Dynamic wetting of a solid surface is a process that is ubiquitous in nature, and also of increasing technological importance. The underlying dissipative mechanisms are however still unclear. We present here dynamic wetting experiments of a droplet on a dry surface, showing that an important part of the dissipation may arise from a friction related to the motion of the contact line itself, and that this may be dominating the viscous friction in the flow adjacent to the contact line. By a combination of simulations and experiments, values of a corresponding friction factor are obtained. By this procedure the contact line friction factor can be distinguished and quantified, also in room temperature where other sources of dissipation are present. Water and glycerin-water mixtures on various surfaces have been investigated. We show the dependency of the friction factor on the nature of the surface, and the viscosity of the liquid.

A canonical example of dynamic wetting is the time dependent spreading of a liquid droplet on a dry substrate. The droplet spreads by motion of the contact line, i.e. the curve where the liquid-gas interface that constitutes the droplet surface intersects the solid substrate. Contact lines are present in a myriad of flow phenomena in Nature and in industrial applications, such as the formation of coffee stains Deegan et al. (1997), how cats lap Reis et al. (2010), droplet deposition in biomedical applications Qian et al. (2009), water collection on wetted spider silk Zheng et al. (2010) etc. Wetting is also utilized in technology, for example in microfluidic systems Song, Tice and Ismagilov (2003), sintering Saiz and Tomsia (2004) and in immersion lithography techniques Winkels et al. (2010). Dynamic wetting has however been difficult to describe theoretically and to model computationally, primarily due to the inherent coupling between molecular and macroscopic length scales. In the immediate vicinity of the contact line microscopic interactions can be important for the dynamic contact angle Ren and E (2007) while the bulk viscosity is known to influence spreading dynamics on the macro-scale Tanner (1979). In addition to these different mechanisms, inertia has also been shown to characterize certain wetting phenomena Bird, Mandre and Stone (2008).
It is well known, Huh and Scriven (1971), that continuum hydrodynamic theory fails to give an adequate description of the dissipation at the contact line, as it predicts a non-integrable viscous stress at the contact line, if a no-slip condition is applied for the liquid flow. Ad hoc models can be generated if the liquid is allowed for instance to slip at the surface Voinov (1976), and these are also adequate for predicting the motion of contact lines for flow situations where the dominating dissipation is due to the continuum viscous flow surrounding the contact line. However, there may be parameter ranges where the dominating dissipation mechanism is local to the contact line, and then nanoscale phenomena must somehow be accounted for.

Several different explanations have been proposed for the nanoscale mechanisms at play in dynamic wetting Bonn et al. (2009). Blake and Haynes Blake and Haynes (1969) describe contact line motion as an activated process where molecules are hopping between potential wells at the solid surface. Prevost et al. Prevost, Rolley and Guthmann (1999) measured the force acting at the contact line of effectively inviscid superfluid helium at cryogenic temperatures (< 2K), where they found that the contact line moved through thermally activated jumps that were related to the roughness of the Cesium substrate. Through molecular dynamics simulations, Ren and E Ren and E (2007) extracted a friction parameter acting at the contact line, and pointed out that for large capillary numbers (given by the ratio between the viscous and surface tension force) the contact line might be closer to a diffusive process. In this parameter regime experiments have also shown that classical theory fails to describe the results Chen, Rame and Garoff (1995). Eggers Eggers (2004) examined theoretically contact line motion at large capillary numbers and pointed out that the interaction between the large scale and the local dynamics near the contact line still holds great challenges.

In spite of the extensive studies of wetting physics, direct measurements of the dissipation in macroscopic wetting has been elusive in both experiments and simulations. Our primary aim here is to quantify the importance of a contact line friction force, and to obtain values for the corresponding friction coefficient. We also want to shed some light on the nature of this contact line friction. To this end we have conducted droplet spreading experiments, with water-glycerin mixtures with a wide range of viscosities, on solid surfaces with different wetting properties. To analyze these experiments, corresponding numerical simulations based on the Cahn-Hilliard equations Jacqmin (1999) have been made. The simulated results allow us to identify the different contributions to the dissipation, which are needed to reproduce the experimental results.

The Cahn-Hilliard equation Cahn and Hilliard (1958); Jacqmin (1999) is based on a formulation of the free energy in the system, and can be used together with
the Navier Stokes equations to model contact line motion, see methods 1.1. The free energy of the system ($F$) is given by a volume ($\Omega$) and a solid surface contribution ($\Gamma$), $F = \int (\frac{\sigma}{2} \Psi(C) + \frac{\sigma}{2} |\nabla C|^2) \, d\Omega + \int ((\sigma_{sl} - \sigma_{sg}) g(C) + \sigma_{sg}) \, d\Gamma$. The volumetric free energy consists of two terms representing the bulk ($\frac{\sigma}{2} \Psi(C)$) and interfacial energy ($\frac{\sigma}{2} |\nabla C|^2$), respectively. $\Psi = \frac{1}{4} (C^2 - 1)^2$ is a double-well function with two minima, being the equilibrium concentrations ($C$) of gas ($C = -1$) and liquid ($C = 1$). $\epsilon$ is the diffuse interface width and $\sigma$ is the surface tension coefficient. On the solid surface, the energy is given by either having a wet ($\sigma_{sl}$) or dry ($\sigma_{sg}$) solid surface, where $g(C) = \frac{1}{4} (2 + 3C - C^3)$ is allowing for a change in surface energy with respect to the concentration. By making a variation $\delta F/\delta C$ in the free energy with respect to the concentration, we obtain an expression for the chemical potential. Another outcome from the variational procedure is a general wetting boundary condition, formulated from phenomenological thermodynamics. This boundary condition for the concentration on the solid surface, has been demonstrated to indeed capture the main features in macroscopic rapid dynamic wetting Carlson, Do-Quang and Amberg (2010, 2009)

$$\epsilon \mu_f \frac{\partial C}{\partial t} = -\epsilon \sigma \nabla C \cdot \mathbf{n} + \sigma \cos(\theta_e) g'(C).$$

(1)

$\mu_f$ is here believed to be a friction factor at the contact line and $\theta_e$ is the equilibrium contact angle. Since a no-slip condition is given for the velocities at the solid surfaces, the contact line moves by interfacial diffusion, overcoming the difficulty that arises at the contact line in classical hydrodynamic theory.

The contact line friction factor ($\mu_f$) that appears in eq.(1) is determined by matching the experimental spreading radii in simulations. A non-zero $\mu_f$ generates an additional dissipation that slows the relaxation of the contact line to its equilibrium state. It allows us to parametrize on a macroscopic level the microscopic effects that generates dissipation at the contact line. After numerically measuring the value of $\mu_f$ we compare directly the evolution of the dynamic contact angle ($\theta$) in the experiment and simulation. Since no external force is applied on the system, the uncompensated Youngs force ($F = 2\pi r \sigma (\cos(\theta_e) - \cos(\theta))$) is believed to be the leading mechanism driving the spreading, thus the rate of change of work done by this force to advance the contact line $\dot{W} = u_{cl} F = 2\pi ru_{cl} \sigma (\cos(\theta_e) - \cos(\theta))$ is also directly compared between experiments and simulations, where $r$ is the spreading radius and $u_{cl}$ is the contact line speed.

We next proceed to formulate the different contributions to the dissipation rate for a drop spreading on a substrate Ren and E (2011). Based on the governing equations three dissipation contributions appear, namely; viscous
Figure 1. Panel a) Illustrates the initial condition for the experiments and the numerical simulations, where a droplet held at the tip of a needle is brought into contact with a dry solid substrate. The dashed box in the figure shows the field-of-view in the experiments. In panels b) and c) are shown the droplet shape near the substrate, at times (1) $t = 0.15ms$, (2) $t = 0.60ms$ and (3) $t = 0.90ms$, after initial contact. Each panel shows a composite of experiment and simulation, where the left half is the experimental picture and the right half the numerical prediction. b) a water droplet spreading on an oxidized Si-wafer, equilibrium contact angle of $\theta_e = 20^\circ$ and viscosity $\mu_{H_2O} = 1mPas$. c) glycerin 82.5% and water droplet spreading on an oxidized Si-wafer, equilibrium contact angle of $\theta_e = 17^\circ$, viscosity $\mu_{glycerin82.5\%} = 85mPas$.

dissipation ($\dot{R}_\mu$), contact line dissipation ($\dot{R}_f$) and a diffusive dissipation,

$$
\dot{R}_\mu = \int \frac{\mu}{2} (\nabla^T u + \nabla u) : (\nabla^T u + \nabla u) d\Omega
$$

$$
\dot{R}_f = \int \epsilon f \frac{\partial C^2}{\partial t} d\Gamma.
$$

(2)

For clarity we have discarded the diffusive dissipation here, as it is found to give a very small contribution. As formulated by De-Gennes (1985),
among others, there can be a dissipation \( \dot{R}_{DG} = 2\pi \mu_f u_{cl}^2 \) at the contact line itself, given as a function of the contact line speed and a friction factor \( \mu_f \). This is in fact the same form as \( \dot{R}_f \) in eq. (2), which is formulated from the boundary condition in eq. (1). In order to see this we estimated \( \dot{R}_f \) as

\[
\dot{R}_f = \int_\Gamma \epsilon \mu_f \frac{\delta C}{\delta r} \frac{\partial C}{\partial t} \, d\Gamma \sim 2\pi \epsilon \mu_f (\frac{\delta C}{\delta r})^2 (\frac{\partial r}{\partial t})^2 \epsilon \sim 2\pi \mu_f u_{cl}^2.
\]

Note that the variation in concentration at the solid surface with respect to the radial direction is \( \delta C/\delta r \sim 1/\epsilon \). This allows us to identify the parameter \( \mu_f \) in eqs. (1, 2) with the \( \mu_f \) in \( \dot{R}_{DG} \). In what follows we will demonstrate that contact line dissipation can be a significant and even dominating source of dissipation in dynamic wetting.

The evolution of a water droplet (\( \mu = 1 \text{mPas} \)) and a glycerin-water droplet (\( \mu = 85 \text{mPas} \)) with 82.5% (glycerin 82.5%) mass fraction glycerin as they spread on an oxidized Si-wafer is shown in fig. 1 through high-speed recording and numerical simulations. Agreement between experiment and simulation is excellent. Fig. 1a describes the initial condition before the start of droplet spreading in the experiments and simulations, where the droplet has an initial radius (\( R \)) of \( R = 0.5 \text{mm} \). Droplets are generated at the tip of a needle, placed perpendicular to the Si-wafers, through a micro-pump system so that the droplets touch the solid surface at a very low speed, see methods 1.2. The left panels in fig. 1b and 1c show the experimental result and the right panel the prediction from the simulation, as the droplets spread in time. The experiments also reveal that the axisymmetric assumption in the simulations is justified (methods 1.2). The interface width has been chosen in the simulations to be the same as the spatial resolution in the experiments \( \epsilon = 7.5 \mu\text{m} \), where the other material parameters are given directly from the experiments. The friction parameter \( \mu_f \) acting at the contact line, which is unknown a priori, is measured by matching the spreading radius in time between the simulations and the experiments. By applying a \( \mu_f = 0 \) the equilibrium contact angle will be enforced at the solid surface and the contact line will propagate faster in the simulations than what is observed in the experiments. If the appropriate value for \( \mu_f \) is introduced, the contact line relaxation will be impeded and mimic the real physics. This has as well a crucial effect on the dynamic contact angle, which relaxes in a physically reasonable way for the correct \( \mu_f \).

As the droplets start to wet the solid surface in fig. 1, the interface forms an apparent contact angle that is much larger than the static equilibrium value. For the case of water spreading (see fig. 1b), the contact line moves rapidly across the dry solid surface. A capillary wave is formed at the incipience of wetting, which propagates across the water droplet. The high viscosity droplet shown in fig. 1c starts spreading by forming a small cusp-region at the solid surface and viscosity here damps any formation of a capillary wave. Still, the apparent
Figure 2. Droplet radius, dynamic contact angle and the rate of change of work due to the uncompensated Youngs stress as functions of time for a pure water and an 82.5% glycerin-water droplet. The dashed curves are simulations and the points with error bars are experimental. a) Droplet radius as function of time. b) The apparent dynamic contact angle $\theta$ as function of time. $\theta$ has been extracted by using the same methodology in the experiments and in the simulations, as explained in 1.2. c) The rate of change of work due to he uncompensated Youngs stress, $\dot{W} = 2\pi r u_{cl} \sigma (\cos(\theta_e) - \cos(\theta))$.

dynamic contact angle differs from its static value. The contact line speed for the pure water droplet is about twice that for the glycerin82.5% droplet.

Fig. 2 shows the evolution of the spreading radius and the dynamic contact angle ($\theta$) as functions of time for the spreading of the water and glycerin82.5% droplets presented in fig. 1. The inset in fig. 2b illustrates how the dynamic contact angle has been defined in the experiments and the simulations, see methods (1.2). As can be seen from fig. 2a, the evolution of the droplet radius is very different for the two cases, with about a factor of two larger speed for the water droplet. The greatest difference can however be observed in the evolution of the contact angle in 2b. For the water droplet, the contact angle evolves in a highly non-linear fashion, while in the latter the contact angle relaxes approximately linearly in time. In both cases a friction factor $\mu_f [\text{Pas}]$ of considerable size is found to be needed in order to obtain the proper wetting dynamics. For the water droplet a friction factor ($\mu_f$)$_{H_2O} = 0.15 \text{Pas}$ is found. For the very viscous glycerin-water droplet ($\mu_f$)$_{glycerin_{82.5\%}} = 1.19 \text{Pas}$. This is an indication that contact line friction is important in the spreading of droplets both at low and high viscosity.

One of the driving forces in the spreading dynamics is the uncompensated Youngs force $F = 2\pi \sigma (\cos(\theta_e) - \cos(\theta))$. In fig.(2c), we compare the rate of work done ($\dot{W} = u_{cl} F$) by this force between experiments and simulations, as the contact line advances across the solid substrate. Since the contact line velocity and the contact angle relaxation (see fig.2b) evolves much faster for water than for the glycerin mixture, $\dot{W}$ is higher for water as observed in fig.2c.
Figure 3. The different contributions to the dissipation from the simulations, viscous $\dot{R}_\mu$ (dashed lines) and contact line $\dot{R}_f$ dissipation (full lines). a) Water droplet $\mu = 1\,mPas$, $\theta_e = 20^\circ$. 
b) glycerin$_{82.5\%}$ $\mu = 85\,mPas$, $\theta_e = 17^\circ$.

$\dot{W}$ slowly decreases in time during the spreading of the glycerin$_{82.5\%}$ droplet.

Having obtained a very good match between simulations and experiments, as shown in fig 3, we will now assume that also the dissipation mechanisms are the same in simulations and experiments. Thus, we will now evaluate the different contributions to the dissipation rate from the simulations, and claim that they reflect the dissipation rates in the corresponding experiments. Fig. 3 shows a comparison between the different dissipation rates ($\dot{R}_f, \dot{R}_\mu$) extracted from the simulations as the water (fig. 3a) and glycerin$_{82.5\%}$ (fig. 3b) droplet spreads in time. The dashed line shows the viscous dissipation ($\dot{R}_\mu$) and the full line the contact line dissipation ($\dot{R}_f$), see eq. (2).

Fig. 3a shows the dissipation as the water droplet spreads on an oxidized Si-wafer. At the incipience of wetting the contact line forms a small cusp region with a large curvature, and the contact line accelerates from a zero-velocity condition explaining the increase in dissipation at the very early stage of the spreading. It is also at the early stage of the spreading that the viscous dissipation is the largest but the spreading dynamics is dominated by contact line dissipation, which is here about five times larger than the viscous dissipation. After a peak in both the viscous and contact line dissipation around time $t = 50\mu s$, they slowly decreases as the contact line decelerates in time.

Also the dissipation in the spreading of the glycerin$_{82.5\%}$ droplet was found to be dominated by contact line dissipation, see fig. 3b. At the very start of the spreading friction at the contact line was observed in the simulations explaining the initial peak in contact line dissipation. The viscous dissipation slowly increases in the start of the process, reaching a peak around $t = 20\mu s$. 
before it slowly decreases. Interestingly, the contact line dissipation is found to be a significant and dominant contribution in the dissipation in the spreading of droplets both for low and high viscosity. At a much later time than the observation time for the experiments presented here, when the capillary number is small ($\ll 0.1$) and the droplet has a spherical cap profile, viscous dissipation is expected to dominate the spreading and Tanner’s spreading law Bonn et al. (2009) is expected to be recovered.

A set of spreading experiments with different water-glycerin mixtures have been performed on Si-wafers coated with oxide, silane and teflon (1.2). The variation in static contact angle with pure water and with a glycerin content is quite small ($\Delta \theta_e \sim \pm 2^\circ$), so only the equilibrium values for pure water are reported in fig. 4. In fig. 4 we show the measured contact line friction parameter as a function of the dynamic viscosity of the mixtures, for the three surfaces. We notice that all of the reported values for the contact line friction factor are much larger than the dynamic viscosity.
The further the droplet is from its equilibrium condition as it starts to spread, the more important contact line friction is in the flow. In the spreading phenomena investigated here the contact angle is initially large, $\sim 180^\circ$, as the droplets start to wet. This explains why the friction factor becomes larger for surfaces that wet well, since the initial condition for the spreading is much larger from the equilibrium state for the droplets. The friction factor increases with respect to the viscosity on all of the solid surfaces. In general, contact line friction is more dominant in wetting phenomena that are far from their equilibrium state.

Our measurements identify contact line dissipation as an essential part in dynamic wetting. The excellent agreement between experiments and simulations indicates that the dissipation is the same in the two. This enables us to distinguish the different dissipation rates in the simulations, for common liquids in room temperature where other sources of dissipation are present. They show that contact line dissipation is a significant and dominant contribution that cannot be disregarded at the early stage of the spreading process. A friction factor appears ($\mu_f$) at the contact line, which generates the dissipation as the contact line moves. This contact line friction factor is believed to parametrize the microscopic interactions at the contact line on the macro-scale. It has, for the first time, been directly measured from experiments for a range of viscosities and equilibrium contact angles. These results help us to quantify an important underlying physical mechanism that governs rapid dynamic wetting, which has been largely unknown. This is in particular relevant for the strategic design of application at small scales, such as microfluidic devices, where moving contact lines are an inherent part.


1. Methods

1.1. Numerical model

The axis-symmetric numerical simulations are based on a solution of the Cahn-Hilliard equation (3), wetting boundary condition (4), the continuity equation (5) and the Navier Stokes (6) equations;

\[
\frac{\partial C}{\partial t} + \mathbf{u} \cdot \nabla C = \nabla \cdot \left( M \nabla \left( \frac{\partial}{\partial C} \Psi'(C) - \epsilon \sigma \nabla^2 C \right) \right) \quad \text{in } \Omega \quad (3)
\]

\[
\epsilon \mu_f \frac{\partial C}{\partial t} = -\epsilon \sigma \nabla C \cdot \mathbf{n} + \sigma \cos(\theta_e) g'(C) \quad \text{in } \Gamma \quad (4)
\]

\[
\nabla \cdot \mathbf{u} = 0 \quad \text{in } \Omega \quad (5)
\]

\[
\rho(C) \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla P + \nabla \cdot \left( \mu(C)(\nabla \mathbf{u} + \nabla^T \mathbf{u}) \right) + \phi \nabla C - \rho(C) g \cdot \mathbf{n}_z \quad \text{in } \Omega \quad (6)
\]

\( \Omega \) denotes the total volume, while \( \Gamma \) denotes the boundary. \( \phi = \frac{2F}{\delta C} \) is the chemical potential and \( M = 8 \cdot 10^{-11} m^4/(Ns) \) is a Cahn-Hilliard mobility. \( \rho(C) = \frac{1}{2} (\rho_g(1-C) + \rho_l(1+C)) + \mu(C) = \frac{1}{2} (\mu_g(1-C) + \mu_l(1+C)) \) are representing the density and the viscosity, respectively, as a function of the concentration. The subscript \( l \) denotes the liquid phase and the subscript \( g \) the gas phase. \( g = 9.81 m/s^2 \) is gravitational acceleration and \( \mathbf{n}_z \) is the normal vector in the z-direction. The primary input in the simulations are given directly from the experiment, meaning that the physical value for the density, dynamic viscosity, equilibrium contact angle and surface tension are applied. The contact line friction parameter \( \mu_f \) in eq.(4) is not known a priori and has been measured by adjusting it to achieve a match between results of simulations and experimentally measured spreading radii.

The equations have been solved with the open-source finite element toolbox femLego. The equations and boundary conditions are described within a single Maple worksheet, which automatically generates the code. The Cahn-Hilliard equation has been solved with a direct solver as described in Do-Quang and Amberg (2009). The Navier Stokes equations and continuity equation are solved with a projection scheme for variable densities Guermond and Quartapelle (2000). The pressure equations are solved with a conjugate gradient solver and the velocities with a general minimum residual method. The mesh resolution \( (\Delta x) \) is of \( \frac{\Delta x}{R} = 0.05 \), where \( R \) is the initial droplet radius, and a dynamic Courant-Friedrich-Levy \( (CFL) \) condition was used to restrict the time marching \( (dt) \) \( dt < 0.15 \cdot CFL \). A single computation took about 10 hours on a single CPU for the droplet spreading up to \( t=1.5 \text{ms} \).
1.2. Experimental protocol

A set of droplet spreading experiments have been performed on Si-wafers coated with an oxide layer, teflon and silane. The surfaces where prepared with a standard silaneization process, where the Si-surface was first immersed in a 2% solution of tri-methyl(vinyl)silane in methanol (Sigma-Aldrich) for 1 hour, rinsed, dried and finally baked at 110 deg on a hotplate. Teflon (Teflon AF 1600, DuPont, USA) 0.5% in FC-40 was spin coated (3000 rpm) on the Si-wafers, then baked at 190\(^\circ\). The oxidized Si-wafers were prepared in a plasma oven. The droplets were made of glycerin-water mixtures. Viscosity was measured with a Viscometer from Brookfield Engineering, and the measurements were found to be in good agreement with tables of water-glycerine solutions available in literature (see Dorsey (1940)). The surface tension coefficient was measured by a pendant drop technique. The values of viscosity and surface tension for the solutions used in the experiments are given in table (I).

<table>
<thead>
<tr>
<th>% glycerin</th>
<th>0%</th>
<th>50%</th>
<th>62.5%</th>
<th>72.5%</th>
<th>82.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu) ± 0.2 [mPas]</td>
<td>1</td>
<td>6.6</td>
<td>14</td>
<td>31</td>
<td>85</td>
</tr>
<tr>
<td>(\sigma) ± 0.2 [mN/m]</td>
<td>73</td>
<td>66</td>
<td>66</td>
<td>65</td>
<td>64</td>
</tr>
</tbody>
</table>

Table 1. The table shows the measured values of the dynamic viscosity (\(\mu\)) and surface tension coefficient (\(\sigma\)) for the different mixtures of water and glycerin. The upper row is showing the mass percentage of glycerin in water.

Droplets were generated at the tip of a needle placed perpendicular to the Si-wafer and connected to a syringe-micro-pump system, which made it possible to accurately control the volume rate of the droplet formation. The time scale for generating a single droplet was about 20 seconds, while the observation time for the spreading was typically less than a millisecond within the field of view. Additional experiments were conducted with higher and lower volume rates of droplet formation without any observable change in the experimental results.

The nominal droplet size was controlled by vertically adjusting the distance of the tip of the needle from the solid surface using a micrometer screw, although the actual size of the droplet was measured more accurately from the digital images. The droplet evolution was recorded with a high-speed camera (Phantom V7) at 150000 frames per second and a resolution of 128 × 48 pixels. A high magnification factor was achieved with a 250mm Nikon lens and five additional extension tubes. The resulting spatial resolution was of 7.5\(\mu\)m. Particular care was taken in choosing the aperture, to ensure that the depth of field was large enough so that the contact line was in focus throughout the
recorded droplet spreading. To maximize the contrast of the droplet edges the background was uniformly illuminated fiber optic cold light source (Schott 2500 KL).

An \textit{ad hoc} Graphical User Interface (GUI) developed in Matlab was used to process the images and extract: time of the incipience of wetting, initial droplet radius, evolution of contact angle and contact line in time. The important inputs for the automatic detection algorithms were set manually using the GUI, which also allowed us to visually evaluate the quality of the results of the detection. A Canny-edge detector was used to find the interface contours as the droplet spreads over the surface in time. The contact line was taken as the intersection point between the detected edge and the solid surface. The position of the solid surface could be identified as the symmetry line between the droplet and its reflection on the surface. The contact angle was measured by computing the tangent, as sketched in the inset of fig 2b over the first seven pixels of the interface contours neglecting the first pixel. Thus the tangent was computed from the remaining six points using the least square method, which allowed us to measure the apparent contact angle with great accuracy. Each experimental case was repeated several times (minimum of four separate realizations), and the error bars presented in fig.(2) and fig.(3) show the maximum deviation between the different realizations of the same case.