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A method for contact angle measurements under flow conditions

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Abstract

In this paper at first, a review of methods for measurements of the contact angle is presented. Following the review for contact angle measurements is developed method based on Langmuir approach. The method is aimed to be use in measurements the contact angle and rivulet's width under vertical flows as well as for the cases when rivulet does not flow down vertically along a vertical plane.
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Keywords: Rivulet; Liquid film; Surface energy; Laser

1. Introduction

The wetting phenomena are present in many processes such as: heat and mass transfer under two phase flow, spray cooling, production of photographic films, washing, oiling engines, painting and many others. For a liquid flow there are two forms of wetting: the first is by the film, when a liquid covers the whole surface of solid phase. Hence, the contact angle is equal to zero. The second case refers to the rivulets, when only a part of solid surface is covered by a liquid and then the contact angle is greater than zero. Under such circumstances the value of contact angle is not only a function of macroscopic material properties of the solid phase, properties of the liquid flowing along it and properties of surrounding gas (or vapour) but also hydrodynamic phenomena and microscopic properties of solid surface, such as its roughness, as well as thickness and composition of surface-active subfilm. The contact angle is the macroscopic observed resultant of these phenomena and properties. From above discussion it appears, that the contact angle is affected by many factors, so measurement of contact angle for a liquid in flow must be very complex.

2. Experimental methods for contact angle measurements

The first experimental investigations of the contact angle for the sessile drop (under static conditions) were conducted by Langmuir and Schaefer [1] in thirties of the XXth century. They constructed the vertical protractor, where 0° corresponds the vertical line and 90° to the horizontal line, see in Fig. 1.

During the measurements the flashlight was held aside of the observer's head. If the angle of incident light

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Nomenclature

a	a measurement value
B	fixed error
d	diameter
h	height
i,j	natural numbers
l	distance
L	distance between laser and an edge of rivulet
w	rivulet width
x,y,z	coordinates

Greek symbols

α	angle
β	angle of laser rotation
γ	horizontal plane
δ	overall uncertainty
θ	contact angle
σ	standard deviation
ω	inclined plane

Subscripts

b	benchmark
l	laser beam
m	value determined as a result of measurements

at the drop was smaller than the contact angle θ then the starlight was observed. By increasing the angle of observation the condition, in which no light was seen, was achieved. Hence it meant that the observer was looking perpendicular to the tangent to the drop at the three-phase point. A pointer attached to the graduated scale was moved until it was in straight line from observer's eyes to the three-phase point. The contact angle's value was read off on the graduated scale θ_m. So the method is based on the looking for the normal to the curved surface. The precision of the method by Langmuir and Schaefer estimated to be 0.5°.

Towell and Rothfeld [2] in their research on the contact angle of rivulets used the idea of seeking for the normal to the surface. Because the rivulet flowed down the plate it was no way to measure the contact angle using a protractor, so they determined the contact angle θ by measurement the l_1 and l_2 distances, see in Fig. 2. Hence the contact angle is calculated from the formula

$$\theta = \mathrm{tg}\left(\frac{l_2}{l_1}\right). \tag{1}$$

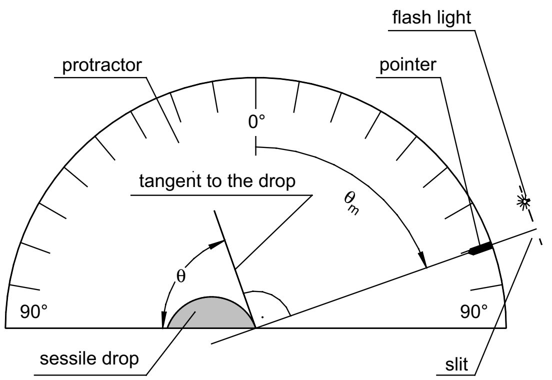

Fig. 1. Reconstruction of Langmuir method based on [1].

The method by Towell and Rothfeld [2] was modified by Semiczek-Szulc and Mikielewicz [3]. They used the laser beam, see in Fig. 3, instead of a lamp. In that case, the laser beam incidences at a selected edge of the rivulet and a fleck of light is observed on the screen after reflection. In turn, a quotient of distances l_2–l_1 equals the tangent of a double contact angle and hence, the maximum value of the contact angle must be less than 45°. The results of the experimental investigations for laminar rivulets driven by gravity are presented by Semiczek-Szulc and Mikielewicz in [3].

The Semiczek-Szulc and Mikielewicz method [3] was used for purposes of the present work in the first experiments. Because the scope of the experiments has been broadened beyond the laminar flow, the contact angles greater then 45° have needed to be measured. To increase the range of measurements a turned plate was used. Since the axis of rotation was set in a distance from the rivulet edge, the distance l_1 changes. As a measurement of the changing value l_1 is impossible (because

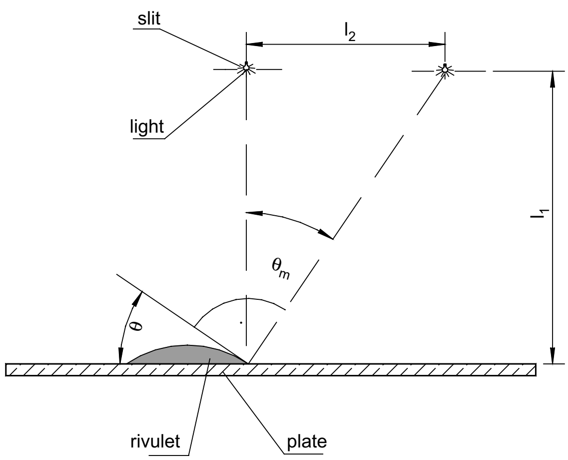

Fig. 2. Towell and Rothfeld method [2].

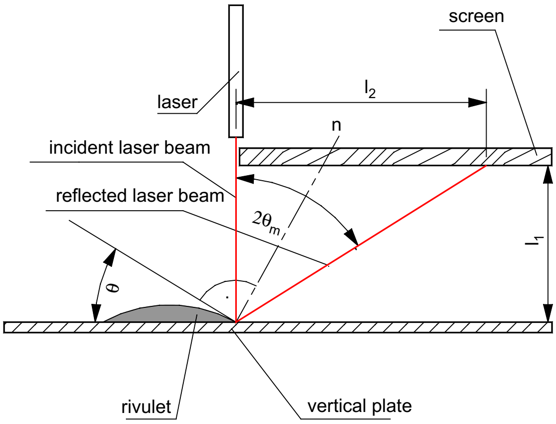

Fig. 3. Semiczek-Szulc and Mikielewicz method.

it upsets the balance of the three-phase system) the second equation must be involved. The proper equation is possible to get by using the second laser beam inclined to the first.

It was observed during the experiments beyond the laminar flow that the shape of the rivulet is not symmetric; hence the contact angles on the both edges of the rivulet have to be measured. This observation is in accordance with Marmur's theory [4], which the contact angle varies on the heterogeneous surface and depends also on its roughness [5]. This result was also confirmed experimentally by Rybnik and Trela [6]. The method and some experimental results are presented in [7]. In spite of unquestionable merits of the method as a chance of contact angle measurements even when the rivulet is flowing down along a curved line and moving across the overall flow direction and the possibility of simultaneous measurement of rivulet's width, the rotation of plate disturbs the flow down a vertical plate. As a result another way of measurement has have to be found.

As a consequence, to measure the contact angle and rivulet's width a digital photographing has been used. The method is described with particulars in work [7]. This way of measurement has a good point—the contact angels on the both edges of rivulet are measured simultaneously. The method works if the rivulet is flowing down exactly along the straight line and the both edges are seen. However, the method fails if the rivulet turns. Then only one edge is seen. In that case not only the contact angle at the second edge cannot be measured but the width of rivulet as well.

3. The present applied method

In order to conclude the above discussion one can say that the desired method should meet the following particular conditions:

1. contact angle must be measured at the both edges of rivulet even it flows down along a curved line,
2. the rivulet widens during experiment, so a measurement system must follow the edges,
3. method must be able to measure contact angles up to 90°.

All of the above criteria are satisfied by the Langmuir's method. Another merit of Langmuir's method is the direct measurement of the contact angle what makes the metrological error small. Hence it is applied the Langmuir method with some modifications, in order to measure the contact angle for the rivulets, that do not flow down vertically. At first the flashlight has been replaced with a laser beam. The laser beam is turned about vertical line "*O*", which is tangent to the rivulet's surface at the measuring point and intersects (or is tangent to) the three-phase line (see Figs. 4, 6 and 7).

The measurement procedure is as follows. The laser is turning until the reflected beam coincides with the incident beam. When the incident laser beam reaches the rivulet's surface it splits into two parts: first part reflects off the surface of the rivulet and second refracts. If the contact angle is not greater then the refracted beam after its reflection off the plate the beam goes out the rivulet and interferes with the first one. But if the contact angle is greater, the second beam undergoes the inter-reflection and goes out at the opposite edge of rivulet. The last case has been observed during the experiments. Because the rivulet's surface is curved and the laser beam possesses some diameter, the first beam reflects in many directions. As a result, the reflected beam is seen at the screen as a red triangle with an elliptical base instead of a red circle, see in Fig. 5. Such view of the reflected laser beam corresponds to the theoretical analysis. During the experiment, the reflected laser beam may be seen in the shape of a line or another no regular plane figure

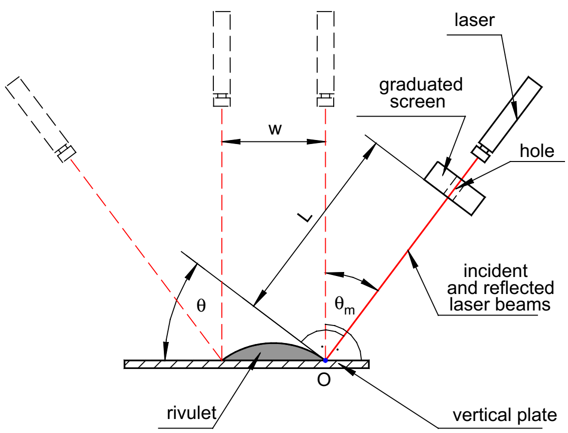

Fig. 4. The idea of the presented method.

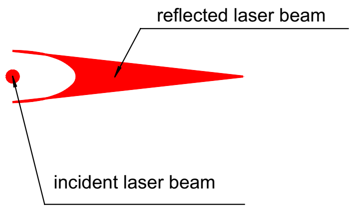

Fig. 5. The view of the reflected laser beam on the screen.

which can oscillate. However a part of the beam that was reflected from the not wetting plate on the screen is seen too. Hence the picture displayed on the screen is very complicated and its interpretation requires a lot of practical experience.

3.1. Determination of the contact angle and the rivulet's width

The situation shown in Fig. 4 is observed when the rivulet flows down vertically. However, if the edges of the rivulet are inclined, then the angle of laser rotation is the projection of the contact angle on the horizontal plane, see in Fig. 6.

In this case, the incident laser beam, reflected beam and normal to the rivulet in three-phase line are lying in the inclined plane ω, but the laser is rotated in the horizontal plane γ. Hence, the contact angle may be calculated from a formula

$$\theta = \arctan\left(\frac{\tan\beta}{\cos\alpha}\right), \tag{2}$$

where α is given by

$$\tan\alpha = -1\cdot\frac{z_1}{x_1} \tag{3}$$

with

$$x_1 = L\cos\left(\frac{\pi}{2}+\beta\right) \tag{4}$$

Because the selected coordinate system is laevo-rotary, so β angle has a negative value for the case presented in Fig. 6.

During the experiments the rivulet width w is measured. Reduction of the measurement error is achieved in the following manner. The laser is moved until its beam reaches the edge of the rivulet. Next the laser is moved to set the opposite side of the beam at the opposite side of the rivulet. In this situation, the shift of laser is greater then the rivulet's width, so the diameter of laser beam must be subtracted. Finally, if the rivulet is inclined then its width is calculated from formula

$$w = \frac{\Delta x - d_l}{\cos\alpha}, \tag{5}$$

where Δx is the laser shift in the x direction, d_l is the diameter of laser beam measured as seen on the plate.

3.2. Experimental stand

The stand developed for experiments with the contact angle as well as the rivulet width is shown in Fig. 7. The experiment laser beam (3) is adjusted initially to be set perpendicular to the plate using elements of precision rotation (23) and (18). This position corresponds to

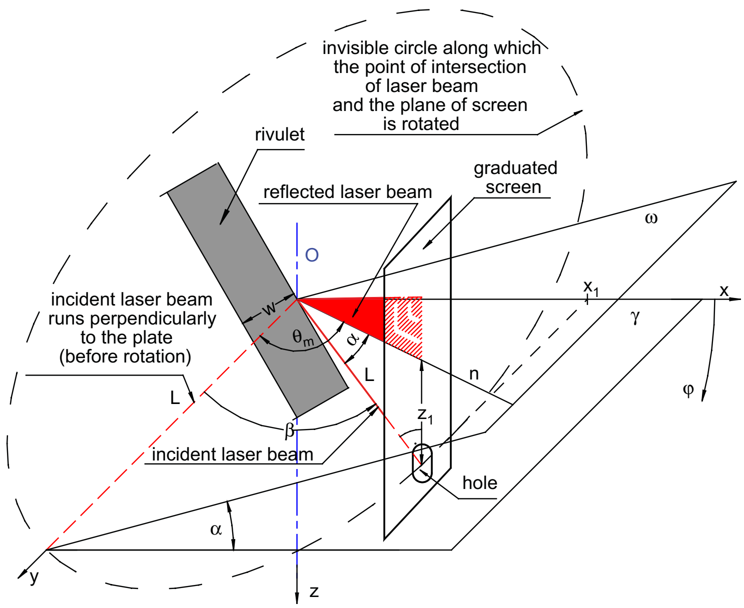

Fig. 6. The illustration of contact angle and rivulet's width measurement.

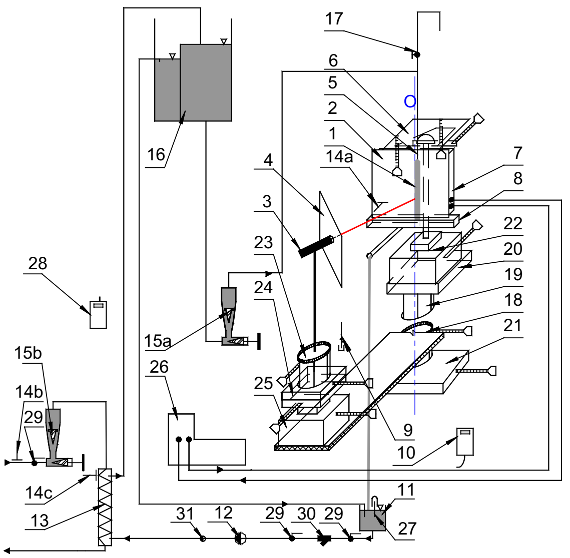

Fig. 7. The experimental stand. 1—Rivulet, 2—test plate, 3—laser, 4—graduated screen, 5—needle, 6—table regulated in three directions, 7—heated plate, 8—drainpipe, 9—relative humidity and temperature probes, 10—thermo-hygrometer, 11—gravity feed tank, 12—pump, 13—water cooler, 14—resistance thermometer probes, 15—rotameters, 16—upper tank, 17—air valve, 18, 23—elements of precise rotation, 19—rotator, 20, 21—tables of precise horizontal movement, 22, 25—elements of vertical movement, 24—table of precise movement in two horizontal directions, 27—thermometer, 28—barometer, 29—valves, 30—filter, 31—return valve.

the zero contact angle and the appropriate value, which may differs from zero, is read from the dial of element (18).

Then the edge of the laser beam is adjusted on the rivulet's edge and the proper value is read from the dial of element (21). After the rotation (as described above) the centre of laser beam is adjusted on the rivulet's edge and second value is read from the dial of element (18). The difference between them is the angle β. Next the laser is moved by element of precision moving with a dial (21) at the second edge of the rivulet and this procedure is repeated.

The element (6) is used to vertical adjustments of the plate (2). The element of precision moving in two directions (24) is used during the procedure for perpendicular adjusting the laser to the plate (2) and to such adjustment of the laser that incident beam goes through the axis of rotation "O".

The geodesic methods are used in order to precise adjustment the plate (2), elements of precision movement (20), (21) and (24).

The flow is forced by pump (12). The upper tank (16) provides the constant flow which is adjusted by rotameter (15a). Because the pumping dissipates to heat the water under flow, so the water must be cooled by a radiator (13). The right volume flow rate of the cooled water is adjusting by the rotameter (15b).

The requested temperature of plate's surface is obtained by heating the water in ultrathermostat (26) and pumping it through the double channel spiral made in the heated plate (7).

The air temperature and humidity are measured by sensors (9). So is the surface temperature by sensor (14). These sensors are connected with a gauge (10). The atmospheric pressure is measured by a barometer (28).

4. Estimation of the measurement errors

The method proposed by Moffat [8] was used to estimate of measurement errors. The estimation was carried out as follows. The Plexiglas round bar was cut off parallel to its axis and the smaller part with shape in the form of a circle segment was used as a benchmark. The value of the benchmark angle was obtained by the procedure. The diameter of the bar before cutting was measured as well as the height of shape of the strip (see w_b and h respectively in Fig. 8). It was done only once in order to prevent from a damage of the strip.

The benchmark angle θ_b was calculated then from the formula

$$\theta_b = \arccos\left(1 - \frac{2h}{d}\right). \tag{6}$$

To estimate the error of the benchmark angle and width the values h, d and w_b was measured 30 times at the end gauges of approximately the same distances as each of above values. The values of errors was obtained from following formulas:

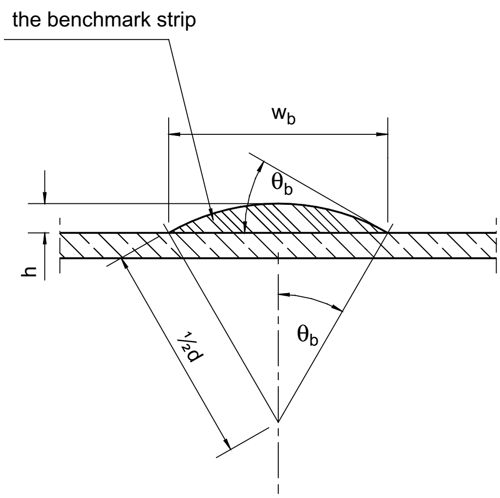

Fig. 8. The contact angle and rivulet's width benchmark.

- error in contact angle

$$\delta\theta_b = \sqrt{\left(\frac{\partial\theta_b}{\partial d}\delta d\right)^2 + \left(\frac{\partial\theta_b}{\partial h}\delta h\right)^2}, \tag{7}$$

- error in rivulet's width

$$\delta w_b = \sqrt{B_1^2 + (2\sigma_1)^2}, \tag{8}$$

where

$$\delta d = \sqrt{B_2^2 + (2\sigma_2)^2}, \quad \delta h = \sqrt{B_3^2 + (2\sigma_3)^2} \tag{9}$$

and

$$B_j = a_{bj} - \frac{\sum_{i=1}^{30} a_{i,j}}{30} \quad \text{for } j = 1, 2, \ldots, 5 \tag{10}$$

with

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{30} (a_{bj} - a_{i,j})^2}{30}} \quad \text{for } j = 1, 2, \ldots, 5. \tag{11}$$

The benchmark strip was stuck on the plate near the plate's corner. The side angle on both edges and width of the strip was measured by method used the laser beam as described above. The sets of 30 independent results of the contact angles at both edges and the rivulet width were taken. The error of single contact angle measurement and width are obtained from the formulas

- error in contact angle

$$\delta\theta = \sqrt{B_4^2 + (2\sigma_4)^2 + (\delta\theta_b)^2}, \tag{12}$$

- error in rivulet's width

$$\delta w = \sqrt{B_5^2 + (2\sigma_5)^2 + (\delta w_b)^2}. \tag{13}$$

As a result the different values of the fixed error (B) and overall uncertainty ($\delta\theta$) for the two edges of the benchmark were obtained for the contact angles. Values of fixed error are equal to 0.156° and 0.183° and overall uncertainty: 1.110° and 1.140° for the each edges. The fixed error and overall uncertainty for the rivulet's width are equal −0.00804 mm and 0.636 mm respectively.

5. Concluding remarks

The range of measurement angles is between 0° and 90°, which is greater than in the method with reflected laser beam. This is impossible when the photographic method is used. The system follows the widening rivulet. The estimated uncertainties at 95% confidence level are reasonable small. The presented method for dynamic contact angle measurement gives the possibility of measurement the contact angle even when the rivulet flows along the curved line. Hence, among above listed methods, the presented method is most designated to a dynamic contact angle measurement.

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