Visualization of liquid droplets on a transparent horizontal surface

Ilia N. Pavlov[1,*], Irina L. Raskovskaya[1], Bronyus S. Rinkevichyus[1], Alexander V. Tolkachev[1]

[1]V.A. Fabrikant Physics Department of National Research University "MPEI", Moscow, Russia
*corresponding author: inpavlov@bk.ru

Abstract The aim of this work is to develop the method for reconstruction of the surface shape of a large drop (liquid film) on the basis of refraction images processing and to study the possibility of determining the critical contact angle and surface tension of the liquid, depending on the characteristics of the substrate. Proposed in the work laser refractive method was used for the diagnosis the shape of droplets lying on the substrate in addition to the previously developed method of frustrated total internal reflection of a wide collimated laser beam.
In this work the methods of determining the shape of droplets having axial symmetry, and the methods to detect microinhomogeneity surface were considered. For this purpose in the simulation of the droplet shape used polynomial approximation of its contour, as well as approaches that combine general approximation drop shape with a local approximation of any of its geometrical parameters. The experimental results were obtained, processed and compared with the simulated data. A fairly good agreement between the calculated and experimental data was received.
Keywords: droplets, surface shape, contact angle, roughness, structured laser radiation, refraction

1 Introduction

Many works are devoted to droplets investigation, both theoretical and experimental. Reseacher's interest in this field explained as need to supplement basic knowledge about the processes occurring in a liquid droplets under different external conditions as well as a huge number of applications of such researches results. In particular, it is quite important issue – determination the droplets surface shape and the contact angle of droplets lying on substrate. Information about surface tension and surface conditions play an important role in many areas of science and technology, such as materials science, nanotechnology, jet-printing, optics, petroleum, metallurgy, instrumentation and others. For example, in [1] describes a device for analyzing nanoroughness and contamination on a substrate from the dynamic state of a liquid drop deposited on its surface. Authors apply it to rapid monitoring of the degree of surface cleanliness of substrates intended to form the microrelief of diffraction optical elements. In [2] discussed how the wettability and roughness of a solid impacts its hydrodynamic properties. It described that hydrophobic slippage can be dramatically affected by the presence of roughness. These effects are being exploited to induce novel hydrodynamic properties, such as giant interfacial slip, superfluidity, mixing and low hydrodynamic drag, that could not be achieved without roughness. Also many works are devoted to investigation of droplets surface shape. For example, in [3] describes a refraction system for studying evaporation of liquid drops from a solid surface. It's based on background-oriented direct-shadow method of visualization of optical inhomogeneous media. It is shown that after spreading of droplet on glass surface there is a redistribution of fluid, this corresponds to colors and shapes changing in droplet images which received by processing experimental data.
Previously authors of this paper successfully applies the method of frustrated total internal reflection (FTIR) of wide collimated laser beam to investigation of physical processes in thin boundary layer of droplet [4-6]. Using this method it is possible to measure such parameters as droplet contact area, evaporation rate, crystallization rate, time of spreading or mixing of droplets on horizontal surface, and change in refractive index of thin boundary layer in liquid a few hundred nanometers thick. To extend the range of measured parameters of droplets by optical non-contact methods, we proposed to develop a new method to determine a droplet surface shape lying on transparent horizontal substrate as well as contact angle of droplet and substrate.

2 Investigation method

The proposed method of droplet surface shape investigation based on probing of droplet by structured laser radiation (wide collimated beam or laser plane), digital registration of refraction patterns, and its subsequent computer processing to restore geometrical parameters of droplet. As a result of passing through transparent liquid droplet initial beam changes depending on the shape of droplet surface, contact angle and liquid refractive index. On the screen we can see the refractive pattern which then compared with simulated model and when they coincide it is concluded about droplets parameters. That is, the inverse problem is solving. When using a wide collimated beam as a probing radiation it can be evaluate the roughness and degree of substrate surface cleanliness. In case of laser plane using it can be determined the droplet surface shape at known refractive index of liquid and contact angle. The described method is very similar to the method of laser refractography which has long been successfully used for visualization and quantitative diagnostics processes of heat and mass transfer in liquids [7].

3 Experimental setup

The scheme of experimental setup is shown in fig. 1. Laser radiation enters the system 1 forming structured laser radiation, after that beam passes bottom-up through the liquid droplet 3 lying on horizontal transparent substrate 2. Undergoing refraction in droplet and diffraction on its edges beam shape changes. Then the beam hits the screen 4 and images obtained on it records by digital camera 5. Distance between substrate 2 and screen 4 may vary. Distance between screen 4 and camera 5 remains fixed.

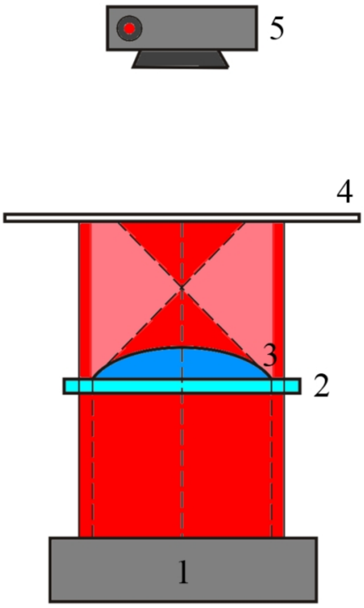


Fig 1. Experimental setup scheme: 1 – system for formation of probing radiation; 2 – transparent substrate; 3 – droplet; 4 – screen; 5 – digital camera

System 1 for formation of probing radiation can produce both wide collimated beam and laser plane. In second case on screen 4 it is observed curved laser line as a result of refraction. The characteristic parameters of its bending determines the shape of droplet surface and contact angle of wetting liquid substrate.

4 Experimental results and comparing with simulated model

In experiments various liquids were used such as distilled water, glycerol, saturated solution of salt in water, denatured and isopropyl alcohol solution in water. Also substrates with different roughness and surface cleanliness were used and few types of probing laser beams.
Typical images which obtained in experiments with using wide collimated beam is shown in fig. 2. Images a, b, c were obtained when substrate with small roughness was used on the same droplet with some time interval. Images d, e, f – the same images for more roughness substrate. It can be seen from fig. 2 that images contain characteristic concave curvatures on its perimeter with weak interference structure.

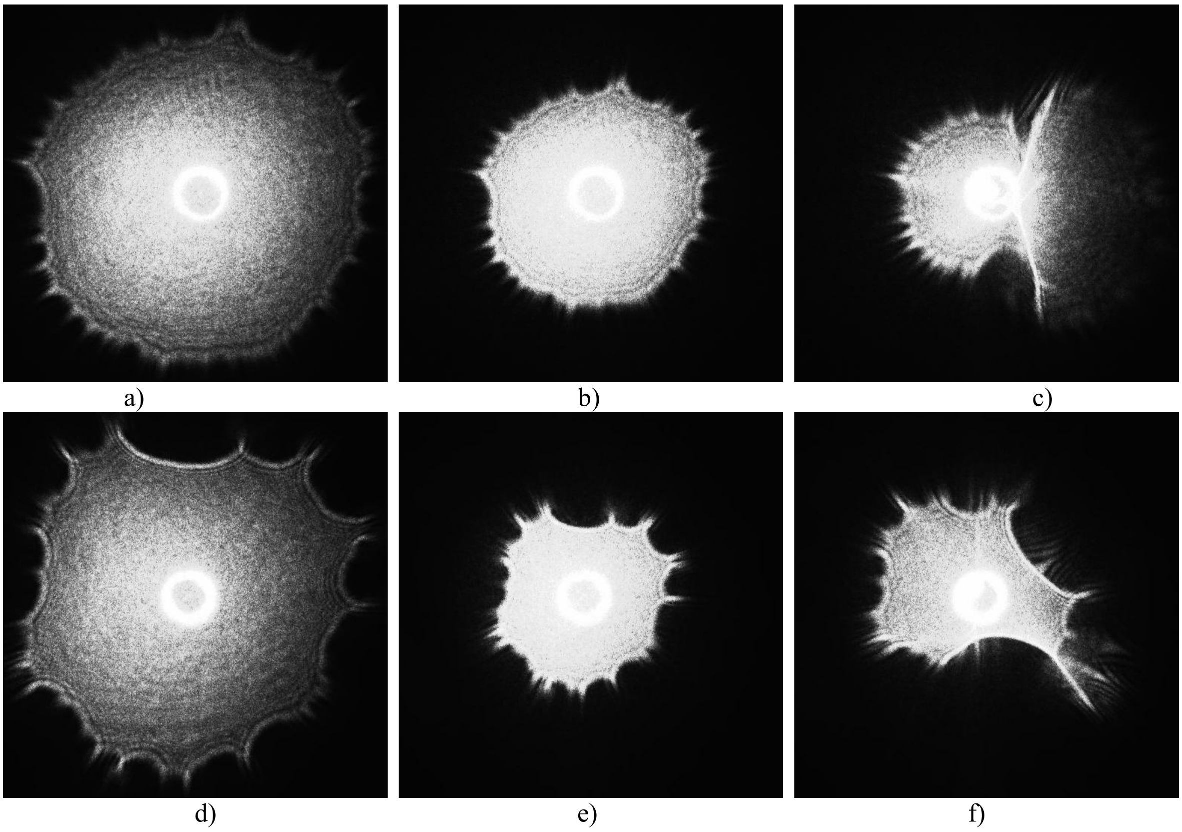


Fig. 2. Examples of experimental images which obtained using wide collimated beam as evaporation water droplet: a, b, c – droplet lies on substrate with small roughness (different moments of time); d, e, f – droplet lies on substrate with more roughness (about the same moments of time)

It was found that the number and radius of curvatures depends on the roughness of substrate – the smaller the roughness is, the more the number and the smaller the radius of curvatures. Definitely what the reason for the origin of these curvatures associated with some small irregularities of the droplet relief surface at edges, because if the beam radius became smaller than droplet radius then specified structure in images disappeared. That's why for these images simulation on the droplet model were imposed irregularities of its relief at edges with radius 1 mm and height 0.05 mm (irregularities centers spaced apart by 3 mm). Used in the simulation droplets parameters: height 1 mm, radius 6 mm, refractive index 1.3220. The simulation was performed in framework of geometrical optics and refraction displacement of geometrical optics rays were calculated by following formulas:

$$x = x_0 + zn\frac{\partial h(x_0, y_0)}{\partial x_0},$$

$$y = y_0 + zn\frac{\partial h(x_0, y_0)}{\partial y_0},$$

where x, y – coordinates of ray on screen located at distance z from substrate when ray passes through substrate at coordinate x_0, y_0; n – refractive index of liquid; h(x,y) – function describing the shape of droplet surface. Thus measurement of refractive displacement of laser beams rays allows to reconstruct shape of droplet surface if refractive index n is known.
Example obtained in the simulation image is shown in fig. 3.

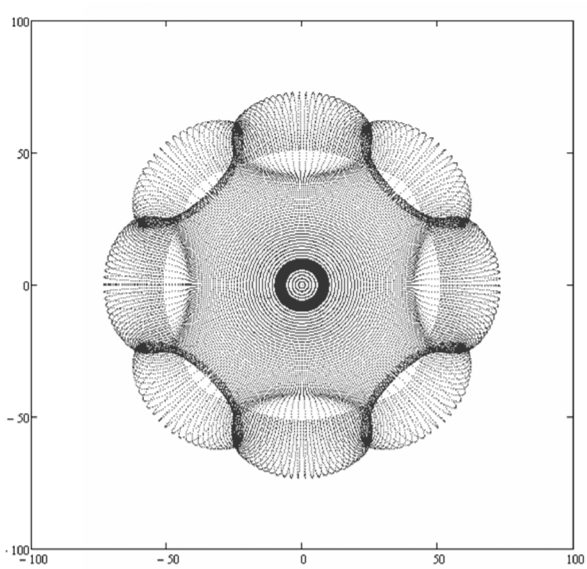
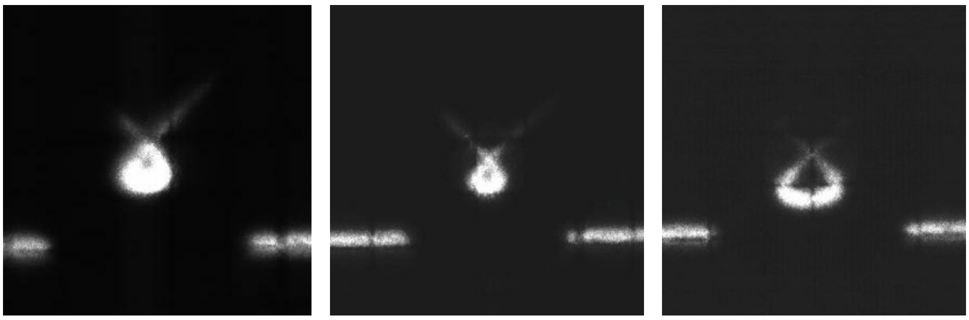


Fig 3. Example of simulated image. Distance between substrate and screen 1 m

Typical images obtained in experiments with laser plane are shown in fig. 4. In this case laser plane is not passed through central section of droplet, and about halfway between the center and the edge of droplet. Light stripe in bottom of images is undeflected part of laser plane which does not pass through droplet. In a dark spot of these images the droplet located. Accordingly, part of laser plane passing through droplet looks like a loop. Moreover, shape of this refracted part of the laser plane depends on distance between substrate and screen. For small values of this distance (up to droplet focus – about a few mm) it looks like a loop. With increasing distance its shape becomes similar to tick and has not changed, only distance between it and undeflected part of laser plane increases.



a) b) c)

Fig. 4. Experimental images obtained with using of laser plane (distance between substrate and screen 5 mm): a – distilled water droplet; b – glycerol droplet; c – saturated salt solution droplet

Using the experimental data it is possible to reconstruct the surface profile of droplet according to the above algorithm. Example of droplet surface shape obtained as a result of such processing is shown in fig. 5.

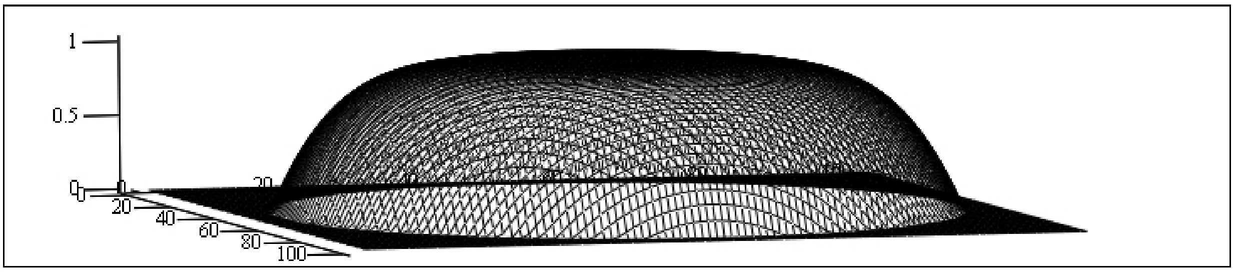


Fig. 5. Reconstructed shape of droplet surface

To verify the results received in processing of experimental data, simulation of laser plane propagation in a droplet with this reconstructed shape of surface was carried out. Fig. 6 shows comparison of experimental and simulation data for this case.

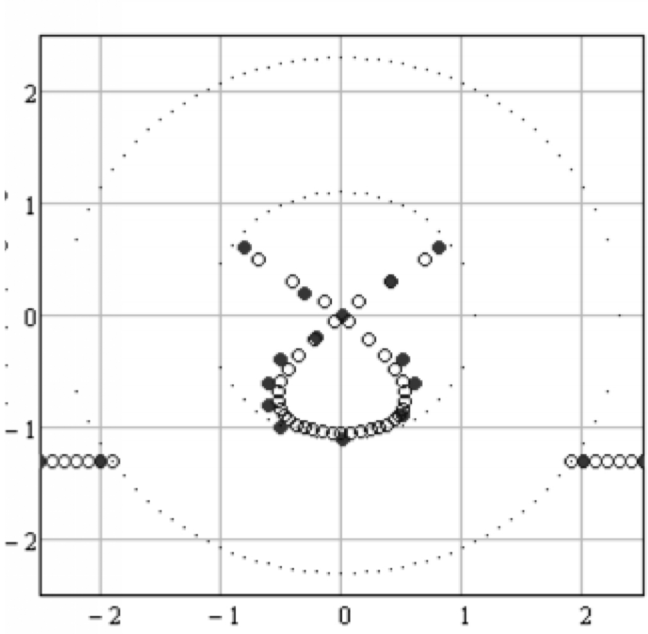


Fig. 6. Comparison of simulation results and experimental data in case of refraction of laser plane in liquid droplet: solid circles – experimental data; outline circles – simulation results

It is evident that experimental and simulation results are in good agreement. This occurs only under a particular set of droplet's model parameters. Some of them are known from experimental conditions (for example, droplet diameter and its refractive index), and some ones are selected (e.g., contact angle). Thus it is possible to estimate value of contact angle in this case by coincidence of experimental and simulation shape of refracted laser plane.

5 Conclusion

Summarizing, the report shows how to determine certain physical and geometric parameters of droplets lying on transparent horizontal substrate by processing of refraction patterns of structured laser radiation. In particular, when using wide collimated laser beam it is possible to evaluate roughness and cleanliness of substrate surface and when using laser plane it is possible to determine shape of droplet surface and contact angle of droplet wetting substrate. For this purpose the new experimental technique was developed, the experimental setup was designed and created, experimental investigations with different liquids, substrates and laser beams are made and computer simulation was carried out. The experimental and simulated results are in good agreement that allows us to conclude on applicability of this method to such problems.

Acknowledgements

This work was supported in part by the Russian Foundation for Basic Research under Grant 14-08-00948-a.

References

[1] Borodin S A, Volkov A V, Kazanskiĭ N L (2009) Device for analyzing nanoroughness and contamination on a substrate from the dynamic state of a liquid drop deposited on its surface *J. Opt. Technol.* 76, pp. 408-412. doi: 10.1364/jot.76.000408.

[2] Vinogradova O I, Belyaev A V (2011) Wetting, roughness and flow boundary conditions *J. Phys.:*

Condens. Matter, vol. 23, no. 18, 184104. doi:10.1088/0953-8984/23/18/184104.

[3] Mikhalev A S, Skornyakova N M (2011) A refraction system for studying evaporation of liquid drops from a solid surface *Measurement Techniques*, vol. 52, no. 12, pp. 1337-1341. doi: 10.1007/s11018-011-9662-7.

[4] Pavlov I N, Rinkevichyus B S, Tolkachev A V (2013) A setup for visualizing the evaporation of a liquid drop using the method of frustrated total internal reflection of a laser beam *Instruments and Experimental Techniques*, vol. 56, no. 2, pp. 242-246. doi: 10.1134/S0020441213020103.

[5] Pavlov I N, Rinkevichyus B S, Tolkachev A V (2014) Experimental visualization of physical processes in transparent liquid drops *Scientific Visualization*, vol. 6, no. 3, pp. 1-13.

[6] Pavlov I N, Tolkachev A V (2014) Visualization of crystallization of the boundary layer of a water droplet by frustrated total internal reflection of a wide collimated laser beam *Optoelectronics, Instrumentation and Data Processing*, vol. 50, no. 5, pp. 528-532. doi: 10.3103/S8756699014050136.

[7] Rinkevichyus B S, Evtikhieva O A, Raskovskaya I L (2010) Laser refractography. Springer-Verlag, NY.