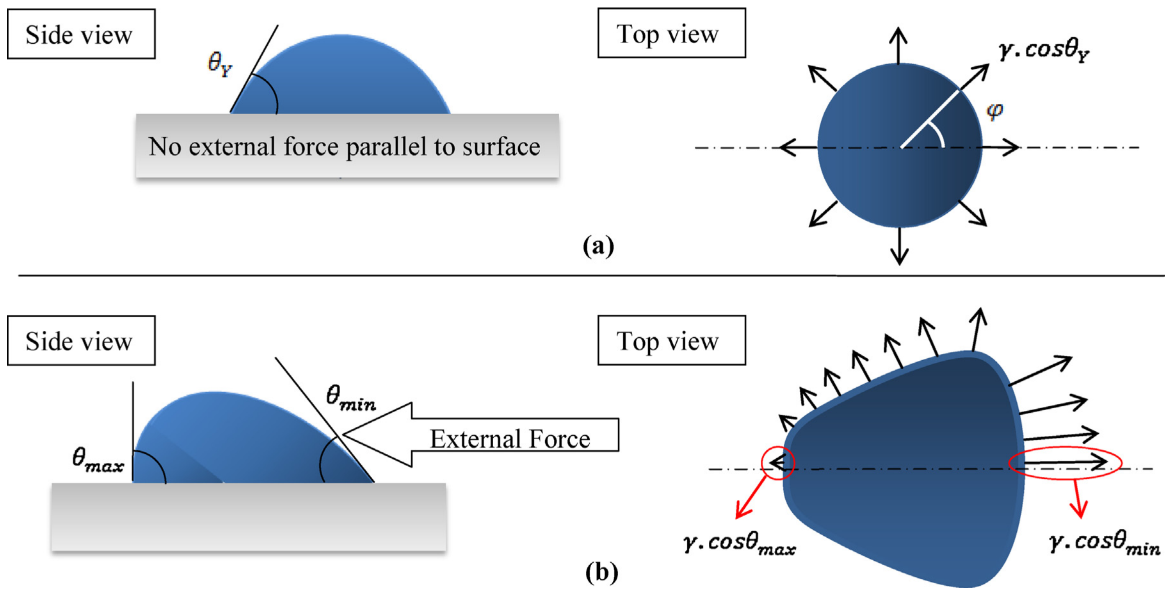

Fig. 1. Side and top views of a drop on a smooth surface are shown where (a) no external force parallel to the surface is operative on the drop. Contact angle along the contact line is uniform, and the resultant surface tension force on the drop is zero. (b) A parallel to the substrate external force is operative on the drop and advancing ($\theta_{\max}$) and receding ($\theta_{\min}$) contact angles are shown, the net adhesion force on the drop is against the external force. Note that the surface tensions are operative on the drop and their reactions operate on the drop substrate. $\gamma \cos\theta$ is the projection of surface tension on the plane of substrate.

force is not directly measured. The other approach discussed in literature is direct measuring the adhesion force: applying an external load and directly measuring the opposing force using AFM (atomic force microscopy) [16–19] or a vertical deflectable capillary stuck in the drop [20]. It was shown that the direct method is more expensive and less accurate [21]. As such, the indirect approach will be used in this study.

2. Indirect measurement of drop adhesion force

Indirect methods add surface tension forces acting on infinitesimal line elements along the three-phase line, to calculate the adhesion force [22]. At any point on the contact line, one can define three operative surface tensions: liquid–vapor (γ), solid–vapor (γ_{SV}) and solid–liquid (γ_{SL}). These surface tensions at any point on the contact line lie in a plane which is perpendicular both to the substrate and to the drop contact line at that point. Young (Eq. (1)) showed that in equilibrium state, at any point on the contact line, the projections in the direction parallel to the substrate of these three surface tensions are balanced as:

$$\gamma_{SL} + \gamma \cos \theta_Y = \gamma_{SV} \quad (1)$$

where θ_Y is the Young's contact angle (see Fig. 1a). The resisting or adhesion force is in the parallel direction to the substrate. In equilibrium, according to Eq. (1), at any point on the contact line, the parallel to the substrate surface tension force is zero. As such, using the mechanical perspective, the drop adhesion force (*i.e.* summation of these surface tensions over the contact line) has to be zero. This does not mean that the normal to the substrate surface tension force is zero.

Assuming the solid substrate is relatively flat, the summation of γ_{SL} and γ_{SV} over the contact line becomes zero *i.e.* $\oint_{\text{Contact Line}} \gamma_{SL} dl = \oint_{\text{Contact Line}} \gamma_{SV} dl = 0$. The reason is that γ_{SL} and γ_{SV} are operative on the contact line, which is a closed curve. The summation of $\gamma \cos\theta$ over the contact line is not always zero. It is only zero when the contact angle along the contact line, or $\theta(\varphi)$, is uniform; where φ is the azimuthal angle (see. Fig. 1a). The followings may change the value of contact angle: applying an external force parallel to the substrate [23] on a drop, adsorption of liquid vapor on to the solid surface [24], the line tension for micron size drops or large drops with local micro size radii of curvature [25,26], impurities [27], electrostatic potential [28,29], surface roughness [30] and heterogeneity [31].

For a drop on a relatively smooth and homogeneous substrate, the contact angle change is only related to the drop deformation due to an external force parallel to the substrate. Deformation makes the $\theta(\varphi)$ non-uniform along the contact line (*e.g.* see Fig. 1b); therefore, the summation of $\gamma \cos \theta(\varphi)$ along the contact line becomes non-zero *i.e.* $\oint_{\text{Contact Line}} \gamma \cos \theta(\varphi) \, dl \neq 0$. The value of $\oint_{\text{Contact Line}} \gamma \cos \theta(\varphi) \, dl$ is equal to the adhesion force. This value is a function of γ, contact line's length (l), and contact angle along the contact line, $\theta(\varphi)$.

For an arbitrary drop shape, calculating the summation of surface tension forces along the contact line may not be easy. Literature has shown that the summation of surface tension force (or adhesion force) is proportional to the contact angle hysteresis ($\theta_{\max} - \theta_{\min}$), *e.g.* [32]; where $\theta_{\max}$ and $\theta_{\min}$ are advancing and receding contact angles found from tilted surface experiments, for when gravity is the driving force, or if shear flow is the driving force, then $\theta_{\max}$ and $\theta_{\min}$ should be found by observations in such experiments as done in [33]; it should be noted that $\theta_{\max}$ and $\theta_{\min}$ are different from advancing and receding contact angles found from sessile drop experiments *i.e.* θ_A and θ_R [33–35]. However, the contact angle hysteresis value does not define the adhesion force accurately. For example, consider two drops with identical contact angle hysteresis values and different shapes or sizes. Contact angle hysteresis values are equal but adhesion forces will be different. Some studies have suggested some approximate relationships which estimate the value of adhesion force. However, the applicability of these