Automation of determining the contact angle of washing liquids wetting

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Abstract. The physicochemical activity of the washing environment is related to the value of the contact wetting angle of the solution and the body being washed and changes rather quickly. In this study a technique and software tool were developed for the rapid determination of the dependence of the contact wetting angle on the concentration of surface-active substances (surfactants) and the selection of optimal values. The technique was based on pixel-by-pixel processing of photographs of cleaning solutions droplets on various types of the studied surfaces with using color contrasting. The data were processed by statistical methods which allow determining the value of the derivative of the surface equation and finding the contact wetting angle. The dependence of the wetting angle on the surfactant concentration was studied using multiplicative power functions. The results showed a decreasing return value of the contact wetting angle from increasing surfactant concentration. It was defined that the influence of potassium monoborate (PMB) together with MS-8 is the most effective. The obtained results allow calculating and optimizing surfactants percentage defining the quality and performance of the washing process at the design stage of the technological process for various options for the combined use of surfactants.

1. Introduction
The process effectiveness of the laundering pollution from the working surfaces of transport and technological machines depends largely on the correct choice of components for washing solutions and the selection of their concentrations. Since in the process of laundering pollution there is quite large number of various types of surfaces, the selection of the concentrations of the components making solutions is an actual production task. The physicochemical activity of the washing environment is directly bound to the size of a contact angle of wetting of solution and the washed body. To accelerate the process of determining the dependence of the contact wetting angle on the concentration of surface-active substances and the choice of optimal values, the technique and software tool has been developed for its realization. The need to develop this technique arose due to the fact that the procedure for determining the contact wetting angle has a number of features [1] that must be taken into account in order to avoid reducing the accuracy of measurements. With low accuracy in determining the contact angle it is not possible to investigate its dependence on changes in the concentration of surface-active
substances, due to the fact that measurement errors of the contact wetting angle are comparable with changes in the angle caused by changes in the surfactant concentration. Analysis of the literature shows that to describe the shape of a droplet on a horizontal surface, various methods are used, ranging from analytical [2–8] based on minimizing the surface energy of the phase separation to numerical and variation detailed reviews of which are presented in work [9]. Researches [10] allowed to develop the generalized method for determining the contact wetting angles. However, taking into account such phenomena accompanying measurements as the hysteresis of the contact angle caused by the increase-decrease in droplet size the dependence of the angle on the droplet size and a number of other points [11–15] leads to the measurement taking about one or two hours. This situation is unacceptable in this case, since the properties of the washing liquid may change during a long period of time due to the fact that physical and chemical processes continue in it. Therefore the technique is developed allowing to accelerate definition of a contact angle of wetting by processing of drops photos of various washing solutions on the test surfaces.

2. Materials and methods

Drops of wetting and non-wetting liquid on a flat slightly inclined surface were the objects of the study (Figure 1).

During photographing the drops the contrasting colors were selected for the background and plane. This made it easier and more accurate to divide the pixels of the image into groups. Then the color differentiation of pixels was produced. At color test of the image along a vertical areas in which the distinction is insignificant (for different combinations of the background and the base plane, it was selected experimentally). Coordinates that determine the shape of the drop surface and the plane of the base on which it was located were found along the boundaries of these areas. Such approach made it possible to obtain a sufficiently high accuracy in determining the boundary coordinates of the interfaces between the phases, since the error varied within the number of pixels having intermediate colors corresponding to transitions from the gas phase to the liquid and from the liquid phase to the solid. Further, after scale recalculation, the coordinates of one hundred points uniformly distributed along the drop were considered. This number, in this case, was quite sufficient for obtaining statistically significant information.
Then the data with coordinates were saved as a file with the .xls extension and the name corresponding to the name of the photo being processed. The file was transferred to MS Excel, the macro for distant information processing was started.

Using the moving average method, surface shape defects were smoothed out, which arise when determining the coordinate due to the color “indistinguishability” of the pixels adjacent to the vertical, which corresponded to the phase boundary. The second-degree polynomial regression coefficients \( y(x) = ax^2 + bx + c \) were determined separately for the left and right regions, and the linear regression \( l(x) = kx + m \) was found for the base surface. The value of the derivative \( l'(x) = k \) determined the angle of inclination of the flat surface \( \gamma \). The coefficients of the regression were determined by the values of the derivatives \( y'(x) = 2ax + b \) at the extreme points of the drop. They corresponded to tangent of the inclination angle and allowed determining the magnitude of contact wetting angles \( \theta_1 \) and \( \theta_2 \) by the formulas:

\[
\theta_1 = \arctan(y'(x)) - \arctan(l'(x)), \tag{1}
\]

\[
\theta_2 = \arctan(y'(x)) - \arctan(l'(x)). \tag{2}
\]

Formulas (1) and (2) allowed to determine the magnitude of the hysteresis of the contact wetting angle. The hysteresis was associated with the difference in values in cases of leakage – dripping on the inclined surface and with the increase-decrease of the drop [10].

3. Results and discussion
With properly selected lighting as well as the colors of the background and the base surface, photographing processes and data processing did not take much time. This allowed (in order to increase statistical reliability) to calculate at least 20 values of the contact angle for each set of values of surfactant concentrations and their various combinations (table 1).

| Table 1. The dependence of the wetting angle from concentrations of SD and MBP. |
|---------------------------------------------|
| MBP, % | Labomid-203, % | MS-8, % | ML-51, % |
|       | 1.0  | 2.0  | 3.0  | 1.0  | 2.0  | 3.0  | 1.0  | 2.0  | 3.0  |
| 0.1   | 64.5 | 55.2 | 46.8 | 55.2 | 46.8 | 37.5 | 70.8 | 61.4 | 48.8 |
| 0.2   | 60.4 | 52.1 | 44.6 | 52.1 | 42.6 | 33.4 | 66.6 | 57.3 | 46.7 |
| 0.3   | 59.3 | 49.9 | 38.5 | 50.0 | 39.5 | 27.1 | 64.5 | 54.2 | 46.7 |
| 0.4   | 55.2 | 47.8 | 34.4 | 44.7 | 34.4 | 24.0 | 63.5 | 52.0 | 45.6 |
| 0.5   | 54.1 | 44.7 | 33.4 | 40.6 | 30.3 | 21.8 | 57.3 | 47.8 | 37.4 |
| 0.6   | 51.0 | 42.6 | 31.3 | 38.5 | 28.1 | 20.8 | 57.3 | 45.7 | 37.4 |

At present, such synthetic detergents as Labomid-203, MS-8, ML-51, etc. are used to increase the washing effect. They are a mixture of surfactants with electrolytes – sodium salts of carbonic, phosphoric, and cream acids. Figure 2 shows an example of photo processing result for calculating the contact wetting angle values. To describe the left and right parts of the drop form, the following equations were obtained:

\[
y(x) = -2.057x^2 - 2.768x - 0.689, \quad R^2 = 0.986, \tag{3}
\]

\[
y(x) = -1.662x^2 + 2.073x - 0.384, \quad R^2 = 0.988, \tag{4}
\]

where \( R^2 \) is coefficient of determinism. In figure 2 it can be seen that the surface is not strictly horizontal and when calculating the wetting angle using formulas (1) and (2) it is necessary to make an amendment according to the equation:

\[
y(x) = 0.002x, \quad R^2 = 0.927. \tag{5}
\]
Multiplicative power functions were used to study the relationship between $\theta$ and concentrations of $X_1$ (potassium monoborate – PMB), $X_2$ (Labomid-203), $X_3$ (MS-8) and $X_4$ (ML-51). The degrees of the variable $X_i$ showed the percentage decrease in the wetting angle caused by one percent change in the concentration of the corresponding surfactant at constant concentrations of other surfactants. Studies of the effect of synthetic detergents on the change in contact wetting angle were carried out for their combinations of two, as they were used in production:

$$\theta = 70.234X_1^{-0.168}X_2^{-0.372}, \quad R^2 = 0.91,$$

$$\theta = 64.803X_1^{-0.286}X_2^{-0.493}, \quad R^2 = 0.92,$$

$$\theta = 74.435X_1^{-0.143}X_2^{-0.335}, \quad R^2 = 0.92.$$  

Dependences (6), (7) and (8) showed that the modulus of the sum of degrees $X_i$ in all cases was less than one; this indicated the decreasing return of the size change of the contact wetting angle from the increase in the concentration of surfactants. At the same time, the effect of PMB was the most effective in the pair of MS-8, since it resulted in the greatest reduction of the wetting angle of all cases (0.286%) and, as a result, the greatest influence of all considered surfactant combinations ($-0.493-0.286 = 0.779\%$).

### 4. Conclusions

The technique and the software were developed for express definition of a contact angle of wetting by processing of droplets of various washing solutions on the test surfaces. By reducing the measurement time, the properties of the washing liquid, which were rapidly changing as a result of physical and chemical processes, were investigated. Processing of the obtained statistical material allowed to reveal the decreasing return of size of the contact wetting angle from the increase in the concentration of surfactants for the considered combinations. It means that the concentration of surfactants exceeded the values at which there is an increasing return from increase in their content in the washing solution, that is, the percentage of surfactant is excessive. The obtained results allow to calculate and optimize the percentage of surfactants at the design stage of the technological process for various options for the combined use of surfactants, thereby improving the quality and productivity of the washing process.
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