Wetting Experiments with a "Web Cam" in an Undergraduate Student Laboratory

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Surface properties are important in a wide variety of applications in chemistry, materials science, engineering, and other areas. Most industrial processes that involve liquids deal with situations where the free surface of the liquids meets a solid boundary, thus forming the so-called three-phase-contact-line *(1)*. The contact line can move along the solid surface, leading to "wetting" or "dewetting". Examples of these interactions are the spreading of films over solids, interactions of drops and bubbles with solid walls and particles (for example ink-jet printing and painting), flow of foams and emulsions, and so forth. Although there are many studies and articles that discuss the surface tension of liquids *(2–5)* and the contact angle between solids and liquids *(5, 6)*, the wetting process is rarely examined in physical chemistry courses for chemical engineering and chemistry students.

Examining a drop placed on a flat solid surface *(7)* is an excellent method to learn about surface, rheological, and fluid mechanics problems as well as to integrate the various concepts involved during the wetting process. A simple, low-cost experiment to demonstrate the wetting dynamics of liquids on solid surfaces is described. A "Web cam" is used to measure the expansion of the drop as a function of time. The advantage of the Web cam is its low cost, which permits an individual setup per student (A typical classroom has a minimum of twenty students). More sophisticated cameras are desirable but not affordable. The results obtained from students with these devices are good and, more importantly, are instructive.

Theory

At a macroscopic level, the front of a liquid drop on a solid surface has the form of a wedge confined by the liquid–solid and liquid–vapor interfaces, which intercept in the contact line with a well defined angle, θ_d (Figure 1). If we define the coordinate x in the direction of liquid movement and $h(x)$ as the height of the liquid from the solid surface, the average speed of the liquid front on the solid, v, must satisfy the Navier–Stokes equation *(8, 9)*,

$$\eta v(x,t) = \frac{1}{3}\left[h(x)\right]^2 \frac{dp}{dx} \tag{1}$$

where η is the viscosity and dp/dx the pressure gradient in the direction of movement.

Several forces contribute to the pressure gradient:

1. The capillary force (Laplace pressure): for small values of θ_d it can be approximated by the term, $-\gamma d^3h/dx^3$, where γ is the surface tension.
2. The hydrostatic force: given by the term, $\rho g dh/dx$, where ρ is the liquid density and g is the gravitational constant.
3. Long-range solid–liquid interactions: denoted by the gradient of disjoining pressure, $d\Pi(h)/dx$, where Π is the disjoining pressure. [From the macroscopic point of view, the disjoining pressure is generally negligible. Nevertheless, it is mentioned because it can be used to introduce the concept of intermolecular forces such as Van der Waals, electrostatic, and so forth *(10)*].

The capillary and hydrostatic forces are included in eq 1, which can then be solved in some cases:

1. For small drops, the hydrostatic pressure can be ignored and because the drop has a constant volume (small evaporation) *(7, 11, 12)* we obtain,

$$R(t) \approx \Omega^{3/10}\left(\frac{\gamma t}{\eta}\right)^{1/10} \tag{2}$$

where $R(t)$ is the radius of the drop wetting the solid surface and Ω is the volume of the drop.

2. For large drops, where the kinetics is dominated by the weight of the drop, the following expression is found *(13, 14)*,

$$R(t) \approx \Omega^{3/8}\left(\frac{\rho g t}{\eta}\right)^{1/8} \tag{3}$$

Experiment

The setup, shown in Figure 2, consists of a camera directly connected to a computer, where the digitalized images of the drop are stored. The camera used in the present experiment takes up to 15 pictures per second with a maximum resolution of 640 × 400 pixels.

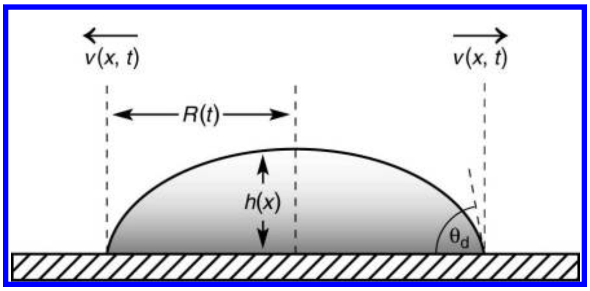

Figure 1. Drop of liquid on a solid surface showing the pertinent variables.

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A paper sheet marked in millimeters is placed underneath a glass plate (the solid). A drop of the liquid is placed on the glass plate in front of the camera.[1] The marked paper is the simplest way to measure the expansion of the liquid drop on the solid as a function of time, $R(t)$.

A Hamilton syringe allows the students to measure the volume of the drop precisely. It is interesting to follow the experimental results, with eqs 1 and 2, as a function of volume but it is not essential. Students can also use a pipet instead of a syringe if safety is a concern. A box (Plexiglas, glass, or acrylic) is used to isolate the drop and reduces contamination from dust and the evaporation.

Student Results

The density, viscosity, and surface tension of the liquid, related to the radius of the drop by eqs 2 and 3, can be measured by the students *(2, 15)*. In the first part of the experiment, students measure the expansion rate of the liquid drop as a function of time, $R(t)$. Typical data obtained by students are shown in Table 1, and the corresponding representations for eqs 2 and 3 are shown in Figures 3 and 4, respectively.

Students must notice that there are two different regimes in the dynamics of drop expansion. It is important that they associate this to the range in which the eqs 2 and 3 are valid. Equation 2 is deduced for small drops where the principal force is the surface tension. With drop expansion (wetting), the drop becomes flatter and the hydrostatic forces become less important. This regime dominates the wetting dynamics for large times (flat drops) and thus $R \sim t^{1/10}$. For sufficiently large drops, the force due to the surface tension is negligible compared with the hydrodynamics forces. Here the weight of the drop dominates the dynamics of drop expansion. Equation 3 is now valid and $R(t) \sim t^{1/8}$.

The first regime is always more clearly defined because it takes place long after the drop injection. Thus it allows the investigation of the influence of surface tension and viscosity on the dynamics of wetting. The students investigate these properties by preparing surfactant solutions (sodium dodecyl sulphate or dodecyl trimethylammonium bromide) of different concentrations. They measure the surface ten-

Table 1. Typical Results for Ethanol–Glass

Time/s	$R(t)$/mm
7.5	10.5
7.9	12.0
8.1	12.5
8.3	13.0
8.8	13.5
9.0	14.5
9.7	15.0
10.9	16.5
12.4	18.0
14.7	19.5
16.5	21.0
17.6	21.7
22.4	23.7
25.9	25.0
28.7	26.0
37.2	27.0

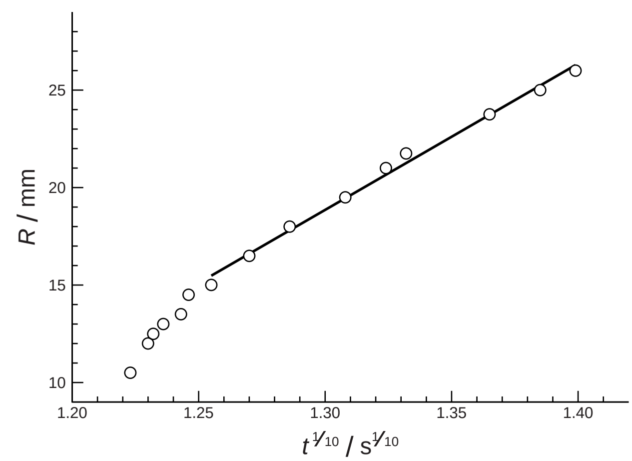

Figure 3. Results from Table 1 fitted to eq 2.

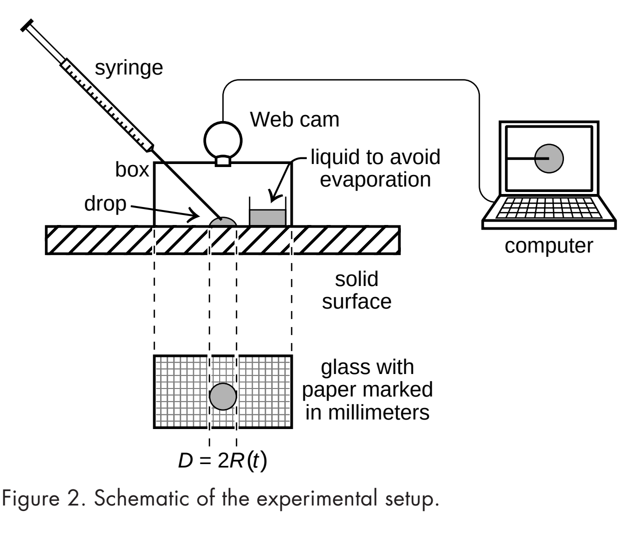

Figure 2. Schematic of the experimental setup.

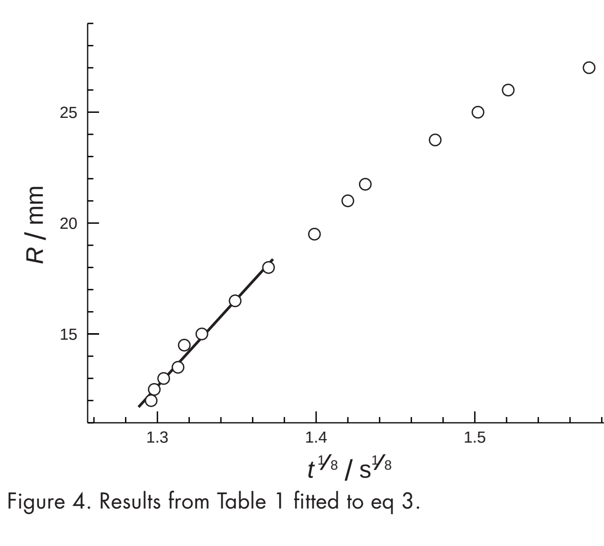

Figure 4. Results from Table 1 fitted to eq 3.

sion of each solution *(2)* and then its wetting dynamics. Because of the 1/10 exponent in eq 2, the difference between the results will be small but observable. It is important that the students realize that, when capillary forces are dominant, greater surface tension results in less wetting (contact angle) and slower rate of liquid expansion on the solid surface (given by eq 2).

To investigate the influence of viscosity, students use xanthan gum at different concentrations to increase the viscosity of surfactant solutions. The retarded rate of liquid expansion with viscosity is related to the energy dissipation inside the drop *(8, 16)*.

One student added dye to the ethanol in an attempt to increase the visibility of the liquid front. Unexpectedly he found another phenomenon—the fingering instability due to the surface tension gradient, the so-called Marangoni effect. This became an opportunity to explain another surface phenomenon to students. An image of fingering of the liquid drop is shown in Figure 5.

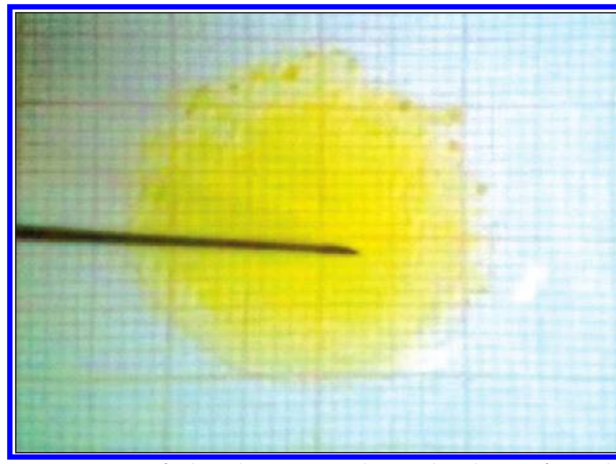

Figure 5. Drop of ethanol containing dye on the glass surface. The phenomenon of fingering is observed. (The black object is the needle delivering the liquid.)

Hazards

No significant hazards are associated with this experiment. The hazards are associated with the liquids and surfactants used in the experiment. Some surfactants are irritating to skin.

Summary

An experiment in wetting kinetics using low-cost cameras, Web cams, was presented. Because of the conceptual wealth of the subject, this experiment is an excellent way to introduce students to the concepts and complexities of applied surface problems. Students begin with an apparent theoretical problem of wetting dynamics, making use of Navier–Stokes equations where the more important surface property, the surface tension, is involved. The reason why detergents (surfactants) are used in cleaning and spreading emerges naturally—we need to wet the solid surface! Often, theoretical and experimental results lead to in-depth questions, such as (i) What is the influence of viscosity? This presents an opportunity to learn about the energy dissipation due to viscous forces in bulk. (ii) What happens if the liquid film on the solid surface is very thin? This leads to the disjoining pressure and then to the long-range forces in thin films. More complicated questions could also be raised by students. For example, instabilities and fingering were found by a student in his experiment.

In conclusion, the determination of the rate of drop expansion on a solid surface is an instructive experiment for physical chemistry laboratory. It integrates a variety of concepts and stimulates the student interest.

Note

1. All interface phenomena are sensitive to contaminants and to physical modifications of the surfaces. Thus, it is very important to carefully clean the solid surface and to avoid contamination from the surroundings.

[w]Supplemental Material

A detailed theory section and notes for the instructor are available in this issue of *JCE Online*.

Literature Cited

1. Adamson, Arthur W. *Physical Chemistry of Surfaces,* 2nd ed.; Interscience Publishers: New York, 1967.
2. Castro, M.; Ritacco, H.; Kovensky, J.; Fernandez-Cirelli, A. *J. Chem. Educ.* **2001,** *78,* 347.
3. Mungula, T.; Smith, C. A. *J. Chem. Educ.* **2001,** *78,* 343.
4. Spanoghe, P.; Cocquyt, J.; Van der Meeren, P. *J. Chem. Educ.* **2001,** *78,* 338.
5. Gesser, H. D. *J. Chem. Educ.* **2000,** *77,* 58.
6. Dionisio, M.; Sotomayor, J. *J. Chem. Educ.* **2000,** *77,* 59.
7. de Gennes, P. G. *Rev. Mod. Phys.* **1985,** *57,* 827.
8. White, Frank. *Fluid Mechanics;* Mc Graw-Hill: New York, 1983.
9. Levich, V. G. *Physicochemical Hydrodynamics;* Prentice-Hall Inc.: New York, 1962.
10. Derjaguin, B. V. *Theory of Stability of Colloids and Thin Films;* Johnston, R. K., Translator; Consultant Bureau: New York, 1989.
11. Marmur, A. *Adv. Colloid Interface Sci.* **1983,** *19,* 75.
12. Tanner, L. *J. Phys. D* **1979,** *12,* 1473.
13. Lopez, J.; Miller, C. A.; Ruckenstein, E. *J. Colloid Interface Sci.* **1976,** *56,* 460.
14. Casabat, A. M.; Cohen, Stuart, M. A. *Prog. Colloid Polym. Sci.* **1987,** *74,* 69.
15. Sorrel, C. A. *J. Chem. Educ.* **1971,** *48,* 252. (Note: Some students used a Pasteur pipet calibrated with glycerin solutions to measure the viscosity of solutions with good results).
16. Landau, L.; Lifchitz, E. *Physique Théorique, Tome 6. Mécanique des Fluides*, 2eme éd.; Librarie du Glob, éditions Mir. 1989 (French edition).