REVIEW

Wetting transitions on biomimetic surfaces

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Biomimetic hierarchical surfaces demonstrate a potential for a variety of green technologies, including energy conversion and conservation, owing to their remarkable water repellence. The design of such surfaces allowing emerging green applications remains a challenging scientific and technological task. Understanding the physical mechanism of wetting transitions (WTs) is crucial for the design of highly stable superhydrophobic materials. The main experimental and theoretical approaches to WTs are reviewed. Reducing the micro-structural scales is the most efficient measure needed to enlarge the threshold pressure of WTs. The trends of future investigations are envisaged.

Keywords: biomimetic surfaces; wetting states; superhydrophobicity; wetting transitions

1. Introduction

Revealing that natural surfaces demonstrate pronounced water repellence (the so-called ‘lotus effect’; Barthlott & Neinhuis 1997; Koch et al. 2009) has stimulated extended theoretical and experimental research of wetting phenomena occurring on rough surfaces. It is already well understood that certain kinds of hierarchically rough reliefs supply extreme water repellency (superhydrophobicity) to interfaces (Shibuichi et al. 1996; Herminghaus 2000; Patankar 2004a; Shirtcliffe et al. 2005). Superhydrophobic properties are demonstrated by plants, birds’ wings, legs of water striders and other natural objects (Blossey 2003; Gao & Jiang 2004; Bormashenko et al. 2007a; Quéré & Reyssat 2008). Various sophisticated experimental techniques including UV-lithography and plasma etching have been applied for manufacturing lotus-like biomimetic surfaces (Blondiaux et al. 2009; Jeong et al. 2009). Typical superhydrophobic wetting is shown in figure 1: an 8 μL droplet is deposited on the polymer water-repellent surface. Detailed recent reviews of the state of the art have summarized the accumulated experience in the field (Quéré 2008; Nosonovsky & Bhushan 2009). Superhydrophobic surfaces demonstrate a potential for a variety of green technologies, including energy conversion and conservation and environment-friendly self-cleaning underwater surfaces (Choi & Kim 2006; Genzer & Marmur 2008; Nosonovsky & Bhushan 2009).

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One contribution of 11 to a Theme Issue ‘Green tribology’.
Wetting of rough surfaces is characterized by the apparent contact angle (APCA), which is different from the local contact angle given by Young’s relation (Marmur 2006). However, a high APCA does not necessarily guarantee true superhydrophobicity and self-cleaning properties. Moreover, high stick surfaces demonstrating a high APCA were reported recently (Feng et al. 2008; Bormashenko et al. 2009a; Caps et al. 2009). Low contact angle hysteresis resulting in low sliding angles and high stability of a ‘lotus-like’ wetting state supply water-repellent and self-cleaning properties to the surface (Gao & McCarthy 2006, 2007a; Nosonovsky & Bhushan 2007). The design of such surfaces allowing emerging green applications remains a challenging scientific and technological task.

2. Wetting states

Wetting of atomically smooth surfaces is characterized by the equilibrium or Young angle $\theta$, given by the well-known Young equation

$$\cos \theta = \frac{\gamma_{SA} - \gamma_{SL}}{\gamma}, \quad (2.1)$$

where $\gamma$, $\gamma_{SL}$ and $\gamma_{SA}$ are the surface tensions at the liquid/air, solid/liquid and solid/air (vapour) interfaces, respectively. The contact angle of a droplet deposited on a solid depends on external parameters, such as temperature. A change in temperature may stimulate the transition from partial wetting to complete wetting of the solid substrate. In this case, we observe a wetting transition (WT) on a smooth solid surface (Bonn & Ross 2001; Humfeld & Garoff 2004).

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The Young equation supplies the sole value of the contact angle for certain combinations of solid, liquid and gaseous phases. Regrettably, the experimental situation is much more complicated; even on atomically flat surfaces, a diversity of contact angles is observed. This is due to the long-range interaction between molecules forming the triple (three-phase) line of the droplet and molecules forming the solid substrate (Yaminsky 2000). It was shown that the drop–surface attraction is time dependent owing to re-orientation of the molecules constituting the solid substrate; this fact hinders experimental tribology investigations of a solid/liquid contact and calls for novel experimental techniques such as the recently reported centrifugal adhesion balance (Tadmor et al. 2009).

The maximal contact angle observed on the surface is called the advancing angle, $\theta_{\text{adv}}$; the minimal one is called the receding angle, $\theta_{\text{rec}}$ (Gray 1965; Extrand & Kumagai 2002; Chibowski 2003; de Gennes et al. 2003). The difference between advancing and receding contact angles, $\theta_{\text{adv}} - \theta_{\text{rec}}$, is called the contact angle hysteresis (Tadmor 2004; Tadmor & Yadav 2008). Experimental establishment of advancing and receding angles is a challenging task, and it should be mentioned that reported contact angles are sensitive to the experimental technique used for their measurement (Decker et al. 1999; Kwok & Neumann 2000; Bormashenko et al. 2008a).

Chemical heterogeneities and roughness strengthen the hysteresis of the contact angle (Bartell & Shepard 1953; Dettre & Johnson 1965). Various models explaining the phenomenon of hysteresis have been proposed (Joanny & de Gennes 1984; Nosonovsky 2007a; Vedantam & Panchagnula 2008; Whyman et al. 2008). The effect was related to pinning of the triple line by defects. Pinning of the triple line produces the potential barrier $U$ to be surpassed by the droplet under its displacement (Whyman et al. 2008). The general expression for the contact angle hysteresis is given by

$$\theta_{\text{adv}} - \theta_{\text{rec}} = \left(\frac{8U}{\gamma R_0}\right)^{1/2} h(\theta),$$

where $R_0$ is the initial radius of the spherical drop before deposition on the substrate; the function $h(\theta)$ of the equilibrium contact angle is given in Whyman et al. (2008). However, a general theory of the contact angle hysteresis has still not been formulated. To study hysteresis experimentally, the manufacture of well-defined microscopically scaled defects is necessary, which is a complicated technological task (Reyssat & Quéré 2009).

Wetting of flat, chemically heterogeneous surfaces is characterized by APCA $\theta^\ast$, predicted by the Cassie–Baxter wetting model (Cassie & Baxter 1944; Cassie 1948). Consider the wetting of a composite flat surface comprising several materials. Each material is characterized by its own surface tension coefficients $\gamma_{i,SL}$ and $\gamma_{i,SA}$ and by the fraction $f_i$ in the substrate surface, $f_1 + f_2 + \cdots + f_n = 1$. The APCA in this case is supplied by the Cassie–Baxter equation

$$\cos \theta^\ast = \frac{1}{\gamma} \sum_{1}^{n} f_i (\gamma_{i,SA} - \gamma_{i,SL}) = \sum_{1}^{n} f_i \cos \theta_i,$$

where

$$\theta_{\text{adv}} - \theta_{\text{rec}} = \left(\frac{8U}{\gamma R_0}\right)^{1/2} h(\theta),$$

and

$$\cos \theta^\ast = \frac{1}{\gamma} \sum_{1}^{n} f_i (\gamma_{i,SA} - \gamma_{i,SL}) = \sum_{1}^{n} f_i \cos \theta_i.$$
where $\theta_i$ are equilibrium contact angles for the $i$th material. The Cassie–Baxter equation can be applied to a solid surface comprising pores (the contact angle for pores is $\pi$, $\cos \theta = -1$; figure 2a). In this case, the Cassie–Baxter equation yields

$$\cos \theta^* = -1 + f_s (\cos \theta + 1),$$  \hfill (2.4)

where $f_s$ and $1 - f_s$ are the relative fractions of the solid and air fractions underneath the drop. The Cassie air-trapping wetting state is also called the ‘fakir state’. The Cassie-like air-trapping wetting results in unusual tribology of the surface, providing easy sliding of water droplets. Slip lengths as high as 200–400 $\mu$m were reported recently (Lee et al. 2008; Lee & Kim 2009).

It is noteworthy that the derivation of equation (2.4) from equation (2.3) is not straightforward, because the triple (three-phase) line could not be at rest on the pores (Bormashenko 2008). Taking into account the fine structure of

Figure 2. Various wetting states occurring on rough surfaces: (a) Cassie air-trapping state, (b) Wenzel state, (c) Cassie impregnating wetting state and (d) mixed wetting state.
the triple line justifies the success of the Cassie–Baxter formula for predicting the APCA on porous surfaces (Bormashenko et al. 2007b; Bormashenko 2008; Choi et al. 2009; Starov & Velarde 2009). When the relief is hierarchical, the Cassie–Baxter equation obtains more complicated forms taking into account the interrelation between scales constituting the topography of the relief (Herminghaus 2000; Bormashenko et al. 2006a, 2008b). It should be mentioned that dependence of the APCA on equilibrium contact angles on the hierarchical surfaces is weak when compared with those on single-scale surfaces (Bormashenko et al. 2008b). Modifications of the Cassie–Baxter equation that take into account the peculiarities of the complicated topography of biomimetic surfaces were reported recently (Nosonovsky & Bhushan 2008; Choi et al. 2009; Larsen & Taboryski 2009).

Wetting of rough chemically homogeneous surfaces is governed by the Wenzel (1936) model. According to the Wenzel model, surface roughness $r_f$, defined as the ratio of the real surface in contact with liquid to its projection onto the horizontal plane, always magnifies the underlying wetting properties (figure 2b). Both hydrophilic and hydrophobic properties are strengthened by surfaces textures. The apparent Wenzel contact angle is given by

$$\cos \theta^w = r_f \cos \theta. \quad (2.5)$$

Actually, pure Cassie and Wenzel wetting situations rarely occur (Erbl & Cansoy 2009) and so Marmur (2003) introduced a mixed wetting state. In the mixed wetting state, a droplet partially wets the surface and partially sits on air pockets, as described in figure 2d. The APCA is supplied in this case by

$$\cos \theta^m = r_f f \cos \theta + f - 1, \quad (2.6)$$

where $f$ is the fraction of the projected area of the solid surface that is wetted by the liquid. When $f = 1$, equation (2.6) turns into the Wenzel equation (2.5).

One more wetting state has been introduced (Bico et al. 2002; Ishino et al. 2004; Ishino & Okumura 2008). This is the Cassie penetrating state depicted in figure 2c. In this case, the liquid penetrates into grooves of the solid and the drop finds itself on a substrate viewed as a patchwork of solid and liquid (solid ‘islands’ ahead of the drop are dry, as shown in figure 2c). The APCA of the Cassie impregnating state is established as (Bico et al. 2002)

$$\cos \theta^c = 1 - f_s + f_s \cos \theta. \quad (2.7)$$

Cassie-impregnating wetting is possible when the Young angle satisfies equation (2.8) (Bico et al. 2002)

$$\cos \theta > \frac{1 - f_s}{r_f - f_s}. \quad (2.8)$$

It should be stressed that equations (2.3)–(2.7) could be applied when the radius of the droplet is much larger than the characteristic scale of surface heterogeneities (Nosonovsky 2007b). The rigorous thermodynamic derivation of equations (2.3)–(2.7) was obtained in a series of theoretical works (Good 1952; Marmur 1998; Bico et al. 2002; McHale 2007; Whyman et al. 2008; Bormashenko 2009a,b).
Various wetting states featured by very different APCAs can co-exist on the same heterogeneous surface. The diversity of the APCA can be easily understood if one takes into account that the Gibbs energy curve for a droplet on a real surface is characterized by multiple minima points (Marmur 2006; Bormashenko et al. 2008c). It has been shown that the Wenzel state is energetically favourable, when

$$r_f > \frac{\cos \theta_{\text{cassie}}}{\cos \theta}, \quad (2.9)$$

where $\theta_{\text{cassie}}$ is the apparent angle of the Cassie wetting calculated according to equation (2.4) (Bartolo et al. 2006). The lowest minimum of the Gibbs energy usually corresponds to the Cassie-impregnating APCA given by equation (2.7) (figure 3). When the APCA changes spontaneously or under external stimuli, we observe the WT. It should be emphasized that physical mechanisms of WT on flat and rough surfaces are quite different.

### 3. Wetting transitions: experimental data

WTs were observed under various experimental techniques using a range of factors: gravity (Yoshimitsu et al. 2002), pressure (Lafuma & Quéré 2003), bouncing of droplets (Bartolo et al. 2006; Jung & Bhushan 2008, 2009; Nosonovsky & Bhushan 2008), evaporation of droplets (McHale et al. 2005; Jung & Bhushan 2007; Moulinet & Bartolo 2007), an electric field in electrowetting experiments (Bahadur & Garimella 2008, 2009) and vibration of droplets (Bormashenko et al. 2007c,d,e, 2008c). An interesting experimental technique allowing the study of an air layer responsible for the formation of the Cassie state was reported recently (Sakai et al. 2009). A superhydrophobic surface exposed to hydrostatic water pressure was irradiated by a laser beam.
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Figure 4. WTs observed by vibration of a 15 μl water drop deposited on a micrometrically rough PDMS surface: (a) the initial Cassie state and (b) the Cassie impregnating state induced by vibrations.

The jump in the reflectivity of the laser beam indicated the occurrence of WTs. Reflection interference contrast microscopy was used for the study of the air–water interface on textured polydimethylsiloxane (PDMS) surfaces (Moulinet & Bartolo 2007). An environmental scanning electron microscopy (ESEM) technique was used successfully for the study of WTs during micro-droplet evaporation (Nosonovsky & Bhushan 2008).

It is generally agreed that WTs are irreversible; however, restoring the initial Cassie state under the application of external mechanical stimuli was reported recently (Nosonovsky & Bhushan 2008; Boreyko & Chen 2009). It should be mentioned that various experimental methods used for the study of WTs supplied close values of the pressure necessary for the Cassie–Wenzel transition, which is of the order of 100–300 Pa for 10 μl droplets deposited on micrometrically scaled rough surfaces (Lafuma & Quéré 2003; Bormashenko et al. 2007c,d). It is noteworthy that the Cassie air-trapping wetting regime observed on natural objects (birds’ wings) was much more stable than that on artificial surfaces (Bormashenko 2008c). Single and two-stage pathways of WTs have been observed, including Cassie (air-trapping)–Wenzel–Cassie (impregnating), Wenzel–Cassie (impregnating) and Cassie (air-trapping)–Cassie (impregnating) transitions (Bormashenko et al. 2008c). The lowest energy state corresponds to a Cassie-impregnating wetting regime. The vibration-induced Cassie (air-trapping)–Cassie (impregnating) transition observed on a PDMS substrate is illustrated in figure 4. The mechanism of WTs will be discussed in detail below.

4. Mechanisms of wetting transitions: statics

(a) Composite wetting state

As mentioned above, the Cassie air-trapping wetting state corresponds to the highest of multiple minima of Gibbs energy of the droplet deposited on a rough surface (figure 3). Thus, for the WT, the energy barrier must be surmounted (Ishino et al. 2004; Patankar 2004b; Barbieri et al. 2007). It has been supposed that this energy barrier corresponds to the surface energy variation between the Cassie state and the hypothetical composite state with the almost complete filling of surface asperities by water keeping the liquid–air interface under the droplet and the contact angle constant, as shown in figure 5. In contrast to the equilibrium mixed-wetting state (Marmur 2003), the composite

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state is meta-stable. For a simple topography, as shown in figure 6, the energy barrier could be calculated as follows (Bormashenko et al. 2009b):

\[ E_{\text{trans}} = \frac{2\pi R^2 h (\gamma_{SL} - \gamma_{SA})}{p} = -\frac{2\pi R^2 h \gamma \cos \theta}{p}, \] (4.1)

where \( h \) and \( p \) are the geometrical parameters of the relief, shown in figure 6, and \( R \) is the radius of the contact area. The numerical estimation of the energy barrier according to formula (4.1) with the parameters \( p = h = 20 \text{ mm}, R = 1 \text{ mm}, \theta = 105^\circ \) (corresponding to low-density polyethylene (LDPE)) and \( \gamma = 72 \text{ mJ m}^{-2} \) gives a value of \( E_{\text{trans}} = 120 \text{ nJ} \). It should be stressed that, according to formula (4.1), the energy barrier scales as \( E_{\text{trans}} \sim R^2 \). The validity of this assumption will be discussed below. The energy barrier is extremely large compared with thermal fluctuations: \( E_{\text{trans}}/kT \approx (R/a)^2 \gg 1 \), where \( a \) is an atomic scale (Ishino et al. 2004).

(b) Critical pressure necessary for wetting transitions

Consider a single-scale pillar-based biomimetic surface, similar to that studied by Yoshimitsu et al. (2002) with pillar width \( a \) and groove width \( b \). Analysis of the
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Figure 7. Pressure-induced displacement of the water front leading to the collapse of the Cassie air-trapping wetting state.

balance of forces at the air–liquid interface at which the equilibrium is still possible yields (Zheng et al. 2005)

\[ p_c > - \frac{\gamma f_s \cos \theta}{(1 - f_s) \lambda} \quad (4.2) \]

where \( \lambda = A/L \) and \( A \) and \( L \) are the pillar’s cross-sectional area and perimeter, respectively. As an application of equation (4.2) with \( \theta = 114^\circ \) (Teflon), \( a = 50 \mu \text{m} \) and \( b = 100 \mu \text{m} \), we obtain \( p_c = 296 \text{Pa} \), which is in excellent agreement with experimental results (Yoshimitsu et al. 2002; Zheng et al. 2005). Recalling that the dynamic pressure of rain droplets may be as high as \( 10^4 - 10^5 \text{Pa} \), which is much larger than \( p_c \approx 300 \text{Pa} \), we conclude that creating biomimetic reliefs with a very high critical pressure is of practical importance (Zheng et al. 2005). The concept of critical pressure leads to the conclusion that reducing the micro-structural scales (e.g. the pillars’ diameters and spacing) is the most efficient measure to enlarge the critical pressure (Zheng et al. 2005; Moulinet & Bartolo 2007). The energy barrier separating the Cassie and Wenzel states is given by an expression similar to equation (4.1) and scales as \( R^2 \) (Zheng et al. 2005). It is noteworthy that neither equation (4.1) nor equation (4.2) explains the existence of Cassie wetting on inherently hydrophilic surfaces (Bormashenko et al. 2006a,b; Safae et al. 2008; Kietzig et al. 2009). Indeed, \( E_{\text{trans}} \) and \( p_c \) calculated according to equations (4.1) and (4.2) are negative for \( \theta < \pi/2 \); this makes Cassie wetting on hydrophilic surfaces impossible.

An alternative mechanism of WT based on the concept of critical pressure has been proposed (Liu & Lange 2006; Patankar 2010). It was supposed that, as the pressure applied to the droplet increases, the meniscus will move towards the flat substrate, as shown in figure 7. The meniscus eventually will touch the substrate, which will cause the collapse of the Cassie wetting and consequently the Cassie–Wenzel transition (Liu & Lange 2006; Patankar 2010).
(c) **Cassie wetting of inherently hydrophilic surfaces: criteria for gas entrapping**

For the explanation of the roughness-induced superhydrophobicity of inherently hydrophilic materials, it was supposed that air is entrapped by cavities constituting the topography of the surface (Bormashenko *et al.* 2006b; Wang & Chen 2008; Patankar 2009). The simple mechanism of ‘geometrical’ trapping could be explained as follows: consider a hydrophilic surface ($\theta < 90^\circ$) comprising pores as depicted in figure 8. It is seen that air trapping is possible only if $\theta > \phi_0$, where $\phi_0$ is the angle between the tangent at the highest point of the pattern and the horizontal symmetry axis O1O. Indeed, when the liquid level is descending, $90^\circ$ angle $\phi$ is growing (figure 8), and if condition $\theta > \phi_0$ is violated, the equilibrium $\theta = \phi$ will be impossible.

In the equilibrium position, small fluctuations of the contact angle lead to the appearance of curvature on the plane air–water interface that is energetically unfavourable. Below the central plane O–O1 where $\phi > 90^\circ$, the equilibrium is impossible in the case of $\theta < 90^\circ$. For a large pore, small fluctuations of $\theta$ can lead to the curved air–liquid interface touching the pore bottom near its centre, followed by filling the pore and consequent collapse of the Cassie air-trapping wetting regime. The effects of compressibility of trapped air on WTs on hydrophilic surfaces have also been considered (Patankar 2009).

5. Mechanisms of wetting transitions: dynamics

The experimental data related to the dynamics of WTs are scanty (Moulinet & Bartolo 2007; Sbragaglia *et al.* 2007; Peters *et al.* 2009). The characteristic time of Cassie–Wenzel transition was established with reflection interference contrast microscopy as less than 20 ms (Moulinet & Bartolo 2007). The dynamics of WT for droplets placed on polymer micrometre-sized square pillars was studied by optical microscopy in combination with high-speed imaging (Peters *et al.* 2009).
Two regimes of the droplet front displacement were observed: zipping and non-zipping. In the zipping regime, the velocity of the front in one direction (to advance to the next row of pillars) is much smaller than the velocity in the other direction (liquid filling up one row of micro-pillars). The topography of the surface (pillar height and gap size between pillars) and water contact angle were varied. It was established that the velocity of the wetting front increases with increasing gap size, decreasing pillar height, or decreasing contact angle (Peters et al. 2009). A velocity of the wetting front as high as $1.5 \text{ m s}^{-1}$ was registered (Peters et al. 2009). Balancing interfacial energy contributions with viscous dissipation yielded universal equations for the zipping and the transition dynamics (Peters et al. 2009).

### 6. Dimension of wetting transitions

One of the debatable problems in the field of WTs is the problem of the ‘dimension’ of the transitions, or, in other words, whether all pores underneath the droplet should be filled by liquid (the ‘two-dimensional scenario’) or, perhaps, only the pores adjacent to the three-phase (triple) line are filled under external stimuli such as pressure, vibrations or impact (the ‘one-dimensional scenario’). Indeed, the APCA is dictated by the area adjacent to the triple line and not by the total area underneath the droplet (Gao & McCarthy 2007b). One-dimensional and two-dimensional scenarios of WTs are illustrated in figure 9. The experiments carried out with vibrated drops supported the one-dimensional scenario of WTs. It has been established that the transition occurs when the condition $F_{cr} = \text{const.}$ is fulfilled, where $F_{cr}$ is the critical force acting on the unit length of the triple line, and the transition is caused by de-pinning of the triple line (Bormashenko et al. 2007d, 2008c). The critical value of de-pinning force $F_{cr}$ has been established experimentally for various microscopically structured surfaces as $F_{cr} \approx 200–350 \text{ mN m}^{-1}$ (Bormashenko et al. 2008c). The energy barrier $\delta E$ to be surmounted for the elementary displacement of the triple line $\delta r$ could be estimated as

$$\delta E \approx 2\pi RF_{cr}\delta r,$$

which scales as $R$. This scaling law corresponds to results obtained with vibrated drops, but contradicts the scaling law given by expression (4.1). The electrowetting-stimulated WTs also supported the one-dimensional mechanism of transitions (Bahadur & Garimella 2009). De-pinning of the triple line was observed directly by reflection interference contrast microscopy (Moulinet & Bartolo 2007). The potential barrier $\delta E$, calculated according to expression (6.1) for a drop with a radius of $R \approx 1 \text{ mm}$ deposited on the LDPE relief presented in figure 6 ($F_{cr} \approx 350 \text{ mN m}^{-1}$, the elementary displacement $\delta r \approx p/2 \sim 10^{-5} \text{ m}$), equals $\delta E \approx 20 \text{ nJ}$, which is smaller than the value predicted by formula (4.1) but still much larger than thermal fluctuations (Bormashenko et al. 2009b).

In contrast, it was suggested that the Cassie–Wenzel transition occurs via a nucleation mechanism starting from the drop centre (Ishino & Okumura 2006). Patankar (2010) in his recent theoretical investigation supposed that both mechanisms of WT (i.e. de-pinning of the triple line and the critical pressure-induced collapse of Cassie wetting depicted in figure 7) are possible. Lack of trustworthy experimental data in the field should be stressed.

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Figure 9. (a) The Wenzel wetting state (two-dimensional scenario of transition is depicted; all pores underneath the droplet are filled by water). (b) The Wenzel wetting state (one-dimensional scenario of transition is depicted; only pores in the vicinity of the three-phase line are filled).

7. Trends for future investigations

The following trends for investigations in the field of WTs are proposed.

— Study of WTs on hydrophobic surfaces with a well-defined and controlled topography. Such experiments will shed light on the impact exerted by the surface topography on WTs.
— Study of WTs on well-defined micro-scaled hydrophilic surfaces. These kinds of investigations will clarify the conditions of air trapping by highly developed hydrophilic reliefs.
— Direct experimental evidencing of the Cassie impregnating state is necessary. Perhaps this could be done with ESEM.
— The experimental study of the dynamics of the triple line under WT is required.
— The study of WTs for various organic liquids is called for (Chandra & Yang 2009).
— Clearing up the true ‘dimension’ of WT is necessary.
— The development of the theoretical threshold criteria of WTs is required.
— The development of surfaces demonstrating highly stable Cassie states is urgent for green applications of biomimetic surfaces such as energy conversion and conservation.
8. Conclusions

The main experimental and theoretical approaches to WTs are reviewed; the importance of WTs for understanding the tribology of rough liquid/solid interfaces is discussed. The threshold pressure and energy barrier necessary for WTs are supplied. The problem of the dimension of WTs is discussed. One-dimensional and two-dimensional pathways of transitions are presented. In spite of the intensive theoretical and experimental effort expended in the study of WTs, the physical mechanism of these phenomena remains unclear. At the same time, a profound understanding of this mechanism is vital for manufacturing ‘green’ biomimetic surfaces with water repellence and self-cleaning properties under external stimuli such as pressure, vibration or impact. The trends of future investigations are envisaged.

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Correction

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